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A SOCIO-TECHNICAL FRAMEWORK TO GUIDE IMPLEMENTATION AND VALUE REALISATION OF DISTRIBUTED LEDGER TECHNOLOGIES (DLT) IN THE CONSTRUCTION SECTOR

JENNIFER J. LI

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A SOCIO-TECHNICAL FRAMEWORK TO GUIDE IMPLEMENTATION AND VALUE REALISATION OF DISTRIBUTED LEDGER TECHNOLOGIES (DLT) IN THE CONSTRUCTION SECTOR

JENNIFER J. LI

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“The pendulum had swung too far, as always, and now was swinging back, and the horror of intolerance had been loosed upon the land.”

— *Clifford D. Simak, Time is the Simplest Thing, 1961*

Abstract

Construction is highly resistant to change. Its many challenges have persisted for decades rooted in a lack of trust, reluctance to collaborate and share information. New technologies offer increased transparency, efficiency, and collaboration. Building Information Modelling (BIM), while being the most successful to advance construction to date, has not done enough to combat the challenges. The aim of this research was to investigate the potential of distributed ledger technologies (DLT) and smart contracts (SCs) to provide solutions for the sector. Through empirical investigations (systematic literature review, interviews, focus groups, survey), a framework to guide implementation and value realisation of DLT and SCs in the construction sector was proposed. A socio-technical approach was taken resulting in a framework encompassing four dimensions of technology, process, policy and society. This approach recognises DLT and SCs are not a panacea in and of themselves and should be used in conjunction with advancements across the four dimensions to de-risk any potential failure of these systems. The framework is made up of several conceptual constructs for use at meso and macro scales to support evaluation of the *as-is* to achieve a desired state and offers progressive roadmaps to reach the point of implementation.

The findings demonstrate the requirement for DLT and SCs to integrate with other systems (e.g., BIM, IoT, AI) to add value. Furthermore, technology alone is insufficient to solve the sector's problems also requiring reform of outdated practices (e.g., procurement, payments, contract management). Contributions to knowledge include: the first known socio-technical framework for systematic and progressive implementation of DLT and SCs in construction. This places equal importance on society *and* technology for the implementation of these new technological systems and will facilitate their success to unlock benefits for the sector amid the myriad challenges it faces; through this socio-technical approach, the framework encourages active involvement of stakeholders placing importance on the realisation that engaging with users of the system is central to its success; the position of an organisation (or group) looking to develop DLT- or SC-based applications at the meso scale or the position of the sector with regard to how it wants to incorporate these technologies into its existing systems and processes at the macro scale can be evaluated using the framework's progressive approach that considers every stage of developing and implementing an application; the constructs considering both meso and macro scales minimise any potential decoupling between policy and practice in terms of implementation; and the framework aims to provide a flexible set of tools to encourage the sector to create an ecosystem ready to support these applications as well as provide guidance in the development of applications.

Keywords: benefits pathways; blockchain; construction challenges; construction sector; distributed ledger technology (DLT); implementation; roadmap; smart contracts (SCs); socio-technical framework; taxonomy.

List of Publications

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Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. Approval was sought and granted by the Faculty Ethics Committee on 1st March 2018 with an amendment approved on 13th September 2019.

I declare that the Word Count of this Thesis is 84,587 words.

Name : Jennifer J. Li

Date: 28th April 2023

Contents

List of tables

List of figures

Glossary and Nomenclature

3D	Three dimensional
AEC	Architecture, engineering and construction
AECO	Architecture, engineering, construction and operation
AHU	Air handling unit
AI	Artificial intelligence
Artefact / artifact	[a collection of] documented information to assist stakeholder(s) in reaching project goals
BAMB	Buildings as material banks
BIM	Building Information Modelling
BoQ	Bill of Quantities
Blockchain	See Section 1.4
Built environment	"*the humanmade surroundings that provide the setting for human activity, ranging in scale from buildings and parks to neighborhoods, transportation systems, and entire cities*" (Kitahara *et al.*, 2018, p. 5)
CAD	Computer-aided design
CAFM	Computer-aided facilities management
Cash farming	"*a cashflow management practice adopted by main contractors that enables them to utilize the supply chain's money*" (Msawil *et al.*, 2022, p. 5)
Chaincode	The term used by Hyperledger Fabric to refer to their inherent smart contracts
Construction sector	Architecture, engineering, construction and operation (AECO) industries
COO	Construction Certification Organisation
DfMA	Design for manufacturing and assembly
Distributed ledger technology	See Section 1.4
DLT	See Distributed ledger technology
DSR	Design science research (see Section 3.2)
Ecosystem	The complex nature and implications of the business environment
EU	European Union
FIDIC	International Federation of Consulting Engineers
GDPR	The European Union's General Data Protection Regulation
GHGs	Greenhouse gasses
GIS	Geographic information systems
GPS	Global positioning services
HLF	Hyperledger Fabric
Information model	A "*set of structured and unstructured information containers*", "*Including sub-directory, information file (including model, document, table, schedule), or distinct sub-set of an information file such as a chapter or section, layer or symbol*" (ISO, 2018, p. 4)

IP	Intellectual property
IPD	Integrated Project Delivery
IPI	Integrated Project Insurance
IR&D	Innovation, research and development
IRT	Image recognition technology
IS	Information systems
JCT	Joint Contracts Tribunal, a standard form contract in use for construction projects
MEP	Mechanical, electrical and plumbing
ML	Machine learning
NEC	New Engineering Contract, a standard form contract in use for construction projects
NFTs	Non-fungible tokens
NPD	National Product Database
Oracle	A trusted source of external data/information (see Section 1.4.3)
P2P	Peer-to-peer
PBA	Project Bank Account
PoC	Proof-of-concept
PoS	Proof-of-stake
PoW	Proof-of-work
QTO	Quantity Take-off
R&D	Research and development
RFID	Radio frequency identification
Smart contracts	See Section 1.4.1
SC / SCs	Smart contract / smart contracts
Tokenisation	See Section 1.4.4
UN	United Nations
Use case	A “*use case captures a contract between the stakeholders of a system about its behaviour*” (Cockburn, 2000, p. 1)
ZKPs	Zero knowledge proofs

CHAPTER 1 | Introduction

1.1 The state of the nation in construction

The construction sector has persisted with many challenges as indicated by UK government-commissioned reports from the last 30 years (Latham, 1994; Egan, 1998; see Wolstenholme, 2009; Farmer, 2016; Hackitt, 2018). This thesis will show that many of those challenges are rooted in problems of trust, collaboration and resistance to change that are ingrained in the fabric of the sector's culture.

A report at the turn of the century looking at the construction sector worldwide cited poor industry image, employment and skills as the biggest challenges to advancement of the construction sector. Its poor image limited its ability to attract and retain talent and there was no funding to train those who did enter the sector. The result of this was poor productivity, poor health and safety, and poor quality construction products (International Labour Organization, 2001). In 2017, McKinsey reported that construction was highly regulated, highly fragmented, with ineffective contract management, insufficient skills, inadequate processes, and lacked investment into research and development (R&D) (Barbosa *et al.*, 2017). Productivity has stagnated over the last 40 years (Castagnino *et al.*, 2016) with a reported gap of $1.6 trillion per year globally (Barbosa *et al.*, 2017). Construction spending accounts for 13% of global gross domestic product (Barbosa *et al.*, 2017) and around 40% of the world's carbon emissions (Renz and Solas, 2016). Countries around the world are experiencing housing crises as a result of 200,000 people moving to urban areas every day putting pressures on existing built assets, infrastructure and services (Renz and Solas, 2016). The United Nations (UN) (2014) reported that 66% of the world's population will be living in urban areas by 2050; the global population is projected to reach nearly 10 billion by 2050 (United Nations, 2017). By 2022, rising energy prices as a result of the Russia-Ukraine war, an increasing demand for energy, and limited oil capacity resulted in some of the highest inflation rates seen in decades (Neufeld, 2022). This caused an increase in the price of building materials, especially those that are energy-intensive to produce (e.g., concrete, bricks, cement), that were already increasing due to COVID-19-related supply issues (van Sante, 2022). At a time when there are requirements to build more for less with fewer available skills and increase capital expenditure through private sector investment (Woodhead *et al.*, 2018), the construction sector finds itself in a state of economic uncertainty and lacks the funds to address the many challenges raised here.

Despite this gloomy outlook, there are many initiatives that have attempted to increase productivity and address the issues around collaboration in the construction sector. Digital technologies are often hailed as the solution to address the many challenges (European Construction Sector Observatory, 2021). To benefit from technological advancement, the sector needs to embrace collaboration and information sharing among stakeholders (Renz and Solas, 2016). However, collaboration alone has proved insufficient (Mason, 2021). Indeed, this was recognised in the Egan Report (Egan, 1998) that recommended first addressing the issues around culture and making improvements to processes before introducing technology.

Digitalisation is cited as the best facilitator of change to fill the productivity gap (Barbosa *et al.*, 2017). But it is widely agreed that the construction sector has been less effective in technological advancements in comparison with other industries that appear to have embraced new technologies such as banking, energy, logistics, automotive and mechanical engineering (Merschbrock, 2012; Cardeira, 2015; Oesterreich and Teuteberg, 2016; Barima, 2017; Mason and Escott, 2018). To date, Building Information Modelling (BIM) has been seen as the best solution for advancement and innovation of the construction industry (Succar and Kassem, 2015; Heiskanen, 2017; Mathews *et al.*, 2017). Despite this, adoption of BIM has been relatively slow (Mason and Escott, 2018), which has been attributed to its associated risks and challenges providing insurmountable barriers for many organisations (Ghaffarianhoseini *et al.*, 2017); limitations of knowledge and understanding of the concept and misconceptions of what it can achieve resulting in disappointment and abandonment of BIM (Panuwatwanich and Peansupap, 2013; Mathews *et al.*, 2017); and investments for short-term rather than long-term gains of BIM (Panuwatwanich and Peansupap, 2013). In the UK, BIM adoption rates have increased significantly over the last several years (NBS, 2021), most likely due to the government mandate that all public procurement projects use BIM from 2016 onwards.

Policy can be a driving factor in the adoption of digital technologies (European Construction Sector Observatory, 2021). This has been shown by the impact of the various BIM mandates around the world (McAuley *et al.*, 2017). Changes and improvements to regulation have been shown to facilitate shifts in construction practices in Singapore, Australia and Germany where positive impacts include more streamlined processes, reduced corruption through increased transparency, investment in R&D, standardisation of building codes, and a focus on project outcomes (Barbosa *et al.*, 2017). If advancement in technological systems is to be a viable and accepted solution in construction, the underlying systemic causes must be addressed in parallel.

1.2 Digital construction

Deloitte defines digital construction as "*utilizing digital technologies to construct more efficiently with higher quality*" (Veldhuizen *et al.*, 2019, p. 4). Another definition is "*the use and application of digital tools to improve the process of delivering and operating the built environment*" (Mills, 2016, para. 3). Between the two, there is consensus that digital technologies can enable the construction sector to do more and be better. In light of this, the construction sector requires a digital transformation to bring it in line with other sectors such as automotive and manufacturing. To understand what this means, three terms are defined – digitisation, digitalisation and digital transformation. *Digitisation* is the conversion from analogue (e.g., paper-based) to digital whereby computers can read, process and store data and information. *Digitalisation* on the other hand is described as a change to social interactions, for example, from snail mail and telephone calls to email and social media – the focus is on how people interact or how processes are changed (Bloomberg, 2018). Gartner describes digitalisation as "*the use of digital technologies to change a business model and provide new revenue and value-producing opportunities*" (Gartner, 2022a, para. 1). *Digital transformation* refers to a step change in business practices that not only incorporates digitisation and digitalisation but also a change in organisational strategy (Bloomberg, 2018).

There have been several attempts at digitalising the construction sector with the most successful being that of BIM, though, as mentioned above, it has not been without its challenges. In addition, recent attention has been focused on moving activities away from the construction site by exploring design for manufacturing and assembly (DfMA) and 3D printing (Abrishami and Martín-Durán, 2021); improving safety onsite through virtual and augmented reality technologies (Li *et al.*, 2018b); the ability to collect and process data at the construction site through cloud computing (Bello *et al.*, 2021); machine learning (ML), deep learning and artificial intelligence (AI) to automate decision-making (Baduge *et al.*, 2022); and the Internet of Things (IoT) is being explored to support many applications including onsite sensoring, closed-circuit television, drones, health and safety, inventory, materials tracking, monitoring of equipment, predictive ordering and servicing, and preventative maintenance (Pednekar and Sumant, 2020). More recently, research has turned to digital twins, a concept aiming to extend the opportunities provided by BIM to enable capture of relationships and behaviours within a built asset to support data-centric decision-making (Shahzad *et al.*, 2022). In amongst these technologies are distributed ledger technologies (DLT) and smart contracts (SCs) that are introduced in the next sections.

In an information economy where digital technologies facilitate the production and sharing of information instantly, collaboration is key to exploiting the benefits this can bring. Construction has been shown to have the highest level of information sharing with external parties when compared with the software, media and entertainment, manufacturing and financial services industries as well as being one of the most decentralised with regards to information (Box, 2014). Despite this, context from academic literature shows that information asymmetry is a problem in construction information management (Cerić, 2019) and collaboration and information sharing are two of the biggest challenges across the sector generally (McNamara, 2020; Shemov *et al.*, 2020).

Given the statistics for urbanisation in the coming years, it is imperative that any further developments and technological advances are done with the integration of people at the centre. This increase will put massive pressure on resources and the built environment. But, with proliferation of the IoT and other technologies, there is the potential to create smart cities which will be better equipped to manage such levels enabling better decision-making, better predictions and better resource use (Kolli *et al.*, 2018).

1.3 Motivations for the research: the potential of DLT and SCs for construction

The literature review in Chapter 2 goes into detail on the research into DLT and SCs for construction sector applications. This section provides a general introduction to their potential in the sector that demonstrates the motivation for this research. This is followed by an overview of how the technologies function and by looking at the related concepts of decentralised autonomous organisations (DAOs), oracles and tokenisation.

Blockchain, the first globally successful DLT, was introduced in 2008 with Satoshi Nakamoto's white paper on Bitcoin[1], the first globally successful cryptocurrency (Nakamoto, 2008). Bitcoin went live in 2009 as a verification tool for cryptocurrencies and while blockchain was initially established for use in financial transactions, it is set to disrupt many industries due to its ability to be used for any type of digital asset (Imbault *et al.*, 2017). These include but are not limited to health care (Azaria *et al.*, 2016), information sharing (Kogure *et al.*, 2017), information management, insurance, automated dispute resolution, real estate (Turk and Klinc, 2017), crowdfunding (Mason, 2017), big data analytics (Zheng *et al.*, 2018), and education (Danilin *et al.*, 2017). It is said to have the ability to provide benefit by changing the structure of societies and operations in political, humanitarian, economic and legal sectors (Mengelkamp *et al.*, 2018).

According to Hamida *et al.* (2017, para. 1), blockchain is not new, rather it is a combination of "*well-known building blocks, including peer-to-peer protocols, cryptographic primitives, distributed consensus algorithms and economic incentives mechanisms*". Bringing each of these things together will fundamentally change how commercial interactions and sharing services are offered (Sun *et al.*, 2016).

DLTs are often touted as disruptive technologies (Nofer *et al.*, 2017; Kiu *et al.*, 2020). According to Quezada *et al.* (2016, p. 23), "*a disrupted regime allows novel solutions a chance to breakthrough and change existing ways of doing things*". It could be argued that, with the level of challenges the construction sector faces, only a technology with the capability to disrupt can truly make an impact in advancing the sector's digitalisation. If BIM is the best solution for promoting collaboration, information sharing and data management, it is suggested that blockchain is a possible solution to eliminating the trust element to

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[1] Note that *Bitcoin* (uppercase B) refers to the Bitcoin Protocol, whereas *bitcoin* (lowercase b) refers the cryptocurrency token.

enable these things (Mathews *et al.*, 2017). Trust is built into the technology through its decentralised nature and its basis of consensus. Decentralised trust is a transfer from trusting people or intermediaries to trusting computational code (Atzori, 2015). Centralised trust, for the most part, is the 'as is' situation where trust is put on one person, organisation or authority based on their knowledge, expertise or power in a certain subject area. Decentralised trust is the new economic order made possible by the invention of blockchain. This represents a paradigm shift from trust to a 'trustless' society (i.e., that in which third parties become redundant) (Trevor, 2015), which ultimately has the potential to reduce costs associated with delivery of projects and risk management (Mathews *et al.*, 2017). Davidson *et al.* argue that up until 2009,

> "…*the economic institutions of capitalism consisted…of firms, markets, commons, clubs, relational contracts and governments, and that these institutions collectively furnished money, law, property rights, contracts and finance through organisations and networks of production and exchange. But since 2009, there has been an additional mechanism for groups of people to coordinate their economic activity, i.e. through the institutional mechanism of a blockchain*" (Davidson *et al.*, 2018, p. 3).

Werbach (2016) suggests trust in centralised systems is waning and that DLTs offer a compelling alternative. While it is not yet known at this stage the extent to which DLT will revolutionise markets, it offers a challenge to the status quo (Davidson *et al.*, 2018).

Blockchain can be a driver for the fourth industrial revolution, also referred to as Industry 4.0 (Mason, 2017), and could become "*as ubiquitous as the internet*" (Winfield, 2018b, para. 6). Industry 4.0 is characterised as having a "*high degree of process automation and digitisation that will increase flexibility and efficiency*" (Khaqqi *et al.*, 2018, p. 9). Blockchain has the power to revolutionise industry, the way we do commerce and drive the economy at a global scale due to its immutability, transparency and ability to re-define trust through "*enabling secure, fast, trustworthy, and transparent solutions that can be public or private*" (Underwood, 2016, p. 15). The internet changed the way society operates; it took around 20 years for that to happen. It is hoped that in the next 20 years blockchain and other DLTs can change the way applications are developed, create efficiencies and drive digital transformation in the construction sector (Mathews *et al.*, 2017).

Following the Grenfell Tower tragedy in 2017 and the collapse of Carillion in 2018, a need for better management and processes was identified to protect organisations and individuals alike (Charlton, 2018). DLT has the potential to provide better record keeping through a traceable, immutable ledger allowing investigators to immediately pinpoint where problems occurred in the supply chain. Events such as Grenfell could possibly even be prevented as people are held accountable for their actions through increased transparency.

SCs are likely to be influential in supporting Britain's achievement to becoming a digital economy as set out in Digital Built Britain (HM Government, 2015) through changing how it operates (Mason and Escott, 2018). An SC can embed funds into the contract to enable automatic payments. SC payments are likely to have most potential in areas where finances are involved and where there are time lags to "*processes, speed of settlement, risk of fraud, back-office costs or operational risks*" (Nowiński and Kozma, 2017, pp. 180–181). Payments can be made faster and simpler and can be ring-fenced ensuring funds go directly to the organisation that completed the work to protect the supply chain from insolvencies. The challenge will be in how to help the construction sector change its culture to better exploit these new technologies that have huge potential for positive change. However, given the early stage of development of the technology with regards to construction applications, there are still many aspects that need to be addressed before it can solve these problems.

1.3.1 Blockchain and SCs as disruptive technologies for construction

The many challenges discussed above, and shown in Appendix D, mean that the pace of change to which the construction sector is accustomed will not be enough to make the impact required to bring it in line with other sectors in terms of productivity and technological advancement. It is therefore argued that a disruptive approach is needed. An early study on technological disruption considered the dichotomy of *sustaining* technologies and *disruptive* technologies (Bower and Christensen, 1995). They described sustaining technologies as those that focus on continual improvement of their desired attributes, always offering something better to their existing customer base, whereas disruptive technologies offer a different set of attributes to customers that are often not as effective in the attributes valued by the customers. For this reason, Bower and Christensen (1995) explain that disruptive technologies are more likely to be seen as valuable in new markets and applications. Given construction is particularly resistant to change [ref] and see value in existing processes and practices, achieving acceptance of blockchain and smart contracts could be challenging. Technological disruption is defined by Millar *et al.* (2018, p. 1) as "*change that makes previous products, services and/or processes ineffective*". This perspective of discontinuity focuses on a displacement of old ways that are no longer effective with new ways of doing things. This is in line with Bower and Christensen (1995). A contemporary example of this in practice is how COVID-19 caused overnight disruption to day-to-day working practices where hybrid and fully remote working are now considered normal, if not preferred, to traditional office-working pre-pandemic. McKinsey (Ribeirinho *et al.*, 2020) reported that two thirds of respondents to a construction sector survey agreed that COVID-19 will accelerate the pace of change across the construction sector. This suggests that the sector may be more receptive to change now than pre-pandemic. Pinch and Bijker (1987, cited in Frizzo-Barker *et al.*, 2020) discuss technological disruption from the position of social change, whether from positive or negative perspectives. This reinforces that technology alone is insufficient to make disruptive change (Pan and Ning, 2015).

Schuelke-Leech (2018) explains a disruptive technology is one that quickly replaces existing technologies and makes processes cheaper and faster while increasing reliability and convenience, often causing upheaval in the market. An example of this is Apple's touch-screen iPod that paved to the way to the smartphone revolution (Mitzkus, 2023). From a position that trust is a social construct (Weber *et al.*, 2003; Evans and Krueger, 2009), Hunhevicz (2022) argues that trust is the disruptive element of blockchain where it is shifted away from a party (i.e., a human) to the system and cryptography.

Evolution within industries comes from improvements in collaboration between participants (Evans-Greenwood and Crough, 2022). It will be shown in this thesis that lack of collaboration is one of the key challenges in the construction sector (see Sections 2.3.42.3.4 and 2.4). Improvements in collaboration will come from increased trust between parties and this can be facilitated by blockchain alongside its other disruptive elements such as providing "a network of value" (Maciel, 2020, p. 402) and offering "data ownership and control" (Maciel, 2020, p. 403). Indeed, it has already been shown to disrupt well-established economic systems (Hunhevicz, 2022). In a sector that has struggled for many years with issues of productivity, labour levels, rising costs and delays, Sipilä (2019) – a director in strategy at KPMG, believes construction is ready for disruption.

Despite the view of blockchain and SCs as disruptive technologies for construction, it is too early in the trajectory of these technologies to say whether they will in fact disrupt the sector. Much of the research conducted on DLT and SCs (see Chapter 2) present applications that propose automation of processes rather than offering new ways of doing things. Some applications such as decentralised autonomous organisations (DAOs) (see below in Section 1.4.2) do offer something different to the status quo and therefore there is potential for these technologies to disrupt. The extent of which will be seen in the coming years.

1.4 Blockchain architecture

The term 'blockchain' has become synonymous with the term 'distributed ledger technology' where the two seem to be interchangeable. However, it should be noted that while blockchain is a type of DLT, the term blockchain does not encompass DLT in its entirety.

A blockchain can either be public or private (Mathews *et al.*, 2017). A public network can be accessed by anyone; in a private network, people need to be granted access to participate (Hamida *et al.*, 2017). Blockchain is a working database containing a ledger of transactions that has been verified and validated through a peer-to-peer (P2P) network of computers, known as nodes (Karafiloski and Mishev, 2017). Unlike a bank, where all transactions are processed and stored by one organisation (i.e., centralised), transactions on DLT are processed and stored across many different computers (i.e., decentralised). Blockchain has several characteristics: it operates across a decentralised P2P network; it is immutable once chained; it has an algorithm ensuring all nodes have the same version of the blockchain; it is a public ledger of transactions; it uses a proof-of-work (PoW) mechanism to validate transactions; and, in the case of Bitcoin, there is a mathematical and deterministic currency issuance mechanism (Kypriotaki *et al.*, 2015; Turk and Klinc, 2017). In addition, blockchain supports the application of SCs, described in detail later in this section, but in brief are pieces of code that automate activation of specific mechanisms upon pre-defined conditions being met.

Bitcoin was the first globally successful decentralised cryptocurrency with the first bitcoin transaction taking place in January 2009. Each user has a unique public key made up of a 27 to 32 alphanumeric string of characters that makes it almost impossible to identify the individual it belongs to so while it is not anonymous it is pseudonymous (Swan, 2015). The underlying technology that allows Bitcoin to exist is the blockchain. The blockchain allows individuals to transact with other individuals or organisations without the need for an intermediary. It is not controlled or managed by one single entity and is accessible by anyone on the network (Underwood, 2016). By design, it is secure and uses cryptography and a distributed consensus mechanism to offer ‘anonymity’, persistence, auditability, resilience and fault-tolerance (Hamida *et al.*, 2017). Bitcoin is generated and given as a reward to those nodes for processing transactions and adding blocks to the blockchain (Swan, 2015). The reward is given to the node that solves a complex mathematical equation first and *mines* (appends) the completed block to the existing chain of blocks – the blockchain (Dorri *et al.*, 2017).

Figure 1.1 shows how a transaction is processed on a blockchain. Upon creation of a new transaction, it is broadcast to the network for validation and verification. Validation of a transaction is to “*run predefined checks about the structure and the actions in the*

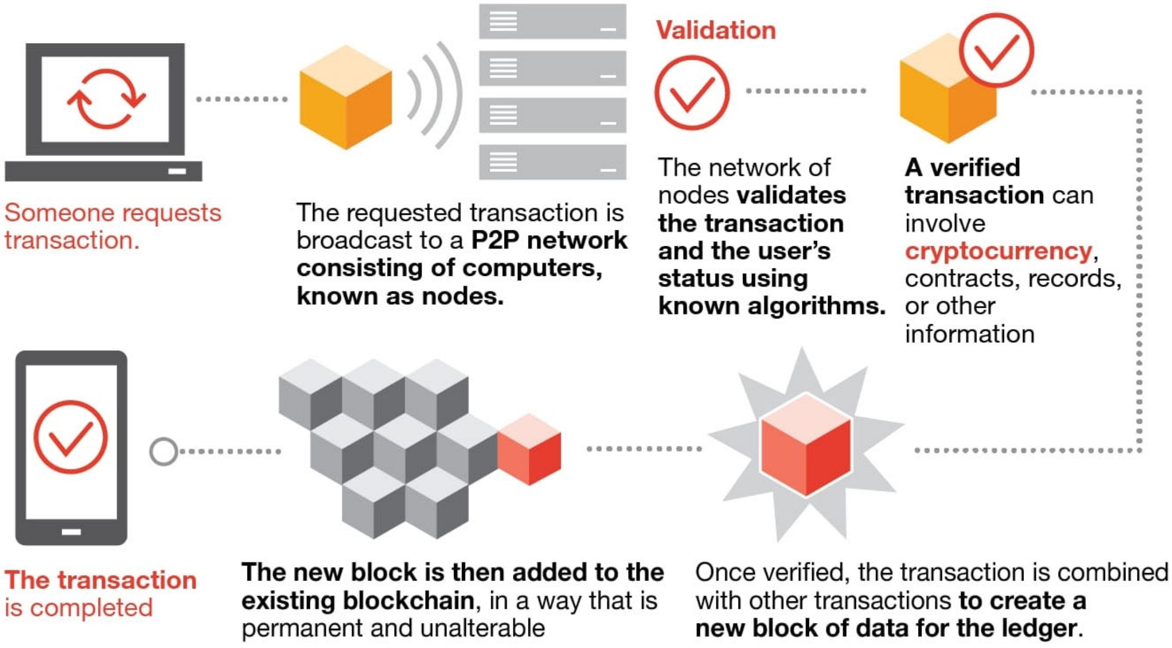

Figure 1.1: How a blockchain works (PwC, 2022)

transaction" (Karafiloski and Mishev, 2017, p. 763); this is done by each node on the network. If a consensus is reached (i.e., agreement from more than 50% of nodes) that the transactions in the block are valid, the block is appended to the blockchain and each node's copy of the blockchain is updated accordingly (Biswas and Muthukkumarasamy, 2016). It will remain there forever and is considered immutable. Requirement of more than 50% consensus ensures malicious attacks are difficult to achieve. They require significant computational power and simultaneous access to each node to be successful (Barima, 2017). In a public blockchain, it is not impossible to change an existing block, but it is very difficult because all blocks thereafter must also be changed as each block contains a hash of the block before it and this will be visible to the entire network (Tapscott and Tapscott, 2016). Moreover, this must be done in the time it takes to mine one block to the blockchain by the network (Yermack, 2017). As all nodes have a complete copy of the ledger, it is easy to see if any block has been tampered with by simple comparison. All blocks are linked all the way back to the genesis block ensuring the blockchain's integrity (Nofer *et al.*, 2017). In a private blockchain, however, it is simply a case that all nodes with access to that blockchain agree by consensus (typically off-line) on a change and then modify the data. Data privacy is stronger in a private blockchain due to access rights (Hamida *et al.*, 2017).

The mining process is designed to become more complex over time. Figure 1.2 illustrates the chaining of blocks that make up the blockchain. The *genesis block* is the first block that is created. *TX 1 … TX n* represent the transactions within the block, the number of which is dependent on the size of the transactions as each block is limited to 1MB in size. *Timestamp* denotes the exact time that the block was mined to the chain (Nofer *et al.*, 2017). Each block of transactions is assigned a *nonce* – a random number generated to indicate verification of the *hash*. A hash is a unique value that is taken from the previous block (its parent) and the element that helps to prevent fraud given that any changes to a block would result in an immediate change in the proceeding block (Nofer *et al.*, 2017; Zheng *et al.*, 2018). To generate a hash, the SHA-256 algorithm is run on the block that turns the information of the block into a sequence of 256 bits (32 bytes), the hash. The SHA-256 algorithm is a one-way cryptographic function that cannot be decrypted back to the original text. Through complex maths, the *nonce* can be changed to generate different hashes until a hash with a required number of leading zero bits is found; the required number is changeable to make the maths more or less difficult. In the Bitcoin blockchain, the first miner who generates the hash with the correct number of leading zero bits wins the right to mine

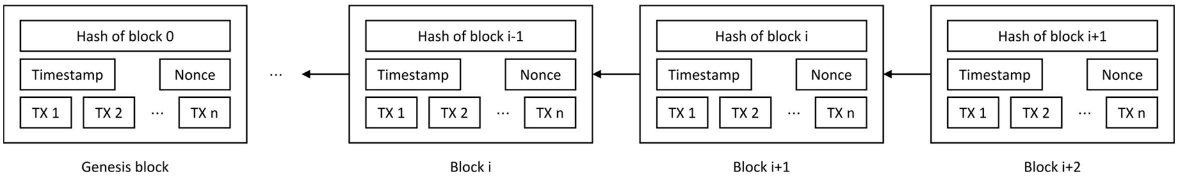

Figure 1.2: Example of a blockchain (Nofer et al., 2017, p. 184)

the block to the blockchain and is rewarded in bitcoin for their efforts. This is known as ‘proof-of-work’. The maximum number of Bitcoins that will ever be generated is 21 million. At Bitcoin’s inception, 50 bitcoins were awarded to the miner who mined a block to the Blockchain. After reaching 210,000 blocks, which took around 4 years, the amount awarded halved to 25 bitcoins per block and so on following each set of 210,000 blocks. This halving process will continue until the reward reaches zero. Once 21 million bitcoins have been generated, rewards to miners will only be paid with transaction fees, no more bitcoins will be generated (Cocco and Marchesi, 2016). This scarcity of bitcoin is what generates its value.

Occasionally, more than one miner’s block is chosen to be mined creating forks on the blockchain. The get around this, miners should work to the longest branch, so, although a block has been mined to the blockchain, it may not remain on the main chain. Software updates can also change how transactions are handled depending on the version a miner is running, which can also create forks. In the case of a public blockchain, this can be more prevalent given the potentially huge number of participants on the network. On a private blockchain, the small number of participants can agree between themselves which branch should be the main chain (Hamida *et al.*, 2017).

To contextualise the processing power of the Bitcoin blockchain it has the capacity to process one block every 10 minutes. In contrast, credit card companies process on average 2,000 transactions per second and have the power to process upwards of 10,000 transactions per second during peak demand (Vukolić, 2016). Scalability of DLT is a challenge given the wide array of applications for which the technology is being considered and the level of transactions these applications process. At some point, the blockchain ledger will be too large for the average user to store (Ammous, 2016).

1.4.1 Smart contracts

The concept of SCs was first conceived by Nick Szabo in 1994 just as the world’s first internet browser, Netscape, was released (Tapscott and Tapscott, 2016). It is defined as:

> *“…a computerized transaction protocol that executes the terms of a contract. The general objectives of smart contract design are to satisfy common contractual conditions (such as payment terms, liens, confidentiality, and even enforcement), minimize exceptions both malicious and accidental, and minimize the need for trusted intermediaries. Related economic goals include lowering fraud loss, arbitration and enforcement costs, and other transaction costs”* (Szabo, 1994).

In simple terms, if/then/else commands make up SCs but once a contract becomes complex such as those in construction projects then the SC code itself becomes complex. Due to the resources required to set up an SC (i.e., time and cost), Boucher *et al.* (2017) suggest they are best used for repetitive agreements and not one-off complex agreements, particularly where the contract is susceptible to change throughout the life of the contract. Once an SC has been coded and embedded into the blockchain, it becomes permanent, unchangeable and irrevocable (Mason, 2017). In the instances of simple, repetitive agreements, this can be considered a good thing. The only way in which it can be adaptable to change is if it is written into the code. In the event mistakes or vulnerabilities are written into the code, due to lack of legal knowledge of the coder or simply human error, once the contract is uploaded to the blockchain it becomes unchangeable and will be executed exactly as it is coded (Boucher *et al.*, 2017). However, SCs can be cancelled and replaced with new ones once they have been uploaded to the blockchain (Cooper, 2018) demonstrating some flexibility, but this would require consensus to be actioned.

There are several advantages of SCs. They can cut "*across gamesmanship by contracting parties to ensure that obligations are met*" (Brydon Wang, 2018, p. 5) by adding certainty to delivery of contracts. Ambiguity is removed as they execute based on pre-agreed conditions between the parties (Nguyen *et al.*, 2019). They are difficult to revoke once enacted requiring majority agreement from the network to do so (Brydon Wang, 2018). SCs can offer transparent, auditable transactions; reduce inefficiencies; save time, costs and resources; and, coupled with ML, they could substantially improve contract drafting (Mason, 2021). Where SCs run on a distributed ledger, they are provided with the same properties as the ledger (e.g., immutability, security and censorship resistance) (Kinnaird and Geipel, 2018). They remove the need for intermediaries who often charge transaction fees. SCs are not restricted in the same way third party programmes are that are limited to the functions of the server on which they run; SCs are restricted only by the skill of the coder and the technologies with which they integrate (e.g., the IoT, BIM software). They warrant more trust than centralised third parties due to their agreement from a distributed network of participants.

There are limitations of SCs that may be resolved with technological developments in the future. They are only as good the code they are given; human error could be an issue (Cooper, 2018), particularly in the early stages of developing SCs based on limited experience of the coder. Robust testing and verification are required to mitigate this. The question of whether SCs represent legally binding contracts has been raised. The UK Jurisdiction Taskforce held a consultation on cryptoassets and SCs issuing a statement in November 2019 stating:

> "*There is a contract in English law when two or more parties have reached an agreement, intend to create a legal relationship by doing so, and have each given something of benefit. A smart contract is capable of satisfying those requirements just as well as a more traditional or natural language contract, and a smart contract is therefore capable of having contractual force. Whether the requirements are in fact met in any given case will depend on the parties' words and conduct, just as it*

does with any other contract" (UK Jurisdiction Taskforce, 2019, p. 8).

SCs, therefore, have the ability to represent legally binding contracts but only if they meet the requirements of such in the jurisdiction in which they intend to be used.

Another potential issue of SC is longevity. Coding SCs today that will be executed in many years (e.g., wills or futures) is a challenge, particularly when external information sources may no longer exist (Mason, 2017). The human-readable contract and associated obligations need to be codified and subsequently verified to ensure that the machine-readable representation of the SC conforms to the specified behaviour. This complexity of codifying SCs could limit mainstream adoption and acceptance of this technology (Frantz and Nowostawski, 2016). Finally, the volatility of cryptocurrencies with respect to value and exchange rates against fiat currencies means their day-to-day use is not yet accepted (Li and Kassem, 2021a). Questions remain in terms of whether cryptocurrencies need to stabilise before they can be effectively utilised in SCs or whether payments need to remain with centralised institutions and payments triggered by the SC. The solutions will be dependent upon how cryptocurrencies and the use cases for SCs evolve in the coming years as the technologies advance.

Ethereum is the most popular and most widely used SC platform (Atzei *et al.*, 2017), proposed by Vitalik Buterin in 2013 and released in 2015. Ethereum comes with its own programming language (Solidity) and cryptocurrency, ether (ETH). Ethereum ran a PoW consensus mechanism until September 2022 when it switched to a proof-of-stake (PoS) mechanism, a much more environmentally friendly consensus protocol to the extent it now consumes 99.9% less energy equated to a megaton of carbon each week (Kessler, 2022).

1.4.2 Decentralised autonomous organisations (DAOs)

A decentralised autonomous organisation (DAO), a collection of SCs running on a blockchain that make up a completely autonomous entity (Hunhevicz and Hall, 2020b), offers the opportunity create new business models for the construction sector (Li *et al.*, 2019a). Governance rules are established and maintained by SCs and through consensus mechanisms meaning DAOs can self-operate and self-evolve (Hunhevicz *et al.*, 2021). Decision making in a DAO is established based on the number of tokens held by a participant (van Rijmenam and Schweitzer, 2018) as well as a reputation rating that can be staked against a vote (Dounas and Lombardi, 2019). DAOs offer disintermediation (Srećković and Windsperger, 2019), reduce running costs and transfer risk (Li *et al.*, 2020).

1.4.3 Oracles

SCs can be deterministic and non-deterministic. The former utilise data already present within the DLT in which it operates; the latter require data from external sources to execute (Fauziah *et al.*, 2020). The external source of these data is referred to as an 'oracle' – third party data of an event external to the system (Wilson *et al.*, 2020) that could be in the form of website data, a radio frequency identification (RFID) tag etc. An oracle can be called upon by the blockchain to confirm an external state during validation of a transaction (Xu *et al.*, 2016).

1.4.4 Tokenisation

Tokenisation refers to cryptocurrencies or cryptoassets that represent value in a DLT (Collet *et al.*, 2019). Examples include bitcoin or ether, native tokens of the Bitcoin and Ethereum blockchains respectively. The value offered by tokens creates incentivisation in social applications with the dual use of deterring malicious actors and encouraging use in a blockchain system (Mathews *et al.*, 2017; Hunhevicz and Hall, 2020b). Tokens, owned by participants of the network, are secured in a digital wallet and can be exchanged for fiat currency via cryptocurrency exchanges.

1.5 Scope of research

The Oxford English Dictionary defines the built environment as "*man-made structures, features, and facilities viewed collectively as an environment in which people live and work*" (Oxford Dictionaries, 2013). Another description offers that it "*is concerned with buildings, their special environment and the people who inhabit that environment*" (Temple, 2004, p. 11). The construction sector, a part of the built environment that focuses on built assets, is the scope of this study. This includes the architecture, engineering, construction and operation industries (AECO) across the lifecycle of built assets from concept, planning and design through to construction, handover, operation and maintenance, and end-of-life. Excluded from this study is real estate, land administration, energy, public administration, smart homes, smart cities, transport, government services, and non-construction specific supply chain research; the exceptions being where there is overlap with the AECO industries of the built asset lifecycle.

In terms of the technologies considered for this research, the primary focus is on DLT and SCs. However, it also considers the interaction of these technologies with other technological systems that support digital construction and digital innovation within the sector. While this thesis does not intend to highlight the areas in which DLT and SCs will or will not be suitable, it does intend to propose a set of tools in the form of a framework that will support the construction sector in identifying those use cases.

This thesis is not a study on the integration of BIM and blockchain, however, it recognises that BIM is prevalent across all areas of the sector given its evolution over time from 3D modelling to a methodology for managing information across the lifecycle of built assets. Therefore, BIM provided an underlying theme and starting point for this study.

1.6 Aim, objectives, research questions

The aim of this research is to propose a socio-technical framework to guide the construction sector in reaching a state of readiness to adopt DLT and SC applications. It achieves this by developing conceptual constructs (Taxonomy of Construction Challenges; Taxonomy of DLT and SC Applications for Construction; DLT Four-Dimensional Model; DLT Actors Model; DLT Benefits Pathways; DLT Macro Roadmap for Ecosystem Readiness; and DLT Meso Roadmap for Application Development and Implementation) through collection and analysis of empirical investigations.

To achieve this aim, three research questions and eight associated objectives are addressed in this thesis.

Research question 1 (RQ1): What are the persistent challenges discussed in the context of DLT and SCs faced by the construction sector in light of the significant effort toward digitalisation over the last decade?

- **Objective 1.1**: Identify the specific construction sector challenges that remain unresolved through a systematic literature review and interviews with industry experts.
- **Objective 1.2**: Create a taxonomy of construction sector challenges in the context of DLT and SCs to relate them to the different application categories of DLT and SCs for construction found within the literature.

Research question 2 (RQ2): What role can DLT and SCs play alongside other technological innovations such as BIM and IoT in addressing the challenges faced by the construction industry?

- **Objective 2.1**: Identify the construction sector applications to which DLT and SCs can be applied as proposed in literature and through consultation with academia and industry.
- **Objective 2.2**: Create a taxonomy of DLT and SC applications for the construction sector aligned with the construction sector challenges identified in RQ1.
- **Objective 2.3**: Establish which construction challenges have the potential to be addressed in part or in full by integration of DLT and SCs into the existing applications classified by the application taxonomy.

Research question 3 (RQ3): How can a socio-technical approach support the construction sector in improving its readiness for the adoption of DLT and SCs by providing a systematic approach that guides the sector in identifying the steps required to add value and realise the benefits from integrating DLT and SCs into existing applications?

- **Objective 3.1**: Identify dimensions of socio-technical systems theory to support analysis of the current state (without DLT and SCs) against the desired state (with DLT and SCs) of construction sector applications and identify the actor groups to be involved and/or affected by such applications along with their roles and responsibilities.

- **Objective 3.2**: Identify the requirements for readiness of the construction sector to adopt DLT and SCs in existing applications through consultation with academic and industry practitioners.
- **Objective 3.3**: Propose the steps required for achieving readiness of the construction sector to support development and implementation of DLT and SCs for new and existing applications.

1.7 Thesis outline

The outline of this thesis is shown graphically in Figure 1.3. It shows the structure of the thesis outline by chapter, indicates where each element of the framework proposed is discussed and shows where contributions of the elicitation techniques were made.

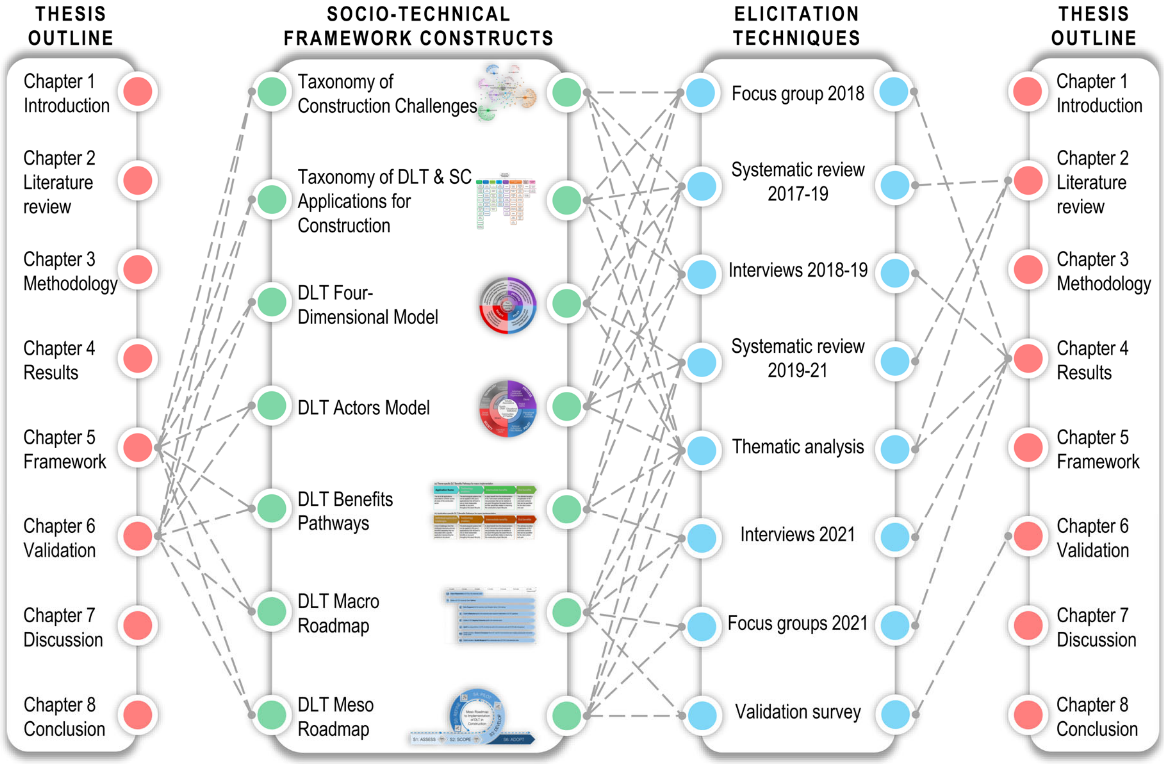

Figure 1.3: Outline of thesis

This first chapter, Introduction, set out the rationale for conducting the research, delineated the scope, provided background and established the research questions that drove the study. Chapter 2 provides the literature review that took place in two waves throughout the study. It offers justification for the socio-technical approach taken in this study and describes the many challenges of the construction sector along with the emerging applications of DLT and SCs that might solve them. Chapter 3 sets out the methodology adopted for the study, giving justification for the methodological choices made and an overview of the elicitation techniques adopted for empirical investigations. In Chapter 4, the results of the empirical investigations are presented and analysed. Chapter 5 describes the framework and its individual components that were developed from the results of the empirical investigations.

Chapter 6 discusses validation of the framework before Chapter 7 discusses the study and establishes the contributions it makes. Finally, Chapter 8 concludes the thesis by answering the research questions and provides recommendations for the sector, highlights limitations of the study and offers directions for future research.

CHAPTER 2 | Literature Review

2.1 Introduction

This chapter aims to fulfil several objectives related to the research questions set out for this study as shown in Table 2.1.

Table 2.1: Research questions and associated objectives fulfilled by the literature review

Research questions	Objectives
RQ1: What are the persistent challenges discussed in the context of DLT and SCs faced by the construction sector in light of the significant effort toward digitalisation over the last decade?	**Objective 1.1**: Identify the specific construction sector challenges that remain unresolved through a systematic literature review and interviews with industry experts.
RQ2: What role can DLT and SCs play alongside other technological innovations such as BIM and IoT in addressing the challenges faced by the construction industry?	**Objective 2.1**: Identify the construction sector applications to which DLT and SCs can be applied as proposed in literature and through consultation with academia and industry. **Objective 2.3**: Establish which construction challenges have the potential to be addressed in part or in full by integration of DLT and SCs into the existing applications classified by the application taxonomy.
RQ3: How can a socio-technical approach support the construction sector in improving its readiness for the adoption of DLT and SCs by providing a systematic approach that guides the sector in identifying the steps required to add value and realise the benefits from integrating DLT and SCs into existing applications?	**Objective 3.1**: Identify dimensions of socio-technical systems theory to support analysis of the current state (without DLT and SCs) against the desired state (with DLT and SCs) of construction sector applications and identify the actor groups to be involved and/or affected by such applications along with their roles and responsibilities.

First, the section discusses the socio-technical systems theory that underpinned this research after first presenting the rationale for doing so. It then presents findings from two systematic literature reviews (SLRs), which includes results of thematic analysis applied to the data collected through the SLRs along with characterisation of the body of literature reviewed (e.g., bibliographic data). The SLRs performed for this study served several purposes; (1) to establish the state-of-the-art of DLT and SCs in the context of the construction sector; (2) to identify the challenges facing the construction sector; and (3) to identify the proposed construction sector applications of DLT and SCs and match them with the challenges. In addition, a summary of the literature published after the second SLR in 2021 is provided to demonstrate how DLT and SC applications are being investigated further.

The initial SLR conducted in 2017-2019 aimed to understand the current level of DLT and SCs in the built environment generally. The results guided development of the research questions presented in Chapter 1 (Section 1.6) that informed this study. The subsequent SLR between 2019 to 2021 was specific to the construction sector given the substantially increased body of literature available on the topic. This Chapter presents the combined results of the two waves of SLR to present a cohesive picture of the state-of-the-art in this field of research. In addition, the literature published following the second SLR up to and including September 2022 was filtered for journal publications only and is summarised at the end of this chapter to provide a complete and up-to-date picture of the research. Data collected through the two systematic reviews were used to inform development of each of the framework construct presented in Chapter 5; more details are provided in Chapter 5 alongside each construct.

Some of the information presented in this chapter was published previously in two journal articles (Li *et al.*, 2019a; Li and Kassem, 2021b), from which some passages have been taken verbatim.

2.2 A socio-technical systems approach

The need to take a socio-technical approach to this study was identified during the early stages of empirical investigation, specifically, during a focus group that took place in January 2018. DLT was identified as socio-technical system and informed development of the research questions and associated objectives that directed the study. The results of the focus group can be seen in Section 4.2.

Socio, referring to people and/or society, and technical, referring to technology and/or machinery make up the term socio-technical (Walker *et al.*, 2008). Originally developed by Trist and Bamforth (1951) with heavy industry in mind, the application of socio-technical systems theory has since broadened to include most other industries (Davis *et al.*, 2014). Further conceived at the Tavistock Institute of Human Relations (Emery *et al.*, 1960), socio-technical systems theory established that new systems could fail to meet the requirements of its users when focusing only on the technological needs and not the social needs (Münch *et al.*, 2022). Münch *et al.* (2022) explain that it stems from complexity research that considers the interrelatedness of both technical and social factors. This approach has seen success in designing new technological systems where the focus is on change within an organisation to be most effective for employees (Sony and Naik, 2020). It is centred on open systems that, unlike closed systems[2], focus on interaction with the surrounding environment where information is "*effectively shared across boundaries*" and is often influenced by the people with which the system integrates (e.g., customers and government) (Münch *et al.*, 2022, p. 4). Advances in technology require change at an organisational level due to the profound effect it can have; consideration therefore must be given to how this will impact organisations (Appelbaum, 1997), acknowledging that all organisations will have different needs.

The construction sector exists to meet the needs of society, therefore, taking a socio-technical approach to development of a technological system that will serve the construction sector ensues. Historically, either technology *or* society has been prioritised, oversimplifying "*the process of technology design and use*" (Sackey *et al.*, 2015, p. 2).

Baxter and Sommerville (2011) considered social and technical factors in the adoption of

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[2] In a closed system, there is no input or output of material; it is independent of other systems (Walker *et al.*, 2008).

computer-based systems, insisting that both be considered to avoid the fate of meeting technical requirements but not social requirements. On this basis, it can be deemed applicable to DLT and SCs as technological systems that aim to benefit society. Geels (2004) offers that consideration of socio-technical systems gives the advantage of co-evolution of both technology and society where "*form and function becomes the focus of attention*" (Geels, 2004, p. 902). Designing with this approach has the benefit of lifting "*the burden of complexity off the user*" (Calero Valdez *et al.*, 2016, p. 483). System developers face uncertainty in predicting the use of a new system, coupled with the ambiguity of change (Lyytinen and Newman, 2008). Therefore, consultation with users during the development of the system increases the likelihood that it will be more flexibly suited for its intended use (Orlikowski, 1992). Use cases can help alleviate uncertainty of a new system where a "*use case captures a contract between the stakeholders of a system about its behaviour*" (Cockburn, 2000, p. 1). Analysing a (new) system and all the ways it can be used, even those unexpected, establishes how users interact with a system in reality rather than the way it was 'designed' to be used, which lies inherent in assumptions. Thus, a system can be developed to respond to real-world interactions that often differ from the perceived or designed interactions. The importance of integrating a socio-technical approach at the design stage of a new system is expressed by Appelbaum (1997) and Munch *et al.* (2022). Appelbaum contrasts this with the ineffectiveness of traditional design of systems that first develops the technology and then "*fit[s] people to it*" (Appelbaum, 1997, p. 453) adding that focus should be on "*providing a high quality of work life to fulfil individual needs*" (Appelbaum, 1997, pp. 453–4) leading to optimisation of users' needs.

It was often thought that automation would reduce the level of interaction between humans and systems (Sony and Naik, 2020). However, this not to be the case where it is said that automation will change how humans interact with technology (Kolade and Owoseni, 2022), and new, more specialised skillsets will be required (Sony and Naik, 2020), hence a need to focus on the social aspects.

Geels (2004) highlighted the importance of the relationship between an innovation and its users in meeting societal needs and considered three aspects of socio-technical systems – production, diffusion and use of technology. Central to these aspects was regulation with regards its ability to produce trust, both of which represent substantial challenges for construction. Development of regulation around DLT and SCs has been limited (Ammous, 2016; Kshetri, 2017); however, this is beginning to change with the International Standards Organisation (ISO) looking into standardisation of blockchain and DLT (Oclarino, 2020). Australia's National Blockchain Roadmap sets out its own regulatory framework and supports the ISO/TC 307 standard (Australian Government, 2020). The UKs National Blockchain Roadmap (British Blockchain Association, 2021) proposes 20 interdisciplinary recommendations to support implementation of DLT in the UK. The United Arab Emirates plans for 50% of transactions to be blockchain-based and the European Commission alongside Norway and Lichtenstein are strategizing to remove uncertainty and fragmentation of blockchain (Clifton and Pal, 2022).

Socio-technical systems theory has previously been applied to a construction context. It was shown in a study on implementation of BIM (Sackey *et al.*, 2015) that the subject of the study—a construction organisation—required much more than just the tools offered by BIM to deliver the organisational objectives for which BIM was adopted and to serve the needs of its heterogenous members. In addition to solving technical and organisational challenges, there was a need to create appropriate social practices and processes. A later socio-technical study on BIM-based construction networks (Merschbrock *et al.*, 2018) found there is significant dependence on social components of a BIM system adding that collaboration success should prioritise people and processes (80%) over technology and information (20%). While these studies relate to a specific technology, it is argued that their findings can apply more generally. In fact, socio-technical approaches have already been applied to DLT and SCs by Kifokeris and Koch (2019a) who adopt sociomateriality in their research.

In light of the outlook of the construction sector discussed in Section 1.1 above and the identification of DLT and SCs as socio-technical systems, the socio-technical systems theory is applicable in investigating its potential to disrupt the construction sector. By considering implementation at both meso and macro scales, shown later in this thesis, the socio-technical approach can be used to ensure the needs of society can be met by the application of technology at different scales of adoption, accounting for different societal needs at each scale. Bringing such a focus in at this early stage of implementation into construction ensures that the socio-technical approach can provide these technologies the best chance of success from the outset rather than it being a buzzword to *appear* as though people and society are considered.

2.3 Emergence of DLT and SCs in construction sector research

The earliest mention of DLT and SCs in construction-based academic literature was in 2015 (Cardeira, 2015). It was a few years later when mainstream construction-related media outlets turned their attention to the technologies, see, for example, Perry (2017) and Cousins (2018). The two SLRs conducted for this study were used to discover several facets of the technologies for the construction sector. First, characterisation of the body of literature is provided using bibliographic metrics (Section 2.3.1). Second, the challenges and opportunities associated with DLT and SCs for construction are presented (Section 2.3.2). It is the categorisation of challenges and opportunities that supported development of an extended socio-technical model presented in Section 5.3. Third, the results of thematic analysis applied to the data extracted from the systematic review are discussed (Section 2.3.3). Finally, eight themes are presented in the context of the challenges identified in the construction sector alongside discussion of how and the extent to which the proposed applications of DLT and SCs could alleviate them (Section 2.3.4).

2.3.1 Characterisation of the SLRs using bibliographic metrics

The first review that took place between 2017 and 2019 (Li *et al.*, 2019a) was more general than the second, and focused on DLT and SC in the built environment (i.e., not limited to construction). The categories identified in the built environment literature (73 papers) included: smart energy (22 papers); smart cities and the sharing economy (7 papers); smart government (12 papers); smart homes (4 papers); intelligent transport (12 papers); BIM and construction management (11 papers); and business models and organisational structures (7 papers). By the time of the second SLR that took place between 2019 and 2021 (Li and Kassem, 2021b), the construction-specific body of literature had grown substantially to 153 papers (see Figure 2.1). This growth enabled the second review to be more specific and exclude domains outside construction.

Literature was collected from Google Scholar and Scopus as the most comprehensive collections of scientific research. Web of Science (WoS) and other databases have smaller collections and all papers retrieved from WoS were available in Scopus and/or Google Scholar. In addition, ongoing notifications from ResearchGate provided additional literature sources that included journal articles, conference papers and grey literature (e.g., industry reports; theses). Figure 2.2 shows the distribution of these sources among the 153 papers. The process for collection of the literature was the same for both reviews and can be seen in Figure 2.3.

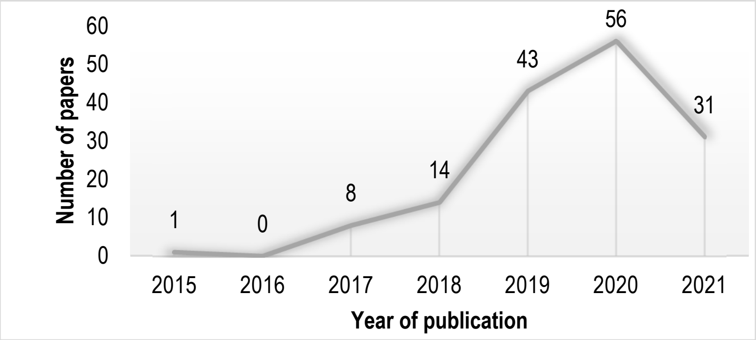

Figure 2.1: Number of papers published per year (Li and Kassem, 2021b, p. 6)

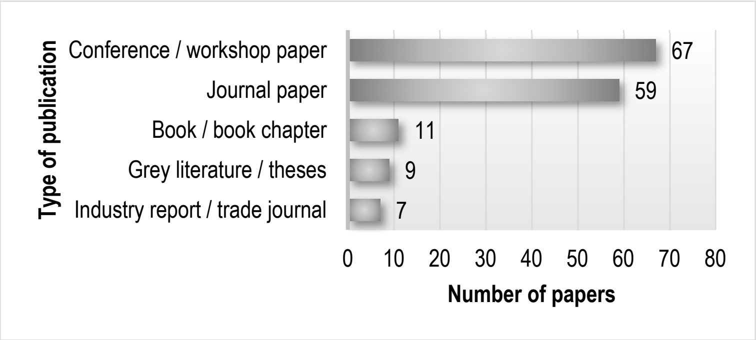

Figure 2.2: Number of publications by type (Li and Kassem, 2021b, p. 6)

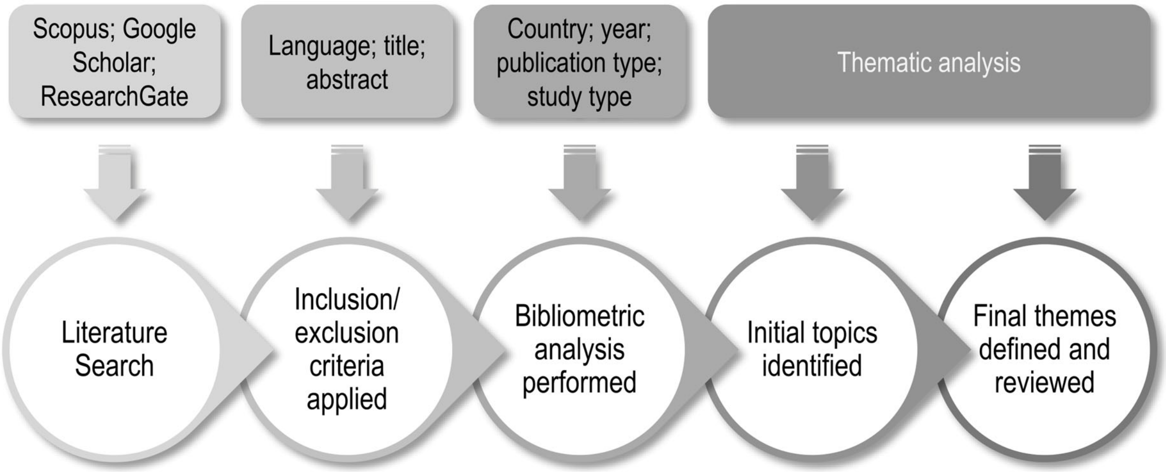

Figure 2.3: Steps taken to perform systematic literature review (Li and Kassem, 2021b, p. 4)

The search string used in Scopus is shown in Figure 2.3. The search terms for Google Scholar were “blockchain” AND “BIM” OR “construction” given its broad scope. The inclusion and exclusion criteria are shown in Table 2.3. These terms and criteria were the same for both reviews. The keywords were derived from consideration of key elements that make up the built environment acknowledging that they contribute substantially to the construction sector and the project lifecycle (concept, design, construction, operation, reuse/demolition). Different types of built assets (e.g., commercial, residential, industrial, infrastructure) were considered when compiling the keywords. The same search string was kept for the second review. The inclusion and exclusion criteria were accounted for in the search string. Next, the papers remaining were subjected to manual inclusion/exclusion criteria based on title and abstract to establish whether it was in scope.

Table 2.2: Search string for Scopus (Li and Kassem, 2021b, p. 4)

TITLE-ABS-KEY ((blockchain OR DLT OR “distributed ledger”) AND ("business model*" OR "building information model*" OR "built environment" OR "SC*" OR "smart cit*" OR "smart building*" OR procurement OR construction OR "construction manage*" OR "project manage*" OR "project lifecycle" OR "project life-cycle" OR "project lifecycle" OR design OR planning OR operations OR "smart service*" OR "smart environment" OR architecture OR engineering OR "smart government" OR infrastructure OR "energy management" OR energy OR "smart grid" OR "traffic management" OR traffic OR sustainability OR "sharing economy" OR sensor* OR urbani?ation OR "urban planning" OR "community management" OR "project bank account")) AND (LIMIT-TO (SRCTYPE,"p") OR LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA,"DECI") OR LIMIT-TO (SUBJAREA,"ENER") OR LIMIT-TO (SUBJAREA,"PHYS") OR LIMIT-TO (SUBJAREA,"MATE")) AND (LIMIT-TO (LANGUAGE,"English"))

Table 2.3: Inclusion and exclusion criteria for the literature search (Li and Kassem, 2021b, p. 4)

Inclusion criteria	**Exclusion criteria**
• Journal papers • Conference papers • Industry reports • Grey literature (e.g., theses, technical reports, working papers) • All available dates • Literature covering the built environment and DLT/SCs (2017-19 review) • Literature covering the construction sector and DLT/SCs (2019-21 review) • English language literature	• Non-English language literature • Studies that are out of scope (e.g., non-construction/non-built environment literature) • Duplicate materials where sources appear in more than one database • Duplicate papers that reported on research that had been previously published (e.g., where a conference paper had been extend into a journal article)

Papers from the same author(s) who had duplicated content across several papers (e.g., through extension of a conference paper into a journal article, or inclusion of the same technical data) were excluded in preference for the most comprehensive source. This avoided double counting of research. Sixteen papers were excluded under this rule and can be seen in Table 2.4 for transparency.

Table 2.4: Papers excluded for double counting of research

Excluded from review	Included in review
(Hamledari and Fischer, 2020b, 2020a)	(Hamledari and Fischer, 2021d)
(Hunhevicz and Hall, 2019)	(Hunhevicz and Hall, 2020b)
(Li *et al.*, 2018a, 2019a)	(Li *et al.*, 2019a)
(McMeel and Sims, 2020)	(McMeel and Sims, 2021)
(McNamara, 2019)	(McNamara, 2020)
(Nawari and Ravindran, 2019c, 2019b, 2019d)	(Nawari and Ravindran, 2019a)
(Qian and Papadonikolaki, 2019)	(Qian and Papadonikolaki, 2020)
(Raslan *et al.*, 2020b)	(Raslan *et al.*, 2020a)
(Siountri *et al.*, 2019a, 2019b)	(Siountri *et al.*, 2020)
(Suliyanti and Sari, 2019)	(Suliyanti and Sari, 2021)
(Tezel *et al.*, 2019)	(Tezel *et al.*, 2020)

The first review took place when little was known about DLT and SCs in construction, hence, a broader view of the built environment was taken. The second review, which was directly related to Research Question 2 (Objective 2.1), revealed how the literature had advanced since the first review and identified the applications that were receiving the most attention. Regarding the analysed data, the 11 construction-specific papers from the initial review were subsumed into the second review of 153 papers.

Figure 2.4 shows the data extraction criteria applied that were the same for both reviews (those items that straddle the central vertical line) and the criteria that were different for the reviews (those items either side of the vertical line). While the research conducted for this thesis was qualitative, quantitative metrics can also be used to support bibliometric indicators (van Raan, 2003). Those items that straddled both reviews consisted of quantitative analysis while the remaining items specific to each review were qualitative. Analysis of bibliometric indicators allows one to make comparisons of a body of international research across a research community and should be: combined with expert knowledge, up to date, accurate, sophisticated and interpreted with care (Moed, 2009). The bibliometric indicators used were number of publications per year (Figure 2.1), type of publication by source (Figure 2.2), country of lead author (Figure 2.5), and distribution of DLT

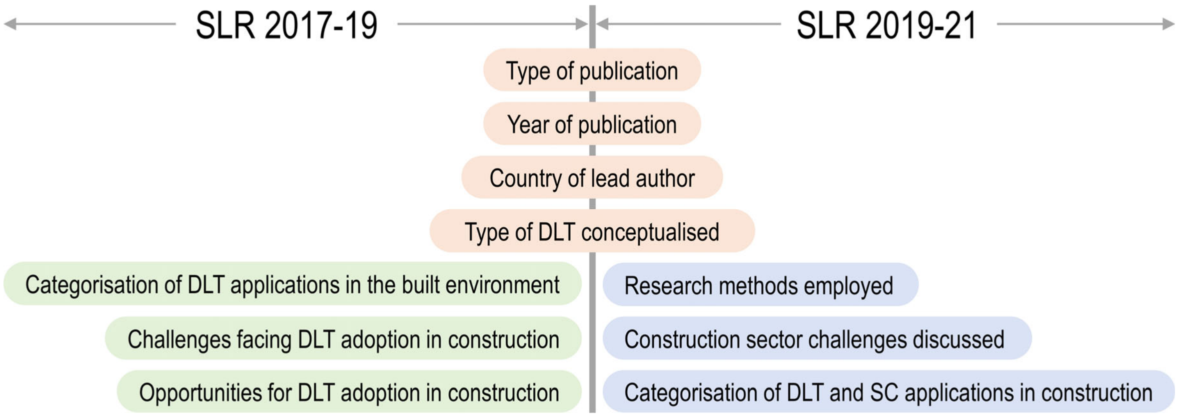

Figure 2.4: Data extraction criteria for both systematic literature reviews

conceptualised in the literature (Figure 2.6). In addition, the metric of research methods employed (Figure 2.7) was applied to SLR 2 (2019-21) to observe the level of development in the technology and consideration of how researchers are exploring its use for construction applications.

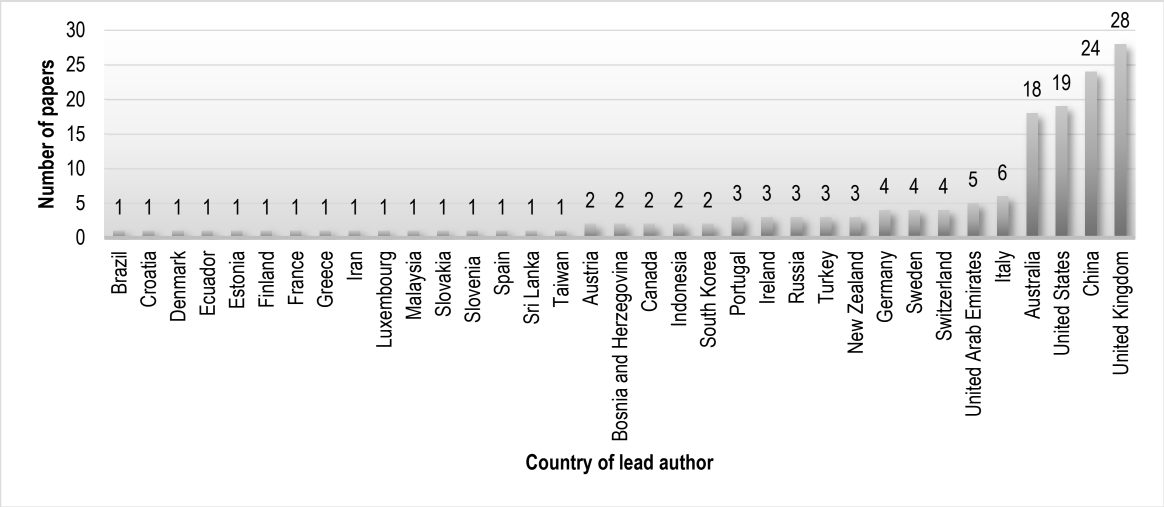

Figure 2.5: Number of publications by country of lead author (Li and Kassem, 2021b, p. 7)

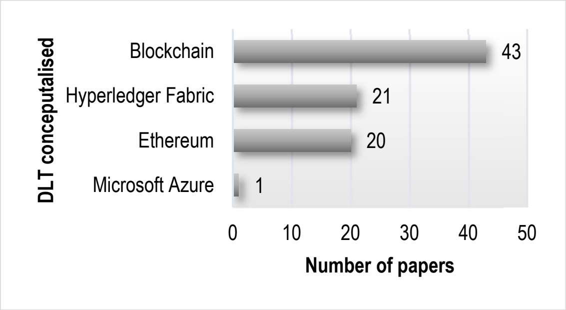

Figure 2.6: Distribution of DLT conceptualised within the literature (Li and Kassem, 2021b, p. 8)

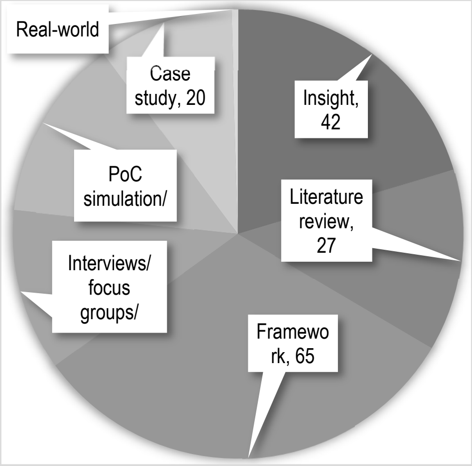

Figure 2.7: Research methods employed throughout the body of literature (Li and Kassem, 2021b, p. 7)

2.3.2 Challenges and opportunities for DLT and SCs in construction

The extensive lists of challenges and opportunities presented by DLT and SCs in construction are presented in Tables 2.5 and 2.6. The items listed above the dotted line in each table are supported by examples that make them specific to construction. The items below the dotted line are equally applicable to construction, however, specific construction examples were unavailable. In light of the socio-technical approach described above, these challenges and opportunities were classified into four dimensions of technology, process, policy and society (referred to as Tec, Pro, Pol and Soc respectively in the table). These categories were used to represent DLT and SCs as a socio-technical system. However, process and policy are broad areas that cannot be covered sufficiently by society and technology. This classification forms the basis of the framework presented in this study in Chapter 5. It should be noted that these challenges and opportunities are not applicable to any and all DLT and SC technologies and therefore represent a range of items to be considered depending on which technological choices are made for an application.

Table 2.5: Implementation challenges for DLT in construction (adapted from Li et al., 2019a, p. 294)

Challenge	Description	Tec	Pol	Pro	Soc
Authentication of data	Ensuring data uploaded to the blockchain is legitimate; could cause fraudulent activity within the supply chain (Nowiński and Kozma, 2017).	•		•	•
Bandwidth & connectivity	Sufficient server capacity required for stability of the system along with continuous internet connectivity (Bocek *et al.*, 2017; Kshetri, 2017). Elements of the supply chain delivery system could fail with lack of connectivity (Bocek *et al.*, 2017).	•			
Coding of SCs	Human error and badly coded contracts could be disastrous (Nehai, 2017). All construction projects are reliant upon well executed contracts that set out all parties' obligations thereunder (Cooper, 2018).	•	•		
Energy consumption	Massive amounts of energy are required to run Proof-of-Work protocols (Kshetri, 2017; Nehai, 2017). This impacts the built environment regarding emissions, grid capacities and demand management (Nehai, 2017).	•	•	•	•
Exchange rate volatility	The value of Bitcoin fluctuated between $1,000 and $20,000 in 2017 (Higgins, 2017). Fluctuations in cryptocurrency valuations means they are not yet stable enough for use in construction projects (Koutsogiannis and Berntsen, 2017).		•		
Interoperability	Where different applications need to communicate, there are challenges with transfer of data. This is already seen as a key challenge to Building Information Modelling in construction (Wang *et al.*, 2017).	•			
Legal	There is a lack of legal precedents and regulations (Winfield, 2018b). Construction relies heavily on legally binding contracts to operate and has problems with enforcing regulations (Hackitt, 2018).		•		
Malicious attacks	Different types of attacks present risks for use of blockchain technologies. Theft of data/currency pose threats to smart cities, construction projects etc. (Dorri *et al.*, 2017).	•			
Readiness for adoption	Full adoption requires information sharing and collaboration from all participants. Some of the construction industry's biggest problems centre on sharing of information, trust and collaboration (Barima, 2017; Belle, 2017).	•		•	•
Resistance to change	Implementation requires process changes at all levels of the organisation (Zamani and Giaglis, 2018). The industry is historically resistant to change so may not realise all possible benefits of blockchain (Koutsogiannis and Berntsen, 2017).			•	
Skills	Given its nascence, there is a significant lack of people sufficiently trained in blockchain technologies (Kshetri, 2017). Fresh new talent is needed in the industry for successful implementation (Cicco, 2018).	•	•	•	
Technological state of the industry	There is an underlying requirement for a certain standard of technology to exist within an industry before implementation. The industry is not yet sufficiently digitalised to take full advantage of blockchain technologies (Koutsogiannis and Berntsen, 2017).	•		•	•
Application programming interfaces (APIs)	There is a current lack of user-friendly application programming interfaces (APIs) within blockchain applications, which makes it difficult for non-computer programmers to utilise the technology (Nathan and Scobell, 2012; Kshetri, 2017).	•			•
Dark net activity	There is a negative stigma surrounding Bitcoin and, therefore, blockchain technology with regards criminal activity (i.e., drugs, money laundering etc.) (Nathan and Scobell, 2012; Kshetri, 2017). Cryptocurrencies could be used in construction projects to finance criminal activity through money laundering and corruption (Barima, 2017).		•		
Data protection	People's 'right to be forgotten' is not adhered to with a permanent and instantly accessible ledger (Kshetri, 2017). With changes to the General Data Protection Regulation (GDPR), where Data Erasure is being strengthened, consideration will need to be given to what data are uploaded to the blockchain and, in the event that an individual withdraws consent, how those data can be erased (Information Commissioner's Office, 2018).	•	•	•	•

Table 2.5 continued…

Challenge	Description	Tec	Pol	Pro	Soc
Equipment tampering	There is risk of physical tampering of smart meters/other physical equipment required to track data/usage (Kshetri, 2017).	•			
Flexibility/requires consensus	Due to their distributed nature, any developments of blockchains need to be done with consensus of a majority of users, which can result in a less flexible, less scalable system (Ølnes *et al.*, 2017).	•		•	
Job security	As technology moves to automate many [daily repetitive] activities that are today done by humans, jobs for humans will decrease. During the development process, it is likely that jobs will increase but at a point in the future, for example, when automated vehicles become mainstream, many human jobs will be lost to artificial intelligence and automation (Simionescu, 2017).		•		•
Nascent technology	DLT is nascent, which brings many challenges and underpins all those identified in this table. It is not likely to be a long-term barrier but these challenges present problems to be solved (Nathan and Scobell, 2012). There is a risk that organisations looking to implement DLT into their business processes will attempt to solve existing problems father than focus on potential future problems that could halt innovation and, therefore, market position (Zamani and Giaglis, 2018).	•	•	•	•
Privacy	Information privacy is sacrificed in place of transparency and auditability (Xu *et al.*, 2016). It is also believed to be possible to write a programme to breach databases and/or private information (Barima, 2017).	•	•		•
Redundancy	Redundancy across the network is very costly, has the only purpose of removing intermediation, and causes issues of storing what will become massive blockchains in the future (Ammous, 2016).	•			
Regulations	There is currently no regulation around blockchain technology and the role of the state is currently unclear (Kshetri, 2017). Governments have no authority to regulate cryptocurrencies nor blockchain applications in their current state, particularly because they operate across jurisdictions with different regulations and are based on consensus of a growing decentralised network of processing power (Ammous, 2016).		•		
Scalability	It is not known how the growth needs of the Blockchain will be financed including processes for the transfer of global financial transactions to the blockchain (Kshetri, 2017). Consensus of majority requirements can halt growth and scalability (Ølnes *et al.*, 2017). As the network grows and the number of processed transactions grows exponentially, users will not be able to store the amount of data processed nor keep up with computational demand (Ammous, 2016).	•			
Security and confidentiality	Confidentiality of transaction information is a challenge, particularly in some applications where people outside of the blockchain can access the information within it (Kogure *et al.*, 2017).		•	•	•
Software updates	Forks can be caused in the event of software updates when different nodes are running different software that can impact on the functioning of the blockchain and/or smart contracts (Bocek *et al.*, 2017; Hamida *et al.*, 2017).	•			
Throughput and latency	The Bitcoin Blockchain currently processes seven transactions every 10 minutes. This is not comparable with global credit card companies who can process upwards of 10,000 transactions per second (Vukolić, 2016). In November 2016, there was a lag of 65,000 Bitcoin transactions waiting to be processed such that users waited up to six hours for confirmation their transaction had been processed (Kshetri, 2017). Increasing processing speed is a challenge currently facing the technology (Kogure *et al.*, 2017). In addition, users wait around 10 minutes for small transactions to be confirmed and in the case of larger transactions, up to an hour or more to ensure prevention of double-spend (Nathan and Scobell, 2012). Small transactions are likely to be set aside in place of processing larger transactions that carry higher transaction fees for miners (Zheng *et al.*, 2018).	•			

Table 2.6: Implementation opportunities for DLT in construction (adapted from Li et al., 2019a, p. 295)

Opportunity	Description	Tec	Pol	Pro	Soc
Collaboration is increased	Data is more transparent so will be shared more freely increasing collaboration and trust between parties (Winfield, 2018a). Tokenisation will reward parties for data sharing (Koutsogiannis and Berntsen, 2017), reputation ratings will encourage more strategic partnerships (Belle, 2017).			•	•
Digital Twinning	A digital replica of a built asset throughout its lifecycle provides valuable information to all stakeholders (Cooper, 2018). With IoT, drones and real-time data, blockchain supports digital twinning by improving inspections (Koutsogiannis and Berntsen, 2017).	•		•	•
Disintermediation	Blockchain removes the need for intermediaries and guarantees execution of transactions; smart contracts automate processes and payments (Koutsogiannis and Berntsen, 2017); clients have more control over project time, cost and scope (Av, 2018).		•	•	•
Efficiencies	Promotes efficiency in international B2B trade; increases access to trade and supply chain finance (Kshetri, 2017). Automating activities allows for reallocation of resources reducing administration, transfers risk and reduces time and cost (Belle, 2017).			•	•

Table 2.6 continued…

Opportunity	**Description**	**Tec**	**Pol**	**Pro**	**Soc**
Faster Processes	Processes become streamlined and therefore faster. Reduces the need for multiple verifications as they can be accessed by all participants on the blockchain, esp. in design and planning (Cooper, 2018).	•		•	•
Immutability	Changing already chained blocks is very difficult so the ledger is considered immutable (Kounelis *et al.*, 2017). Timestamping, smart contracts, multi-signature transactions, smart oracles create real work depositories of information (Turk and Klinc, 2017). Client (often the taxpayer) sees cost reductions (Barima, 2017).	•	•	•	•
Low Transaction Costs	Intermediary costs are eliminated; efficiency is increased in international payments; property registration costs are reduced (Kounelis *et al.*, 2017; Kshetri, 2017).			•	•
Proof-of-Ownership and Rights	Ownership, IPR and rights can be recorded for many types of assets from vehicles to buildings to bonds (Yermack, 2017) and can be made explicit for shared BIM models leading to better trust between parties (Kinnaird and Geipel, 2018).		•	•	•
Provenance	Blockchain and IoT-enabled devices allows for supply chain tracking of goods and services in [near] real-time (Kim and Laskowski, 2016). Procurement and supply chain activities are streamlined and allow for more robust and quicker investigations (Barima, 2017; Mathews *et al.*, 2017; Zheng *et al.*, 2017).	•	•	•	•
Reduces Human Error	Automation of tasks, use of sensors, artificial intelligence and smart contracts reduces risk of human error. Certification/verification of coding through blockchain will provide quality assurance for construction projects (Cooper, 2018).			•	•
SCs	Automatically satisfies conditions set out in the contract upon meeting pre-set obligations. Construction contracts written into code will change how organisations operate, speed up payments, reduce disputes etc. (Cardeira, 2015; Boucher *et al.*, 2017; Zheng *et al.*, 2017).			•	•
Societal Benefits	Blockchain will put the needs of society and challenges at the centre over technology development (Ølnes *et al.*, 2017). Can help extend asset lives through better facilities management with scheduled activities and monitoring with IoT (Belle, 2017).				•
Traceability and Auditability	Immutability adds transparency to agreements and transactions; allows for better visibility and real-time tracking of materials in projects and supply chain from provenance (Atzori, 2015).		•	•	•
Workflow Improvements	Open project environment through increased collaboration and transparency results in accountability and project control; may solve some BIM adoption issues as sharing increases (Koutsogiannis and Berntsen, 2017); workflows can be automated and made faster (Fiander-McCann, 2018).			•	•
Compensation for created value	Compensation for created value is set to be a big opportunity for the likes of musicians and artists who are using the blockchain to grant rights to people for access to their creations based on smart contracts (Tapscott and Tapscott, 2016).				•
Cross-border trade	Particularly where cryptocurrencies are involved, cross-border trade can be made easier without the need for international exchange rates and border controls. However, this has the potential to interfere with the current international economic order (Maupin, 2017). Where [sub]contractors are based in countries other than where the client and/or project is based, cryptocurrencies can mitigate exchange rates and fluctuations in currencies (Barima, 2017).		•	•	
Corruption is reduced	It has the power to reduce corruption, for example through setting specific controls within code to say how ownership of land titles can be transferred (Kshetri, 2017).		•		•
Decentralisation	The distributed nature of DLT leads to decentralisation, which has both positive and negative connotations. On a positive note, it takes power away from central elites and gives citizens and communities more democracy; on a negative note, it has the potential to descend into anarchy where one person or group of persons sees an opportunity to take the power that has been lost by the central elites (Atzori, 2015).		•	•	•
Democracy	The technology promotes democracy giving power to the many and taking it away from the few (Shipworth, 2018).		•		•
Differentiation and competition	Differentiation and competition will be more prevalent than it is now through the emergence of new markets, for example, the increase in prosumers being able to offer competitive energy prices (Shipworth, 2018).				•
Inclusion	At the centre of blockchain is inclusion, the idea that economies function best when they are working for everyone, and blockchain has the ability to function across mobile networks through mobile phones, not just computers with full internet access. This makes the technology more accessible to millions of people in developing countries as well as those in poorer parts of society (Tapscott and Tapscott, 2016).				•
Integration of services	The Internet of Things, coupled with blockchain, will allow for full integration of services through smart devices that interact with almost every aspect of a person's daily activities (Tapscott and Tapscott, 2016).	•		•	•
Predictive capabilities	Predictive capabilities are increased through big data analytics where the blockchain provides full, original datasets (Zheng *et al.*, 2018). Prediction markets can be made "more resistant to failure, more accurate, and more resistant to crackdowns, error, coercion [and] liquidity concerns" (Tapscott and Tapscott, 2016).	•	•	•	•

Table 2.6 continued…

Opportunity	Description	Tec	Pol	Pro	Soc
Prosperity	Coupling of IoT and blockchain will give people increased prosperity through granting them better accessibility to the global economy and, therefore, new lines of credit and funding, suppliers and potential partners and greater opportunities to invest (Tapscott and Tapscott, 2016).				•
Resilience	Resilience is built into the technology making it resistant to external threats (Biswas and Muthukkumarasamy, 2016). Its decentralised nature eliminates single point of failure (Tapscott and Tapscott, 2016; Kounelis *et al.*, 2017).	•			•
Transparency	All data uploaded to the blockchain is visible by everyone and will remain there forever making it extremely transparent and immutable making tampering or fraud infeasible (Kounelis *et al.*, 2017; Kshetri, 2017). This transparency will hold people to account, for example, allowing people to see whether a corporate executive truly deserved his multi-million dollar bonus (Tapscott and Tapscott, 2016).				•
Trustless	The distributed nature and consensus protocol means trust is not required in blockchain technology (Kounelis *et al.*, 2017).	•		•	•
User empowerment	Being community-led results in user empowerment with communities being in the knowledge that they are in control of transactions and data (Kounelis *et al.*, 2017).				•
Value-driven society	As the technology develops and is focused on individual and community needs, the move will be towards a value-driven society and away from a price-driven economy (Pazaitis *et al.*, 2017).				•

2.3.3 Thematic analysis of literature

The elicitation technique of thematic analysis is introduced in Section 3.7.4. Using this technique, eight themes of DLT and SC applications in construction were identified from the 153 papers reviewed. These themes formed the basis of the taxonomies presented in Section 5.2 and are used to describe the current state of the art of DLT and SCs in the subsequent sections. The final themes were selected based on the prevalence of papers to a particular concept or application and then interpreted objectively regarding their potential contribution to construction sector practices. The three stages of coding can be seen in Figure 2.8, which demonstrates use of the constant comparator method between the stages. Stage one shows 30 initial codes that were refined to 12 codes in stage two and finally refined to eight *DLT application themes* plus *technology enablers* in stage three. These technology enablers represent the specific technologies that are discussed alongside the themes as part of the technological system for the applications. As BIM is seen as the *de facto* methodology for management of construction projects (Li *et al.*, 2020), and is inherent across all applications, it is not given an individual theme; this is indicated by the dotted line in the selective coding column of Figure 2.8.

As papers were analysed, they were reviewed for their contribution to the field but were not excluded for reasons of quality (unless for poor readability or disorganisation of ideas). As the body of literature was still relatively small, there was a need to capture the research across the whole spectrum to present a comprehensive picture of the state-of-the-art.

Figure 2.9 shows how the body of literature reviewed change from 2017-19 to 2019-21 through elimination of built environment-specific papers and re-categorisation of those that were relevant, namely, *business models and organisational structures* and *BIM and construction management*. It should be noted that while the former category was kept for consideration of, for example, decentralised autonomous organisations (DAOs), the papers

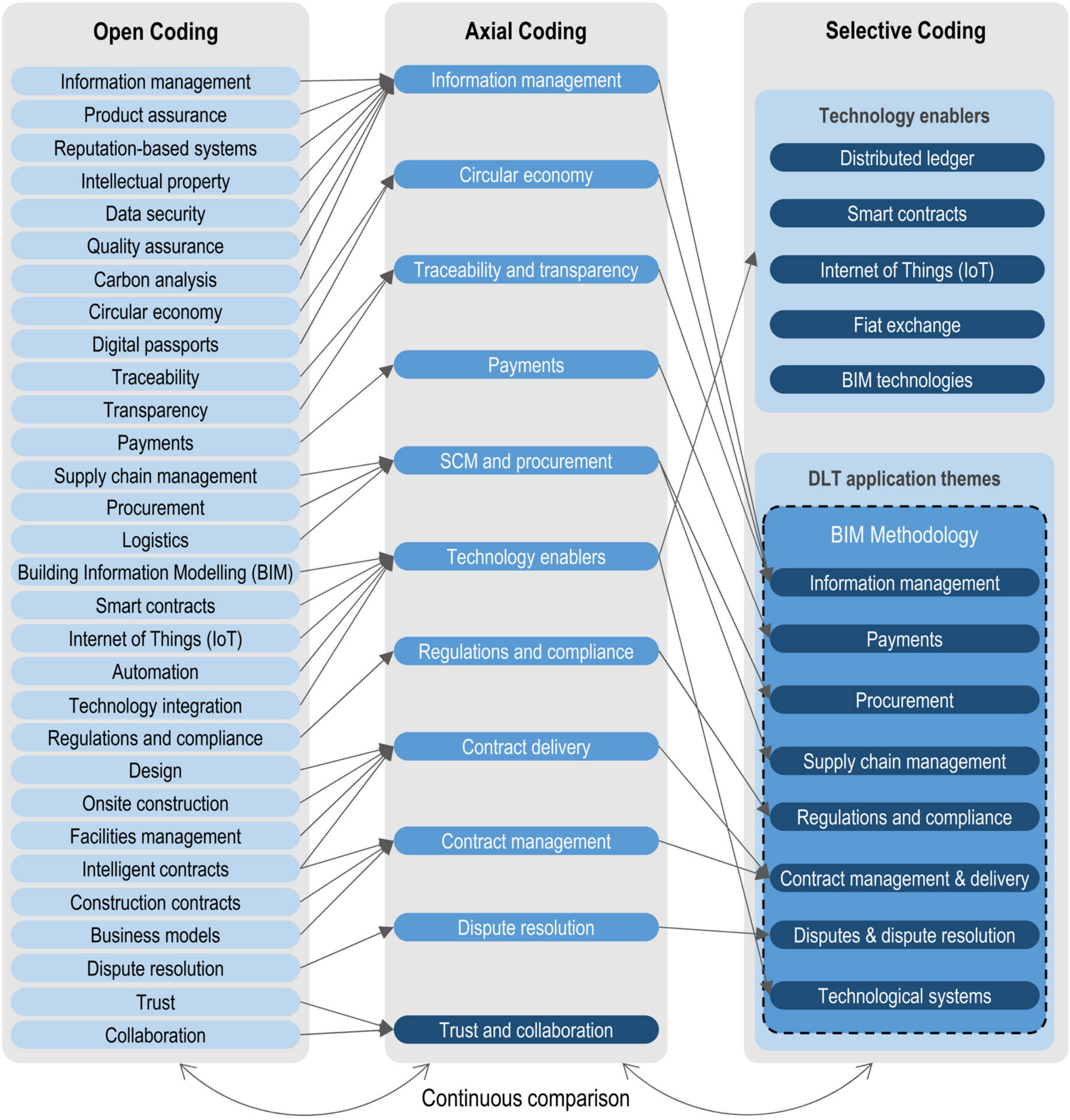

Figure 2.8: Three-step coding from thematic analysis of DLT applications (Li and Kassem, 2021b, p. 5)

from the first review were not specific to construction so did not carry over, but new papers specific to construction were added for the 2019-21 review.

2.3.4 Application themes for DLT and SCs in construction

This section provides details of the challenges within each of the eight themes identified through thematic analysis of the literature followed by the DLT and SCs applications that are proposed to provide solutions to them. The structure of these subsections may appear repetitive; however, it was felt this logical approach was the best way to present the data.

2.3.4.1 Information management

Traceability and transparency are considered a subset of information management, justified by the fact that the root of the challenges in respect of traceability and transparency are in the context of information management.

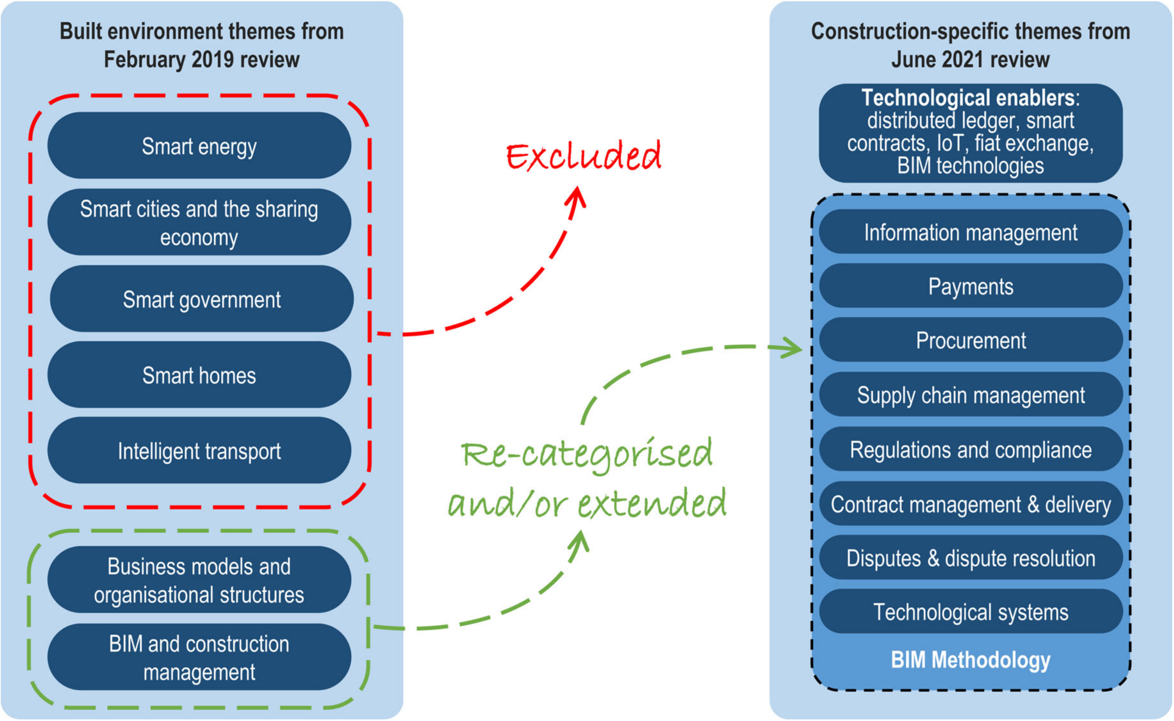

Figure 2.9: Comparison between themes from February 2019 systematic review to June 2021 systematic review (Li and Kassem, 2021b, p. 6)

Challenges

Often papers refer to challenges with ‘current systems’ in information management. This is understood to mean there are challenges with current practices (where practices refer to an ecosystem of standards, processes and technologies).

Several issues with current information management processes were identified in the literature. Trust and networking costs are cited as challenges to information and digital collaboration (Belle, 2017). Lack of effective communication, collaboration and reluctance to share information between parties (McNamara and Sepasgozar, 2018; Penzes, 2018; Ye *et al.*, 2018; Hargaden *et al.*, 2019; Li and Kassem, 2019b; Li *et al.*, 2019a; McNamara, 2020; Shemov *et al.*, 2020; Yang *et al.*, 2020) results in poor quality information when it is shared, especially where there is no incentive to the sharing party (Pattini *et al.*, 2020) and parties provide the minimum information required (Nawari and Ravindran, 2019a). Lack of collaboration results in issues around traceability, compliance, flexibility and stakeholder relationships (Goh *et al.*, 2019). Information or data asymmetry, where parties receive different information or data, is raised in many papers (Cerić, 2019; Ganter and Lützkendorf, 2019; Maciel, 2020; Pattini *et al.*, 2020). Omission of information in BIM workflows (Dounas *et al.*, 2020a) causes poor communication (Cerić, 2019; Shemov *et al.*, 2020), information and data fragmentation (Hijazi *et al.*, 2019a; Shemov *et al.*, 2020), and information gaps between the parties (Zhong *et al.*, 2020) and can be compounded by incompatible systems (Hodgkinson and Kaelin, 2008). This also results in an issue of data veracity (Salama and Salama, 2019). Issues related to standardisation of documentation add to the reluctance to change where there are inadequacies in the leading BIM protocol and a lack of established workflows for working with non-proprietary formats such as Industry Foundation Classes (IFC) (Mason, 2017). This also results in difficulties in traceability and exchange of information (Xue and Lu, 2020). Exchange information requirements (EIRs) and BIM execution plans (BEPs) are often misunderstood or underestimated with little training and education around BIM requirements (Maciel, 2020).

When information is exchanged, there is often time wastage (Heiskanen, 2017; Erri Pradeep *et al.*, 2019), information redundancies (Fitriawijaya *et al.*, 2019), and it is of poor quality (Hunhevicz and Hall, 2020b). This is due to absence of a single, integrated and accessible information management system (Shojaei *et al.*, 2019; Xiong *et al.*, 2019). Wang *et al.* (2017) and Goh *et al.* (2019) highlight this in asset management due to incomplete documentation post construction, which can undermine occupant safety (Wilson *et al.*, 2020). Record keeping is poor (Li *et al.*, 2020) and data storage of current and historical projects is weak (Perera *et al.*, 2020).

Information models face challenges of model ownership, modification rights, distribution rights, liability for changes/errors, copyright protection, risk allocation, distributed design decisions, software agents, traceability and confidentiality of data (Turk and Klinc, 2017). Kinnaird and Geipel (2018) highlight BIM technologies' inability to reliably verify if certain information has been authorised by the issuing party. There is a failure to maintain security of information, particularly regarding IP especially when tracking changes is difficult (Zheng *et al.*, 2019). There can be unauthorised viewing or editing (Erri Pradeep *et al.*, 2019) opening the door for alteration or tampering (Zhong *et al.*, 2020). Information security is cited as a problem by Lemeš and Lemeš (2020). Issues of cyber security (Liu *et al.*, 2019), data security (San *et al.*, 2019; Singh and Ashuri, 2019; Villegas-Ch *et al.*, 2020) and data privacy (Tezel *et al.*, 2020) are prevalent in current information management practices. Problems with model and data ownership (Mathews *et al.*, 2017; Ye *et al.*, 2018; Erri Pradeep *et al.*, 2019; Mason, 2019) are complex and difficult to manage, especially where there is collective authorship (Dounas and Lombardi, 2019) and the nature of current practices is such that information models often become fragmented over multiple files (Dounas *et al.*, 2020b). Model reuse and adoption strategies are unclear (Liu *et al.*, 2019) along with IP access rights (Mason, 2017; McNamara and Sepasgozar, 2018; Ye *et al.*, 2018; Erri Pradeep *et al.*, 2019; Liu *et al.*, 2019; Tezel *et al.*, 2020). Finally, current practices are ineffective in meeting the growing need for real-time information sharing (Ye and König, 2021).

There are several reasons for lack of traceability and transparency in construction: limited digitalisation (Hultgren and Pajala, 2018) related to BIM (Hargaden *et al.*, 2019); low trust between the parties; issues around security of deliverables (Nanayakkara *et al.*, 2019b); not wanting to share commercially sensitive data; not receiving any direct benefit from the data shared; the potential for uncovering or transferring liability (Wilson *et al.*, 2020); and lack of accountability (Yang *et al.*, 2020). These cause difficulties in pinpointing the cause of poor-quality work and goods (Zhong *et al.*, 2020) and inability to trace products with regard to quality and condition monitoring (Sivula *et al.*, 2018). These issues in turn cause distrust and reluctance to collaborate with adverse effects on efficiency and productivity (Zhong *et al.*, 2020).

Applications

Given the broad spectrum of information management applications in construction, the applications in this category are sub-categorised as general information management; digital record and circular economy; intellectual property (IP); and traceability systems.

General information management

This sub-category relates to data and information management of across the construction project lifecycle. This involves the creation, processing, maintenance, storage and exchange of such data and information. Many challenges of information management stem from: lack of an effective platform (Shojaei *et al.*, 2019), information asymmetry (Cerić, 2019), poor communication between the parties (Cerić, 2019; Shemov *et al.*, 2020), and poor information exchange (Heiskanen, 2017; Hunhevicz and Hall, 2020b).

Several authors propose blockchain to offer a single source of truth where all participants can access the same distributed ledger of information on data-driven projects (Penzes, 2018; Ye *et al.*, 2018; Hijazi *et al.*, 2019b; MEED Mashreq Construction Partnership, 2019; Di Giuda *et al.*, 2020b). According to Jaskula and Papadonikolaki (2021), DLT, through its inherent characteristics such as cryptography, can offer a level of security currently lacking in common data environments (CDEs) and provide effective historical record keeping (Dounas and Lombardi, 2018) with version control (Dounas *et al.*, 2019) and better information exchange (Erri Pradeep *et al.*, 2019). This improves model handover (Hijazi *et al.*, 2019b) and facilitates data or model sharing (Nawari and Ravindran, 2019a).

Suliyanti and Sari (2021) simulated information exchange secured by HLF for a BIM project. Oliveira Júnior *et al*. (2020) presented a framework for an information validation system incorporating blockchain, IoT, BIM and SCs increasing confidence of project information flows. Blockchain can facilitate historical record keeping of BIM data providing provenance and data integrity (Fitriawijaya *et al.*, 2019; Zheng *et al.*, 2019). Information asymmetry can be minimised (Cerić, 2019; Erri Pradeep *et al.*, 2019) where blockchain adds a layer of security to IoT fostering inter-firm trust (De La Peña and Papadonikolaki, 2019) or by automatically updating the ledger with IoT data using SCs (Li *et al.*, 2019a). Information security is achieved through integration of BIM, IoT and DLT (Erri Pradeep *et al.*, 2019) avoiding data loss, especially when owners change during asset transfers (Ganter and Lützkendorf, 2019). Better information management systems can be achieved through secure recording of transaction exchanges between parties in a BIM project (Aleksandrova *et al.*, 2019) and managing model modifications (e.g., who did what, when) (San *et al.*, 2019) offering reliable infrastructure for collaboration and increased transparency (San *et al.*, 2019; Shojaei, 2019). An information exchange prototype facilitated by blockchain and SCs addresses privacy, corruption, integrity and longevity issues, designed and tested by Erri Pradeep *et al.* (2021). Their results show reduced occurrence and management of disputes during and post construction. Blockchain offers data integrity for collaborative computer-aided design (CAD) environments (Lemeš, 2020). Regarding data quality, Hunhevicz *et al.* (2020b) propose blockchain to incentivise complete data sets for technical information that is used in subsequent phases, and commercial information through SCs that establish from whom and when to request/reward data drops. A framework incorporating a consortium blockchain-based quality information management system is proposed to record product state, organisation state and process state of projects (Sheng *et al.*, 2020a).

Better project governance and streamlined contract administration can be achieved from SCs updating information models with site data reflecting actual progress and triggering automated compensation events (Shojaei, 2019), as well as facilitating the link between physical and digital entities (Shojaei *et al.*, 2020). Zheng *et al.* (2019) explain how provenance and accountability can be obtained from such data. Nguyen *et al.* (2019) highlight blockchain's ability to facilitate security, liability, transferability and live data collection in BIM projects. An electronic document management system can be created that stores project documentation (San *et al.*, 2019) with blockchain providing a "*trustworthy infrastructure for information management during all building lifecycle stages*" (Turk and Klinc, 2017, p. 638). SCs can be used for document approvals and indexing based on a unified, decentralised document management system where blockchain traces workflows and facilitates version control (Das *et al.*, 2021a). Two frameworks are proposed to approve updates to information models, and to increase security of BIM data exchange through data encryption. Consensus from the parties is obtained prior to updates via cryptographic signatures minimising risk of unauthorised actors accessing the system (Das *et al.*, 2021b). A trigonal lattice structure for information is proposed by Koo *et al.* (2019) to increase quality assurance of information on materials, personnel and documents that supports rapid retrieval of information. Blockchain captures design development and dataflow in Singh and Ashuri's (2019) framework.

A consortium blockchain and SCs support compliance code checking in Zhong *et al.* (2020), offering improved quality management, better information sharing and enhanced mutual trust. In Xue and Lu (2020), blockchain and IFC are integrated to secure information and simultaneously to address information redundancy. To ensure consistent file exchange between parties, global unique identifiers (GUIDs) are no longer randomised as in the current way of working. Changes to BIM files are captured as opposed to storing and exchanging entire files to reduce the amount of data exchanged. Two-party public key encryption for user authentication is used to demonstrate data exchange and confidentiality by Cheng *et al.* (2020) and evaluation of blockchain to decentralise secure storage of BIM project data with multiple parties is made by Bukunova and Bukunov (2019).

To integrate digital twin into construction, Götz *et al.* (2020) find the necessary prerequisites include a user-friendly system, accessibility and robust user implementation manuals. Their framework combines IoT, the physical asset, digital twin and blockchain across three pillars of functionality, interoperability and integrability enablers. Lee *et al.*'s (2021) framework addresses data sharing and communication by integrating digital twin with blockchain. The digital twin updates in real-time and a compliance statement can be compiled from it. Only the compliance statement is stored on-chain minimising blockchain storage issues. The authors simulate a case study based on prefabricated bricks assembled onsite where the digital twin demonstrates compliance with brick placement and brick type using global positioning systems (GPS) and RFID.

Digital record and circular economy

Proposed by the Hackitt Report (Hackitt, 2018), the digital record was conceived to address safety of built assets. In this context and broadening its use to encompass circular economy principles, a digital record "*provides traceability through a secure, immutable and auditable electronic record of all required information, actions and decisions taken to assess and achieve compliance of a built asset with relevant standards and regulations at a point in time*" (Watson *et al.*, 2019, p. 498). The circular economy aims to achieve better use of resources from design through construction to operation and demolition. It focuses on waste reduction through material reuse, whether through elimination of chemicals which might prevent reuse, material recycling, or any activity that replaces the concept of end-of-life (Ellen MacArthur Foundation, 2013).

Several authors propose the concept of a digital materials passport. Cooper (2018) discussed a digital passport to record the material lifecycle and asset certification information. More specifically, a product passport can hold information about materials and give them value for recovery and reuse (Kinnaird and Geipel, 2018). Data such as source, characteristics, manufacturing, shipping, installation and maintenance can facilitate blockchain-enabled circular economy for materials reuse at a later stage (Shojaei, 2019). Nguyen *et al.* (2019) discuss a material passport to hold details on past, present and future performance that can support reuse at end-of-life. The record links to the digital asset providing up-to-date information. Sustainability is also achieved through materials transparency from provenance including whole lifecycle cost, carbon emission estimates, and raw material verification (Shojaei, 2019). Ganter and Lützkendorf (2019) propose building passports and consider how data can be managed across the lifecycle of a built asset with regards to data generation, storage, longevity and traceability, plus the ability to track responsible parties to clarify compliance and address legal issues and potential new business models. Pellegrini *et al.* (2020) discuss the use of blockchain and SCs to increase the amount of data stored about the materials in a built asset across its lifecycle to reduce construction waste by supporting circular economy principles and designing in reuse and recycle strategies in BIM projects from the outset.

RFID data are used by Copeland and Bilec (2020) to integrate geospatial mapping, BIM and blockchain for buildings as material banks (BAMB) recording location of materials across the lifecycle to support the circular economy. BAMB can be used to revalorise materials at end-of-life where blockchain secures data of tracked materials, and SCs update ownership of materials, end-of-life responsibilities and material claims putting accountability onto contractors and suppliers to plan for end-of-life at the design phase (Akbarieh *et al.*, 2020). In this use case, the BAMB provides data to the information model providing the most up-to-date and complete materials information of the asset. In addition to BAMB, Fiore *et al.* (2020) discuss the role of blockchain and SCs in material passports along with their role in advancing BIM through reliable data gathering and sharing across the lifecycle of a built asset.

Blockchain links and secures IoT, BIM and circular economy in the 'Blockchain of Circular BIM Things' (Kinnaird and Geipel, 2018). Blockchain facilitates two-way communication between the built asset and information models across the asset lifecycle providing real-time facilities management and accurate information on recyclability of building components when no longer required for their initial intended purpose. Continuing with circular BIM, reuse strategies are identified at the production stage to facilitate collection of appropriate data across the lifecycle enhancing efficiency, performance and sustainability (MEED Mashreq Construction Partnership, 2019). HLF is used to demonstrate the ability of SCs to facilitate the circular economy using a synthetic case study based on production, installation, use and salvage of a heating, ventilation and air conditioning (HVAC) unit collecting data about source and performance (Shojaei *et al.*, 2021).

The only construction-specific paper found on non-fungible tokens (NFTs) is by Dounas *et al.* (2021), which looks at infrastructure for the circular economy starting with architectural design. The NFTs represent components in a building organised through topological graphs.

Intellectual property (IP)

DLT and SCs are discussed as having the ability to add a layer of visibility and transparency to IP (Erri Pradeep *et al.*, 2019; Di Giuda *et al.*, 2020b). They offer an immutable record of ownership of assets (Hunhevicz and Hall, 2020b). The primary application to improve IP in construction is through tokenisation where IP rights are assigned to physical and/or digital components or assets indicating ownership. SCs track model authors and grant or limit access rights to information models (Ye *et al.*, 2018). Collaborating parties can use this to calculate IP rights (Penzes, 2018) and blockchain can be used for the protection or licensing of IP (Belle, 2017). This makes IP ownership and rights more explicit and transparent (Li *et al.*, 2019a). Using cryptocurrency as a token of ownership, for example, an air handling unit (AHU), a mechanical, electrical and plumbing (MEP) engineer, would be the designer and owner of the AHU. At the point of transfer from the MEP engineer to the onsite contractor, the digital representation of ownership of the unit is transferred to the contractor's digital wallet as well as the contractor taking ownership of the physical AHU proving they now have ownership responsibility of the AHU (Kinnaird and Geipel, 2018). McMeel and Sims (2021) propose a token economy to trade construction waste using financial incentives to manage and reuse construction waste. TTTcoin gives waste a value where it currently has none in today's environment incentivising manufacturers and material owners to repurpose waste.

Traceability systems

Wilson *et al.* (2020) propose a framework to incorporate DLT into information exchange within in a traceability system between supply chain participants who are not motivated to share information but may do so under incentive. Yang *et al.* (2020) demonstrate increased traceability and transparency in construction processes. Case study 1 employs HLF in the design of external cladding for a large-scale apartment building; case study 2 employs Ethereum to avoid complexity when procuring a distillation tower from overseas for an international mega project. In both case studies, SCs facilitate procurement, transportation and payment of the equipment. Zhang *et al.* (2020) integrate a hybrid public-consortium blockchain and SCs to increase quality traceability of precast components in construction. Their framework incorporates "*hybrid architecture, hybrid consensus, dual storage mode, off-chain storage, extended backup database, and separate chaining of classified data*" (Zhang *et al.*, 2020, p. 16). The multipurpose National Product Database (NPD) proposed by Li *et al.* (2020) supports compliance with regulations where blockchain and SCs push notifications to facilities managers when regulations change, and to provide a traceable system of information for products and components in built assets.

2.3.4.2 Payments

The construction sector has been challenged with payment-related issues for many years. Given blockchain was initially established to support financial transactions, there are several applications proposed to solve them. They are discussed below.

Challenges

Security of payment is an area of concern for almost all construction project participants. Cash flow, specifically with regard to late and non-payments, was discussed as having negative impacts on projects in numerous papers (Cardeira, 2015; Ahmadisheykhsarmast and Sonmez, 2018, 2020; Jagannathan and Prasad, 2018; Ye *et al.*, 2018; Abrishami and Elghaish, 2019; Nanayakkara *et al.*, 2019b, 2019a; Chong and Diamantopoulos, 2020; Perera *et al.*, 2020). This often causes contractual disputes, insolvency and delays (Badi *et* *al.*, 2020; Chong and Diamantopoulos, 2020) and leads to adversarial relationships between the parties (Luo *et al.*, 2019).

Hamledari and Fischer (2021c) highlight several issues with current payment practices as being time-consuming and reliant on human-centred workflows resulting in late or non-payments; centralisation restricts automation of payments; centralised and siloed methods of data capture prevent payment-related single source of truth due to product flow (e.g., progress updates) and cash flow (for payments) requiring verification as a result of data fragmentation; centralisation skews the concentration of power creating bottlenecks that can slow down payment processes; and lack of trust makes it impossible to automate payments as parties constantly need to validate and verify facts. Several papers raised the issue of payment structure where payments are cascaded down the supply chain from the main contractor (Wang *et al.*, 2017; Brydon Wang, 2018; Mason, 2019) alongside poor, unfair, or outdated payment practices (Kifokeris and Koch, 2019a; Li and Kassem, 2019a; Mason, 2019; O'Reilly and Mathews, 2019; Das *et al.*, 2020; McNamara, 2020). This inadequate promptness and security of payment for subcontractors and suppliers is often the cause of contractual disputes, insolvency and delays (Ahmadisheykhsarmast and Sonmez, 2020; Badi *et al.*, 2020; Chong and Diamantopoulos, 2020). According to Yang *et al.* (2020), inconsistent payment terms and cash flow arrangements cause disputes on withheld payments, quality, fraud and data authenticity. With regards to supply chain management, decoupling of payments for transport and delivery services and the logistics solutions/services (Kifokeris and Koch, 2019c) results in poor economic flows (Kifokeris and Koch, 2019a). On top of these challenges, Altay and Motawa (2020) discuss complexity of payment regimes, Nanayakkara *et al.* (2019b) highlight the expensive cost of finance, and Li *et al.* (2019a) and Brydon Wang (2018) add financial fragility. Ahmadisheykhsarmast and Sonmez (2020) highlight the limited use of Project Bank Accounts (PBAs), a system designed to address payment problems (see Griffiths *et al.*, 2017) due to implementation costs, loss of cash flow benefits and resistance from main contractors, staff training, company policy, administrative demands, and their complex nature.

Applications

SCs are central to the discussion on automating payments and changing payment practices with many authors discussing them in general (e.g., Brydon Wang, 2018; Li *et al.*, 2019a). Shortly after the establishment of Ethereum (the first DLT that enabled decentralised applications via SCs), SCs were proposed to solve construction sector payments (Cardeira, 2015). Additional use cases for SCs include faster payments, lower transaction fees (Barima, 2017), and reduced payment administration (Shojaei, 2019). Wang *et al.* (2017) add procurement to automated payments while Luo *et al.* (2019) add that payments by SCs support formalisation of construction contracts.

A framework to link payments to 4D and 5D BIM, which triggers payments upon milestones being achieved, is offered by Abrishami and Elghaish (2019). Automated billing based on 5D BIM data and integration of blockchain with a CDE to provide an immutable track record of project activity is proposed by Ye and König (2021) negating the need to store data on-chain. Further, information models are used for quantity take-off (QTO) and to produce bill of quantities (BoQ), that link to SCs for payment. A conceptualised billing model made up of an information model, BoQ and QTO processed by an SC to automate contract, invoice and billing management is later demonstrated (Ye *et al.*, 2020).

Several studies by Hamledari and Fischer (2021c, 2021b, 2021d) explore automated payments facilitated by Ethereum-based SCs to disintermediate the payment supply chain. SCs integrate with reality capture technologies to confirm and trigger payments for two onsite construction projects eliminating the need for payment applications from contractors. Accuracy of 95% for reality capture and 100% for payment processing was achieved. Integration of cryptoassets is considered for supply chain payments to replace fiat currency based on higher granularities of cash and product flows. Real-world data used in simulated experiments validated the thesis presented. Lastly, comparative analysis on the ability of blockchain and SCs to increase visibility of the construction supply chain for payments was made. Findings showed blockchain and SCs could increase completeness and accuracy of information at different levels of granularity for retrieval of information. They reported conventional systems have 45% less accuracy than blockchain and SC systems and scalability of Ethereum is not a barrier for construction projects.

Progress payments were simulated by Ahmadisheykhsarmast and Sonmez (2020) facilitated by SCs utilising real-world construction project data and Ahmadisheykhsarmast *et al.* (2020) simulated the automation of retention payments through coding an SC with payment conditions and embedded with contract funds. Data were captured via a Microsoft Project plug-in with payment made based on those data.

To address the flow of payments through the main contractor, Mason (2019) discusses the use of SCs to facilitate direct contracts and payments to the supply chain. This approach does not remove the main contractor from managing performance. Kinnaird and Geipel (2018) discuss coding SCs to make immediate payments for contractors upon work being completed with interim payments being triggered by big data or IoT devices to verify completion (Mason, 2017). Chong and Diamantopoulos (2020) suggest integration of different systems (DLT, IoT, SCs, BIM technologies) can provide security of payment. SCs integrate with data from oracles (Dounas and Lombardi, 2018) or proof-of-work (Shojaei, 2019) to monitor project performance and facilitate payments as and when tasks are completed, the so-called inch-stone approach (Mason, 2019). These approaches allow contractors and suppliers the ability to plan activities knowing they can fund them if cash flow is improved (Nguyen *et al.*, 2019). A framework by Das *et al.* (2020) executes and records semi-automatic interim payments with a high degree of immutability. Blockchain facilitates selective transparent sharing of project payment information; automates conditions of interim payments via SCs; and provides data confidentiality between contracting parties through a cryptographic key management system.

Automated payments based on proof from IoT sensors can create a more reliable supply chain when in direct connection with delivery of goods and services (Ahmadisheykhsarmast and Sonmez, 2018; Kifokeris and Koch, 2019c; Shojaei, 2019). This includes tracking of construction phase activities (Tagliabue *et al.*, 2019) and for payments in integrated project delivery (IPD) projects (Elghaish *et al.*, 2020).

Additional use of SCs in payments include funding management (e.g., crowdfunding, cryptocurrencies, transparency of spending budgets as a results of immutable recording) (San *et al.*, 2019), and facilitation of cross-border transactions for international construction projects reducing risk of currency fluctuations (Barima, 2017).

2.3.4.3 Procurement

Procurement is of particular significance in construction as is directly linked to financial management, contract management and delivery, and supply chain management among others. Procurement decisions reverberate throughout the remainder of the asset lifecycle and is the point at which any and all contracts are created for a construction project.

Challenges

Mason and Escott (2018) believe there are failures in the current construction procurement system. The often-preferred model of public sector organisations of lowest tender wins infrequently offers long term value-for-money for the taxpayer (Odgers *et al.*, 2011). Harty (2019) and O'Reilly and Mathews (2019) cite lowest tender wins as a specific construction sector challenge; others cite the related challenge of low profit margins (Barima, 2017; Li *et al.*, 2019a; Ye and König, 2021) and adversarial pricing (Li *et al.*, 2019a). Shemov *et al.* (2020) state that lump-sum and lowest bidder procurement are the main issues in building trust. Frequently, this causes cash flow challenges as discussed in the previous section of payments. Occasionally, it results in significant insolvencies such as those following the collapse of Carillion in 2018 that saw a 20% increase in the following first quarter over the same period of the previous year (Smithers, 2018). Bids resulting in low and even negative profit margins have a knock-on effect to the supply chain who are then squeezed on their profit margins by the employing contractor to compensate for this, invariably resulting in disputes as discussed further in Section 2.3.4.7. Moreover, economic pressures from recession push investors to require more for less and increase capital expenditure through private investment (Li *et al.*, 2019a).

Applications

SCs to automate activities are at the core of discussions to improve procurement practices. Maciel (2020) suggests integrating SCs with computational legal contracts to effect procurement. Kinnaird and Geipel (2018) propose that digital contracts, hashed, signed and timestamped on a blockchain will speed up processes. Automated triggering of tenders based on monitored or estimated stock levels and automated payment upon procurement objectives being met are suggested by Barima (2017). Li *et al.* (2020) suggest automating procurement for maintenance and repairs of built assets through integration of a DAO, an e-Marketplace, a computer-aided facilities management (CAFM) system, a National Product Database (NPD) to ensure compliance with regulations, and a Construction Certification Organisation (COO) to ensure competence of those completing the work. Automated equipment leasing at the operation phase is discussed by Wang *et al.* (2017). Pattini *et al.* (2020) address transparency in procurement where SCs facilitate the tender phase through sharing of tender documentation based on the client's evaluation criteria. Better than net-zero-energy buildings are incentivised by considering new methods of procurement in O'Reilly and Mathews (2019). Blockchain-integrated e-procurement mitigates human error, reduces disputes, saves costs, and provides an efficient and effective process in Perera *et al.* (2021). Gunasekara *et al.* (2021) proposed a framework to demonstrate the impact of blockchain and SCs on pre-tendering, tendering and post award phases of construction projects following survey of blockchain and SCs to facilitate e-procurement for facilities management where they support communication, data exchange, approvals, speed up processes, and clarify roles. McMeel and Sims (2021) suggest SCs can simplify, streamline and clarify the management of procurement processes.

2.3.4.4 Supply Chain Management

Supply chain management in construction concerns the relationships between suppliers and contractors for goods, services and resources that help to ensure a project is delivered on time and to budget.

Challenges

Construction supply chain activities add to the generation of carbon emissions worldwide. Forty percent of which is attributed to the 'take, make, waste' model that sees raw materials go from extraction, through manufacture, installation and ultimately disposal at landfill (Copeland and Bilec, 2020). Supply chain fragmentation (Kifokeris and Koch, 2019b; Nawari and Ravindran, 2019a; Perera *et al.*, 2020) accounts for many construction sector challenges. Supply chains are complex (Nanayakkara *et al.*, 2019b; Perera *et al.*, 2020; Tezel *et al.*, 2020) resulting in low transparency and traceability (Wang *et al.*, 2017; Perera *et al.*, 2020) and a lack of continuity (Nanayakkara *et al.*, 2019a) often with conflicting interests of participants (Wang *et al.*, 2017; Shemov *et al.*, 2020). Hijazi *et al.* (2019b) place construction supply chain maturity at the *ad-hoc* level, which results in low levels of trust (Shemov *et al.*, 2020). Supply chains for DfMA are often lengthy (Xue and Lu, 2020) and there is often unclear provenance and supply chain data (Shojaei *et al.*, 2019). Logistics issues include material flows, congestion on site (Kifokeris and Koch, 2019a) inability to track products with regard to quality and condition monitoring (Sivula *et al.*, 2018), and inefficiencies in storage, which in turn can cause delays and inflexible transport options (e.g., part-loads) (Lanko *et al.*, 2018). Area disposition plans (e.g., drawing-based materials and storage management plans) are static; there is inefficient regulation of delivery entries at construction sites; and clients do not actively participate in construction supply chain information flows (Kifokeris and Koch, 2020).

Applications

Traceability and transparency of supply chain activities are increased by DLT and SCs (Hultgren and Pajala, 2018; Fitriawijaya *et al.*, 2019; San *et al.*, 2019). DLT-based construction supply chains integrated with sensors can offer efficient tracking of provenance and movement of products through the supply chain resulting in automated payments upon reaching the construction site (Fitriawijaya *et al.*, 2019). Direct purchasing between the source and end user and material tracing facilitated by SCs can support sequential and proportionate payments (Shojaei, 2019). Kifokeris and Koch (2020) demonstrate how blockchain can integrate into the Swedish construction supply chain simplifying and integrating economic, information and material flows. Processes are speeded up; delivery failures, delays, withheld payments, imprecise data retrievals and data transfers are reduced. Significant cost reductions were achieved in an SC simulation by Wang *et al.* (2020) when ordering and taking delivery of precast components through automation and improved information sharing. Trust in supply chain management is addressed by Hijazi *et al.* (2019b) through integrating blockchain and BIM. Supply chain data are linked to information models and used throughout the asset lifecycle improving the facilities management of a building. Shahrayini *et al.* (2021) discuss integration of BIM and blockchain and how it can enhance project management and integrate with IoT to increase efficiency of sustainable supply chain management. Norta *et al.* (2020) propose a decentralised platform for supply chain management and project management to enhance information flows and cost and time reductions for better quality services. DLT and SCs can impact other supply chain management activities including logging of shipping documentation including approvals on blockchain, increased security of certifications, fraud detection, provenance tracking (Penzes, 2018; Hargaden *et al.*, 2019), material production data (e.g., extraction, processing) (Lanko *et al.*, 2018), and reputation scores about participants (Fitriawijaya *et al.*, 2019).

Embodied carbon estimating in construction supply chains considers the sustainability perspective facilitated by blockchain in Rodrigo *et al.* (2020). Shemov *et al.*'s (2020) framework focuses on the prevention of possible attacks during supply chain activities to maintain security and Xiong *et al.*'s (2019) framework secures private keys for construction supply chain participants. Qian and Papadonikolaki (2020) find the need for trust is reduced as uncertainty is reduced when integrating blockchain and self-enforcing SCs into construction supply chains. System-based and cognitive-based trust are increased through transparency, decentralisation and applications.

Three scenarios are proposed to improve information management in construction supply chains (Pishdad-Bozorgi *et al.*, 2020): a blockchain-based information sharing platform to create a decentralised environment for P2P transactions and removal of third parties; transparency of blockchain encourages participants to behave honestly combatting counterfeiting, fraudulence, and sub-standard materials; and mitigation of the Bullwhip Effect—a downstream demand shock—where decreased information asymmetry increases information sharing though blockchain reducing the need for stakeholders to conduct their own material forecasts. SiteSense, a real-world application by Intelliwave Technologies (Greenwald, 2020) tracks and records activity on equipment, workforce and materials through integrating blockchain with RFID, GPS, barcodes, drones and augmented reality.

Reverse-auction tendering, PBAs and asset tokenisation are presented as three cases for supply chain management in construction (Tezel *et al.*, 2021) providing several opportunities (e.g., reduced disputes, streamlined transactions, transparency) and challenges (e.g., regulatory and judiciary challenges, need for more use cases, need to align standard and bespoke contracts). Nanayakkara *et al.* (2021) identify issues in construction supply chains that blockchain can provide solutions to including addressing issues with partial payments, delays, non-payment, cost of finance, long payment cycle, retention, and security of payment.

2.3.4.5 Regulations and compliance

This section concerns compliance with regulations, orders, warrants, specifications, rules, standards, terms, conditions or requests.

Challenges

Construction regulations and compliance with regulations are deemed inadequate. Allison and Warren (2019) discuss the poor regulatory environment for product assurance in New Zealand; McNamara (2020) highlights poor regulation and compliance in Australia and the UK; and Li *et al.* (2020) write about the findings of the UK's investigation into building and fire regulations following the Grenfell Tower fire in 2017 that include ambiguous and inconsistent regulations and guidance, weak compliance processes, patchy competence across the system, and opaque and insufficient product testing, labelling and marketing. There is ignorance around regulations and compliance (Li *et al.*, 2019a), lack of enforcement of regulations and compliance (Li and Kassem, 2019b) and inadequate regulatory oversight (Li *et al.*, 2019a). Brydon Wang (2018, p. 5) discusses the onus on the sector indicating it is the "*failure of parties to comply with their legislative and contractual obligations*" that is the problem. Graham (2019) discusses the lengthy process for applying for permits; Nawari and Ravindran (2019a) discuss the same contextualised in post disaster recovery. Pattini *et al.* (2020) believe that digital transition can support the regulatory gap that exists in an industry that is slow to establish standards for digital cooperation (Belle, 2017).

Applications

Automation and evaluation of compliance is discussed by Shojaei (2019) while Tagliabue *et al.* (2019) integrate compliance verification with an information model connected to blockchain. Integrating BIM and DLT can provide the effect of someone looking over your shoulder to bolster compliance with regulations (Li and Kassem, 2019b). Regulatory compliance is integrated into the National Product Database (NPD) that holds information about building products and components including standards and regulations with which they must comply (Li *et al.*, 2020). Push-pull notifications ensure facilities managers are always aware of changes to standards and integrates with maintenance schedules. Nawari and Ravindran's (2019a) conceptual framework reduces the time required to issue permits in post-disaster recovery through automating administration with blockchain and SCs. They also discuss increased collaboration, transparent data ownership, cybersecurity and automated code compliance checking. Nawari (2021) demonstrates how HLF can be used in a BIM workflow through employing an automated code compliance checking system. Model data and building code rules are stored on the network, and chaincode[3] is used as the model checker service and building permit issuer.

2.3.4.6 Contract management and delivery

This theme addresses challenges to contract management and delivery and is then followed by discussion of different categories of applications including contract management, design, physical construction, operation and business models.

Challenges

Challenges in this theme are separated into contract management and handover that emerged as distinct categories under the theme of contract management and delivery.

Contract management

With many clients not specifying BIM requirements (Belle, 2017), there is an inadequate demand and drive to foster BIM adoption (Elghaish *et al.*, 2020) and a lack of knowledge to incorporate BIM into development plans (Belle, 2017). Successful contract management and delivery relies on trust and collaboration. The construction sector is adversarial in nature (McNamara and Sepasgozar, 2018; O'Reilly and Mathews, 2019), which leads to a lack of trust in construction projects (Penzes, 2018; De La Peña and Papadonikolaki, 2019; Goh *et al.*, 2019). Lack of trust results in reluctance to collaborate which stems from an

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[3] 'Chaincode' is the term used by Hyperledger Fabric to refer to their smart contracts.

industry that has become fragmented over time (McNamara and Sepasgozar, 2018; Shojaei, 2019; Hamma-Adama *et al.*, 2020) as a result of one-off teams forming for each new project (Hijazi *et al.*, 2019b) that disband at the end of the project (Xue and Lu, 2020). These short-term contractual relationships compound fragmented project organisational structures (Cheng *et al.*, 2020). There is a lack of meaningful automation of construction contracts (Norta *et al.*, 2020). Contract management is described as slow and complex (Faraji, 2019; Luo *et al.*, 2019; Shojaei *et al.*, 2020) as a result of inefficient practices (Hargaden *et al.*, 2019; Hamma-Adama *et al.*, 2020; McNamara and Sepasgozar, 2020) such as continuation of paper-based administration (Hargaden *et al.*, 2019) and large amounts of administration work prone to human error (Nanayakkara *et al.*, 2019a), or loss of or stagnated productivity (Mathews *et al.*, 2017; Penzes, 2018; Graham, 2019; Lokshina *et al.*, 2019; Siountri *et al.*, 2020). Inefficient project governance (Penzes, 2018; Ye *et al.*, 2018; Fitriawijaya *et al.*, 2019) from managing geographically dispersed teams (Hargaden *et al.*, 2019) results in poor project control (Penzes, 2018; Chaveesuk *et al.*, 2020) and causes a waste of resources (Ye *et al.*, 2018), time and money (Morvai, 2018; Prasad and Koner, 2019) compounded by lack of accountability and responsibility (Penzes, 2018; Hargaden *et al.*, 2019; Liu *et al.*, 2019).

Fragmented cooperation results in a lack of trust (Qian and Papadonikolaki, 2020). Trust is negatively influenced by traditional methods of information sharing (Di Giuda *et al.*, 2020b), lack of transparency in the supply chain (Hamma-Adama *et al.*, 2020), the level of complexity, risk and uncertainty in projects (Hargaden *et al.*, 2019), distrust in construction contracts (Mason, 2017; Wang *et al.*, 2017), and distrust between contracting parties resulting in employment of third party intermediaries (Das *et al.*, 2021a).

Early contractual problems in a construction project can escalate throughout to affect the completion date (Shemov *et al.*, 2020) and quality, through inadequate design specifications (Sharma and Kumar, 2020) or a constant change of requirements (Wang *et al.*, 2017). Discontinuity of phases through design, manufacturing, transportation, and site work can result in inferior quality, escalating costs, delays, and limited productivity (Xue and Lu, 2020; Yang *et al.*, 2020). There is often little coordination between project participants (design architects, contractors, subcontractors, suppliers) (Sharma and Kumar, 2020). Suboptimal coordination between stakeholders results in lost productivity, rework, delays and increased fees (Maciel, 2020); on occasion, this results in onsite accidents (Baek *et al.*, 2020). Two key challenges to contract management and delivery include silos of design exploration and design validation; and the focus of technology taking over the design process (Dounas *et al.*, 2020a). In addition, application of BIM on construction sites is limited due to lack of: content in information models, onsite mobile technologies, and sufficiently trained personnel (Li *et al.*, 2020).

The onerous nature of administering construction contracts aids distrust from contracting parties (Mason, 2017; McNamara and Sepasgozar, 2020) especially where terms are inconsistent and/or ambiguous (McNamara and Sepasgozar, 2018). This results in confrontational contractual relationships (Zhong *et al.*, 2020), delays to projects (Prasad and Koner, 2019), and poor quality of works (Chaveesuk *et al.*, 2020). On occasion, participants may even cut corners then deflect blame to other participants (Zhong *et al.*, 2020). Current verification mechanisms are inappropriate for approval of milestones (Chaveesuk *et al.*, 2020). There was consensus among interviewees in McNamara and Sepasgozar (2020) that the contract is used as a tool when things go wrong rather than for delivery of the project.

Handover

Though BIM has seen successful application at the design and construction phase (Li *et al.*, 2020), there is a lack of knowledge and understanding of BIM generally (Li *et al.*, 2019a), and specifically around awareness and knowledge of BIM for FM (Salama and Salama, 2019). There is no continuity of data usage between construction and operation, there is a significant cost to verifying and re-entering management and operations data for buildings (Wilson *et al.*, 2020). This is in part because the increase of digital adoption has so far been scattered and fragmented across the sector (Zhong *et al.*, 2020). Handover is often seen as the end of the contract (Harty, 2019) with poor arrangements in place for transfer of information across phases (Salama and Salama, 2019) or when asset owners/facilities managers fail to continue using the information model citing issues of information quality. Hunhevicz *et al.* (2020b) argue that data sets handed over at the end of construction projects are poor quality due to poor documentation, difficulty in finding the data and low reliability of information. Reconstruction of data sets is expensive and time consuming. Documentation for maintenance and repairs of built assets (e.g., reports, guarantees, warranties, invoices) is often-paper based with no digital back-up making long-term storage an issue (Li *et al.*, 2020).

Applications

This theme relates to the contracted supply of goods and services for the delivery of a built asset. It has been separated into contract management across all phases of delivery (design, physical construction and operation) as well as business models that support delivery.

Contract management

Construction contracts are complex; many activities are administrative, repetitive and add no financial value to clients. DLT and SCs can assist in the delivery of tasks to reduce time, money and effort spent on these non-value adding activities (Dakhli *et al.*, 2019). These administrative activities include submissions, recording interactions, approvals, quality control, document control, performance updates, and compliance and risk management. For example, the logging of hours worked during design or hours spent onsite by workers are required for payments but create no added value for the project (Penzes, 2018). In addition to reducing administration, automation through SCs can reduce human error (Ye *et al.*, 2018).

Tracking of who did, what, when and how on a distributed ledger during a construction project could have a positive impact (Li and Kassem, 2019b) such as recording and managing modifications to an information model (San *et al.*, 2019) thereby adding a layer of transparency and accountability to projects. SCs can be used in land transfer and ownership (Ye *et al.*, 2018), to measure contract performance (Li and Kassem, 2019b) or to support quality acceptance in construction projects (Sheng *et al.*, 2020b) where logging of transactions between stakeholders is automated for internal administrative purposes (Hunhevicz and Hall, 2020b). The introduction of DLT and SCs can allow for better balancing of risk and more effective contract delivery (Faraji, 2019) through establishing stronger contract governance offered by clearer terms and automation of manual processes (Shojaei, 2019). An intelligent platform integrating cyber-physical systems, IoT, BIM and blockchain for smart product-service systems was developed and demonstrated via simulation by Li *et al.* (2021a) to show innovation in prefabricated housing construction. The platform offered management of: the project, information model, production, transportation, on-site assembly, and knowledge and its effectiveness was demonstrated using real-world project data. Benefits included enhanced sustainability through integration between the prefabrication supply chain and the platform facilitating information sharing across the lifecycle; traceability of components leading to lean construction and the ability to use SCs for classification authority and security assurance; increased visibility of costs through real-time data and feedback supporting decision making and identification of potential delays, labour shortages and improper installations. Li *et al.* (2021b) demonstrate how integration of blockchain, BIM, big data and AI can guarantee accuracy and completeness of data. Findings from a construction project in Guangdong Province, China revealed the enhanced ability to forecast material prices, perform cost analyses, define accountability of contractual terms, provide reliable evidence of activity for stakeholders, and coordinate the project schedule.

Comprehensive research into intelligent contracts is provided by McNamara (2020) and McNamara and Sepasgozar (2018, 2020, 2021) who believe they will become central to the construction process. Their application, the iContract, offers intuitive and sophisticated functionality including real-time response to changing situations (e.g., on construction sites); optimised contract formulation and negotiation; contract administration and efficiency; improved communication, collaboration and trust; supply chain efficiency; real-time scenario analysis; performance analysis and forecasting; increased traceability and accountability; stability of the payment process; and reduced disputes. Maciel (2020, p. 398) sees intelligent contracts "*as a logical extension to BIM whereby the contractual* *performance itself becomes automated*" and Mason (2017) describes them as contracts that seek to manage themselves. The iContract is proposed to drive efficiency in procurement through digitalisation; facilitate disintermediation of a highly fragmented supply chain; facilitate direct payments across the supply chain and even, as proposed by Mason (2019), move toward 'inch-stone' payments rather than 'milestone' payments. The minimum requirements to realise intelligent contracts include 'BIM Level 3', blockchain-based cryptocurrencies, IoT/big data, appropriate payment mechanisms and liability arrangements (Mason, 2017). There are challenges with intelligent contracts where they lack flexibility and judgement that traditional contracts offer suggesting semi-automation that allows for human input could be a suitable option.

A new contractual structure is proposed by Morvai (2018) based on IPD—Block-Build—that aims to: decentralise responsibility, reduce costs, reduce waste, enable early knowledge of firm costs, increase quality, and reduce administrative burden. A reputation-based system utilising tokenisation that rewards intrinsic value to project participants (Mathews *et al.*, 2017) could improve contract management. With proper implementation, reputation could be an effective driver to increase efficiency, productivity and quality.

Design

Many potential applications centre on information exchange between participants at project design. Based on analysis and process modelling of a BIM workflow, Srećković *et al.* (2020) discuss the use of SCs to facilitate design approvals between the architect and the structural engineer. Di Giuda *et al.* (2020a) propose a framework for the design phase of construction projects that incorporates BIM, DLT, and payments, where DLT ensures data reliability and decentralises the CDE. Payments are released once the work has been validated and verified during the review process, assuming all obligations have been met. Lemeš and Lemeš (2020) and Singh and Ashuri (2019) propose using blockchain to generate hashes of model changes and store them on a distributed ledger providing data integrity and traceability. Liu *et al.* (2019) apply BIM and blockchain to sustainable design and SC-enabled BIM processes in order to address BIM implementation risks, IP and cybersecurity issues, individual levels of responsibility, and a new type of contract regarding BIM responsibilities, limitations, and liabilities. The authors apply the concept to a smart city setting (Liu *et al.*, 2021). Lokshina *et al.* (2019) consider the integration of BIM, IoT, and blockchain in the system design of a smart building as complementary developments that can work together to enable secure storage and management of data and information related to building operation. Pattini *et al.* (2020) propose SCs to facilitate payments during design while adhering to contract deadlines and integrating with information models.

Dounas and Lombardi (2018) simulate designing an apartment layout using blockchain to obtain consensus from participants via a decentralised application (DApp) where voting rights are based on tokens and reputation. In later work, an automated architectural design process using shape grammars and DAOs to promote collaboration, decision-making, and distribution is proposed (Dounas and Lombardi, 2019) and validated (Lombardi *et al.*, 2020). Design optimisation is facilitated by SCs and distributed storage on an InterPlanetary File System (IPFS) (Dounas *et al.*, 2019). Consensus is reached through a stake mechanism that assigns tokens to participants based on expertise and reputation, providing transparency and resilience to the process. Ethereum is used as the DLT in all proofs of concept. Finally, the concept of a decentralised BIM, which conceptualises a decentralised design team, employs incentivisation each time a team member creates and then edits a file, and is built on top of a shared infrastructure for CDEs (Dounas *et al.*, 2020a). The ability to scale the system and interoperability between digital tools are demonstrated in Dounas *et al.* (2020b).

Physical construction

Applications have been proposed that use SCs to automate or partially automate processes during the physical construction of built assets. Examples include managing product installation during construction, which results in automated payment (Li *et al.*, 2019b); installing microchips during production that are tracked on a blockchain and directly linked to the information model, allowing physical products to be linked with their digital counterpart, saving time from underproductivity (Kinnaird and Geipel, 2018); and the recording of transactions for the installation of several off-site-fabricated building components, where the data recorded can later be used for communication or automatic payments (Blumberg, 2019). To address the issues the COVID-19 pandemic highlighted with travel restrictions, Li *et al.* (2021c) developed a Two-layer Adaptive Blockchain-based Supervision (TABS) model for supervision of off-site modular housing production (OMHP). The HLF prototype showed how sidechains could be used to maintain the confidentiality of business data while still allowing for the sharing of project-related transaction data. In order to help contractors fulfil their environmental obligations, Woo *et al.* (2020) suggest converting carbon credit documentation into SCs for semi-automated credit acquisition.

According to Li and Kassem (2019b), the integration of BIM, DLT, and SCs can control supply chain activities by monitoring workflows and executing pre-coded SCs in accordance with deadlines and milestones, thereby reducing the frequency of onsite variations (Pattini *et al.*, 2020). IoT devices can improve site management procedures and increase efficiency, examples being RFID for real-time monitoring (Shojaei, 2019), and enabling automated site access (Penzes, 2018).

A framework for blockchain-based verification of adequate scaffolding is proposed to make sites safer and remove the requirement for onsite inspections (Baek *et al.*, 2020). The framework uses image recognition technology (IRT), and the data is secured by blockchain. A framework for integrating IRT with image matching, IoT sensors, and blockchain is proposed by Park *et al.* (2020) to secure and verify data in the automation of quality control events, activities, and tasks currently carried out by humans. A framework that incorporates blockchain and SCs and addresses the GDPR with regard to workforce performance monitoring onsite was developed by Calvetti *et al.* (2020). In Blumberg (2021), a framework for installing off-site manufactured components is presented where SCs facilitate approvals. In order to transform a physical construction site from a traditional to a smart site, Kochovski and Stankovski (2021) present the findings of a Horizon 2020 project that combined IoT, AI, SCs, and blockchain. 'DECENTER' is a fog computing and brokerage platform and allows the site to secure data, improve health and safety on-site, and maintain quality of service. Response times for anomaly detection were significantly improved, costs were cut, access to AI models and techniques was improved, and SC implementation increased privacy in the industrial setting. This is the only study that exhibits a real-world application for SCs and blockchain.

Operation

Facilities management, which includes maintenance and repairs, happens during the asset lifecycle's operation phase. Application of BIM during the operation phase is still uncommon but could spread more widely with the aid of DLT and SCs. Information models can be linked with SCs and programmed to manage building performance, schedule proactive or reactive maintenance and repairs (Belle, 2017; Hijazi *et al.*, 2019a; Li *et al.*, 2020), to enable automated part replacement purchasing (MEED Mashreq Construction Partnership, 2019), to monitor and manage building performance (Harty, 2019), and to update information models and the blockchain ledger (Pattini *et al.*, 2020). Zuberi (2021) presented a simple PoC for issue management in facilities management where a BIM element reference library represents the facility that links to user-reported problems and SCs facilitate issue resolution based on predefined roles and conditions.

To increase transparency and traceability in operations and maintenance, data from various lifecycle phases are linked together to produce provenance data (Wang *et al.*, 2017). By integrating blockchain technology into the building management system of a smart museum, data quality and security are achieved making it is possible to control access to a building, allow information updates, and prevent unauthorised access to data about building operations (Siountri *et al.*, 2020). Blockchain secures the data layer for an IoT-equipped university campus where security is guaranteed by peer-to-peer architecture in Villegas-Ch *et al.* (2020). Bindra *et al.* (2019) discuss automated access throughout a building that is controlled by sensors and actuators and based on pre-defined access rights. To achieve better than net-zero energy buildings, O'Reilly and Mathews (2019) used IoT sensors connected to a BIM-based building to track energy performance and enable the sale of excess energy produced. In Tagliabue *et al.* (2019), real-time data collection and response in CognitiveBIM guarantee occupant safety and comfort. Raslan *et al.* (2020a) investigate the idea of combining asset information models, BIM, and a private blockchain to support stakeholders’ visualisation and decision-making in a project.

Business models

Decentralised applications (DApps) and decentralised autonomous organisations (DAOs) make up the discussion on business models. The main distinction between the two is such that DAOs do not require human interaction due to the autonomous component. A DAO can be a DApp but a DApp is not always a DAO. The primary advantage of a DApp is that there are no intermediaries, eliminating any potential censorship outside of the constraints set by the code (Hunhevicz and Hall, 2020b). According to Srećković and Windsperger (2019), the addition of real-time insights during the planning phase facilitated by DOAs can support BIM workflows by enhancing transparency, accelerating planning, and streamlining communications. The DApp suggested by Dounas and Lombardi (2018) will trigger a payment when a digital CAD asset is used in a decentralised architectural office offering objective data on prospective employees and contractors without the need to share personal data. In the context of automated facilities management, a DAO can support cost cutting, improve health and safety, monitor building performance, provide reactive and scheduled maintenance, etc. (Ye *et al.*, 2018; Li *et al.*, 2020). In practice, however, the proposed DAOs are sufficiently distinct from DApps because they permit human interaction in situations where technology is not sufficiently developed to do so, such as when determining if a work package has been completed ‘satisfactorily’. Such systems could be regarded as truly autonomous once AI is adequately developed to accurately replicate reasoning and learning elements of human intelligence. Blockchain is suggested by Hunhevicz *et al.* (2020a) for IPD governance and organisational structures to digitise processes and for incentive mechanisms. This encourages the transition of IPD processes to an automated and transparent system.

2.3.4.7 Disputes and dispute resolution

Arcadis (2020, p. 8) defines a dispute as “*a situation where two parties typically differ in the assertion of a contractual right, resulting in a decision being given under the contract, which in turn becomes a formal dispute*”. This section considers disputes and resolution of those disputes.

Challenges

While not included in the literature review for being out of scope, figures from the Global Construction Disputes Report (Arcadis, 2020) are included to add additional context to disputes in construction. According to Arcadis (2020), construction disputes are both costly (with an average value of $30.7 million U.S) and lengthy (15 months on average to resolve). In 2019, the top three causes of disputes were (1) poorly drafted or incomplete and unsubstantiated claims; (2) failure to make interim awards on extensions of time and compensation; and (3) owner/contractor/subcontractor failing to understand and/or comply with its contractual obligations.

Several different categories of disputes are discussed in the literature around: data ownership (Harty, 2019), contractual issues (Chaveesuk *et al.*, 2020; Hamma-Adama *et al.*, 2020) such as ambiguous contract terms (Shojaei *et al.*, 2020), specifications (Chaveesuk *et al.*, 2020), protocols (Wang *et al.*, 2017), payments (Goh *et al.*, 2019) and liability (Sharma and Kumar, 2020). They stem from lack of effective communication channels; lack of corrective information sharing on site; poor document control systems (Goh *et al.*, 2019); and the sheer number and diffusion of project participants (Singh and Ashuri, 2019). Disputes can have an impact on security of payment for subcontractors due to their lengthy duration (McNamara and Sepasgozar, 2018) that causes problems of cash flow and can lead to insolvency and delays (Chong and Diamantopoulos, 2020). Payment-related disputes can be particularly lengthy (Jagannathan and Prasad, 2018). This results in adversarial relationships between the parties (Luo *et al.*, 2019).

A study found that construction industry practitioners consider dispute management as an inevitable part of day-to-day operations stating that, "*the loose, flexible and ambiguous nature of construction contracts is somewhat deliberate to allow, more often than not, the bigger player in the agreement the ability to bully other stakeholders when the inevitable issues arise*" (McNamara and Sepasgozar, 2020, p. 439).

Applications

Immutable digital records have the potential to reduce disputes over information validity (Barima, 2017; Shojaei, 2019). Such data recording can assist with auditing (Barima, 2017). SCs can reduce disputes as they require clearer contract terms than those found in traditional written contracts (Mason and Escott, 2018; Li and Kassem, 2019b). De La Peña and Papadonikolaki (2019) contextualise a blockchain-secured IoT system as a tool to locate the point of failure in materials that are damaged when they arrive at the job site. Through the chain of data, the source of the damage can be identified, allowing for allocation of responsibility and liability.

2.3.4.8 Technological systems

This theme concerns the new and existing technological systems in the construction sector and the impact introduction of DLT and SCs will have on these systems.

Challenges

A capitalist-driven society has encouraged competition between providers, which is good to drive up quality and drive down cost. However, in collaborative construction projects it is restrictive, particularly in terms of interoperability. Interoperability is seen as a challenge between building components (Bindra *et al.*, 2019), between heterogenous software platforms (Cardeira, 2017; Erri Pradeep *et al.*, 2019; Salama and Salama, 2019), at handover (Salama and Salama, 2019), and between actors' business processes (Kifokeris and Koch, 2019a). One of the results of these interoperability challenges is the insufficient and slow pace of digitalisation throughout the sector (Lokshina *et al.*, 2019; Perera *et al.*, 2020; Siountri *et al.*, 2020). This is closely but not exclusively linked to the sector's resistance to change (Lokshina *et al.*, 2019; McNamara, 2019). However, as digitalization becomes embraced by the construction sector new risks emerge. As the world becomes increasingly connected by the internet and the IoT, the associated risks increase (Cooper, 2018). Central IoT systems are vulnerable to attack (Ye *et al.*, 2018), so too are cloud platforms to attacks related to data loss, denial of data access, partial control over sensitive data (Cheng *et al.*, 2020; Das *et al.*, 2021a), BIM platforms' lack of data security and transparency (Shi *et al.*, 2021), and current IT systems' inability to ensure security, traceability and transparency of quality information (Zhong *et al.*, 2020). There are legal and security issues (Hargaden *et al.*, 2019) with respect to using a cloud platform (Turk and Klinc, 2017), security of BIM-IoT architecture, uncertainties, vulnerabilities and security challenges related to the openness and decentralisation of BIM (Siountri *et al.*, 2020), and insufficient cyber-resilience of software platforms (Nawari, 2021).

Applications

DLT can add a layer of security to the integration of technology into connected systems (Cooper, 2018), particularly regarding the IoT (Ye *et al.*, 2018). In Tagliabue *et al.* (2019) IoT sensors are attached to a prototype building and linked to SCs to gather information about its state. This paper demonstrates how a wider project—in this case, a cognitive building that responds to occupants—integrates elements of blockchain and SCs to support the wider ecosystem despite not being the primary component. Blockchain is viewed by Aleksandrova *et al.* (2019) as a component of a larger digital ecosystem built around BIM, which they believe is the foundation for integrating all other technologies to reduce fragmentation, integrate project participants, and lower project costs.

According to Cardeira (2017), SCs could use BIM as an oracle to automate contractual agreements. In addition, blockchain and SCs have the capacity to support software interoperability if BIM data is in XML format resulting in a technological system offering lower administrative costs, transparency, accuracy, speed, and real-time data. In a BIM environment, Lemeš and Lemeš (2020) show how data is secured on a blockchain. Kinnaird and Geipel (2018) discuss various BIM aspects that can be enhanced by blockchain integration and claim that blockchain adds security, liability, transferability, and live data to BIM.

2.4 Evaluation of the body of literature

Now more than ever, the construction sector needs to adopt new technologies and processes that can address its key challenges. The eight application themes identified in this thesis provide the first taxonomy of DLT and SC applications in construction at this level of granularity. This is evidenced by the fact that the applications and benefits of DLT and

SCs can cover the entire lifecycle of built assets. Classification of BIM across all application themes (and not distinct from them) is in line with the shift of focus toward BIM as a methodology rather than an application, as reflected in the ISO 19650 suite of standards (ISO, 2018).

There is a level of interconnectivity between the themes where one application might be categorised under one theme but in reality contributes to two or more themes. Automatic payments via SCs, for example, is clearly aligned to the *payments* application theme, but can also link to *procurement, contract management, supply chain management* etc. This interconnectivity provides the opportunity that SCs, in combination with other technology enablers (e.g., IoT, BIM, AI), can transition through and across application themes to offer a joined-up ecosystem the construction sector needs to advance its position from one of the least digitised sectors globally to one of the most advanced.

From the first identified publication in 2015, the number of papers increased substantially up to 2021 to the 153 papers reviewed here. Many of the papers offer insights only as to what these new technologies can offer construction, but many researchers are beginning to move toward proof-of-concepts (POCs) studied in simulated environments. With 27 POC studies and 20 case studies between 2017 and 2021, such interest is rapidly emerging. This suggests that the next stage of research will begin to uncover the benefits DLT and SCs can offer as investment is made into application development, research and real-world pilots. This reinforces the consensus from researchers that these technologies will have positive impacts on the sector in the future. The application themes of information management and contract management and delivery have received the most attention to date.

Many authors list several benefits of DLT and SCs integrated with BIM where, for example, transparency and trust are increased, and corruption and inefficiencies are reduced (Maciel, 2020); or DLT increases collaboration between parties as a result of trusted data entry, reliable data flows, explicitly assigning responsibilities and transparent tool interoperability (Dounas *et al.*, 2019); or SCs enabling inch-stone payments moving away from the rigidity of milestone payments in practice today as suggested by Mason (2019). It is proposed that the integration of BIM with blockchain is highly likely, and the focus should be on *how* rather than *if* that should happen (Xue and Lu, 2020). However, until real-world application through pilots and mainstream adoption can support realisation of the benefits, these claims of advancement through DLT and SCs risk being considered as mere hyperbole. This is exacerbated where claims come from dissemination of the same concepts through different channels without going back to the original source (Sheng *et al.*, 2020a). The optimism seen through current attention could see Gartner’s ‘trough of disillusionment’ (Gartner, 2022b) a reality if DLT and SCs fail to deliver what is promised.

The taxonomy presented here offers themes that are connected to researchers' work in the construction management and informatics literature and therefore offers traction in this field of research to add value across the domain. The application themes for DLT and SCs together with the mapping of the type of existing studies (e.g., insight, literature review, framework, proof-of-concept, case study) offer easily accessible information and a point of departure in this expanding field of research.

2.4.1 Socio-technical evaluation

In light of the socio-technical stance taken for this research and the four dimensions uncovered in previous sections (technology, process, policy, society), a socio-technical evaluation of the literature is made.

Technology

There are several *technology*-related challenges facing adoption of DLT and SCs in construction. First, redundancy of IT is considered when buildings typically have a lifespan of 50+ years but technology advances at a much more rapid pace to the extent a new technology could have superseded a proposed technology before a built asset is completed (Harty, 2019). Planned obsolescence of technology should be accounted for when choosing technology options where upgrading some devices and systems is straightforward (e.g., replacing modular control panels) but others are more complex (e.g., replacing sensors in cavity walls). Second, the nature of construction contracts suggests the level of support and regulation required by those adopting new DLT-/SC-based systems should be considered, especially during transition to SCs that could be unpredictable until properly tested (Di Giuda *et al.*, 2020b). While a technology challenge, this can also be linked to process and policy dimensions reiterating the need to consider all four dimensions.

Third, continuing with construction contact complexities, coding of SCs presents a challenge. Whether they are used to automate activities or represent legally binding constructs, they require rigorous testing to ensure they execute as planned before being deployed to ensure any incidences that are not right first time are minimised. The security considerations for SCs to ensure safeguarding against risks, threats and vulnerabilities in the code include confidentiality, integrity, non-repudiation, authentication and authorisation (Hasan and Salah, 2018). It is suggested that lawyers working with SCs must have an intimate knowledge of the many construction sector challenges as well as having an understanding of "*the singular operative approach allowed by the final form of the code*" (Brydon Wang, 2018, p. 4). Another threat posed by SCs is their reliance on external oracles that are not protected by the characteristics of an immutable DLT (Mason, 2017) raising the question of what happens if those data sources are no longer available? This challenge should also be considered under the process dimension due to the impact potential errors in coding could have on operations, and the policy dimension with regards the regulatory environment surrounding financial transactions where SCs are used for payments. The current instantiations of blockchain technologies are not designed to manage large volumes of data (Lee *et al.*, 2021) such as that required in management of BIM data (Das *et al.*, 2021b), while current DLT solutions are unable to offer the perfect triangle of security, privacy and decentralisation (Lee *et al.*, 2021), the likelihood of new platforms emerging in the near future is high. DLT provides a level of security to IoT data during processing and transmission, but devices could be tampered with and, therefore, provide erroneous data leading to ill-informed decisions (Penzes, 2018). This is referred to as 'The Oracle Problem' (Wilson *et al.*, 2020). Private blockchains can offer confidentiality of data, scalability and throughput from a smaller network of participants than in public blockchains but they remain open to malicious attack due to reduced security. Hybrid on- and off-chain storage could offer solutions to address this, for example, through integration with the IPFS for off-chain storage (Shahaab *et al.*, 2022).

Process

The main *process* challenge stems from resistance of the construction sector to the implementation of DLT and SC technologies due to disruption to current processes, costs of implementation, and potential unbalanced benefit distribution. Sargent *et al.* (2012) cite user acceptance as a critical success factor in the adoption of new technologies. There can be parallels with BIM adoption that could be more accentuated for DLT/SCs given the necessary process innovation required to support their development and implementation such as regulatory reform (a slow and arduous process) and technological advancements in other systems (e.g., BIM, IoT). This suggests that incremental changes that limit disruption during adoption will be more palatable to the sector. Indeed, the integration of DLT and SCs into existing systems will be more acceptable through a longer process to achieve the level of disruption required in the sector. Many organisations are still only at the start of digitalisation and so limitations in technological abilities arise (Graham, 2019). Innovators and early adopters must embrace interoperability (Lamb, 2018), which will reduce potential failures longer term.

An important consideration for organisational adoption will be tangibility of benefits and relative advantage to be gained. Tangible benefits (e.g., time and cost savings) on transactions that can be measured will drive decisions to adopt or reject a new system. However, benefits measurement is challenging due to inability to make like-for-like comparisons on construction projects due to their unique, one-off nature.

Policy

The *policy* dimension concerns regulation of DLT and SCs in a sector that is known for poor compliance with regulations and already requires reform. Data privacy is a challenge, particularly in public networks (Perera *et al.*, 2020) where the ethos of the first successful blockchain and Bitcoin was transparency of data. The 'right to be forgotten' – inherent in the GDPR – contradicts the immutability of DLT. Off-chain storage can provide a solution to this but then raises the issue of data security (Hamledari and Fischer, 2021a).

Admissibility of data on a DLT as evidence and liability of errors in SC code are likely to require a body of case law to be established. Reform of payment practices is required before new payment processes built on DLT/SCs can be embraced. Gradual adoption, the reality of most technological systems, will allow for steady technological and institutional change (Iansiti and Lakhani, 2017) that could see a change resistant sector open up to new possibilities eventually leading to transformation. Clients will be required to commit funds at the start of projects if they are to be embedded in SCs (Chong and Diamantopoulos, 2020) representing both a policy and process challenge in terms of revising payment structures and how they will impact businesses. Moreover, such benefits require sector-wide adoption if they are to be maximised (Li and Kassem, 2019a) such that a critical mass is achieved to cause disruption to the system where, "*to gain mainstream adoption, a platform has to be 'reliable'. It should move beyond being an intriguing innovation to becoming a mechanism for reliably solving a pain point and/or delivering benefit*" (Choudary, 2015, sec. 3). Such sector-wide adoption would not happen all at once; it could start with central government spending agencies (e.g., Highways England) and then migrate slowly to quasi-public and then private sector projects. The final policy challenge concerns tokens and cryptoassets that require underpinning "*by a well-defined regulatory framework*" (Collet *et al.*, 2019, p. 3) that sets out the terms of use. This is important as the application of NFTs are further explored.

Society

The final dimension, *society*, considers two points. First is the imposition of DLT-/SC-based systems on unaware end-users. Acceptance of changes to processes (e.g., automated recording of work completed), the required use of software platforms, and consent for the collection, processing and storage of data would be required for the participation of all project parties, which Iansiti and Lakhani (2017) identify as prerequisite for deriving maximum value from DLT. The second point concerns the impact of the new technological systems on individuals, organisations and the sector as a whole. Trust and change resistance are closely correlated; whether that is trust in the system specifically or in the advocate of the system (Culmer, 2012). DLT's disruption takes place at an institutional level where the two "*interact and mutually influence each other*" (Janssen *et al.*, 2020, p. 307). Societal acceptance will be key to the success of adoption of DLT and SCs, especially where financial and legal aspects are perceived as risky to change.

Where the four dimensions (technology, process, policy and society) intersect, aspects of co-evolution of DLT and SCs and the technological systems with which they will integrate are important. DLT and SCs are not standalone technologies, they will work in conjunction with other existing and emerging technologies to deliver the applications in the themes identified in this chapter. It is important to investigate how they would integrate with the current landscape of processes, standards and technologies adopted within the construction sector, or whether they would exert an innovation-led change of currently available processes and regulations within the sector.

2.4.2 Gaps in the literature

The systematic reviews, bibliometric analysis, and thematic analysis has offered a comprehensive review of the literature available on the subject of DLT and SCs in construction up to 2021. Gaps have been identified in the literature that warrant attention from industry and academia going forward.

Technological integration is lacking. There are only a few studies considering integration with digital twins (Götz *et al.*, 2020; Lee *et al.*, 2021), though it is gaining traction across all areas of the sector (Jones *et al.*, 2020). Further investigations here could unlock new capabilities in construction. NFTs, a complementary component of SCs, have seen little attention in construction with only Dounas *et al.* (2021) exploring their use for circular economy. NFTs are increasing in popularity in art and music (Hissong, 2021; Kastrenakes, 2021) and represent potential new applications for IP in construction. NFTs represent digital assets that can connect with real-world physical assets and be traded using secure digital wallets. They could lead to new business models and applications as more becomes known about their functionality. As discussed above in the process dimension, benefits management surrounding DLT and SCs requires focus. Studies are emerging that demonstrate benefits through simulations and PoCs, but real-world application is essential to show the real benefits. Finally, research is lacking that considers integration of DLT and SCs across the entire project lifecycle. Typically, the focus is on discrete applications rather than how DLT and SCs integrate across entire ecosystems with only Tagliabue *et al.* (2019) offering this. More attention is required as this presents many opportunities for the sector.

The essence of blockchain for financial transactions (e.g., Bitcoin) was to decentralise power, distribute consensus and provide transparency. Private DLT do not inherently encompass these aspects and public DLT struggle to overcome the issue of privacy (Hijazi *et al.*, 2019a). A lead of The Weather Ledger project was asked during a webinar (Wilmott Dixon, 2020) whether The Weather Ledger was to be deployed on a public ledger or a private ledger. The response was that it was to be a private ledger but hoped that in the future such applications would be deployed on public ledgers to embrace the true value of DLT. In a sector that is inherently resistant to change, it could be difficult to transition to public DLT even if deemed more appropriate once a precedent is set. Public DLT are more secure than private DLT and do not require trust whereas a private DLT operates on a much smaller network making it easier for malicious players to control the system (Sharma, 2020). Acknowledging that privacy is an issue in public DLT, solutions to this problem are being explored through the likes of EY's *zero knowledge proofs* (ZKPs) project that allows private transactions on a public ledger (EY, 2019) by assuring privacy of verified data without revealing the data itself (Pop *et al.*, 2020). In addition, the argument put forward for private ledgers with regards the speed of transactions in a public ledger and lack of scalability (Shojaei *et al.*, 2020) is a problem to be solved. The likes of the Lightning Network address this challenge by facilitating scaling of transactions on a public ledger, specifically, the Bitcoin blockchain.

Finally, there is a gap in the literature on the Building Safety Act 2022 (Department for Levelling Up Housing and Communities, 2022). Given the systematic reviews took place up to and including 2021, this is not surprising. However, it is also not present in the review of papers up to and including September 2022 discussed in the next Section 2.5. Future research should consider how the Building Safety Act 2022 will affect the construction sector and its implications for DLT and SCs.

2.5 An up-to-date review of literature on DLT and SCs in construction

Following publication of the systematic review in 2021 (Li and Kassem, 2021b), further papers were collected following the same protocols set out in Section 2.3.1. An additional 143 papers were collected up to and including September 2022. Given the increased number of publications over this period, only peer-reviewed journal articles from this collection were reviewed here. SLRs and studies not focused on applications or use cases of DLT and SCs (i.e., studies considering the potential of these technologies rather than proposing use of them) were excluded to direct focus to more advanced research (e.g., PoCs, real-world application). These exclusions resulted in an additional 29 noteworthy papers. The most populous theme was information management and almost all papers considered an element of this. This demonstrates recognition of the growing importance of information in construction projects and the role DLT and SCs can play across the asset lifecycle. There were no papers covering procurement reinforcing this as a gap in the body of literature to be filled. A summary of their content is provided below to demonstrate the latest research in the field of DLT and SCs in construction.

Information management received increased attention with several PoC studies demonstrating how blockchain can integrate with existing technologies to improve sharing, processing and storage of information. The IPFS was implemented by several authors (Tao *et al.*, 2021, 2022; Das *et al.*, 2022) to facilitate off-chain storage of data that is linked with blockchain. Tao *et al.* (2021, 2022) and Wang *et al.* (2022) propose this integration for collaborative BIM design whilst Das *et al.* (2022) use them alongside SCs in document approval workflows where the blockchain tracks versioning to provide immutable recordkeeping. Other research on information management includes a document management system to reduce disputes based on recording of email traffic on projects (Kim *et al.*, 2022); facilitate a single source of truth for the construction supply chain of BIM projects (Hijazi *et al.*, 2022); secure information (Pan *et al.*, 2022); provide provenance data based on real-time monitoring and data recording (Celik *et al.*, 2023); ensure integrity and authenticity of information (Lou and Lu, 2022); facilitate a secure and private chatbot communication platform (Adel *et al.*, 2022); reduce discontinuity and fragmentation of information sharing in modular integrated construction (Jiang *et al.*, 2021); offer notarised and certified information on-chain while data are stored off-chain (Cocco *et al.*, 2022); and reduce human error and increase transparency and reliability of onsite decision-making based on IoT devices and multi-party signatures (Ciotta *et al.*, 2021).

Payments received some attention primarily facilitated by SCs to automate payments based on BIM tender documents (Sigalov *et al.*, 2021), and the retrieval of information on cost and schedule from a BIM project required to estimate the value of each milestone transaction payment (Elghaish *et al.*, 2022). Ibrahim *et al.* (2022) automated cryptocurrency payments to satisfy the payment clauses of a construction contract whilst guaranteeing security of transactions reducing human interaction, time and cost.

In supply chain management, Li *et al.* (2022) proposed a decentralised architecture integrating BIM, IoT and blockchain to offer a single source of truth and eliminate a single point of failure in modular construction. Regulation and compliance was considered by van Groesen and Pauwels (2022) who simplified asset tracking using QR codes integrated with SCs to semi-automate compliance checking and payments for supply chains.

Wahab *et al.* (2022) demonstrated the speeding up of contract management by 90% through integrating blockchain and SCs whilst also achieving 100% more accurate data in comparison to traditional processes. Regarding onsite construction, health and safety was improved by deploying an unmanned aerial vehicle to automatically detect safety helmets using IoT, SCs and blockchain (Xiong *et al.*, 2022). SCs monitored emissions and evaluated environmental performance in the detection of pollutants at the construction site reducing conflict and disputes through trustworthy data (Zhong *et al.*, 2022). A consortium blockchain built on HLF for was integrated with IoT and ontology technology to automate on-site construction quality inspection activities and demonstrated reduction of workload for onsite inspectors (Wu *et al.*, 2021). And Wu *et al.* (2022) applied blockchain to provide more accurate information sharing for the assembly of modules onsite.

From a business model perspective, Lu *et al.* (2021b) addressed the challenge of governments adopting a decentralised blockchain system while maintaining a level of centralisation. This eliminated the need to change institutional practices in the supervision of construction projects. A two-level model illustrated by HLF was composed of a sidechain to maintain private records of transactions and a mainchain to provide proof of the transactions.

A decentralised platform to reduce construction disputes, increase transparency and reduce cost, time and effort was proposed following testing of a generic dispute resolution platform based on real-world data from two construction projects (Saygili *et al.*, 2022). The proposed framework aims to incorporate direct, on-time payments on a hybrid-blockchain. A smart construction objects-enabled blockchain oracles (SCOs-BOs) framework was proposed by Lu *et al.* (2021a) to achieve decentralisation and data authenticity based on SCs.

Research on digital twin was conducted by Teisserenc and Sepasgozar (2021) to improve cybersecurity, trust, efficiencies, information sharing and management, and sustainability in construction, and Hunhevicz *et al.* (2022) to automate performance-based payments demonstrated using Ethereum and Siemens' digital twin platform.

2.6 Summary

This chapter analysed the current state-of-the-art of research, and development of applications for DLT and SCs in the construction sector. It was established that these technologies be considered as socio-technical systems. Through evaluation of the literature, specifically, drawing out challenges and opportunities, four dimensions were identified that extend the socio-technical theory to include technology, process, policy and society. This extended socio-technical approach can demonstrate the potential success of any new DLT/SC implementation along with any challenges it may need to overcome as it will address political, legal and societal enablers alongside the technologies that are required to allow them to thrive. It has identified several challenges faced by these new systems that require attention before they can be accepted and integrated into construction sector practises. They include the security and privacy aspects of SCs, acceptance of DLT and SCs by individuals and organisations, and the robust regulatory environment required to allow these new systems to succeed.

Attention in DLT and SCs has substantially increased since the first paper in 2015 to the 153 sources systematically and thematically analysed revealing eight distinct themes of applications, plus the 143 additional papers collected following the second SLR in 2021, of which 29 were reviewed. The eight themes included: information management, payments, procurement, supply chain management, regulations and compliance, contract management and delivery, disputes and dispute resolution, and technological systems. Analysis of the data collected uncovered that DLT and SCs are part of wider technological systems such as BIM and IoT that have the potential to overcome some of the many challenges highlighted in the sections above. While many of the studies offer only insights to the domain, there is an emerging body of literature offering proof-of-concepts and case studies that present more tangible examples of potential benefits of these systems. The increasing and widespread attention these technologies are receiving in the construction domain demonstrate that they do have the potential to make positive and lasting change to the arguably archaic way in which the construction sector operates. What is required going forward is investment into technological integration projects and real-world pilots. This study's research and findings serve as a springboard for further advancement in the field of DLT and SCs for construction. The comprehensive extraction and consolidation of data from the wealth of available research enables industry and academic investigators to use the findings as a resource directory to support their research and development activities in this rapidly growing field.

CHAPTER 3 | Methodology

3.1 Introduction

This chapter presents the methodology adopted for this thesis. The ontological and epistemological positions within the research philosophy are discussed along with the research design chosen to underpin the research conducted. It then highlights the type and approach of the research before discussing the research methods applied. It finishes with ethical considerations. Figure 3.1 demonstrates the methodological choices as set out in the remainder of this chapter starting with research theory on the left moving to research practice on the right. The numbers in each box correlate to the sub-section in which they are discussed below. The items underlined in Figure 3.1 represent the choices taken for each methodological element; the items greyed-out are the options considered but not selected for this study.

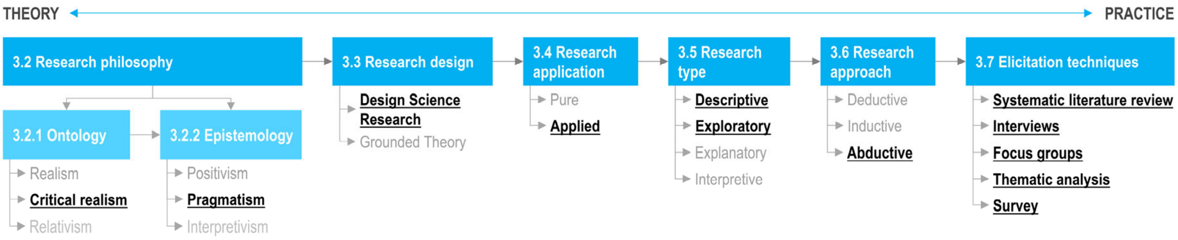

Figure 3.1: Methodological choices from theory to practice

Figure 3.2 shows the elicitation techniques employed for this thesis and indicates to which elements of the framework they contributed.

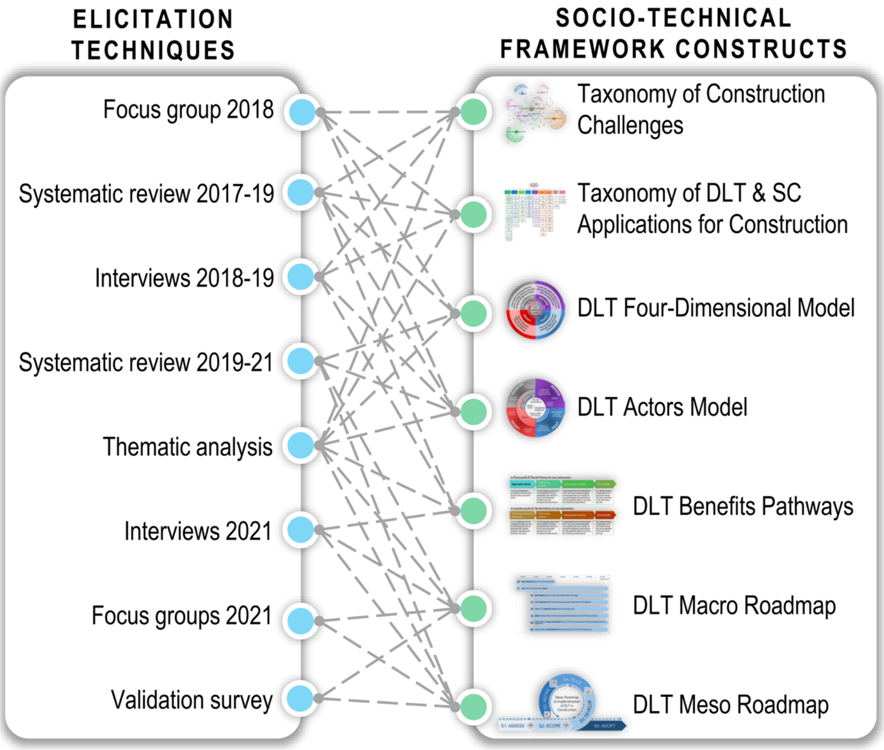

Figure 3.2: Research methods and the framework constructs they supported

3.2 Research philosophy

The research undertaken for this study was qualitative in nature, that is, understanding phenomena from the perspectives of the individuals as participants (Ritchie *et al.*, 2014). Qualitative research paradigms tend to take the view that there is not only one version of reality (Clarke and Braun, 2013). Robson and McCartan (2016) view the social dimension as key to addressing problems and issues in real-world research. This section will describe the ontological and epistemological positions considered and the choices taken for this research.

3.2.1 Ontological position

Ontology refers to the philosophy of *what is* – "*the kinds and structures of objects, properties, events, processes and relations*" – for every facet of social reality (Smith, 2003, p. 155). It is about the relationship between individuals and the world in which we live (Clarke and Braun, 2013). Three branches of ontology are discussed: relativism, critical realism and realism.

One ontological position is that the world exists entirely separately from human experience and that there is a single truth, referred to as ***realism*** (Clarke and Braun, 2013). Realists do not hold the view "*that socially constructed realities describe the universe of influences or even the most critical influences on human experience*" (Tebes, 2005, p. 220), but that in fact, experience comes from common sense and is the basis of understanding (Tebes, 2005). An alternative position considers that human experience and the world are inseparable, that human perspective indicates how we think about the world and there are several 'truths', referred to as ***relativism*** (Clarke and Braun, 2013). ***Critical realism***, on the other hand, allows for a middling view where the real world exists independently, that human experience and interpretation are also valid constructs, and that the two are not mutually exclusive (Peters *et al.*, 2013). Critical realism, established by Bhaskar (2008), has three domains; "*the real (the mechanisms that generate phenomena at the level of the actual), the actual (the events that occur) and the empirical (our experience of those events)*" (Peters *et al.*, 2013, p. 338).

This research takes the position of critical realism as it allows collection of the views of multiple perspectives and the ability to then make generalisations. Blockchain and other DLT are technological systems that exist to support societal functions. It is on this basis that the research conducted for this study aimed to observe the social interactions of the construction sector and how day-to-day interactions of individuals across projects and organisations can be impacted by their integration. It aimed to consider the real-world challenges of the construction sector from a subjective stance to ensure that any proposed solutions meet the needs of those intending to use DLT and not the needs of pre-prescribed standards and procedures that are rarely followed as intended.

3.2.2 Epistemological approach

Epistemology relates to the acceptable knowledge of a discipline (Bryman, 2016); it is a facet of philosophy concerning "*the origins, nature, methods and limits of human knowledge*" (Fellows and Liu, 2015, p. 70). Epistemology concerns how knowledge is obtained of the world and reality that we live in (Ritchie *et al.*, 2014). Two epistemological approaches appear to dominate construction management research, positivism and interpretivism; both are discussed alongside a third, pragmatism, that offers a more flexible approach.

Positivism separates observation as a practice, the observer and the observed. It is rooted in data collected from unbiased perspectives (e.g., objectively) under controlled conditions (Clarke and Braun, 2013). Positivism was established from the perspective of a staged process to uncover universal laws moving from "*the theological, to the metaphysical to the positivist or scientific*" (Schweber, 2016, p. 842). Positivists hold the view that social science research should in fact be carried out in the same way as in the natural sciences (Henn *et al.*, 2005). From Love *et al.* (2002, p. 296), facts are considered "*distinct from values or meanings*", theory is generated from the testing of hypotheses and looks for cause and effect relationships. Henn *et al.* (2005) explain that in positivist research, empirical investigations are continually trying to falsify a previously established theory through repeated observations, and through failure to falsify it, confirm the theory.

Interpretivism relies on subjective interpretations of the social world (Ritchie *et al.*, 2014; Bryman, 2016). It acknowledges that there are several realities each valid in their own right; it is the job of the researcher to interpret these realities (Fellows and Liu, 2015). Three levels of interpretations take place in interpretivist studies – interpretation of the subject, that is then interpreted by the researcher, that is then re-interpreted in the context of existing theories, concepts and literature (Bryman, 2016). The focus is on the perspectives of those individuals who have lived the experiences accounting for factors of psychology, society, history and culture to shape their cognisance of the world (Ritchie *et al.*, 2014). Researchers choosing this approach often struggle with objectivism and the separation between the nature of reality and what is perceived by individuals (Robson and McCartan, 2016). For this reason, it is open to prejudice and subjectivity but equally can be applied to a small-scale data sample "*utilising a thorough yet descriptive position of the phenomena*" (Ahmed, 2019, p. 60).

Pragmatism does not subject the researcher to just one approach, rather it is grounded in the idea that flexibility to choose the most appropriate research design will yield the best results (Ritchie *et al.*, 2014), specifically, choosing "*what works*" (Robson and McCartan, 2016, p. 28) to investigate the problem at hand. This approach purports that problems of the real-world can be solved by employing a mixture of methods (Feilzer, 2010). It allows for changes in truth over time and accepts that both the natural and social worlds are important. Pragmatists are more likely to utilise research methods that provide the best environment to answer the underlying questions rather than being limited by the dichotomy of positivism or interpretivism. However, there is an argument that pragmatism provides the researcher with an option to reject more traditional philosophies and often fails to answer the question of whether the solution is useful (Johnson and Onwuegbuzie, 2004).

The fundamental difference between positivism and interpretivism is that they ask different types of questions; positivism assumes a stance of a single reality, whereas interpretivism assumes multiple realities (Schweber, 2016). The former can also be of a natural scientific school of thought while the latter a social scientific school of thought (Love *et al.*, 2002).

This research adopted the pragmatist approach given the field of DLT and SCs is still considered a new concept for the construction sector. Therefore, this means there are limitations on the population sample that could be selected for participation with sufficient knowledge to elicit robust findings. The subjective opinion of the participants was material to this study as it attempted to understand how academics and industry practitioners perceive the world based on their subjective experiences to support creation of a framework that would be applicable to the those using it rather than offering an objective framework. However, understanding the objective reality in light of the sector' resistance to change demonstrated throughout this thesis as found in literature and empirical investigations, is as important as understanding subjective positions of the participants. On this basis, a pragmatist approach was deemed most appropriate to allow for a broader scope of inquiry.

3.3 Research design

Research design provides a framework upon which to conduct research supporting data collection and analysis whilst offering indications of appropriate research methods (Walliman, 2011). Design science research and grounded theory have become popular research strategies to adopt in information systems (IS) research (Gregory, 2010). Both are discussed forthwith.

As a research paradigm, ***design science research*** (DSR) (Hevner, 2007) is relatively new gaining traction since the 1990s (Peffers *et al.*, 2007). It has been used successfully in software engineering, computer science and information systems research (Succar and Poirier, 2020). It is well-suited to the development of socio-technical artefacts (Herselman and Botha, 2015). DSR is defined by Hevner and Chatterjee (2010, p. 5) as "*a research paradigm in which a designer answers questions relevant to human problems via the creation of innovative artifacts, thereby contributing new knowledge to the body of scientific evidence*". March and Smith (1995, p. 251) define the outputs of such innovative artefacts as "*representational constructs, models, methods, and instantiations*". Included in these are social innovations or indeed any designed artefact that embeds a solution to a research problem (Peffers *et al.*, 2007). The rigour of DSR lies in the ability of the researcher to select the suitable theories and research methods to support development and evaluation of the artefact (Hevner, 2007) as well as demonstrating proof of usefulness (Peffers *et al.*, 2007). It meets at the intersection between traditional scientific inquiry and context-aware solving of problems derived from practical situations that suit both traditional academic research and the ability to solve real-world problems (Dresch *et al.*, 2015).

A DSR methodology (DSRM) process model (Figure 3.3) made up of six activities is offered by Peffers *et al.* (2007): identify problem and motivate; define objectives of a solution; design and development; demonstration; evaluation; communication. While the activities are shown as a sequence, they do not need to be tackled in a sequential order (Peffers *et al.*, 2007) and its iterative nature allows for contemporaneous development and evaluation of artefacts (Succar and Poirier, 2020). Figure 3.3 shows the different entry points for following this methodology for DSR (as indicated in the box at the bottom of Figure 3.3). This demonstrates flexibility and suitability to many different IS-related research projects.

Glaser and Strauss (1967) conceived of ***grounded theory*** with the vision of generating theory from data. It was developed from a backdrop of sociology but has since been used in other fields of inquiry including organisational research (Länsisalmi *et al.*, 2004) and IS research (Japhet and Usman, 2013). It is a methodology for data analysis of qualitative studies (Länsisalmi *et al.*, 2004). Grounded theory is an iterative process of the systematic discovery and development of theory from collected and analysed data that involves five core tenets: (a) the constant comparative method, which involves the simultaneous activities of data collection, coding and analysis; (b) theoretical coding, where the data are interpreted and then categorised and grouped to identify properties, boundaries and dimensions of each category; (c) theoretical sampling, that guides the research sampling in a logical manner based on analysed data already collected to direct further samples with which to refine the theory; (d) theoretical saturation, this is the point at which no new information can be gleaned from the collection of more data – the categorisation is considered saturated; and (e) theoretical sensitivity, which is the ability of the researcher to

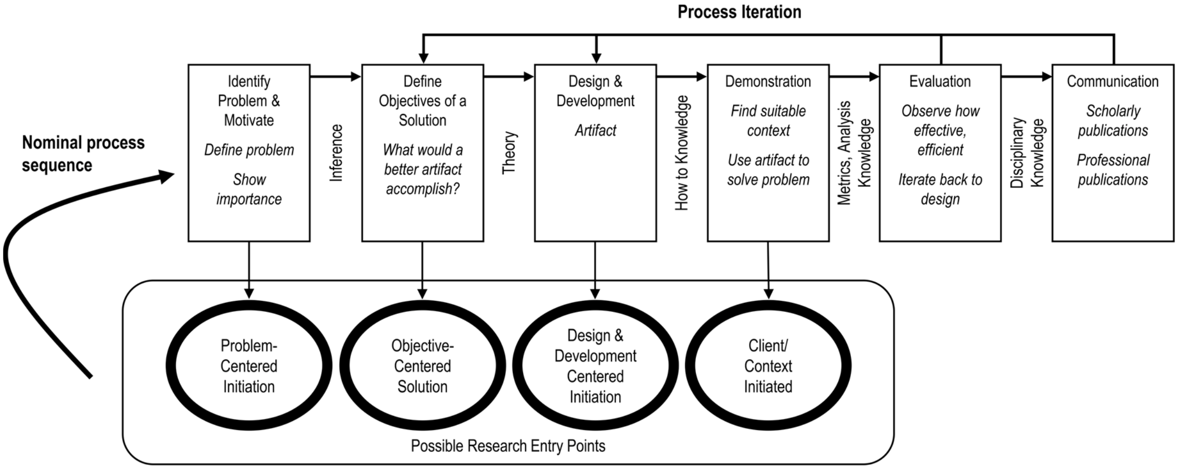

Figure 3.3: DSRM Process Model (recreated from Peffers et al., 2007, p. 54)

provide meaning to the data collected and identify those data relevant to the emerging theory (O'Reilly *et al.*, 2012).

Grounded theory is a rigid methodology and failure to follow the steps as designed will likely result in poorly conceived theory. Indeed, O'Reilly *et al.* (2012) highlight cases in which researchers have applied only the coding element of the methodology and not its core which is to develop robust theory. Four pitfalls of grounded theory are discussed (O'Reilly *et al.*, 2012). First, getting trapped by the concentration site – researchers fail to move beyond the initial theoretical sampling where data collection starts resulting in omission of variants and therefore limitation of meaning. Second, failure to follow the story in the data – not employing the constant comparator method resulting in limitations in the data analysis. Third, coding for content, not theory – researchers use grounded theory only for data coding and analysis and miss the other important tenets of the methodology. And fourth, using grounded theory where it is not well suited such as areas that are already well versed in literature, already have tested hypotheses, or seek to imitate other studies.

Given the nascence of this field of research, grounded theory was considered as a research methodology to apply as no theory currently exists on which to test hypotheses. However, it was felt the rigidity of the methodology restricted the research to specific avenues of inquiry whereas DSR offered a more flexible approach. Therefore, DSR was the chosen methodology for this research.

It will be shown throughout this thesis that the dimension of society plays a large part in the success of information systems. It is often a dimension that is forgotten or intentionally omitted in IS research (Neff *et al.*, 2010). The construction sector has many challenges that have remained unresolved for many years (see Section 5.2.1 for the taxonomy of construction sector challenges). Often, blockchain and DLT are discussed as "*a solution looking for a problem*" (Niranjanamurthy *et al.*, 2019, p. S14749); Hevner (2007) opines that DSR is about potentiality, that is identifying opportunities to make improvements before problems emerge. While the problems are clearly present in construction, there is a potential solution in DLT and SCs that seek to solve problems with both technological and societal systems and DSR is used to investigate the intersection between the two (Lee, 2001, cited in Hevner and Chatterjee, 2010, p. 6).

Following DSR, Figure 3.4 shows how this study followed the DSRM process model starting with the entry point of problem-centred initiation. The only activity that has not been completed for this study is demonstration, which will constitute further work that will see the framework applied to real-world projects that seek to explore the implementation of DLT and SCs in construction sector applications.

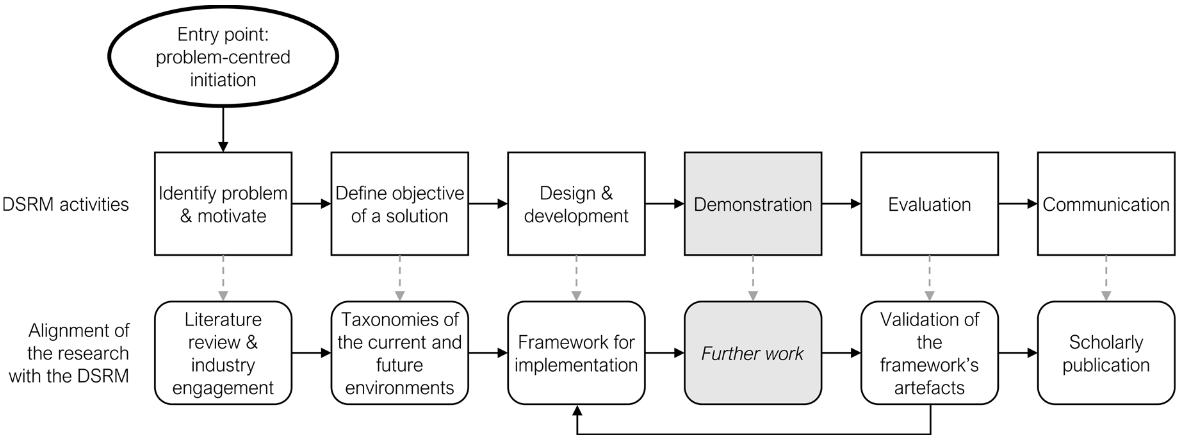

Figure 3.4: Alignment of the research with the DRSM process model

3.4 Research application

There are two distinct types of research application: pure research and applied research. ***Pure*** research focuses on making generalisations about an idea and the discovery of theories whereas ***applied*** research aims to solve the problems a society, organisation or industry is facing (Pócza and Dobos, 2018). This can be done through the creation of artefacts developed through DRS (Gonzalez and Sol, 2012). In construction, a large portion of the research conducted takes the form of both pure and applied research (Fellows and Liu, 2015). Carvalho (2012, p. 6) explains the aim of applied research to serve "*some practical human purpose*", a stance from which design research can be viewed. The research conducted for this study can be described as applied research in that it aims to solve problems in the real world by proposing a socio-technical framework that could be used to inform policy and support creation of an ecosystem ready for the adoption of new technologies.

3.5 Research type

There are several types of research that define the underlying basis for inquiry. This section considers descriptive, exploratory, explanatory, and interpretive types.

Descriptive research looks at the state of a concept in its current existence by asking *what* type questions (Gray, 2018). It uses historical and current data to draw inferences and the researcher has no control over the variables (Kothari, 2004). It is often used for frequency data (Pócza and Dobos, 2018). It looks to record all elements of a particular phenomenon, process or system and will be conducted from a specific perspective with a particular purpose in mind. Objectivity and comprehensiveness are key to descriptive research. This research type typically uses surveys and/or case studies and leads to categorisation of the subject matter (Fellows and Liu, 2015). ***Exploratory*** research is used when little is known about a phenomenon through, for example, literature reviews, talking to subject matter experts and holding focus groups (Gray, 2018). Where theories exist, research will be used to test those theories through development of propositions or hypotheses. Studies conducted under exploratory research are also referred to as "*formulative research studies*" (Kothari, 2004, p. 2) that involves formulating a problem or the discovery of new constructs and variables for further in-depth investigation (Pócza and Dobos, 2018). ***Explanatory*** research is similar to exploratory research in that it looks to generate hypotheses of a certain theory and test them through research. However, more is generally known about the theory in explanatory research than exploratory research (Fellows and Liu, 2015). *How* and *why* questions are asked in explanatory research to discover causal relationships between the variables under investigation (Gray, 2018). ***Interpretive*** research is used when empirical data cannot be collected, for example, analysis of a historical event is required. Findings from experiences are fit to existing theories or models where interpretation is made based on the understanding and actions of the people experiencing events or analysis information (Fellows and Liu, 2015). Typically, interpretive studies are inductive and are rooted in qualitative research methods (Gray, 2018).

The majority of the research conducted for this thesis took the form of exploratory research given that very little is known about the blockchain/DLT phenomenon within the context of construction. In addition, the study utilised descriptive research to consider the current state with regards DLT and SC applications in construction and the challenges the sector faces. A small quantitative element was employed for validation of constructs. This mixed methods approach also enables triangulation. Bryman (2016, p. 697) defines triangulation as research conducted using "*more than one method or source of data in the study of a social phenomenon so that findings may be cross-checked*". Triangulation has the benefit of being able to corroborate findings from one form of research against another (e.g., using qualitative research to support quantitative findings and vice versa, where one set of results may differ to the other based on the research approach taken). Gray (2018) adds that different research questions require different research methods, each with their own strengths and weaknesses, so methodological triangulation is often more appropriate as it helps to provide a balance between different sets of data.

3.6 Research approach

Research approaches can be put into three categories: deductive, inductive and abductive. In ***deductive*** reasoning, a common theory already exists and empirical research is conducted to test hypotheses around that theory (Bryman, 2016). An *a priori* position is taken (Johnson, 2004). ***Inductive*** reasoning is loosely based on the opposite approach where theories are borne out of observations and/or findings from empirical research, including when that research is qualitative (Bryman, 2016). The evidence from empirical research forms the "*genesis of a conclusion*" (Ritchie *et al.*, 2014, p. 6) that generates knowledge and theory. Here, an *a posteriori* position is taken (Johnson, 2004). Qualitative studies are often considered inductive in nature; however, this oversimplification neglects the reality that studies often combine both deductive and inductive approaches if not only from the base knowledge of the researcher that will influence how inductive research is conducted (Ritchie *et al.*, 2014). Thus, this leads to ***abductive*** reasoning, which draws on both deductive and inductive theories where theoretical understanding is gained from the participants' view of the world (Bryman, 2016).

Although many of the constructs presented in this thesis were derived from data and not first grounded in theory, they were developed with prior knowledge of similar theoretical constructs and research methodologies that influenced how they were constructed. On this basis, the research that underpinned this thesis was abductive in nature.

3.7 Elicitation techniques

Generally, no single research method or elicitation technique can be considered consistently appropriate as good research practice because different projects and contexts require different approaches (Zowghi and Coulin, 2005). This study, therefore, uses several research methods for different stages of enquiry. They are depicted graphically in Figure 3.2 at the beginning of this chapter.

3.7.1 Systematic literature reviews (SLRs)

Systematic literature reviews (SLRs) have been widely used since the 1990s (Tranfield *et al.*, 2003). Originally adopted by the medical field, they are now used in all research areas (Becheikh *et al.*, 2006). This approach provides evidence required for robust decision making on a global scale. The purpose of SLRs is to understand the current level of research of a particular field and to guide development of research questions to further the body of knowledge (Tranfield *et al.*, 2003). Kitchenham (2004) explains that SLRs allow a researcher to identify gaps in the research used to direct further investigation, offer background to support framework development in the case of new research, and support or challenge theoretical hypotheses. The methodology of an SLR is such that all existing studies are located within the parameters set by the researcher who then follows a selection process to evaluate, analyse and synthesise the body of research on a specific subject to draw conclusions about what is or is not known about that subject (Denyer and Tranfield, 2009).

In contrast to traditional literature reviews, SLRs typically offer explicit objectives and measurement criteria applied to the totality of research, which gives the results integrity due to application of a robust methodology with conclusions used in key decision-making (Becheikh *et al.*, 2006; Bronson and Davis, 2011). Failure to highlight strengths and weaknesses of work being reviewed, including one's own and that which supports a researcher's contribution, is a weakness of the researcher. Therefore, they should take an objective opinion of the research ensuring justified, fair and critical analysis is conducted considering all strengths and weaknesses regardless of whether they support the researcher's contribution or not (Baumeister, 2013). The advantages and limitations of

SLRs are highlighted in Table 3.1.

The technique of SLR was chosen for this study initially to understand the current level of interest and research into DLT and SCs for construction. These advantages and limitations were taken into consideration to maximise the quality of the reviews and minimise any potential emissions or biases. Subsequently, continuation of the SLR was adopted to track advances in the field of research throughout the duration of this study. Two SLRs were conducted for this study. The first took place in 2017-19 when the literature specific to construction was sparse; the second took place in 2019-21 when the construction-specific literature had substantially increased. The results of the SLRs are presented in Chapter 2.

3.7.2 Focus groups

According to Stahl *et al.* (2011, p. 381), focus groups "*can be particularly valuable in exploring and recognising the socio-technical nature of IS*". Having proliferated substantially over the last century, focus groups are now used in many different sectors, within and across boundaries to discover collective opinions through a group interview setting (Kamberelis *et al.*, 2018). Focus groups allow a researcher to engage with and obtain specific and directed information from a group of purposefully selected individuals (Saunders *et al.*, 2012) facilitated by a moderator (Stahl *et al.*, 2011). They can be used for a range of purposes including exploration of new topics; evaluation of a product, service, intervention etc.; and to obtain diversity of views (Hennink, 2020). In contrast to group interviews where individuals are asked questions in turn, focus groups are designed to promote discussion *between* participants on the topic in question allowing for agreements, disagreements and debate about pertinent issues (Wilkinson, 2006). They offer flexibility in terms of their effectiveness for groups known or unknown to each other, and for one or more groups once or on many occasions (Wilkinson, 2006). They draw on participants' "*attitudes, feelings, beliefs, experiences, and reactions in a way that is not feasible using other field methods*" (Stahl *et al.*, 2011, p. 381) such as interviews or surveys. And they can limit gaps in individuals' knowledge, experience or memory through providing prompts and

Table 3.1: Advantages and limitations of Systematic Literature Reviews

Advantages of SLRs	Limitations of SLRs
• If done effectively, SLRs can help to avoid bias through critically reviewing literature (Baumeister, 2013). However, risks remain that the sources being reviewed could contain bias from the outset (Kitchenham and Charters, 2007). As the full body of knowledge is being reviewed, SLRs have the ability to self-right any bias and help to prevent researchers by being swayed by that bias (Petticrew and Roberts, 2006). • Researchers can see all perspectives of a subject especially if it has been researched from different angles and different methodologies have been applied. This highlights both consistencies and inconsistencies and demonstrates the strength of the research (Kitchenham and Charters, 2007). • Quantitative metrics can be applied to evaluate studies, particularly where the body of knowledge is large, which can help to synthesise the work integrating the findings and enrich the understanding (Cronin *et al.*, 2008).	• Given that significantly more sources are typically reviewed as part of an SLR, they take substantially more time and effort to complete than traditional literature reviews (Kitchenham and Charters, 2007). • Depending on the level of interest and/or newness of a subject area, researchers could find themselves inundated with hundreds or thousands of papers for review. Applying inclusion and exclusion criteria is good practice within SLRs but there is the possibility the literature could be narrowed too much to the extent the remaining literature loses meaningful contribution as a whole (Stewart and Tierney, 2002). • Qualitative analysis of the literature is subjective with regards methodological judgements that support the reviewer's decision to include/exclude an article based on quality (Bryman, 2016).

recollection by other participants in the group.

Given the group setting of focus groups, they can sometimes be challenging to control and participants may be reluctant to participate (Queirós *et al.*, 2017) if one or more people tend to dominate discussions (Nili *et al.*, 2017). There is also a risk that the participants are not representative of the population (Queirós *et al.*, 2017). Several researchers discuss a limitation of analysis of focus group data whereby researchers analyse the content only and omit the interactions between participants that can be critical to the findings (Wilkinson, 2006; Stahl *et al.*, 2011; Nili *et al.*, 2017).

Adopting a semi-structured approach to this method, this qualitative elicitation technique was chosen at different stages of the research. First, it was used to gauge the interest of individuals on the topic of DLT and SCs in construction and discuss the proposed plan of research for this study. A face-to-face focus group with eight participants took place in January 2018 in Newcastle-upon-Tyne in the UK, the results of which can be seen in Chapter 4. Two further focus groups were conducted in April 2021 to support development of a roadmap for the implementation of DLT and SCs in the construction sector. Given the geographical dispersion of participants, these two sessions took place synchronously and online lasting two hours and one hour and 15 minutes respectively. The synchronicity mimicked face-to-face interaction and the online approach allowed for access to a wider pool of participants, was inexpensive to run, and facilitated framing of the research problem in a short period of time (Abrams and Gaiser, 2017). The second focus group had eight participants from the United Kingdom (UK), the United Arab Emirates (UAE), Hong Kong and Australia while the third focus group consisted of six participants dispersed throughout the UK. Time differences for participants can be an issue (Abrams and Gaiser, 2017). However, the Australia-based participants were happy to join the session in the evening, which suited the Western-based participants where it was morning. They were conducted via Zoom to allow for consented video recording and accessibility for all participants. Miro, an online, visual collaborative whiteboard was used to record written contributions and facilitate discussions. The results of the focus groups are presented in Chapter 4.

3.7.3 Interviews

Interviews are the most widely used form of qualitative research method employed due to their flexibility for the researcher (Bryman, 2016). They are used to gain insights into the perspectives and experiences of participants of a specific issue, situation or event (Kaplan and Maxwell, 2006). They are distinct from other research methods because they engage "*participants directly in a conversation with the researcher in order to generate deeply contextual, nuanced and authentic accounts of participants' outer and inner worlds*" (Schultze and Avital, 2011, p. 1).

Interviews can take three forms – structured, semi-structured and unstructured. Structured interviews resemble a questionnaire where the researcher asks the participant predefined questions without wavering from those questions and records their response; there is little flexibility in this approach. At the other end of the spectrum, unstructured interviews involve the researcher raising a topic for discussion and recording what the respondent says, typically with little or no prompting other than to keep the discussion (or monologue) going. This requires substantial skill on the part of the researcher to execute this successfully and can result in "*lack of comparability*" between interviews with different participants (Kothari, 2004, p. 98). Between the two sits semi-structured interviews. Here, the researcher might have set questions or prompts to direct the conversation though they are less rigid than with structured interviews. This approach allows the researcher to direct the discussions whilst allowing the participant to raise points that may otherwise be missed. This adds structure to collection of the data (Fellows and Liu, 2015). Analysis of interviews requires objectivity from the researcher to understand and interpret the views of the interviewees as they intended, from their perspective (Fellows and Liu, 2015). The strengths and weaknesses of interviews are shown in Table 3.2.

Table 3.2: Strengths and weaknesses of interviews

Strengths of interviews	Weaknesses of interviews
(i) More information than other research methods can be obtained and often in greater depth (Kothari, 2004).	(i) Conducting interviews can be expensive, particularly when the sample population is widespread geographically and face-to-face interaction is required (Kothari, 2004).
(ii) Interviews provide the possibility of exploring several levels of meaning within a subject (King, 2004).	(ii) Bias of the interviewer and the participant could be present (Kothari, 2004).
(iii) It is possible to obtain an almost perfect sample of the general population as the researcher selects respondents carefully to meet their objective (Kothari, 2004).	(iii) Certain participants (e.g., government officials, corporate executives) may not be forthcoming with relevant data (Kothari, 2004).
(iv) Through the skill of the researcher, samples can be controlled more effectively so non-response generally remains very low (Kothari, 2004).	(ix) Conducting interviews can be time-consuming, particularly when the sample size is large (Kothari, 2004). Equally, they can be time-consuming for the participants (King, 2004).
(v) Interviewees are typically happy to be interviewed and often like to be given the opportunity to talk about their work, which results in rich data (King, 2004).	(x) Processing of the data can be overwhelming due to the amount to data interviews can produce (King, 2004).
(vi) Unstructured and semi-structured interviews offer flexibility to restructure questions as the need arises (Bryman, 2016).	(iv) Effective interviews require rapport between the interviewer and interviewee to facilitate free and frank responses. Where participants are not known to one another in advance or the relationship between the two is challenging, this can affect the responses (Kothari, 2004).
(vii) The interviewer can adapt their language to the respondent based on, for example, level of education, to avoid misinterpretation of the questions (Kothari, 2004).	(v) There is a risk interviewees could use the interview process to leverage organisational change and respond to questions accordingly (Schultze and Avital, 2011).
(viii) Supplementary data of the respondents' characteristics can be captured to support interpretation of results (Kothari, 2004).	

Interviews were chosen as an elicitation technique for this study because it was important to understand the challenges individuals face in their day-to-day activities and to identify if DLT and SCs have the potential to address some of these challenges. A semi-structured approach was adopted to guide the discussions to meet the objectives of the interviews as well as allowing important aspects to arise that might be impeded by a structured approach.

Interviews took place at two stages during the study. First, a series of semi-structured interviews was conducted with 13 people from across the construction sector between April 2018 and June 2019. The results of these interviews are presented in Chapter 4 (Section 4.3). The second stage of two consultation interviews took place in April 2021 with industry practitioners who were involved in establishing DLT-/SC-based applications for the construction sector. These interviews were precursors to industry focus groups and are discussed in Chapter 4 (Section 4.4.5).

3.7.4 Thematic analysis

Analysis of qualitative data can follow several methods such as analytic induction, content analysis, and thematic analysis. ***Analytic induction*** looks for causal explanations in qualitative research (Katz, 2001), which is not the purpose of this research; rather this research aims to allow the data to present a picture of the construction sector in its current state whilst engaging with industry practitioners to determine the proposed and/or preferred future state. ***Content analysis*** can be used for both quantitative and qualitative analysis and aims to make sense of data where phenomena are reduced to defined and meaningful categories (Harwood and Garry, 2003). Content analysis uses well-defined rules of coding to organise large sets of data relatively easily (Stemler, 2000). Using such defined rules could stymie the ability of the data to speak for itself. On this basis, ***thematic analysis*** was the elicitation technique chosen for this research. It is defined by Braun and Clarke (2012, p. 57) as "*a method for systematically identifying, organizing, and offering insight into patterns of meaning (themes) across a data set*". This systematic methodology was conceived as grounded theory by Glaser and Strauss (1967) in which a reviewer takes a collection of qualitative data and reviews it repeatedly to discover codes, which are then grouped into concepts and, finally, categories (Allan, 2003). This data-driven approach allows codes to emerge from data due to lack of existing theory in a field (DeCuir-Gunby *et al.*, 2011). While the research design methodology of grounded theory was excluded for this research, as explained in Section 3.3 above, thematic analysis as a standalone method of data analysis was applied to allow such systematic review of the data.

A three-stage process of thematic analysis was proposed by Williams and Moser (2019). The first stage, *open coding*, aims to identify broad, initial themes to support interpretation of the data and concepts that arise. These initial themes should not be coded with any preconceived ideas of what the final themes might represent. This way, the body of literature can be viewed objectively. The second stage, *axial coding*, refines the initial themes and aligns them into something more meaningful. The *constant comparator* method was applied throughout this stage that allows revising codes and going back over initial literature as the themes emerged ensuring all relevant data were extracted. The final stage, *selective coding*, further refines and consolidates the themes into meaningful expressions.

Thematic analysis was used to analyse data from the SLRs, the interviews and the workshops to evaluate and categorise the data.

3.7.5 Survey

Validation is addressed separately in Chapter 7; however, this section introduces the need for validation of artefacts and the elicitation technique—a survey—used to conduct validation of the roadmaps.

Surveys allow a researcher to collect a large amount of data in a short period of time from a sample that is geographically dispersed. They take the form of well-defined and well-written questions to elicit information from individuals without the need for interaction with a researcher. They are low cost and typically easily disseminated (e.g., via email or social media). Limitations of surveys include limited depth of data; follow-up questions are often not possible due to either anonymity of the respondent or inability to connect with them directly; responses can often be impacted by the mood of the respondent on the day, especially when feelings on the subject matter are being sought (Lazar *et al.*, 2017).

Evaluation is a central facet of DSR (Sonnenberg and vom Brocke, 2012), the research methodology adopted for this study. Evaluating the validity of a developed artefact is key to measuring its potential impact on real-world application. Without such, the validity of the artefact is threatened due to difficulties in assessing whether the desired goals have been met (Remy *et al.*, 2018). Indeed, the artefact's quality is rooted in the context in which it is applied (Fischbach *et al.*, 2020).

For this research, the focus is on external validity of the framework artefacts and, specifically, validation of the two roadmaps produced following focus groups with industry practitioners. External validity evaluates the ability of findings to be "*generalized across different social settings*" (Clark *et al.*, 2021, p. 363). A mixed methods survey was employed to validate the roadmaps. Given the scope of the roadmaps and framework in its entirety, this study did not aim to verify and validate all the models therein in terms of real-world application; this is included in future work (see Section 8.6). However, it did aim to obtain views of the roadmaps from industry practitioners and academics including those who participated in the focus groups and those who did not. The survey elicited opinions of the roadmaps regarding clarity, accuracy and usefulness. These metrics are in line with DRS as per Peffers *et al.* (2007) who discuss usefulness as central to artefacts developed under this methodology. The results of the survey are presented in Chapter 7.

3.8 Research ethics

This research was subject to ethical scrutiny by Northumbria University with approval granted under reference 4653. The ethical considerations for this study included confidentiality; potential harm to participants; data storage; and informed consent for each elicitation technique involving individuals.

The interview and focus group participants of this study were provided with detailed participant information sheets setting out the research, their role in it, and how their data was to be processed and stored. Participants were asked to sign a consent form agreeing to how their data would be used. An example of the participant information sheet and consent form can be seen in Appendix B. Survey respondents were informed of their role in the study and provided with details of how their data would be used. By completing the survey, the respondents gave their consent to their anonymised data being used.

3.9 Summary

This chapter has presented the philosophical and methodological choices made for this study. It opted for a critical realist ontology whilst adopting a pragmatist epistemology given the qualitative nature of the research conducted alongside the need for subjective opinion of the participants engaged. Design science research (DSR) was chosen as the best methodology for developing artefacts for information systems that has a focus on evaluation of their effectiveness in the real-world. The study can be considered applied research as it aims to solve the problems of society. The study adopted an exploratory type of research given the novelty of the field. It was abductive allowing for the inductive nature of research to generate new theory from data whilst applying well-established methodologies to ground that development through deductive means. A range of elicitation technique were applied resulting in a mixed methods approach to allow for triangulation to check for consistencies in the findings. A systematic literature review was conducted in two waves accounting for the increasing interest in DLT and SCs throughout the duration of the study. Three focus groups were utilised at different stages of the research; first, to understand general consensus and potential of the technologies and, second, to elicit expertise to support readying the ecosystem for these technologies. Interviews were conducted in a similar manner to the focus groups – first, to obtain early opinion on the potential of the technologies and then to support the development of implementation roadmaps. Thematic analysis was employed to make sense of the data collected through the focus groups and interviews. Finally, a survey was conducted to validate the roadmaps. The ethical considerations given to this study were also highlighted.

CHAPTER 4 | Data Collection, Results and Analysis

4.1 Introduction

This chapter presents the findings of the empirical investigations conducted for this study. First, the results and findings of a focus group that helped to set the direction for the research are given. Next, the findings of semi-structured interviews with industry practitioners and academics are presented. And finally, analysis of industry consultations via interview and additional focus groups that took place to understand the future potential for DLT and SCs in the sector are provided.

The research questions and associated aims addressed in this chapter are highlighted in Table 4.1.

Table 4.1: Research questions and associated objectives addressed in this chapter

Research questions	Objectives
RQ2: What role can DLT and SCs play alongside other technological innovations such as BIM and IoT in addressing the challenges faced by the construction industry?	**Objective 2.1**: Identify the construction sector applications to which DLT and SCs can be applied as proposed in literature and through consultation with academia and industry. **Objective 2.3**: Establish which construction challenges have the potential to be addressed in part or in full by integration of DLT and SCs into the existing applications classified by the application taxonomy.
RQ3: How can a socio-technical approach support the construction sector in improving its readiness for the adoption of DLT and SCs by providing a systematic approach that guides the sector in identifying the steps required to add value and realise the benefits from integrating DLT and SCs into new and existing applications?	**Objective 3.1**: Identify dimensions of socio-technical systems theory to support analysis of the current state (without DLT and SCs) against the desired state (with DLT and SCs) of construction sector applications and identify the actor groups to be involved and/or affected by such applications along with their roles and responsibilities. **Objective 3.2:** Identify the requirements for readiness of the construction sector to adopt DLT and SCs in existing applications through consultation with academic and industry practitioners. **Objective 3.3:** Propose the steps required for achieving readiness of the construction sector to support development and implementation of DLT and SCs for new and existing applications.

4.2 Focus group: A socio-technical approach to implementation of DLT and SCs in construction

The first of the three focus groups took place in January 2018. The purpose of this first one was to gauge opinion on DLT in the construction sector. At this stage in the technology's development, little literature was available on the topic and general knowledge within the sector was low. There were eight participants consisting of five academics, four of whom had prior knowledge of DLT; two PhD candidates investigating Building Information Modelling (BIM) and digital construction; and one industry practitioner involved in dispute resolution. Their profiles are shown in Table 4.2.

Table 4.2: Profile of focus group 1 participants

Role	Specialisation	Experience
Researcher, academia	Architecture	26 years
Professor, academia	Contract management, BIM, blockchain	40 years
Associate Professor, academia	BIM, digital construction, blockchain	17 years
Senior lecturer, academia	BIM, construction management	17 years
Researcher, senior lecturer	Smart construction	21 years
PhD Candidate, academia	BIM, BREEAM	9 years
PhD Candidate, academia	BIM, smart technologies	7 years
IT systems developer, industry	Dispute resolution, software development	16 years

The session lasted for one hour beginning with a presentation on the technology and the potential applications as discovered from literature review. Semi-structured discussions centred on the participants' views of DLT in the built environment and their benefits and implementation challenges.

The key finding from the focus group was that DLT in the built environment "*must be considered as a socio-technical system*"; this was a key contribution to the development of this research. While conversations on this aspect were limited during the focus group, this theory formed the basis of the socio-technical framework proposed in this thesis. Its theoretical underpinning is discussed in the Literature Review in Chapter 2.

DLT was also highlighted as having "*the potential to address one of the biggest challenges in the construction industry, which is trust*". Topics of discussion included the suitability of decentralised systems for projects and organisations across the sector and whether they would still benefit from a more centralised ledger. The frequency of transaction processing (e.g., real-time, near-real-time, hourly, weekly, monthly) was considered in light of the challenges and opportunities presented by cryptocurrency transaction processing (i.e., the limitations of Bitcoin versus the speed of Visa transactions) and how it relates to construction project transactions plus any impact on the system requirements of any technological system implemented.

With regards data authenticity, discussions turned to the construction supply chain with a participant commenting, "*blockchain doesn't remove the fact that people can be dishonest. RFID and IoT-enabled smart dust don't guarantee that a shipment has reached its place of delivery just because the blockchain says it has when people can deliver the sensor from a shipment of bricks without the bricks and have the shipment automatically register as complete*". Final thoughts turned to the types of information to be recorded as data on a distributed ledger throughout a construction project to include financial transactions, communication, asset/IP information, labour etc, and whether DLT and SCs have the ability to improve the functioning of these transactions throughout the sector.

The findings from this focus group and, specifically, the identification of DLT as a socio-technical system guided the research questions and associated objectives established for this thesis. They directly informed development of the DLT Four-Dimensional Model and the DLT Actors Model introduced in Section 5.3.

4.3 Interviews: Elicitation of early views on DLT and SCs from industry

A series of semi-structured interviews were conducted with 13 people from across the construction industry. Due to the limited research that existed on DLT in construction at the time of the interviews (April 2018 to June 2019), this qualitative research method aimed to support the preliminary findings from the literature review and contribute further to the discussion on what the technology can do to address some of the construction sector's biggest challenges. The interviews were instrumental in gathering information about the current state of DLT and SCs in the construction sector, which served to capture the level of knowledge and understanding of these technologies as well as how they were perceived as technological systems across the sector. The interviews were also used to identify the use cases that the construction sector is most interested in at this early stage of development, and to consider how DLT might integrate with other technological innovations in use today. These interviews contributed to the development of the taxonomy of construction sector challenges, the Taxonomy of DLT and SC Applications in Construction, the DLT Four-Dimensional Model, the DTL Actors Model and the DLT Benefits Pathways. Further details are provided alongside the constructs in Chapter 5.

The criteria for selecting the participants were as follows:

- Senior experts from across the construction sector.
- An understanding of the key challenges facing the construction sector.
- Experience of engaging with different types of organisations across the sector from contractors at all tiers to public sector clients.
- Knowledge and understanding of the potential for DLT in the construction sector.

Table 4.3 shows the profile of the participants. To provide an holistic view of DLT across the UK's construction sector, the participants were located across the UK from organisations ranging from micro-businesses to industry associations and large contractors. They were identified using a snowball sampling approach.

Table 4.3: Profile of interview participants

ID	Role in the Construction Sector	Experience	Type	Date	Duration
P1	Chief executive of an industry association, barrister	33 years	In-person	Apr 2018	3hr 30m
P2	Head of construction in a national law firm	38 years	In-person	Nov 2018	0hr 50m
P3	Founder of a construction technology start-up utilising DLT	14 years	In-person	Dec 2018	2hr 0m
P4	Senior counsel of a global construction contractor	19 years	In-person	Dec 2018	0hr 30m
P5*	Professor in construction law	44 years	In-person	Dec 2018	1hr 0m
P6*	Research associate, architect	17 years	In-person	Dec 2018	1hr 0m
P7+	Director of an information management consultancy that uses blockchain	19 years	In-person	Apr 2019	0hr 50m
P8+	Researcher on blockchain for construction supply chains	13 years	In-person	Apr 2019	0hr 50m
P9	Head of an industry association, solicitor	30 years	In-person	Apr 2019	1hr 50m
P10	Lecturer of architecture and researcher researching blockchain for trust	38 years	In-person	June 2019	1hr 45m
P11	Entrepreneur proposing the use of DLT for a whole-lifecycle application	17 years	Telephone	June 2019	2hr 0m
P12	Head of DLT for an innovation centre	11 years	Telephone	June 2019	0hr 50m
P13	Director of an international engineering consultancy	26 years	Telephone	June 2019	0hr 45m

**Participants 5 and 6 were interviewed together; + Participants 7 and 8 were interviewed together.*

The interviews took place over 14 months as developments and interest across the sector increased generally. After completion of 11 interviews with 13 participants, saturation had been reached in terms of the understanding and information obtained from practitioners.

A set of questions specific to DLT and SCs were devised based on findings from the initial results of the SLR that was conducted in parallel to the interviews taking place. Due to the novelty of the topic being investigated, the interviews were allowed to evolve to adapt to the participant's level of knowledge, expertise and interest in the subject, to provide flexibility to the process and to avoid suppressing potential findings that would otherwise have remained undiscovered. A structured approach would not have been appropriate given the newness of the subject area and an unstructured approach could have been too broad to ensure focus was given to the areas considered important by the interviewer or may have resulted in missing key areas of interest (Pócza and Dobos, 2018). The semi-structured questions asked for the participant's views around the following:

- What DLT and SCs offer that current technologies do not.
- The potential benefits of DLT and their ability to support advancement of the construction sector.
- The potential use cases for DLT and SCs.
- The extent to which SCs will be used in construction and for which use cases.
- The ability of SCs to replace or complement traditional construction contracts.
- The interplay between DLT and SCs with existing technologies (e.g., BIM and IoT).
- How the adoption of DLT and SCs will affect current roles in the sector.
- The barriers to adoption of DLT and SCs in the construction sector.

Braun and Clarke's (2012) six-phase approach to thematic analysis was adopted; see Figure 4.1. First, each interview was transcribed; second, the data were coded based on initial analysis; third, the data were categorised into themes across all transcriptions capturing conceptual differences; fourth, the themes were quality checked against the data and revised based on deeper analysis; fifth, the themes were clearly defined; and sixth, the resulting categories were collated and interpreted to provide meaningful contributions to the field of DLT in construction. The transcriptions ranged in length from 4,074 words (interview 4, participant 4) to 14,590 words (interview 7, participant 9). It was not possible to record interview 1 (3hr 30m duration) due to the circumstances in which the interview took place, therefore, detailed notes and direct quotes were taken as appropriate. Generating initial codes from the 11 interviews resulted in direct quotes totalling 20,000+ words, which were reviewed repeatedly up to and including phase five of the thematic analysis.

The initial codes identified in Phase 2 can be seen in Table 4.4 along with the number of interviews in which the code was identified and the number of occurrences of each code

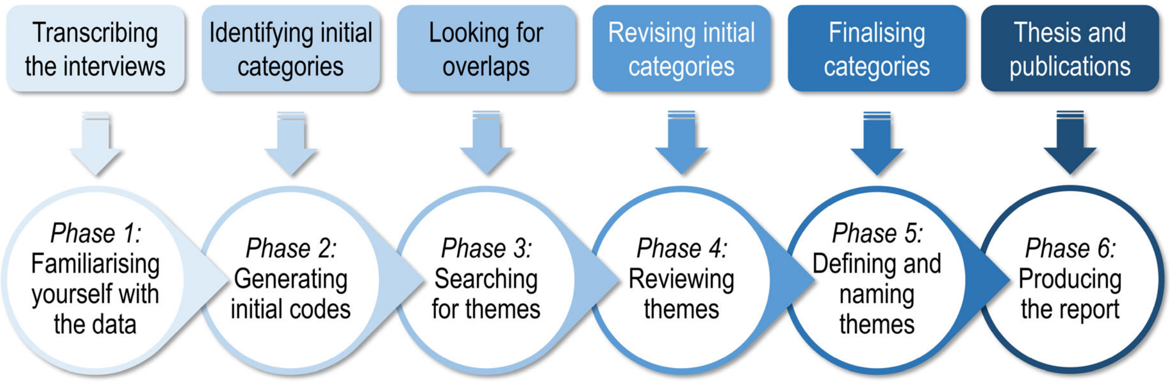

Figure 4.1: Applying the Six-Phase Approach to Thematic Analysis

across all interviews. The indented codes (3.1, 3.2, 7.1, 12.1, 12.2) were immediately identified as child codes to the parent code due to similar ideas but those which warranted distinction from the parent. The codes with the highest number of occurrences from across the interviews were blockchain/DLT characteristics, construction industry challenges, SCs and use cases.

Table 4.4: Initial codes from Step 2 of the Six-Phase Approach to Thematic Analysis

#	Initial code	No. of interviews	No. of occurrences
1	Building Information Modelling (BIM)	4	5
2	DLT/Blockchain adoption	1	3
3	DLT/Blockchain characteristics	10	27
3.1	Blockchain challenges	2	10
3.2	Layman's perception of blockchain	3	4
4	Business models	6	8
5	Collaboration and trust	1	4
6	Construction industry challenges	10	25
7	Design development process	3	6
7.1	Details of who, what, where, when, how	6	8
8	General Data Protection Regulation	3	3
9	Payments	5	6
10	Regulation and compliance	2	8
11	SCs	7	22
12	Confusion of SCs	4	4
12.1	Payments via SCs	3	4
12.2	Replacing traditional contracts	3	4
13	Technological integration	1	2
14	Traceability and transparency	4	4

Phases three and four were followed by a deeper review of the interview transcripts to look for overlaps and either eliminate or merge codes as well as align them with the final themes from the SLR. This can be seen in Figure 4.2.

The findings of the interviews provided an industry perspective on the key aspects surrounding the application of DLT in construction to complement the findings from the literature review. Eighteen individual challenges were identified and consolidated as shown in Figure 4.3, which indicates to which interview participant(s) the challenges are attributed using their IDs from Table 4.3. The challenges raised were not applicable across all eight themes as the amount of literature reviewed (153 papers) represents substantially more data than was collected via the 13 interviews. Where challenges overlap two or more themes, they are categorised in the theme most appropriate for the context of the challenge. The analysis identifies challenges that reflect the historical issues cited in major industry reports over the last 30 years (Latham, 1994; Egan, 1998; see Wolstenholme, 2009; Farmer, 2016; Hackitt, 2018) reconfirming that many of these challenges are indeed still prominent in the industry today and identifies those that have the potential to be addressed in part by DLT. The challenges identified here have been incorporated into the taxonomy of challenges in Chapter 5 (Section 5.2.1) alongside those identified through the SLRs.

The following sections discuss the construction sector challenges raised by interview participants and alongside the proposed applications of DLT and SCs with the potential to alleviate some of those challenges. As the data collected were aligned to the themes

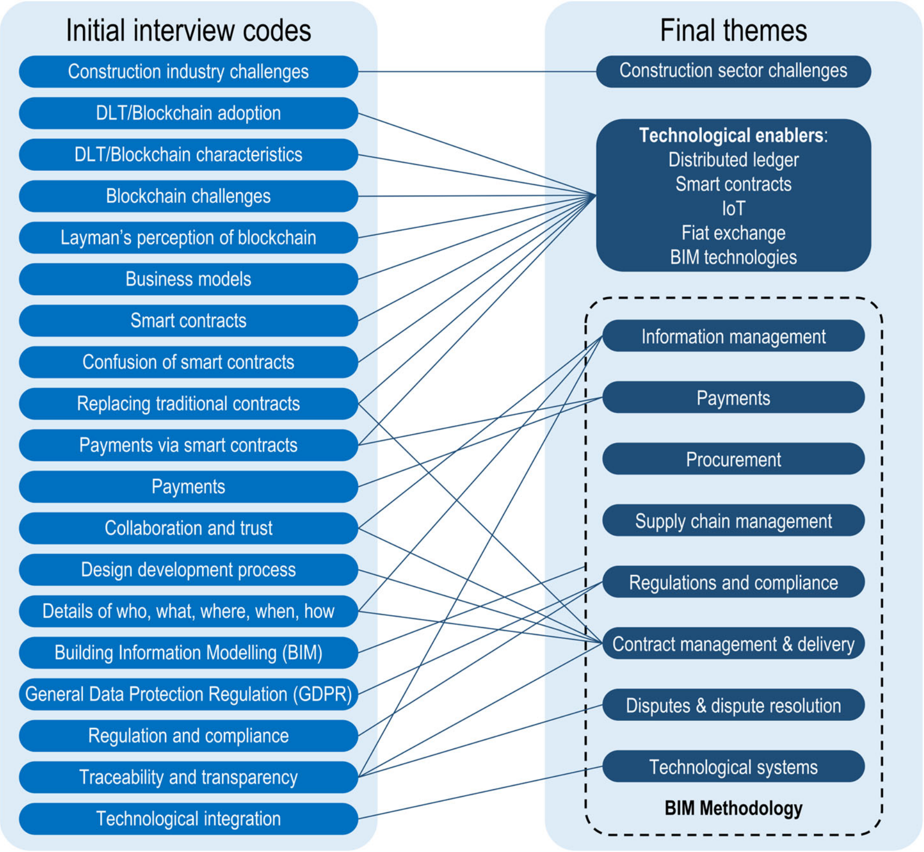

Figure 4.2: Alignment of interview coding with SLR themes

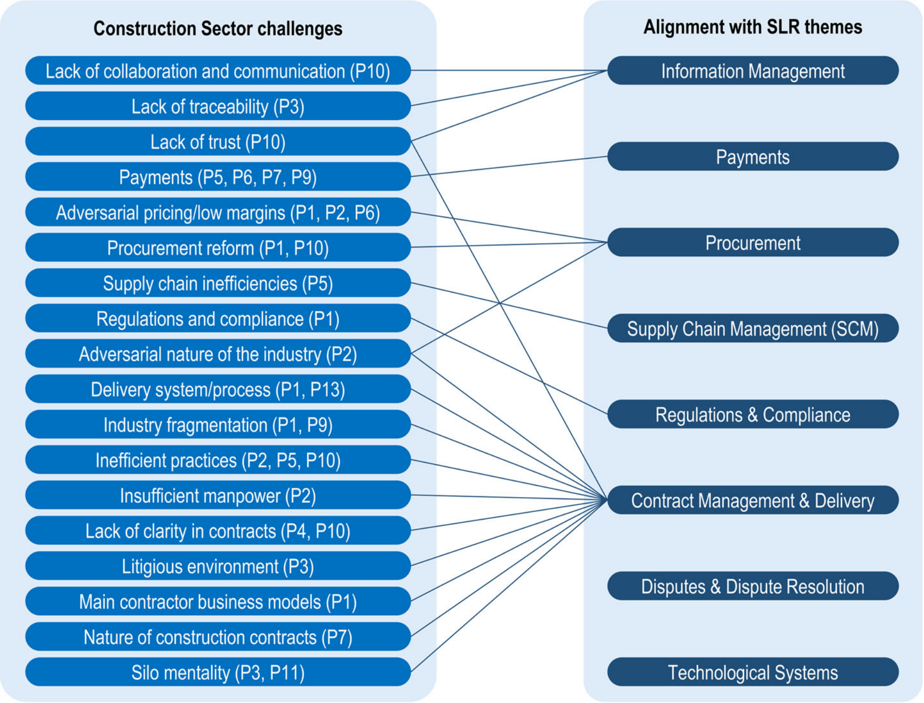

Figure 4.3: Construction industry challenges identified by interviewees and aligned to SLR themes

identified from the SLRs, there are some themes that were not addressed in the interviews and, therefore, do not have headings in this section. Following this, discussion of the compatibility of DLT and SCs with construction and identification of the open challenges of their implementation in the sector is presented.

4.3.1 Information management

Many inefficiencies in construction stem from ineffective information management. Interviewee P5 describes several inefficiencies related to the supply chain such as "*arbitrary decisions, subjective decisions that delay payment, people who intervene, breakdowns in communication, a whole range of things that stop money passing down the supply chain. But also, that interfere in the records of what has been provided*". In construction supply chains, there is a reluctance to foster long-term relationships between main and sub-contractors due to the short durations of projects and physical distances between them. This slows down the continual improvement in the maturity of project coalitions across key topics including collaboration, trust and information management. Consequently, it leads to poor information flows that provide little transparency and limited exchange of information and communication in general (Dallasega *et al.*, 2018).

Regarding data ownership, owners are only now "*starting to realise it doesn't matter what happens, they're the ones that foot the bill at the end of the day and they either foot it at the front end or they pay for it later*" (P7). The introduction of DLT and SCs will provide owners with clearer contract terms and conditions setting out who owns what and who is responsible for what throughout the project and asset lifecycles, which will allow them to receive the full value of what they are paying for. But "*you have to write it into the contract*" (P4) to make sure the parties' obligations are formalised.

The Hackitt Report proposed a digital record to represent the 'golden thread of information' (Hackitt, 2018) throughout the lifecycle of higher risk residential buildings. This could benefit all built assets (Watson *et al.*, 2019). P13 pointed out that the then current RIBA Plan of Work (RIBA, 2013) does not "*have the digital thread running through it*". The Plan of Work was updated in 2020 and while it lacks a clear link to the 'golden thread', the latter is referred to in the Plan of Work document demonstrating recognition of its importance to the sector (RIBA, 2020). To get to a point where effective record keeping in the construction industry is business-as-usual requires cultural and procedural changes as highlighted in the literature review.

One of the biggest barriers to true collaboration between contracting parties is trust. If the trust relationship can be changed or bolstered by process, P10 believes "*BIM with embedded blockchains, true collaborative, multi-disciplinary teams, with the incentives in terms of reward for work well done*" is what will create a "*scaffold of truth…amongst a whole set of actors*", which enables one to say, "*You trust me, and I trust you*" (P10). What that means is both parties can share the rewards, but they also share the responsibility if things go wrong. Currently, lack of trust in information that has passed from one party to another resulting in the tendency "*to recalculate everything again*" (P13). If, for example, a private DLT-based system is employed on a construction project where parties agree value transactions by consensus before it is put onto the ledger, this would eliminate any trust issues. With validated information accessible to all parties, this has the potential to reduce "*things like onsite variations…, requests for information, any disputes as to gaps in information or discrepancies in information*" (P4).

It could be argued that in the initial stages of implementation of DLT, trust will be a barrier with users (e.g., labourers) on whom the new technological system is enforced where it may be seen as a 'Big Brother' exercise. However, once the time has passed to demonstrate benefits and address any issues with the system, its perception will likely change where people begin to realise, "*I can trust as to who did what here*" (P10). This assumes that a new DLT-based system will deliver benefits to construction projects. If, further still, the tokenisation element of DLT is introduced as a reputation-based system where tokens are rewarded from one party to another based on the quality of work done, it is "*a possible way to incentivise collaboration*" (P10).

A lack of trust has resulted in silos where individuals and organisations look out for themselves, which costs projects more in the long run (P3, P11). Trust is not only an issue in construction; blockchain was created to support the Bitcoin protocol to disrupt the finance industry to challenge powerful, centralised banks and its use is being explored in almost every other industry (Li *et al.*, 2018a). The fact that technologies such as blockchain are developed in the first place shows that trust is waning on a global scale and individuals and organisations are becoming more and more reluctant to trust third parties. This is troublesome on a construction project where, for example, misinformation provided to senior management cascades down to the construction site where "*everybody goes into defensive mode in terms of how they go about their business*" (P10). P3 questions who to trust with regards provision of data – "*Do you trust a big organisation who's collecting that data? The manufacturer? Or do you trust the blockchain?*" P10 believes blockchain can be the incentive for teams "*working together in a true collaborative sense…working toward the same goal as it moves along"* providing much-required culture change.

Trust is the basis of relationships between parties and the extent of that trust dictates how well the parties will work together. The construction industry is not known for developing highly functioning teams that regroup project after project; typically, teams disband at the end of projects and new teams are formed as new projects are initiated (Xue and Lu, 2020). This does not foster long-term relationships. However, one use case that could be considered leftfield is the development of a parallel design and construction industry (P10) that flips current practice on its head. The model is centred on collaboration from the outset where all parties engage and establish project costs based on the quality and scope of work rather than being built on lowest-tender-wins mentalities. While this, and indeed most use cases discussed in this study, does not rely on the use of DLT, DLT has the ability to standardise, formalise and automate many processes and relationships if implemented from the beginning of a project. From experience of applying blockchain to a real-world project, P13 indicates "*if you do it from a Greenfields*[4] *perspective… it's a lot easier*".

These findings demonstrate that inefficient practices have arisen from a lack of information exchange, poor record keeping, competition and desire to protect IP. This is, in part, due to industry fragmentation and an embedded culture that has been fostered over many years making parties reluctant to share information through project delivery (P1, P9). Each of these adds to poor decision making that is non-attributable to any one individual or organisation. This makes changing these practices almost impossible without effective intervention and enforcement. Proof-of-ownership and timestamping on a distributed ledger (San *et al.*, 2019) can alleviate many of the issues around IP resulting in a change in trust and therefore generate more willingness to share information and collaborate. Increased collaboration and information sharing will support better delivery of projects with fewer disputes between the parties (P4).

4.3.2 Procurement

Procurement and contracting processes are separate activities within a construction project that are distinct yet interlinked. The former is a delivery system, and the latter provides legally binding agreements between the parties setting out what each is responsible for. For this study, the two were categorised as distinct themes through thematic analysis with *procurement* as an individual theme and *contract management* as a sub-theme to *contract management and delivery*. The challenges discussed during the interviews demonstrated the interconnectedness between the two concepts, therefore, they have been discussed under procurement in this instance.

According to P1, to-date, "*blockchain applications have been seen in industries that already have integrated procurement and delivery and are already technology driven; they are more open and receptive to digital advancements. For blockchain applications to be successful in construction, first, the whole procurement and delivery processes need to be fixed*". Poor procurement practices have been ingrained over many years and low profit margins encouraged main contractors to create business models around the use of project funds to finance their business. These practices have continued to result in clients requiring more for less and top tier contractors pushing the financial burden down the supply chain putting quality and safety standards in jeopardy. P1 believes it is the client that needs to "*insist on different procurement procedures and perhaps break up the contracts to award smaller contracts for the same project to different and smaller contractors*".

Pricing of contracts based on a *lowest-tender-wins* ethos puts in jeopardy safety and quality standards of built assets. Procurement processes are not digitised and therefore do not support technological advancement of the industry in its current state. This instils poor

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[4] In this instance, a "Greenfields" perspective refers to a project that has limited constraints on it from the outset.

practices from the outset that reverberate throughout the project and asset lifecycle. Subjectivity based on human experience and judgement is required in the delivery of construction contracts. These elements are not yet automatable as artificial intelligence is not sufficiently advanced to replace human judgement, but consideration needs to be given to the human interaction points and those elements that can be automated. The industry should take steps to digitise current procurement processes to result in computable documentation (e.g., exchange information requirements) that can be transferred directly into SCs and information models to speed up activities and support automation. While technology develops to the extent that these aspects can be replaced by artificial intelligence, exploration of the extent to which traditional construction contracts can be automated to generate efficiencies and reduce human error in construction projects should be made and development of standardised, off-the-shelf SCs could speed up their adoption at the macro scale. DLT (and other technological systems such as BIM) require digital input to function optimally. A move toward electronic, digitised procurement processes would give a boost to digital transformation that the construction sector requires. Delivering elements of traditional construction contracts with SCs enforces parties to standardise and clarify clauses at the pre-contract stage that will realise efficiencies throughout the project and asset lifecycles (P1).

4.3.3 Payments

Payments have implications for many challenges identified from these interviews including inefficient practices, adversarial nature of the industry and procurement, which is why it is seen as "*one of the most important things that really needs to be addressed*" (P6). Payments are made, and in many cases delayed or not made at all, because of what is written into construction contracts. Complexity of contracts is discussed in Section 4.3.5 below, but what is relevant here is that payments made throughout construction projects are reliant on clear and concise contractual clauses. Current contracts are often ambiguous which leaves the possibility for variations and disputes. However, sub-contractors often "*reach agreement because they do not have the profit margin, size of business, legal support or any of those issues that they think, 'We can fight this'*" (P9). P9 provided the analogy of buying a loaf of bread that is for sale for £1. Construction is like taking that loaf of bread to the checkout and offering to pay only 70p for it – "*You don't get to tell the seller, as a buyer, what you're willing to pay, which in construction you do*" (P9). Add to that the "*domino effect in how that payment needs to go down the supply chain*" (P6) before reaching the appointed party, and you have a volatile, risk-averse industry.

A clear consensus across the interviews was the ability of DLT and SCs to reduce the time taken for subcontractors to receive payment from the main contractor. SCs and changes to procurement processes threaten to remove financial control from the main contractor to create a more stable environment for the supply chain, which in turn makes construction projects less risky for the client. Current business models are dictating how the construction sector operates where financing of projects relies on how and when main contractors distribute project funds through the supply chain. This makes the construction sector a volatile place in which to operate, particularly for the lower-tier contractors who wait months to receive payment for work completed, often on time and to required specifications. P1 states, "*Use of supply chain capital was a deliberate business policy used by Carillion*". Their collapse in January 2018 reverberated throughout the industry on a global scale to the extent that many creditors could have expected to receive less than £0.01 for every £1 owed (Chapman, 2018). P13's proof-of-concept that tracked the movement of goods and services within a construction project on behalf of the client saw subcontractor payments being made in eight days of work being completed. This is a major change in efficiency where, previously, payments were taking 90 days to reach the subcontractor after completion of works. The new process created an environment where the main contractor "*can't hide*" (P13). In this case, they were given the choice to comply with quicker payments based on proof via a private distributed ledger or lose the contract. This is one approach that could disrupt the industry driving change from the client. P1 agreed that change needs to come from the client. P13 does not think "*there are going to be benefits as such for the main contractor*". In contrast, P12 does not believe client-led solutions are always the right way to go as "*they will attack the wrong problem, at the wrong time, in the wrong way*".

In convincing main contractors to adapt their business models, P2 believes "*you would have to make the alternative sufficiently attractive to them in terms of return that they would be happy to lose that funding buffer*". Subcontractors will benefit greatly from a change such as that implemented by P13 where speed of payments would allow their businesses to operate more effectively and efficiently. At the same time, transparency will be increased to the point they know "*what's coming down the line, because if they're owed £50k but they're told they're only going to be paid £40k*" (P9), that provides flexibility and time to plan how they will use the money they will actually receive.

P4 expresses the need to consider the Construction Act where "*you can issue Payless Notices, Payment Notices, you can report money in certain circumstances. So, whilst you can build that into the coding, there'll need to be a stepped process. It won't be, if you get to this milestone, you get paid*". This is the point where tasks or activities can be coded with partial payments to be released at certain check points. P5 provides an example of an order for goods being placed where the first payment (e.g., 50%) is coded to be released once the goods are dispatched, the second payment (e.g., 50%) is coded to be released once the goods are installed on the project and the owner can be sure they are doing their job.

The cryptocurrency aspect of DLT is not yet stable enough to be used as a form of currency in the construction industry; however, creating SCs that lead to automated triggering of payments of fiat currency is a possibility (Shojaei, 2019). If SCs are to be implemented, PoCs will be required to integrate into existing systems and processes such as payments via banks and tracking of goods through existing supply chains. With the proliferation of sensors and digital tracking, available off-the-shelf technology should allow these PoCs to emerge. SCs can then be used as a tool to measure contract performance, "*things like payments, ordering materials, anything that requires no level of judgement*" (P4). When buildings become subject to "*extensive sensoring and monitoring, we will have a lot more information about the state the building is in…which will enable us to know for sure…, or with far more certainly, whether a certain stage has been reached, which would trigger a payment*" (P2). It will not be possible to code every eventuality in a construction project from a resource point of view and, indeed, every eventually is not known. Whether it is confirmation of delivery of goods on site or granting approval that a brick wall is built to contractual specifications, human interaction points will be required and coded to the SC until AI is sufficiently advanced.

PBAs have been discussed to drive payment reform in construction. Client funds are held in a ring-fenced bank account with payments being made directly from the PBA to the subcontractor upon completion of contractual arrangements without being cascaded down through the supply chain (Griffiths *et al.*, 2017). P1 believes that if SCs are applied to PBAs, payments will be more standardised and could also reduce the cost of construction projects. Further, this paves the way for procurement reform in which "*blockchain can play a huge part*" (P10).

Following current practices, payments can take up to 120 days to be processed from the appointing party before it reaches the appointed party's bank account (Penzes, 2018). Disputes and variations around quality and scope often arise, delaying payments which impact on organisations' cashflow. Potential use cases that support payment processes and reform include: PBAs (P11); automated weather-based compensation payments (P12) as an example of an element of construction contracts that could be implemented with little change required to current practises; reducing payment times using a digital record as proof of work complete (P13); automated staged payments based on where goods are at a point in time (e.g. 50% payment on shipping of materials, 50% payment on successful installation) (P4, P5) which is in agreement with Shojaei (2019); increased transparency for payments including when payment will be made, how much of the payment will be received and reasons for delays or reduced payments (P9) to make the payment process clearer for appointed parties who use the information for better planning; once sufficiently stable, introduce the use of cryptocurrency in place of fiat currency to speed up payments (P2, P10). PoCs are needed through simulations and pilot studies to show how proof is recorded on a distributed ledger and how that can lead to increased transparency of payment processes. Undisputable, validated and verified proof that work has been completed to specified requirements will force appointing parties to pay appointed parties quicker, especially if written into the contract by the client.

4.3.4 Regulations and compliance

Mentioned eight times by two interviewees, regulations and compliance is one of the key issues highlighted in the Hackitt Report (Hackitt, 2018). There is lack of enforceability where "*people are not clear what it is they're enforcing and, therefore, can't hold people to account if they don't know who did what, when. There is lack of accountability*" (P1). When 72 people were killed when Grenfell Tower burned down, several "*serious safety breaches*" (Mendick *et al.*, 2018, para. 7) were identified by investigators that included: non-compliant safety doors; a "*culture of non-compliance in fire safety*" (Mendick *et al.*, 2018, para. 27); the use of combustible cladding; a failure of the lift system; a water pipe system and smoke removal systems that did not comply with regulations and did not function as required; windows were surrounded by combustible material and were installed without fire-resistant cavity barriers; and firestops between windows were incorrectly installed (Booth and Davies, 2018; Mendick *et al.*, 2018). This litany of failures resulted in the greatest loss of life in a single residential building in the UK over the last century, and failure to comply with building regulations is a direct result of failure to them. Following the fire at Grenfell Tower, billions of pounds were needed to address the same and similar failures in over 446 other residential buildings with similar safety failures across the UK, many of which are still awaiting remediation. This was the figure only for residence over 18 metres in height; the number of residence under 18 metres with unsafe cladding and other materials is unknown (Glover, 2022). To compound matters, residents of Grenfell Tower had repeatedly reported issues to the building management company indicating that it was a "*death trap"* (Mendick *et al.*, 2018, para. 26). The Hackitt Report cites one of the factors that allowed such an incident to occur was due to "*lack of complete, accurate and maintained building information*" (Hackitt, 2018, p. 102) providing no accountability when things go wrong.

P1 describes DLT as having the effect of "*someone looking over your shoulder*" and the importance of having oversight from the outset of a project. "*Use of technology to bolster regulation would ensure there were repercussions for having the blockchain as a regulatory tool that would reverberate throughout industry standards, procurement, delivery etc."* (P1). In addition, DLT can be used in identity management of building components or a *passport* that provides data upon request such as ratings against which to prove compliance with building regulations. P1 believes that DLT "*will lend integrity to building safety and accountability*", it can make it easier to "*enforce the delivery processes to quality and safety standards,*" it will force "*people to account in quality factors [and] will change how people operate".*

Given blockchain's nascence in construction, P4 believes that regulations for DLT in construction will be driven from outside the sector (i.e., Europe or other sectors such as fintech) but "*how applicable those regulations will be to [construction] and how they will* *interact with say, the Construction Act, and such will get complicated. I think there will probably be case law first before regulation just by the nature of things*" (P4). It may be the case that innovators demonstrate proof-of-concept by *just doing it* which will drive retrofitting of regulation to new systems of working. Penzes explains the likelihood that other industries have similar processes to construction supply chains such that established "*principles can be used specifically in the construction industry as well*", adding, "*every detail of their transportation, together with the relevant origin certificates, specifications and standards, need to be available in a transparent and accountable way*" (Penzes, 2018, p. 30).

Immutable recording of certifications and compliance with regulations will provide proof that projects and assets are compliant (P13). A new DLT-based system will encourage contractors to work to better safety and quality standards if their work is to be recorded forever, based on the who, what, where, when etc. principle discussed by several interview participants (P1, P2, P3, P4, P5, P7, P10). Current regulation and compliance guidance should be reviewed and updated to ensure organisations are working to the right standards and regulations to prevent the likes of Grenfell Tower happening in the future. How GDPR fits into the new environment requires consideration as an immutable ledger is in direct contrast to an individual's 'right to be forgotten'. However, once that aspect is addressed (e.g., through ZKPs), there is potential to use DLT systems for things like: personal identities demonstrating a person's training and skillset, linked to payment systems to speed up payments further still (P3); support to the creation of corporate identities (P12) where information that should be public (e.g., aspects associated with compliance) is made available where appropriate information that should be private but accessible to permissioned parties (e.g., financial accounts) is protected cryptographically using public and private keys; and internationalisation of business (P12) that allows organisations to operate more effectively across borders opening up possible new revenue streams and resolves issues of international financial transactions.

4.3.5 Contract management and delivery

Today, construction contracts are seen as *"all stick and no carrot"* with *"no incentive to over deliver and all the risk is basically pushed down the supply chain"* (P7). Where everything stems from the contract throughout a construction project, P4 believes *"it's just as important to say what you are not responsible for as what you are responsible for"* in an environment where *"people don't read their contracts"* that are complex and full of unknowns. This signifies a need for construction contracts to be clearer and more standardised. However, every construction project is different from one to the next. Standardising traditional construction contracts presents a significant challenge where standard form contracts such as the NEC or JCT suites allow for flexible terminology (e.g., exercising reasonable skill and care). SCs do not have this flexibility as they execute automatically based on the instructions the coder gives them. It is possible, however, to code an SC that requires human input to, for example, tick a box to show reasonable skill and care has been exercised by a contractor and the work was signed off by an inspector.

Current insurance policies protect individual organisations from project risks; therefore, the individual organisation bears the cost when those risks are realised. This means "*you can't hold your hand up to an error because it invalidates your insurance policy*" (P2). The concept of Integrated Project Insurance (IPI), which promotes a "*no blame/no claim culture undertaking between the Alliance members*" (Atkinson and Wright, 2017, p. 98), is a method to combat the adversarial nature of administering construction contracts where "*the project is insured, not the individual organisations*" (P1) above an agreed pain share limit. P10 envisions lawyers and insurance brokers working together at "*the collaborative table…as part of the design so that they can inform on the risk as it's being designed rather than a catch-all contract or a catch-all insurance policy*". Currently, many organisations from main contractors to the lowest tier labourers are at risk of litigation and/or insolvency until collaboration between project parties becomes business-as-usual. However, a consideration of IPI is cost of implementation where "*you'd have to have a project big enough to bear the cost*" (P2).

Culture in the construction industry is one of the hardest aspects to change. P2 explains, "*the adversarial nature of construction…seems so engrained it's almost impossible to overcome*". Delivery of construction projects has remained largely unchanged in the last 100 years even when there was a move "*from the drawing board to CAD [that] was just efficiency change*" (P10). What now exists is an industry where adversarial pricing of contracts and low profit margins are inherent because of poor procurement systems that have evolved over time to a 'lowest tender wins' mentality. This discourages collaboration and information sharing where parties are required to heavily protect their IP in a highly competitive market. P2 and P6 highlighted the incredibly low profit margins construction contractors are working with, which means business models have evolved to be built around "*using supply chain funds as cashflow to finance their businesses*" (P1) – known as cash farming (Msawil *et al.*, 2022). At a time of political and economic uncertainty, this puts enormous pressure on the supply chain and creates "*the siloed behaviour that's costing so many people so much money*" (P3) where "*the designers look at design stuff, the contractors look at contract stuff, and facilities management people look at facilities management*" (P11). While people who operate the industry are reluctant to implement a transformational change of processes and are unable to transform cultures and mentalities, innovation-led changes presented by digital technologies such as DLT and blockchain have the potential to enter the sector to disrupt current working practices and force that change rather than wait for cultural change to come from the people.

Industry fragmentation is offered as an overarching challenge to delivery resulting in the UK having "*one of the most expensive construction industries in Europe*" (P1). According to P9, "*it's somewhere near 300,000 businesses, 99% of which are SMEs […] you get tier 1 subcontracts, tier 2 subcontracts, tier 3, 4, 5 is probably suppliers only with either labour or materials, but it means there's a huge crowd of tiny businesses at the bottom who are actually the delivery point"*. Those contractors at the bottom bear the highest risk and are negatively impacted by poor practices where the use of supply chain capital is being used to finance main contractor businesses, with major insolvencies such as that of Carillion (Thomas, 2013) reverberating across the globe. "*For clients to ensure against insolvency, they need to insist on different procurement procedures*" (P1). P10 does not think it is possible to reform current processes as it is "*just too convoluted and there's…too much legacy, there's too many people hanging on in there*" (P10). A report published in June 2018 (ONS, 2018) stated 32% of the total UK workforce was aged 45 and over from a three-year pooled dataset between 2014 and 2016 and up to 65% of the workforce could be unskilled individuals with limited experience of using advanced technologies. Therefore, achieving reform with buy-in from all occupations within the UK construction sector, coupled with the aging workforce could require disruptive technologies. P13 believes blockchain could be one of those.

Contract management

SCs have been discussed as having the potential to replace traditional construction contracts where, in the context of the Accord Project (2020), P7 explains, "*It's producing that contract language programmatically using a data model so you can then produce your traditional contract but you can have a data model that you can then hang things off and do all the things you can do with a programming language*". However, this is contrary to the view of the legal participants interviewed for this study. P4 states, "*One of the things it's not going to do is completely replace [traditional] contracts, purely because there are elements which require subjective viewpoints, for example, whether someone exercises reasonable skill and care".* P2 asks how far subjectivity can be removed from traditional contracts adding, "*You have to basically write a contract that doesn't contain the word 'reasonable' in it. You need an 'unreasonable contract' because there is your subjective element*". P5 says, "*it's so unlike a conventional contract that I don't want our discussions to suggest that there's anything in there that looks like a normal contract*". SCs remove the flexibility that is seen in traditional contracts, therefore, P5 believes they "*only come into play after we've frozen our design development. There's no space once you're into the world of smart contracts…so if you haven't crystallised that and made all the necessary decisions and been sure there's no more provisional items, there's no more change, no more refinement…you're not ready for smart contract transactions*".

P2 suggests a "*hybrid contract*", a blend of a traditional and SCs, will be used in the future "*giving flexibility to any judgement, which is necessary…in the context of a marriage with the subjective elements of the contract*". P4 adds that in time there will be off-the-shelf SCs, "*readymade sets so you shouldn't have to start from scratch every time you go to a project because it'll require a combination of lawyers and coders and commercial teams all coming together saying, well, this is how we want it to work*". If traditional contracts do become entirely coded, P12 believes a "*stepwise transformation*" is required, but "*companies still wouldn't take advantage of those because it's just not ingrained in their corporate culture, it doesn't integrate with their existing processes*". While the ability to code the likes of the NEC and JCT suites of contracts is not yet available, P4 expects that in time, "*readymade algorithms*" will be available in an off-the-shelf format to reduce rework from project to project. Once such a point is reached, P1 believes SCs will "*offer far greater transparency*" as they are "*more difficult to amend than traditional contracts*". This additional clarity will likely reduce the number of disputes raised during construction projects.

Thoughts on SCs differ between the interviewees. P13 thinks they represent "*where the real efficiency is going to come*" while P10 sees more value in the ledger itself. P2 sees them as "*smart transactions*" and P5 thinks there is "*a great landscape of activity that shouldn't ever find its way into a smart contract*". P12 questions how SCs should operate, what level of human interaction there should be, where the line is between the space in which SCs function and when a judge should step in to adjudicate and above all how can an SC be coded reliably? AI may become sufficiently advanced to make decisions currently requiring human judgement and experience but until then, SCs will need to be integrated with human input (P4).

The conversation on whether SCs have the ability to replace traditional construction contracts raises confusion as to what they actually are. Several participants (P2, P4, P9, P12) agreed that an SC is not a contract in the traditional sense of the word as "*it's got nothing to do with legal bias*" (P13). A legally binding contract has offer, acceptance, consideration, intent and capacity. As highlighted in Section 1.4.1, the UK Jurisdiction Taskforce put out a statement that SCs can be considered legally binding provided they meet the requirements of such (UK Jurisdiction Taskforce, 2019). This offers two possibilities for SCs; first, to automate activities without the intention of replacing a traditional contract, and second, to represent a legally binding agreement. In the case of the latter, they must still satisfy the requirements of the jurisdiction in which they are being used to be considered legally binding. Additionally, the construction contract may still be required to make clear which processes are running on DLT and SCs.

Design

The application of DLT provides projects a platform to track the design process as it moves between designers. This includes recording the decisions that result in changes and variations from the concept design allowing visibility of the development and evolution over the design phase.

One of the strongest use cases for DLT-based systems arises from their ability to track who did what, where, when and how. Construction projects currently lack adequate accountability due to poor record keeping. If a DLT-based digital record was applied to all built assets, public and private, "*installed at the outset of the procurement process*", it "*would give oversight of the delivery team and would give a massive boost to the regulatory system*" (P1). Users could pinpoint a problem throughout the project lifecycle giving accountability backed up by data (P1, P3, P5). It would reduce the number of disputes and onsite variations because "*you can see what happened and when*" (P7). You have a "*single source of truth*" (P10) with untamperable data (P4, P7) leading to better version control (P1, P2).

With a ledger of record "*you can always prove what it was at a given point in time*" (P7) whether it is acceptance or rejection of a model, proof of a decision at the highest level, or comments from architects at the design phase. It provides "*a digital audit trail of what the data was at its original source*" (P7). If you then have a set of structured data and documents sitting below the ledger you can avoid "*vendor lock-in*" (P7) allowing you to switch seamlessly from one system to another, and while it does not track veracity, it provides a complete set of traceable data that can be interrogated back to source.

Business models

The introduction of DLT-based systems also presents new revenue streams for businesses, particularly around the manufacture of goods and building management systems. If manufacturers can track performance of their products in-situ, they can offer a proactive rather than reactive aftercare service and create better products based on the data generated (P3). This is in line with Tata Steel's pilot to track a steel beam throughout its lifecycle from fabrication, through the supply chain to in-situ using a unique, trackable ID tag that allows either reuse or recycling at end-of-life (Penzes, 2018). Similarly, this provides facilities managers with real-time or near-real-time data about components in their buildings, which supports better maintenance and repairs. P7 proposed a "*Spotify for engineering equipment*" type model that commoditises data from products based on the amount of times data about a certain product is accessed by a client with "*two sets of digital passports: one for products and another for the individual of that product*" (P7).

4.3.6 Technological systems

While this study does not tackle the question of whether DLTs should be public or private, permissioned or permissionless (for this should be decided on a case-by-case basis), it does highlight this as a point to be considered when establishing DLT-based applications for construction. When IP is part of the discussion, organisations may opt for private platforms to keep most information out of the public domain. On the other hand, they may want to share certain records, for example, "*if they've achieved sustainability goals*" (P13). A public platform can provide immutable proof of ownership so a change of mindset may be what is required rather than the existing mindset of privacy to maintain competitiveness.

When details of a publicly funded defence project could have associated security and privacy issues, a private, permissioned ledger would likely be more appropriate. An argument for public platforms might, for example, apply to building occupants of public buildings (i.e., such as the case of the renovations of Grenfell Tower; had the details of the renovations been public, perhaps there might have been fewer incidences of non-compliance). Circumstances, type, use and life expectancy of a built asset differ from one project to the next; each should consider its characteristics and select an appropriate DLT structure.

In the Literature Review (Chapter 2), BIM was discussed alongside a number of different concepts and applications proposing its integration with DLT, SCs and IoT. Through thematic analysis and recognising the importance of BIM in construction, it was not given its own theme as it is (or should be) inherent across every facet of construction projects. As a collaborative system trying to get an industry of traditionally non-collaborative professionals to collaborate and share information via digital processes, P1 describes attempting to integrate BIM in construction as "*trying to integrate processes using a digital mechanism on top of shaky foundations*". The limited success seen by adoption rates of BIM (NBS, 2019) across the project lifecycle to date is in part due to the sector's reluctance to collaborate and share information (Farmer, 2016; Barima, 2017; Belle, 2017). Construction has several technologies available to it to deliver projects – BIM, IoT, GIS, DLT etc. The interplay between each of these technologies is important in consideration of their abilities to effectively support construction projects. P4 sees them as "*tools to implement the contractual arrangement between the parties".* Which tool is used at which time will depend on the contractual requirements as "*there's a need to…realise that they have an element of dependency too*" (P6). P13 conceives DLT to be part of "*a combination of a number of technologies that bring a solution built on blockchain as the recording of what's happened*". Those that have the foresight to provide integrated, packaged solutions utilising the best, most appropriate tools available will likely reap the best rewards. End users of applications will not be aware that they are using systems built on DLT. DLT is not the selling point; how the technology interplays with the other available technologies to offer seamless, efficient delivery is.

Interoperability presents a major challenge in BIM (Shirowzhan *et al.*, 2020). The construction industry could influence how DLT systems are integrated with other key technologies such as IoT and BIM technologies to prevent vendor lock-in from the outset. However, IT companies offering applications for construction are likely to be those who try to influence how it is adopted by offering solutions built on DLT that are proprietary to their systems. P13, who has implemented a DLT PoC to a real-world project, when discussing technology integration "*wouldn't say it's a walk in the park but if you do it from a Greenfields perspective, which we have done, it's a lot easier. Especially configuring the systems in a* *way that you've got a common information and data protocol*". At early stages of adoption, cost will be the biggest barrier of DLT and, given the complexity of retrofit projects in construction, PoCs may be implemented on new construction projects rather than retrofit, regeneration and refurbishment projects. However, depending on the use case DLT is applied to, this will be case-by-case in the initial stages of adoption.

It was clear from the literature and interviews that DLT is not offered as a standalone solution to solve the construction sector's many challenges and it should be considered alongside alternative options to support digital transformation and reform of the construction sector. Hence, researchers and developers of DLT seeking to develop or use DLT to address specific use cases and challenges in construction should consider the ecosystem of digital technologies and their surrounding societal, procedural and political environment. This emerging recommendation is in-line with several developments in literature proposing DLT-based solutions for various challenges such as in Cerić (2019), Brydon Wang (2018) and Li and Kassem (2019b).

4.3.7 Compatibility of DLT characteristics with sector challenges

Through discussions on DLT as a new technological system, aspects emerged related to its characteristics, challenges for its implementation, and perception within the construction sector. They are discussed in turn.

DLT characteristics

It has often been said that blockchain is a solution looking for a problem (Risius and Spohrer, 2017) and on that basis it is logical that people identify its characteristics and fit those characteristics to potential problems to be solved. An extensive list of DLT characteristics can be seen in Section 2.3.2 where they are classed as challenges or opportunities for construction.

P1 describes blockchain as "*a process for delivering data*". P2 adds, "*through verification processes, [it is] a way of ensuring the authenticity of that information*". From a data storage perspective, P2 describes DLT as "*a very secure repository of information*" and P11 highlights "*security of the ledger*" as a key benefit of the technology. P2 analogises DLT as being "*like a really secure piggybank into which you can put whatever you want and, if you have a permissioned DLT, you can take out what you want*". P7 adds that, "*blockchain is really good at…writing information that's very hard to tamper with*". This secure storage of data provides a secure digital record of asset information. A digital record to represent the *golden thread* then gives you the ability to "*go back and interrogate all that information*" (P2) that may be required, for example, for demonstrating compliance at a project milestone, conducting investigations following incidents, or providing information to an owner at the point of sale or handover. That same record can then be used to facilitate "*sharing data between organisations*" (P3) but only "*insofar as people have the technology to view it, [and]* *the processes are put in place*” (P4). Information exchange via a DLT offers a “*single source of truth*” (P10) by “*giving transparency and a current consensual truth…regardless of the issues*” (P9). This single source of truth is obtained via consensus that can, for example, take place at information gateways where proof of that consensus is recorded on a distributed private ledger or by a consensus protocol within a public ledger. However, one thing DLT will not do is ensure veracity of the data, DLT will instead “*track liability*” (P12). According to P7, the application of DLT will not give data more integrity or make the people better at their job but they are “*hoping it'll make people a bit more honest*” about what they've actually done, which is in agreement with P10 who believes “*its greatest property is its propensity to change and influence human behaviour*”.

Tokenisation provides the ability to assign value of any kind through a digital coin (e.g., ether) to a transaction. P2 discusses “*DLT in the form of a cryptocurrency*” as part of wider “*digitisation of the built environment*” and P10 sees reward through tokenisation as the “*incentiviser*” that will make its use exciting to potential adopters. P11 offers supply chain management and payments as use cases for tokenisation. For example, if a client's project funds are held in escrow with funds being “*extracted by a proof-of-work or something like that…it means that we create a whole new world where the [internet protocol] address of the property is now requesting, digitally, that whoever's supposed to comply complies*” (P11). This concept not only ensures contractors and sub-contractors get paid, but it also tracks that work is completed satisfactorily, as per the contract. In addition, this offers possibilities to working across borders where DLT helps with “*internationalisation of the future business*” (P11), particularly if DLT systems become robust enough to support cryptocurrencies as viable and stable currency in the construction sector.

Challenges of implementing DLT

At this nascent stage of DLT's development, just as there is a focus on the benefits of applying DLT's characteristics to construction sector use cases, there is also a focus on the challenges of implementing it. DLT is often compared to the internet. In the late 1980s, email was a new application, but it did not have the critical mass of users required for it to be an effective, reliable form of communication. Today, it is the go-to form of communication due to its speed and global proliferation. For DLT, P12 states demand is “*just not there, no one's crying out for their processes to be disrupted and improved*” and offered four reasons for this lack of demand as follows: 1) technology instability and lack of technological maturity, for example, where no one type of distributed ledger has proved to be better than another for a specific use; 2) governance uncertainties, particularly concerned with trust boundaries in-house and between organisations where current processes are not aligned and organisations operate “*in a monopolistic business mindset where winner-takes-all, that sort of zero-sum approach*” (P12); 3) lack of proven business cases available in the public domain. Several “*secret blockchain projects*” (P12) are underway where failures are not presented, and successes are hidden for the time being. Indeed, P13 discussed a successful PoC but was limited in the information divulged to protect their IP at the time of the interview; and 4) unknown business models where blockchain/DLT developers do not yet know how many parties are required, whether the product is the blockchain itself or a blockchain-based solution, or how it integrates with existing systems and who is responsible for integrating them. To allow the industry to progress in these four areas, P12 suggests one of the biggest challenges is "*overcoming…corporate inertia and reluctance*" that has halted technological innovation of construction for many years. To do this, one could ask, "*Can this blockchain do better, more efficiently and improve the process that we are already using?*" (P10). The answer lies in PoCs. While organisations are still facing the challenges of implementing BIM processes into their business-as-usual activities, now they are being asked to consider yet more complex technologies and processes. P10 thinks it is "*going to be very difficult*".

If DLT is to form part of a solution to drive digital transformation of the construction sector, change (e.g., procurement reform, payment reform and cultural change) is required. DLT "*doesn't address volatility of payments in the supply chain*" (P1), it relies first on ensuring "*the right mechanisms are in place*" (P1). This reinforces the idea that DLT may form *part* of a solution, but it is not *the* solution. Construction is a "*notoriously laggard industry and an industry that does not readily accept change and is not either physically or culturally set up to embrace change quickly*" (P10). Thus, any changes should consider how they will be perceived by users and aim to minimise negative impacts.

The EU's GDPR (Otto, 2018) came into effect in May 2018 giving individuals more rights and control over their data. Interview participants saw this as a specific challenge for DLT where personally identifiable data is entered onto an immutable ledger. P4 raises issues around contract termination and parties' rights to their information being deleted, the impact that will have on the ledger of information and how data can be deleted from an immutable ledger. P10 describes GDPR as "*pulling against the nature of a blockchain*", which is in agreement with P12 who said, "*it doesn't comply with…the right to be forgotten*", particularly where the actual record is kept on the ledger rather than a signpost to the record. Two tensions between DLT and the GDPR are discussed by Finck (2019), which accord with the participants' views as 1) the assumption that there is one person (e.g., a data controller) responsible for enforcing individuals' rights under EU data protection legislation. A DLT by its nature is decentralised where power is distributed across many different parties meaning allocating controllership of the data is not a simple process; and 2) inability to modify or remove data from a distributed ledger is one of its characteristics that makes it attractive to many use cases such as proof that something happened at a point in time. However, Articles 16 (Right to rectification) and 17 (Right to erasure – often referred to as 'right to be forgotten') of the GDPR give individuals the right to modify and/or erase data pertaining to them provided doing so does not result in non-compliance with overriding EU or Member State laws. Finck (2019) highlights that private, permissioned DLTs will be easier to implement ensuring compliance with the GDPR over public, permissionless DLTs as parties are known and can agree on what can and cannot be done with the data. Despite these tensions, IBM discusses two projects dealing with digital identity in support of how DLT can support the GDPR – a permissioned blockchain to support Know Your Customer (KYC) requirements by *Crédit Mutuel Arkéa* which offers visibility of a customer's documents within a bank's distributed network; and a digital identity service by *VChain Tech* for airlines to safely share and store verified data about passengers boarding connecting flights without data exposure for the airline (Compert *et al.*, 2018). The different architectures available to DLT developers (e.g., public, private, permissionless, permissioned) allow for applications to be built around a use case's requirements in terms of the data to be stored and/or exchanged, the parties involved and the role of the distributed ledger.

The way business models change or adapt to new technological systems such as DLT will impact on how projects and financial processes are structured going forward. Whether projects choose public or private distributed ledgers will depend on the circumstances. A project from the supply chain and logistics industry demonstrates that there are challenges with private DLTs. TradeLens, a shipping blockchain established by IBM and Maersk (Shankland, 2018), was set up as a private system but faced challenges of signing up sufficient major shipping organisations as they did not want their data in the hands of competitors via a private blockchain. The Maersk-IBM partnership was later able to sign-up three of the world's biggest container shippers to give TradeLens the ability to track 90% of the world's traded goods (Gronholt-Pedersen, 2019).

Governance of establishing DLT-based systems is raised by P12, particularly with regards consortium or permissioned systems. Importance is placed on assigning powers to the parties and rights to introduce new parties or reject existing parties. In the event of chains crossing over, for example, DLT-based supply chains meeting construction chains, whose governance structure overrides, and what each party is responsible for requires consideration. It may be simple enough to follow the chain of custody of a physical product or component moving through the system but when that product is a service it may be harder to track. "*I think you will have multiple sharded*[5] *sub-chains that update state to a master chain once every epoch. But I think even further than that they're going to split off into private domains where they take care of certain business but have an interoperability layer across to another*" (P12).

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[5] *Sharding* is a concept that breaks the distributed ledger network into smaller pieces assigning nodes on the network to individual shards where they process transactions within the assigned shard rather than processing the entire distributed ledger. The purpose of this process is to increase throughput and address issues of scalability with the likes of the Blockchain (Pauw, 2019).

The final challenge to implementation of DLT discussed during the interviews is the layman's perception. It is very apparent that selling 'blockchain' as a solution to people who do not know about or understand blockchain is the wrong approach to obtain its buy-in for a new system. P3, P4 and P13 agreed on this issue: "*I think the moment you start using the word, then people will just shut down*" (P13), particularly with the concept of immutability of the data: "*people get very nervous when people say, 'Well, if you upload information and you can't amend it…', it sounds quite scary*" (P4). P3 believes education of the system is required where people who have had 30-years long careers in construction without digital processes will be asked to agree to more stringent record keeping of what they do, how they do it, when they do it etc. and the education needs to be around what exactly is being recorded – "*it's not the data that's there, it's the proof of the data*" (P3). As the developer of an application based on DLT, P3 believes people will use it "*not because it's blockchain-based but because it actually makes their working day better*". When offering a blockchain-based solution to a client, P13 said they "*had to think of another way to show them a better outcome*" to current working practices.

While there are many opportunities to be exploited, there needs to be PoCs proposed by innovators and early adopters to drive change at the macro scale to pull along the early majority, late majority and, eventually, the laggards. P12 believes driving that change through public funds is the wrong approach – "*if the companies don't put skin in the game they can walk away at any stage*" – but getting companies to agree to fund development, particularly as part of a consortium, is the challenge where they are reluctant to invest in untested technologies and where competitors also reap the same rewards. BIM is a driver for collaboration in the construction industry and while most organisations agree that collaboration will benefit the industry, most are reluctant to collaborate because capitalist business models are driving the bottom line. For DLT systems to be successful in construction projects, they require adoption across the project and asset lifecycles, from the owner down to the lowest tier contractors, all working together and regularly updating information models to realise the highest benefits.

P9 analogises the difference between the Netflix model and the Blockbuster model. Netflix's business model exploited technological advancements to offer customers an accessible, varied service; Blockbuster's business model did not adapt to reflect new technologies or human behavioural changes. Netflix is a global leader; Blockbuster is no more. Those that adapt and drive change are likely to be more successful than those who do not. There is education required as to how DLT systems are presented to potential adopters. If the system is sold as a disruptor – "*this juggernaut is coming and it's going to disrupt your industry*" (P12) – it instils fear; if the system is sold as an ally – "*you can improve your tax compliance, you can improve your regulatory compliance*" (P12) – it presents an opportunity.

There are many aspects to be considered before macro scale implementation of DLT can be enacted successfully with interaction from actors across the sector engaging from the outset to consider what a DLT-based world should look like.

4.4 Consultation interviews and industry focus groups: Scenario building for the future of a DLT-based construction sector

Upon understanding the state-of-the-art of DLT and SCs for the construction sector and identifying the underlying challenges the sector is facing, the next stage of the research involved establishing roadmaps to support implementation of DLT and SCs. To facilitate this and to provide direction, scenario building was adopted.

Scenario building supports analysis of the potentials of the future. It is not about predicting what will happen in the future, rather it is to focus on the identification of potential risks and opportunities based on possible scenarios to support better decision-making (Goodier *et al.*, 2010). Scenarios allow one to identify possible events, the associated actors and their motivations for doing something different in the future along with the ability "*to test strategies against those potential developments*" (Robson and McCartan, 2016, p. 368). This part of the study aims to contribute to the *when* and *how* of blockchain by implementing the scenario building technique to propose two roadmaps to support the implementation of DLT and SCs at both the meso (application) and macro (sector) scales. Two industry focus groups formed the basis of understanding the steps required to reach a state of readiness for the sector and the steps required to develop and implement new and adapted systems based on DLT and SCs.

First, the concepts of scenario building and the scenario axes techniques are introduced. Next, evaluation of existing roadmaps for DLT and/or the construction sector are reviewed. Then, development of the roadmaps through industry consultations via interviews and focus groups is presented. The consultation interviews industry focus groups contributed directly to the development of the meso and macro roadmaps presented in Section 5.5.

4.4.1 Scenario building

According to Durance and Godet (2010, p. 1489), "*a scenario is a description (usually of a possible future) which assumes the intervention of several key events or conditions which will have taken place between the time of the original situation and the time in which the scenario is set*". According to Martelli (2014), the scenario building approach supports development and identification of the progression needed to achieve the future situation from the present situation. Further, Fitt *et al.* (2018) believe it can support responses to change by proactively shaping the future as it emerges.

Scenario building has been used as an effective tool for corporate strategy since the 1960s (Ramírez *et al.*, 2017) proving successful for organisations such as Royal Dutch Shell who was able to predict and therefore plan for changes in the oil and gas landscape (Martelli,

2014) in response to the 1973 oil crisis (Ramírez *et al.*, 2017). Scenario building supports achievement of a future goal (Sarshar *et al.*, 2002) that should be revisited and updated as progress is made toward (or indeed away) from the desired state. Additional benefits of scenario building and planning include the ability to look at longer time horizons; develop new options; traverse uncertain, ambiguous or turbulent conditions; facilitate strategic discussions; and encourage collaborative strategies (Ramírez *et al.*, 2017).

The scenario building approach acknowledges that it is not possible to predict the future and that it could go in many different directions. Therefore, there should be no expectation that any proposed future scenario, however plausible, will become reality (Snoek, 2003). Durance and Godet (2010) believe a scenario building study should be sufficiently robust and of an adequate quality to stand the test of several years. Moreover, with the certainty of an ever-changing world, exploration of possible futures can prepare decision-makers to change strategy and deal with the unforeseen (e.g., a global pandemic or a sudden drop in materials supply) (Gürdür Broo *et al.*, 2020). Factors that shape the future can be identified; through scenario analysis, indicators of how to influence these factors can be gained (Snoek, 2003). This culminates in the ability to take a longer view of the world required by the construction sector through engaging with a wide, diverse group of participants with the ability to add creative thinking to the mix (Goodier *et al.*, 2010).

As a qualitative tool, scenario building is not without its limitations. Goodier *et al.* (2010) highlight a tendency of group think where the participants will follow the same train of thought stunting creativity, or participants from the same organisation (or at least with similar objectives) create alliances to push a specific agenda. They add it could also be a steep learning curve for participants to whom scenario building is new. Considering these limitations, it is not the intention of this study to generate new scenarios. Rather, it is the intention to establish how DLT applications might fare in the light of already proposed scenarios. Many scenario building studies follow rigorous research methodologies and are formulated over several days of workshops and interviews with participants, either internal to an organisation or interorganisational, depending on the objectives of the study. Some examples are discussed in the following section.

4.4.2 The scenario axes technique

A well-practised scenario building technique involves the use of scenario axes, that is, two uncertainties that support formulation of four plausible scenarios for the future (van't Klooster and van Asselt, 2006). While there are innumerable future uncertainties, Quezada *et al.* (2016, p. 6) explain that "*As with any model, scenarios must simplify a more complex reality in order to inform decisions*". The two uncertainties are plotted on a cartesian graph providing four quadrants that represent different plausible future scenarios (Kavuri *et al.*, 2020). Figure 4.4 illustrates the technique reported in six publications.

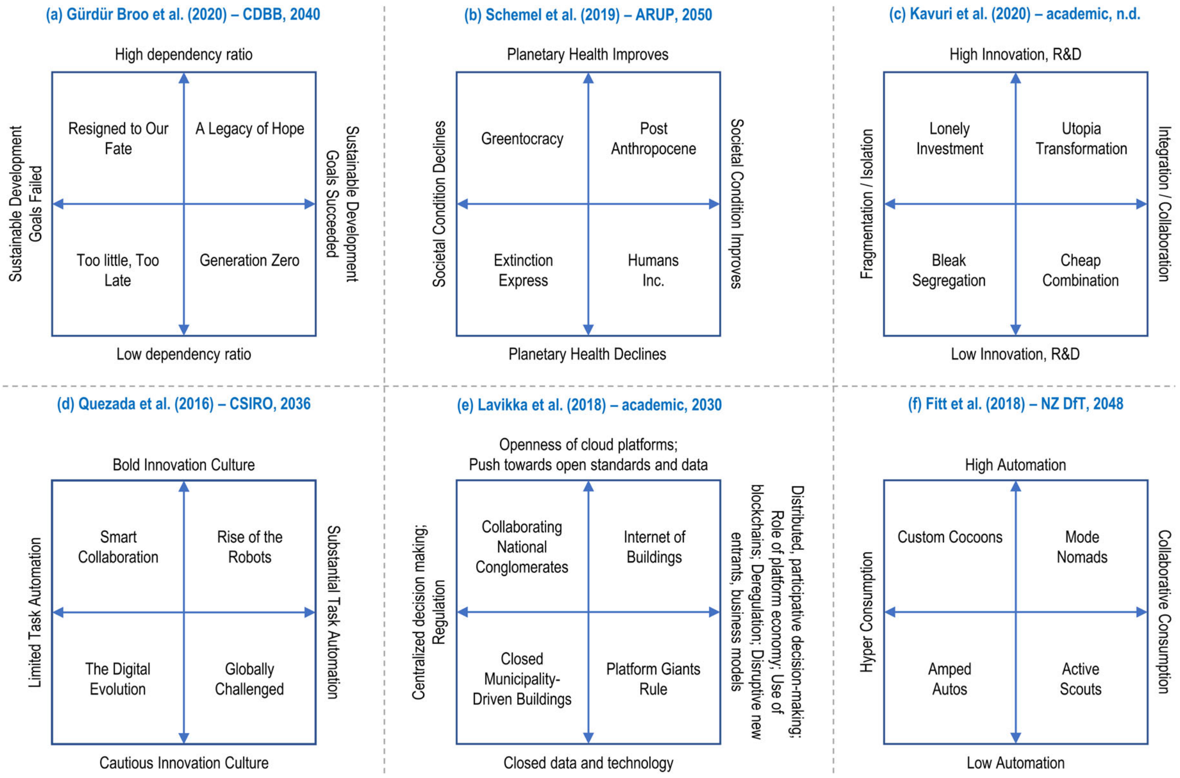


Figure 4.4: Comparison of four plausible future scenarios from six different studies

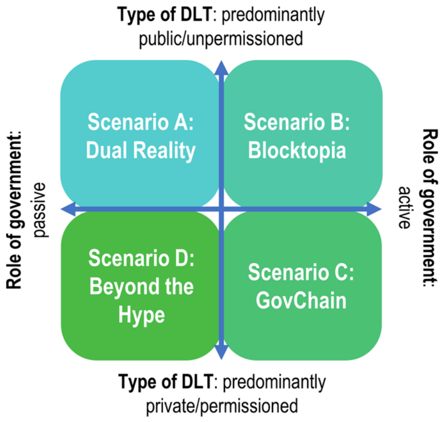
The Centre for Digital Built Britain (CDBB) devised four futures for 2040 shown in Figure 4.4(a) (Gürdür Broo *et al.*, 2020) centred on dependency ratio and meeting the UN Sustainable Development Goals. Arup's proposed scenarios in Figure 4.4(b) (Schemel *et al.*, 2019) are based on the uncertainties of societal conditions, and planetary health in 2050. Both CDBB and Arup adopted a similar approach; scenarios were developed through workshops with participants internal to their organisation and considered the trade-off between economic growth (through technological advancement) and prioritising the environment. An academic study by Kavuri *et al.* (2020), Figure 4.4(c), considered the digitalisation of the construction industry across axes of level of innovation, research and development (IR&D), and level of collaboration and integration across the industry. This study did not indicate a timeframe. The four scenarios by Australia's Commonwealth Scientific and Industrial Research Organisation shown in Figure 4.4(d) (Quezada *et al.*, 2016) were focused along two axes of automation and innovation culture in 2036. While they differentiate the two, automation could be considered a subset of innovation so in fact both axes are focused on the level of development of technologies and associated systems. Another academic study by Lavikka *et al.* (2018), Figure 4.4(e), used the timeframe 2020-2030. The axes of uncertainty considered seven factors: the openness of cloud platforms in the built environment; distributed & participative decision-making; role of platform economy increases; (municipal regulatory) push towards open standards and data; blockchain; de-regulation; and disruptive new entrants, business models. Finally, New Zealand's Ministry of Transport in Figure 4.4(f) (Fitt *et al.*, 2018) considered the proliferation of autonomous vehicles across two axes of the level of automation of autonomous vehicles and the level of consumption in society in 2048.

While not always explicitly stated along the axes of uncertainty, each of these examples considers technology and/or innovation and how they will impact the plausible futures. This demonstrates acknowledgement that technological advancements, either directly or as a driver for economic growth, are certain in any future; the extent of the advancement and its integration with other uncertainties (e.g., economic growth or societal collaboration) is the element of uncertainty. All the examples end with a statement that puts the emphasis of realising the preferred scenario on the general public to be instrumental in achieving the future in which they would like to live.

As stated above, the purpose of this study is not to devise plausible futures for the construction sector, rather its purpose is to envisage what any of these futures might mean for the development, adoption and diffusion of DLT and SCs in the construction sector. To do this, future scenarios from van Rijswijk *et al.* (2019) were used to consider their impact on the construction sector. This set of scenarios was chosen above others as it considered two axes that are likely to impact the development of DLT in construction: the role of government – discussed in previous studies (Salama and Salama, 2019), and the predominant type of DLT. In construction to date, there is no one predominant type of DLT given the lack of adoption and its early development. Therefore, these two axes of uncertainty are suitable to consider the future of DLT in construction. Indeed, given the uncertainty for the future and construction's inability to radically effect change in its current state (e.g., resistance to change, low digitalisation), it is argued that the importance of this study is not what the axes of uncertainty are but rather how potential DLT applications for construction could respond to any potential future. So, although these axes were devised for a study on taxation, the plausible futures represent four potential options for the future that may or may not occur.

The study by van Rijswijk *et al.* (2019, p. 18) was conducted to understand "*the potential impact of distributed ledger technology on society, and ultimately on revenue bodies*" with a timeframe of 2025. It was conducted in collaboration with the Netherlands Tax and Customs Administration (NTCA) to explore the future of taxation. The authors acknowledge the limited influence the NTCA has on DLT developments; the same could be said for the construction sector given its low rate of investment into IR&D (Li *et al.*, 2019a). A timeframe of five years from the date of the focus groups taking place was used. The forecast to c.2026 might seem close for a 'future gazing' study. However, given the two applications considered for this study are at or approaching the pilot stage, it is not unreasonable to expect some level of adoption by 2026 following a successful pilot.

The cartesian graph in Figure 4.5 shows the four plausible futures devised by van Rijswijk *et al.* (2019). The written descriptions on the right of Figure 4.5 (referring to *governance,*



Governance. Legislation, regulatory frameworks and government supervision all contribute to the survival rates of innovations. The government can take on different roles in influencing innovations, for example as a user, launching customer, a funder or a regulator and supervisor.

Industry. The extent to which industry invests in research and development of a new technology contributes to the ultimate success and impact of an innovation. Businesses not only need to focus on the invention of new technologies, but also in its applications and the distribution of these applications.

Acceptance of and trust in DLT by society. Innovations will only be successful if they match existing systems and if they are accepted by users and by society. Acceptance consists of the awareness of the innovation, the deliberation and decision to adopt and the use of the technology in daily life.

~~**Extent of DLT (de)centralisation**. Decentralisation is one of the main characteristics of DLT. Yet, there also exist DLT models that are much more centrally organised, with one or a few parties in control over access and content. The impact of DLT on society may depend on the extent of (de)centralisation of the dominant DLT type applications.~~

Figure 4.5: Most important uncertainties of DLT developments mapped along two axes and the four scenario building blocks (adapted from van Rijswijk et al. (2019, p. 23))

industry, acceptance of and trust in DLT by society, and *extent of DLT (de)centralisation*) show four additional components used to define the plausible futures as it was seen that DLT was too complex to consider just two uncertainties. While this is not typical practice in the scenario axes technique, they add more context to the futures, which will be useful in the development of scenarios for the applications. The four components are not specific to taxation and have been identified as important factors in the adoption of DLT in construction (Li *et al.*, 2019a). Of the four components, this study has included *governance, industry* and *society* given the extent of DLT (de)centralisation is inherent in the axis of type of DLT based on the description given in Figure 4.5. In addition, it extends the governance component to include the overseeing, control and direction of an innovation; and industry is extended to include receptiveness and willingness of the industry to embrace new innovations.

Summaries of the four plausible futures in the context of the two applications are provided in Appendix C. While the original descriptions are centred on the Netherlands and the European Union (EU), these summaries have been made region-agnostic to allow the scenario-building process to adopt an appropriate region for the applications being explored.

4.4.3 Existing roadmaps in construction and other sectors

Technology roadmaps provide "*a comprehensive approach for strategy planning to integrate science/technological considerations into product and business aspects as well as to provide a way to identify new opportunities in achieving a desired objective from the development of new technologies*" (Daim and Oliver, 2008, p. 690). The purpose of a roadmap at this juncture of DLT and SCs is to support the sector with its itinerary toward implementation and adoption. A roadmap will provide a more streamlined approach to adoption of a new system allowing the industry the opportunity to have all supporting infrastructure in place prior to implementation; it allows time to educate users/beneficiaries of the new system about its benefits whilst highlighting any potential challenges they should prepare for; and it supports the development of industry standards and regulations

(Kauffman *et al.*, 2018).

Literature related to roadmaps of DLT and SC in the construction sector is lacking. Prakash and Ambekar (2020) presented a five-step roadmap focused on increasing productivity in construction as follows: identify a suitable use case; define a minimum viable product; design the nodes; start hiring new talent; and start scaling the efforts. However, this is unvalidated and fails to consider elements such as regulatory frameworks, processes and integration with supporting technologies.

Studies have been conducted across other industries at varying scales of analysis such as: logistics and supply chain management at an individual scale (Queiroz and Fosso Wamba, 2019); maturity of blockchain generally (Wang *et al.*, 2016); acceptance of Bitcoin and Blockchain at an individual scale (Folkinshteyn and Lennon, 2016); and organisational adoption of blockchain (Holotiuk and Moormann, 2018). Kolli *et al.* (2018) offer a micro level roadmap that is not specific to any one sector that asks four questions: “Do I really need Blockchain now?”; “What’s the impact on my existing business?”; “What are my choices for implementation?”; and “How do I prepare for long-term sustainability?”

There are DLT roadmaps and strategies available at micro and macro scales that are not specific to construction. For example, the UK National Blockchain Roadmap (NBR) was published in July 2021 endorsed by UK members of parliament (British Blockchain Association, 2021). The NBR consists of 20 recommendations that aim to reform the UKs DLT landscape. The recommendations focus on the development of evidence and standards to support the blockchain ecosystem but there is limited detail of how to implement them and the document is based on literature primarily from one publication—The Journal of the British Blockchain Association—run by the team that consequently authored the NBR. Australia published its blockchain roadmap in February 2020 outlining a vision for the future (Australian Government, 2020). Australia has since formed a National Blockchain Roadmap Steering Committee and awarded funding (upwards of AUS$24 million) to begin delivering on the roadmap (Enwood, 2021). The EU does not have a formal roadmap. However, their blockchain strategy is focused on the EU becoming a leader in the field and is centred on seven goals: building a pan-European public services blockchain; promoting legal certainty; increasing funding for research and innovation; promoting blockchain for sustainability; supporting interoperability and standards; supporting blockchain skills development; and interacting with the community (European Commission, 2021).

Several technology companies have produced roadmaps and/or strategies to support the blockchain/DLT agenda. However, very few consider construction given their focus across different sectors rather than being sector-specific. IBM discusses three types of blockchain projects: new business (network) models; modernising an existing ecosystem; and joining an existing (blockchain) ecosystem. While they do not have a formal blockchain roadmap, they are one of the leading organisations offering blockchain solutions across oil and gas, trade finance, supply chain, letters for guarantee, invoice reconciliation, contactless ticketing, and voting (IBM, 2019). Unisys discusses the capabilities, opportunities and challenges of blockchain from an enterprise perspective (Unisys, no date). Autodesk, one of the leading construction software organisations globally, does not have a formal stance on blockchain but appears to be considering its use (Alexandre, 2019) and briefly covers blockchain as part of Autodesk University (Autodesk, 2019). The Blockchain Training Alliance offers a micro level roadmap based on five phases: pain point identification; use case exploration and prioritisation; solution architecting; network architecting; PoC (Richardson, 2019). This is designed to be delivered via consultancy and is aimed at an individual organisation.

The construction sector is often discussed as being different from all other sectors. There are several factors that highlight this point: complexity of projects; uniqueness due to the one-off nature of projects; mobility of facilities where services and materials all have to move to the construction site, which is considered an uncontrolled environment; multiplicity of regulatory agencies with which to comply; ad-hoc labour force that is often seasonal and migratory; conglomerate of contractors as a result of a highly fragmented sector; a range of stakeholders in construction work at times with conflicting objectives; complex inter-relationships and interactions managed by complex contracts; lack of organisational setup compounded by the high-risk and uncertain nature of projects; safety hazards due to work being carried out on an active construction site with temporary and/or semi-finished structures; labour quality caused by scarcity or manpower; and productivity, which has remained stagnant for several years (Toor and Ofori, 2008; TechnoFunc, 2020). Considering these challenges, existing roadmaps and strategies to implement DLT and SCs are not sufficient to deal with their development and adoption in a construction context.

4.4.4 Roadmap development

Development of a new system brings uncertainty and ambiguity as a result of change (Lyytinen and Newman, 2008). Consultation with users during the development of the system increases the likelihood that it will be more flexibly suited for its intended use (Orlikowski, 1992). This was the approach taken to develop an artefact—roadmaps—to support implementation of DLT and SCs in construction through focus groups to engage with developers of DLT/SC-based construction sector applications. The seven steps taken in this study are shown in Figure 4.6.

In *Step 1*, individual consultations were conducted via interview with the application owners/team members to obtain detailed information of the application, its objectives and status. Discussions were held on the impact that the three components (governance, industry and society) might have on the application in the different plausible futures in day-

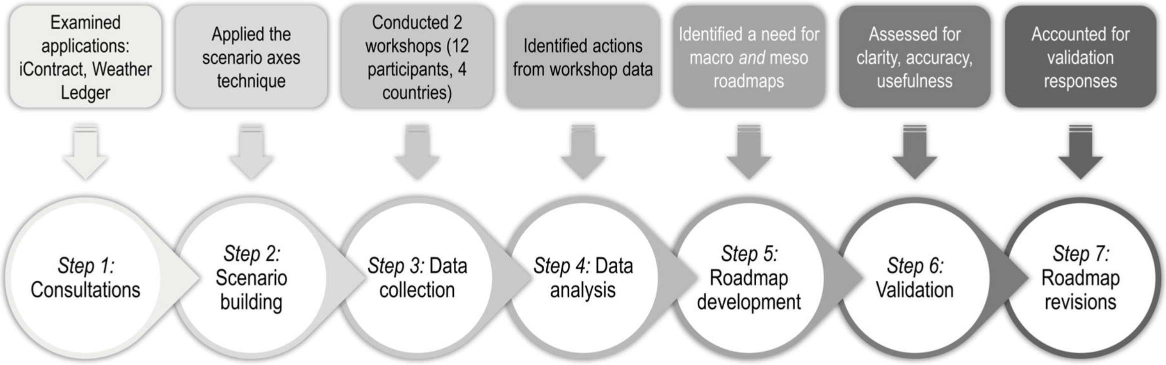


Figure 4.6: Steps taken to support development of roadmaps

to-day operations. Application owners were given the opportunity to contribute to the topics to be discussed at the focus group associated with their application to ensure the data collected were beneficial for the study and to add value to the development of their application. They also contributed to the identification of focus group participants.

Step 2 involved developing narratives for the application in the different scenarios based on discussion from Step 1. The scenarios were sent to the application owners for agreement/approval. In *Step 3,* two focus groups took place with 8 and 6 participants respectively. Following the focus groups, *Step 4* consisted of analysing the data and drawing implications for the applications representing the potential for DLT and SC implementation into the construction sector. S*tep 5* saw development of the roadmaps. Upon analysis of the data in Step 4, it was apparent there was a need for two roadmaps, one meso roadmap for development and implementation of specific applications and one macro roadmap specifically for readying the construction sector ecosystem to enable successful implementation of DLT and SC applications. The roadmaps were developed based on the data analysed and supported by academic literature where there were gaps in the data collected from the focus groups. *Step 6* involved validation of the roadmaps. Feedback was obtained from industry practitioners based on three metrics—clarity, accuracy, usefulness. The roadmaps were sent to focus group participants and industry practitioners not at the focus groups to obtain views from the delegates based on the three metrics. Details of the validation activities can be seen in Chapter 7. Finally, in *Step 7*, amendments were made to the roadmaps based on the feedback from the validation activities and are presented in this thesis.

The two focus groups took place in April 2021; both were structured identically. In advance of the focus groups, participants were sent details of the four plausible futures (see Appendix C) for consideration along with an overview of the application on which they were participating. During the focus groups, they were asked to discuss the application in the context of several areas: the level of complexity and plausibility of realising the application; identification of any prerequisites for both the pilot stage and mainstream adoption; internal and external factors; the possible impacts and benefits of the application; identification of any risks, opportunities and limitations for the application; and actions that are required to take place for the application to be realised. Where appropriate, participants were prompted to consider the four dimensions (technology, process, policy, society) from the socio-technical dimensions identified in the Literature Review in Chapter 2.

The two DLT-/SC-based applications were identified based on:

- Applications at or near the pilot stage.
- Contains a DLT/SC element.
- Accessible through researcher's own network.
- Applications distinct from one another.

The purpose of choosing two real-world applications was to support development of a roadmap that would meet real-world requirements rather than being based on a hypothetical situation. The two applications included the iContract and the Weather Ledger. The iContract will automate the construction contract using SCs running on a DLT. The Weather Ledger automates weather compensation events for projects at the construction phase. A consultation interview and a focus group took place for each application.

4.4.5 Consultation interviews

The consultations via video provided a collaborative approach to work with the developers/owners of the chosen applications that ensured they received benefit from participation in the study through: identification of possible risks and opportunities of their application; engagement with industry practitioners and academics who might have different perspectives to those which may have already been sought in the application's development to date; and the opportunity to feed into the roadmap that could be later used to inform policy supporting DLT implementation. Discussions were held on the impact that the three components (governance, industry and society) from van Rijswijk *et al.* (2019) might have on the application in the different plausible futures in day-to-day operations. Application owners were given the opportunity to contribute to the topics to be discussed at the focus group associated with their application to ensure the data collected were beneficial for the study and to add value to the development of their application. They also contributed to the identification of focus group participants. Narratives for the application in the different scenarios were developed based on discussions from Step 1 then sent to the application owners for agreement/approval.

4.4.6 Focus group findings

In this section, the results and findings of each focus group are presented. Consideration of cryptocurrencies was omitted by both applications given their current state of volatility. This is not to say that when these applications reach mainstream adoption cryptocurrencies will not form part of the solution; however, it was felt that their many variables did not warrant consideration at this time. Each focus group is presented separately. First, an overview of the application is given followed by the results and findings. Then, an evaluation of the two applications is made considering the scenario building technique applied. Descriptions of the applications were devised from the consultation interviews.

4.4.6.1 iContract

An intelligent contract is a self-executing contract containing electronically drafted provisions that can automate a variety of processes in accordance with the terms of the contract. The iContract is in development where the main product proposed is a software application based on intelligent contracts that will [semi-]automate terms of the construction contract. The iContract is currently in the concept phase where the design of the solution is being scoped; a pilot is estimated to take place in 2022 for which a collaboration is in place between iContract and PT Blink (iContract Technologies, 2022). The primary objective of the iContract is to de-risk projects by making contractual terms clearer and removing the possibility of misinterpretation by different parties. The iContract does not propose to do anything a well-written, traditional construction contract would not do. It aims to solve the disconnect between parties interpreting a clause. Contracts need to be flexible to cover all eventualities, especially as they are written well ahead of time. Automating the traditional contract through the iContract will result in increased efficiency, accuracy and speed. As work is carried out, tasks and activities in the work breakdown structure can be marked as complete as the work progresses and inspections can take place as soon as the system indicates something is ready for inspection, rather than waiting for a payment claim to come through at the end of a payment period. Data from IoT devices onsite will provide an instant upward or downward flow of data that would instantly update or retrieve data from the project schedule creating a waterfall effect of flow of information.

The iContract will act as one process where subcontracts will ‘plug and play’ into the main contract rather than having several layers of subcontracts as in today’s environment. This removes gaps of exposure between the contracts. The iContract will offer standard template contracts that can easily identify differences that need to be addressed – similar to clash detection in BIM. One seamless process will remove the ability for ‘deviant parties’ to operate. Inbuilt with ML algorithms, the iContract will learn the contracting process over time to the extent it will prepare a contract template with 80-90% accuracy leaving the remaining 10-20% to lawyers to negotiate. The extent of the ML algorithms will be reliant on the data input into the system acknowledging that *garbage in is still garbage out*.

Once the iContract software is established, the focus will include real-time analysis and forecasting based on streamlining processes for the parties. The real-time and historical data facilitated by an immutable ledger of what has transpired, who did/said what, what was sent via email, which drawings were used etc. will remove the space for ambiguous interpretation by the parties. This will significantly reduce the number of minor disputes throughout the project allowing the parties to fulfil the terms of their contract as intended.

Table 4.5: iContract focus group participants

ID	Role	Organisation type	Experience	Location
iC1	Director, performance improvement	Consultancy	19 years	Australia
iC2	Deputy director	Central government	19 years	United Kingdom
iC3	Lawyer, speaker, consultant, academic	Consultancy	26 years	Australia
iC4	Digital engineering and compliance manager	Tier 1 contractor	11 years	Hong Kong
iC5	Professor specialising in BIM	Academia	18 years	United Kingdom
iC6	Project director	Consultancy	21 years	Australia
iC7	Project manager with contract management experience	Tier 1 contractor	13 years	United Arab Emirates
iC8	Professor specialising in construction management	Academia	40 years	United Kingdom

iContract focus group

The profile of the eight participants who took part in the iContract focus group can be seen in Table 4.5. The criteria for selection of participants was based on their level of experience in the construction sector; knowledge of DLT/blockchain and SCs; understanding of key challenges facing the construction sector; and experience engaging with different organisations across the sector. In addition, participants were sought from different countries to enable perspectives across different regulatory environments and cultures. Prior to the focus group taking place, participants were sent a consent form and participant information sheet. The participant information sheet set out the objectives of the focus group, the participant’s role in it, how their data would be processed, and details of the plausible futures devised with the application owner during the consultation interview.

The construction contract is an artefact that ties all elements of a construction project together. To automate this is complex and potentially has a wide reach given the lifecycle of built assets. The intention to get the iContract to market is to first identify small areas that are appropriate to automate rather than attempt to automate the entire construction contract from the outset. The following subsections consider the complexity and plausibility of realising the iContract, highlight the challenges associated with implementation of the iContract; identify propositions for its use in the sector; identify considerations that should be given to the application prior to and during its development; and identify some of the benefits that could be realised from its implementation.

Complexity and plausibility of realising the iContract

The discussion centred on the year 2026 when it is expected there will be early adoption of the iContract in the sector. Participants were asked to indicate on a Likert scale how plausible iContract implementation would be in this timeframe, and how complex. The responses can be seen in Figure 4.7[6].

It was seen as being a highly complex application by almost all participants who placed it between 4 and 5 on a five-point Likert Scale with only one participant placing it at 3.5. This is as would be expected given the level of disruption expected by the iContract and the

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[6] Note that one participant joined the focus group during this activity, another joined after. Therefore, complexity received six responses and plausibility received seven even though there were eight participants overall.

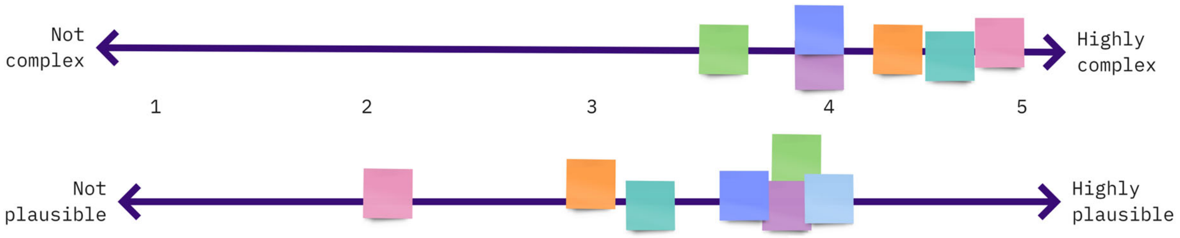

Figure 4.7: Screenshot of participants' views on complexity and plausibility of realising the iContract

complexity of digitalising a traditional construction contract. The issue of regulatory frameworks was cited as they "*are the last things to change in a market. You could find a new technology comes in and through some kind of disruption changes a bit but for this, you're talking about an active policy maker within 5 years, and I think that's quite complex*" (iC2). iC4 agreed stating, "*There are so many moving parts that may change and make a system difficult to implement in practice (e.g., a change in regulatory frameworks)"* but was also of the view that "*it is surely doable*".

iC8 felt the complexity lay in the length and nature of supply chains where currently, "*the thought of a sub- sub- subcontractor engaging properly with this and exploiting all the advantages of the system seems rather difficult, to put it mildly*". iC4 added, "*I don't think technology is the barrier, it's going to be the people and the system changing it*".

Most participants felt the application was relatively plausible to realise giving a score of between 3 and 4; only one participant scored 2. iC4 offered two scenarios where the iContract could be plausible: "*One where the contractor is trying to drive efficiency in the downstream supply chain, and it has a lot of control in that scenario. Or otherwise in an alliance/collaborative scenario where the overall best for project motivators are being shifted to the point that you actually have owner and contractor buy-in to run an iContract model, as opposed to a traditional 'we're at loggerheads' master-slave type relationship*". iC8 believes these are feasible scenarios but adds where you're "*dealing with terms like 'in the opinion of the engineer…' I think that would cause immense problems*". iC5 agreed with the application being plausible but added, "*I think trying to do a whole contract is challenging*". And while the long-term goal of the iContract is to digitalise the entire contract management process, it was recognised that initially there will be small PoCs starting with "*the low hanging fruit in terms of what contractual clauses are easily automated*" (iC1). "*I don't see any reason why it wouldn't happen as part of a mechanical process. I can see why it wouldn't happen as part of people and process, but I think it's definitely plausible*" (iC4).

Challenges for construction management applicable to the iContract

Challenges were discussed from two perspectives. First, contract management challenges were raised. There was a consensus that current contract management practices in the construction sector are not fit-for-purpose. The participants raised this as a key factor as "*a lot of the contracts actually need to be completely reassessed*" (iC4). iC6 explained, "*standard forms are just the template as much to almost bastardise them to the point of non-recognition*". The participant representing UK government indicated that "*bespoking contracts and inventing endless z clauses*[7] *that [parties] write into their own contract terms*" (iC2) is what drives inefficiencies and waste in construction projects and "*as a general rule of thumb, we don't really want to see people fiddling with the more standard terms and conditions; it doesn't help anybody*" (iC2).

Second, challenges to implementation of the iContract were discussed. To automate current standard form contracts such as the JCT, NEC or FIDIC in their current format and under current practices would result in a need to recode the iContract for each project. This is impractical given that an objective of the iContract is to speed up the contracting process. However, the current process is not fit-for-purpose and to update the current process and await its acceptance across the sector prior to introduction of the iContract would take considerable time. iC3 opined that, "*if you create business-as-usual, you're going to get more resistance to the adoption of the technology because business-as-usual is a non-trust sort of relationship*". These two contrasting views of automating the construction contract highlight the challenges the sector would face in adopting the iContract. iC3 asked how data can drive the change in a bottom-up approach: "*What processes do we want to use to prove that the concrete is being poured, and it's this volume, and this is the amount of money that should flow with that? And then the contract just does a few things above that*". A clear finding with regards standard form contracts is that they are not suitable for managing construction projects in their current versions and while this study does not attempt to provide a solution to this challenge it raises the question of how best the sector can reform construction sector contracts.

Propositions of the iContract

Currently, construction contracts are drawn up at the outset of a project and often only retrieved when problems occur. In contrast, the iContract is proposed as Software-as-a-Service (SaaS) intended to be "*a tool that you would use on a daily basis… letting people know how they should be acting*" (iC6). It becomes a live artefact that has a central role in delivery of construction projects that connects to project management software with daily task lists and objectives linked to payments. The iContract integrates with other technologies such as IoT in the form of an oracle to collect data that the iContract can utilise to progress the project, for example, "*the contract will draw on data that it was scanned in at x date, the concrete was x strength, and party y and party z contributed to that under the work breakdown structure as part of the schedule and that's where the payments would kind of go through a waterfall*" (iC6). This draws on the idea that better data processing can unlock value to increase efficiencies and productivity provided it is the right data in the right

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[7] A 'z clause' in the commonly-used NEC suite of contracts provides an opportunity for a party to insert a specific condition into what is otherwise a standard form.

format at the right time. iC4 commented that "*technologies are driving better behaviours in project management…the plans have to be more real because [the parties] know they're going to be measured against them. If people know they're going to get paid off their plans, then they'll put a lot more effort into the accuracy of their plan. It drives more of a proactive behaviour to monitor what you're doing to plan better*". This confirms that technology can change current practices, not forgetting that it requires process and cultural change and overcoming the likely resistance to these.

In a sector that has one of the lowest levels of digitalisation, integrating more technologies and moving toward automation must be accompanied by tangible benefits to all parties before the added value is recognised as worthwhile. iC2 is in agreement with this where they believe "*technology tends to augment either positive or negative behaviour by human beings, but it will never solve the problems and it will never generate positive outcomes*" adding that "*if the industry is not committed to changing its approach, changing its culture, and focusing on delivering value and performing better, then all of these initiatives and technologies will fail to have the impact that they could, because people will find ways and means of obstructing them*" (iC2).

While the iContract is the first of its kind, iC5 sees this as a precursor to "*a landscape of this contract technology. Some are specialised in recording deliveries to site; some may be specialised in defect or quality control on sites*". In addition, it is proposed that it forms a layer within an existing technological platform such as project management software where the iContract is "*capturing snapshots of these information flows and this is built around the information lifecycle, the data lifecycle, and just plugging into it as if there's a platform for information exchange and the iContract becomes the contractual layer connecting it*" (iC1). How, where and when the technology is adopted and evolves overtime will determine the level of impact it can have on the sector.

Considerations prior to implementation of the iContract

The role and stance of government of the market in which the iContract is deployed will be a key component in its success or failure. For example, "*if a government is already a coercive government or prescriptive government implements this, it's very different to that being implemented horizontally in a market*" (iC1). Comparisons with BIM can be seen in this instance where countries like the UK mandated the use of BIM on publicly funded projects post 2016 and has seen significant adoption across certain parts of the project lifecycle (e.g., design). Many other countries have or are introducing mandates (McAuley *et al.*, 2017) based on the successes of the likes of the UK. While it is too early in the trajectory of the iContract's maturity to say whether a mandate will be required, this infers that the client could have a leading role to play in early adoption of such technologies. iC1 commented that the challenge of realising the iContract is at the "*process layer, not at the data [layer]*". This is aligned with the idea that technology alone cannot solve the sector's problems. In contrast, iC6 believes "*one of the biggest challenges is having a central source of truth that lasts throughout the whole project lifecycle, having a uniformity of data format, having standardisation of data*". This is pertinent given the focus on interoperability across technology in the sector.

Benefits the iContract could bring

There are several benefits of the iContract, namely, automation to speed up and standardise the contract management process. In addition to these, cost is a driving factor. iC5 referred to a recent study they were aware of showing that blockchain platforms are cheaper than existing commercial platforms (e.g., for document management). This could be a major driver for adoption of blockchain and other DLTs if the new system, whether based on business-as-usual or new/adapted processes, is seen as a cost-saver. iC1 questioned what the iContract might do to the power balance on a project. iC6 responded that the iContract would not necessarily adjust the power balance, rather it would increase transparency through creating a more logical process and ensure that all parties are aware of the status of the project at any given time. iC3 added that "*simplicity and transparency are very, very good starting points*".

Another element to be considered that could apply to all innovations in construction is the idea of "*democratising the benefit*" (iC5). "*It doesn't matter how attractive the technology or innovation you go with to the project parties is, if it's not beneficial for everyone, they say, 'What's in it for me?' … the technology has to offer some form of democratised benefit to facilitate its adoption*" (iC5). This, along with minimising negative impacts on project participants in respect to current working practices, requires attention if it is to be successful in its endeavours.

4.4.6.2 Weather Ledger

The Weather Ledger is an Innovate UK-funded project lead by Digital Catapult in partnership with EHABITATION Limited, Clyde & Co, Connected Places Catapult, Ferrovial Corporation and BAM Nuttall. A Weather Ledger pilot project was completed in April 2021 to demonstrate proof-of-value for DLT and IoT in the automation of compensation events during the construction phase of a project. In the UK, claims for adverse weather conditions (so-called 'weather events') make up only 5% of compensation event claims but their administration is arduous because of the requirements for collection and compilation of evidence, documentation and manhours of site staff and project managers in preparing the claim. The result is lost hours of productivity that impacts both project delivery and profitability. The Weather Ledger project aimed to: "*provide trusted ultra-local weather data; automate the detection of weather-based compensation events; make an adjudication; notify parties of the contractual implications; prevent disputes and recover labour*" (Digital Catapult, 2021, p. 6). The Weather Ledger represents minor disruption to current practices; however, it forms the basis for potential disruptive changes by other DLT-based applications.

Digital Catapult (2021) reported several benefits demonstrated by the Weather Ledger pilots. *Improved transparency and trust of weather data*: there was one single reference point for data for all participants to view, which made communication of and agreement on weather data easier. This had a positive knock-on effect to manage the stakeholder relationship. Unexpectedly, this also made record keeping easier and resulted in more streamlined communications between the users. Typically, data are collected by site managers and sorted on spreadsheets and PDFs in different locations from different sources. This project provided a central repository for all relevant data which improved productivity as there was no need for multiple sets of data. *Integrated weather data improved productivity*: there was a significant reduction in time that site managers spent searching several weather reports for anticipating potential disruption to site activities from ~30 minutes/day to around 5 minutes equating directly to monetary savings. *Improved project planning and rescheduling of tasks*: typically, weather reports arrive 36 hours prior to possible delaying weather events. The Weather Ledger was able to provide data beyond 36 hours giving site managers more time to plan and reschedule activities that may be impacted by adverse weather conditions. Advance warnings contribute to projects savings where, for example, equipment hire costs are scaled depending on when cancellations are made (i.e., longer notice periods result in less or no charges). The ability to cancel equipment hires with more advance notice can result in thousands of pounds of savings across an organisation's annual spend. This also flows through to cancellation of scheduled workers, materials and equipment and the ability to reschedule other events that can be done in the downtime of weather events.

Weather Ledger focus group

Six participants took part in the Weather Ledger focus group; the profiles can be seen in Table 4.6. The criteria for selecting participants was the same for that of the iContract: their experience in the construction sector; knowledge of DLT/blockchain and SCs; understanding of key challenges facing the construction sector; and experience engaging with different organisations across the sector. Selection of participants had the addition of knowledge of the Weather Ledger given its stage of development and the number of people who have been involved in the project to date. As the Weather Ledger pilots took place in the UK, all focus group participants were UK-based.

Table 4.6: The Weather Ledger focus group participants

ID	Role	Organisation type	Experience
WL1	Director, architect, academic	Professional services, academia	21 years
WL2	Software developer/technologist, academic	Professional services, academia	20 years
WL3	Academic, digital economy, parametric insurance	Academia	15 years
WL4	Head of technology, industry association	Research and innovation	10 years
WL5	DLT application developer	Software development	8 years
WL6	Professor, digital construction, engineering, BIM	Academia	18 years

The results and findings of the Weather Ledger focus group are discussed next. In contrast to the iContract, which is still in the concept phase, the Weather Ledger is close to being deployable onsite. For this reason, propositions for the Weather Ledger were not discussed and therefore are not considered here. Challenges, considerations and benefits that were raised are highlighted.

Complexity and plausibility of realising the iContract

As with the iContract focus group, the Weather Ledger focus group considered a timeframe of five years into the future when there would be some adoption of the application in the sector. Thoughts on complexity of realising this application varied between participants ranging between 1.5 (low complexity) to 3.5 (somewhat complex) as illustrated by Figure 4.8. The main issue around complexity was to do with the governance structure. The pilot involved several organisations, and most were willing to participate as necessary, but this was backed by Innovate UK funding, so the participants did not have "*skin in the game*" (WL4) explaining that when organisations are asked to fund such applications, there is less willingness to engage. Regarding plausibility, all participants felt the Weather Ledger was highly plausible. The application for the Weather Ledger already exists and the pilot project shows it works. However, there were issues with deploying the application directly to the project, so it ran as a shadow simulation with real-world data collected by IoT weather sensors on site. The application will continue to be developed thus by 2025 it is hoped to be integrable into existing systems. Given the scope of the project and the small area of focus, participants felt it was very plausible this application be adopted by the sector.

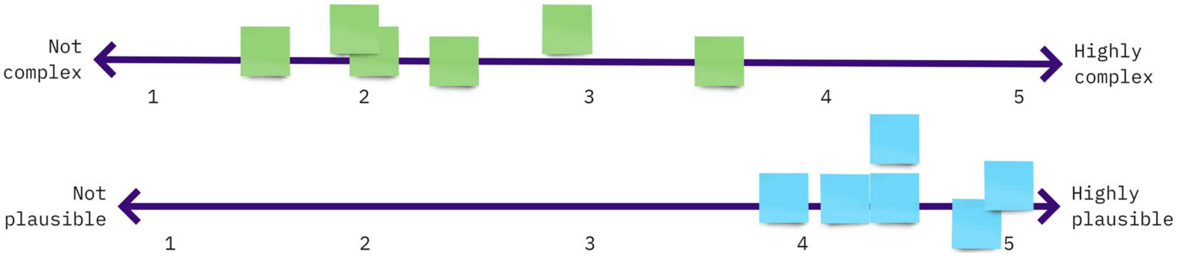

Figure 4.8: Participants' views on complexity and plausibility of realising the Weather Ledger

Challenges for weather compensation processes applicable to the Weather Ledger

The question as to whether current weather-related compensation practices are fit-for-purpose was discussed. Currently, standard form contracts use the metric of a once-in-a-10-year weather event for payment of compensation where delays occur to projects because of adverse weather on a construction site. There was discussion on whether this was a fair measure, particularly since weather stations are often far from the construction site and therefore do not provide accurate weather data. WL5 provided an example of when this might occur: "*it's February and your one-in-10-year event is 100 millimetres of rain. And you're 10 miles from the nearest Met Office station. Even if it's one mile, local weather effects can be different, right? And so, you get 99 millimetres of rain at your Met Office* *weather station; that might mean 101 millimetres or 110 millimetres of rain at your actual site. And that difference…might be the tipping point at which the site floods*". On top of this, current Met Office weather data is not stored on a blockchain "*and therefore it's not a resilient option*" (WL1). This and other current tools to measure weather data and manage the associated risk lack sophistication that is required for complex construction contracts.

Considerations prior to implementation of the Weather Ledger

Several open challenges were discussed in respect of how the Weather Ledger will function. First, WL2 raised the scenario of a dispute and what happens to the contract thereafter. They questioned how the outcome of the dispute will be recorded once it is resolved, asking "*How does the outcome of that actually end up back on-chain again? How do you update the state or do some kind of compensation transaction to get the state of the DLT back to what everybody agrees is what it should be?*" This appears to be more of a process challenge rather than a technological challenge on the basis that the ledger can be updated with the details of the dispute and its outcome, both of which could be required on the ledger by the project as a matter of record.

Another issue that arose from the pilots is having redundancies onsite for powering data sources where, for example, "*there were issues with the IoT devices not being able to draw enough power in some cases*" (WL5). While the focus of this study is the DLT and SC element of a system, there is the acknowledgement that they do not operate standalone. This comment reiterates that other technologies need to evolve and/or be robust enough to integrate with the application, in this case the IoT facilitating the collection of data and the tools to process the data with appropriate power and connectivity.

From a digitalisation point of view, consideration was given to the skills and resources required to operate such an application. New, young entrants are invariably digitally minded and will likely adapt easily to new technologies and new systems. However, it will be sometime before they become managers and decision-makers. On this basis, "*you do have to hit the top of the food chain at some point*" (WL4) meaning that skills programmes at either a macro or meso level will be required to ensure that the appropriate resources have the skills to implement advanced digital systems.

From a more pragmatic rather than technological perspective, it will be challenging to change current processes given the sector-wide issues such as change resistance. "*Ultimately, whether it's right or wrong, people see their ability to fight over a claim as a way to make more money*" (WL5). Through SCs, the Weather Ledger can analyse data objectively and give a probability of outcome for the claim. In the event the person does not agree with the projected outcome because of "*an entrenched attitude*" (WL5), they could reject the new system "*because we feel that we could argue for more*" even though they may only ever receive around 80% of the claim. This came up in the pilot and resulted in the weather data not being "*recognised by the clients in those conversations*" (WL5). This demonstrates the need for much more real-world data to prove the accuracy of project outcomes by SCs and any associated savings based on whether a claim was made or not.

The final item for consideration is that of the governance structure. The Weather Ledger pilot had several organisations involved and most were willing to participate as necessary. Disruption to the sector will drive a change in mindset but there will likely remain resistance given the entrenched attitudes mentioned above. Demonstrable benefits, particularly cost-saving or profit-making, are essential to change mindsets and practices of the sector. At that point, effective governance will likely come from the individuals and organisations who reap those benefits. WL1 commented that, "*normally when you have a novel technology like these, when clients demand that in their projects the adoption is much easier. […] It's not a kind of final strategy, but it's an intervening strategy that helps adoption. You need more visionary clients*" (WL1). The success of BIM on construction projects was in part driven by the demand (via a mandate) for its application on publicly funded projects. Clients are in the position that they can dictate the use of certain technologies or processes through tender and contracting, and it is then upon the organisations within the sector to respond.

Benefits the Weather Ledger could bring

It was made apparent that the Weather Ledger is a risk management tool. The focus is not on the fact that it is built on DLT, it is focused on a better way to manage weather risk through "*having more shared access to information, whether that's client, contractor, insurer, and having better models and information*" (WL5); DLT is just the technology being explored to deliver that through the Weather Ledger. Better access to data and therefore modelling "*prevents a lot of the risks that might lead to a compensation event even happening*" (WL5). This can be particularly powerful where the "*insurance sector generally is quite slow to move*" (WL3) – if they are presented with demonstrable benefits from real-world case studies, they may be more susceptible to new models of insurance.

It was discussed that the benefits from the Weather Ledger might not lie in the money that can be awarded through claims but rather the cost savings that can be made from better weather data and therefore better modelling. Earlier warnings of adverse weather means a better chance to reschedule the project resulting in less downtime. "*The majority of the cost savings come if the client can achieve a lower initial price of the contract and if the contractor can increase their chance of winning their bid*" (WL5). What this equates to is the ability to "*minimise workers on site or equipment call to site or equipment used, when actually it's not able to be used. More effective, efficient project scheduling is less fuel burned, less dust kicked up*" (WL4).

4.4.6.3 Evaluation of the applications

It was apparent from both focus groups that current construction sector practices related to the two applications are not fit-for-purpose. The construction contract is central to construction projects and while standard form contracts have tried to adapt to new ways of working or drive change through more standardised terms, it is clear there are still major issues with contractual practices. Discussions around the iContract highlighted the common practice of amending standard forms or adding in "*endless z clauses*" (iC2) that defeat the object of using a standard form contract in the first place. The Weather Ledger discussions focused on the unfairness of contractual terms (e.g., once-in-a-10-year weather event) that do not account for reliance on weather data that is not reflective of the actual weather at a construction site. Where the iContract attempts to change that from within through digitalising the construction contract and making it standardised through technology (e.g., allowing only certain parts of the contract to be amended), the Weather Ledger is creating a system built around current practices. This relies not on making changes to the contracts but rather through better collection and management of data to respond to changing conditions such that the contractual clause has less of an impact (e.g., rescheduling equipment to site if earlier warnings show potential flooding). Reform of sector practices will not be easy nor quick. If applications such as the Weather Ledger can make positive changes whilst reform takes place, little wins to improve the sector could add to up bigger change over time.

With these new technological systems comes new data requirements. Inevitably, introduction of new technological systems will result in better leveraging of those data. As highlighted by the Weather Ledger focus group, having a central point of collection for data has made efficiencies for individuals who often spend substantial time searching for data with which to make a compensation claim. The Weather Ledger better organised the data for those who needed it. This led to better data modelling and better decisions, which in turn can drive better behaviours. The iContract aims to do the same through standardising data requirements that in turn can drive better decisions and responses to future events. More data leads to better modelling, which leads to efficiencies and therefore cost savings. Once these applications and others in development can demonstrate these values to the sector through more pilot studies and real-world applications, the more attractive they will become.

Both applications chose to eliminate discussion or inclusion of cryptocurrencies at this stage in their development. Automated payments were actively avoided by the Weather Ledger as its working group perceived them as losing control over project payments. For the iContract, they are not stable enough at this stage to be considered for their inclusion. However, when DLT and SCs advance and data demonstrate the benefits that these technologies offer, at the point of mainstream adoption and beyond, they will be considered again. Until then, current banking systems are sophisticated enough to be integrated with SCs to trigger fiat payments, particularly with the speed at which fintech is advancing.

Consideration of the four futures

The four futures that formed that basis of pre-focus group information for the participants were used to prompt thinking around the impact the potential futures could have on development and implementation of the applications. As outlined above, the purpose of the focus groups was not to focus on what the potential future could be, but rather how the applications might fare in any of the uncertain futures.

In *Scenario A: Dual Reality*, use of DLT is driven by industry rather than governments to the extent they adopted their own standards and regulations. Society's trust is limited with regards DLT leading to their reluctance to use it day-to-day. In this scenario, the Weather Ledger could be seen as more of a process change and one that would likely be driven by industry's use based on efficiencies, specifically time savings and better resource allocation. The iContract on the other hand would require a more substantial backing (i.e., through clients dictating its use) given the role of the construction contract across all aspects of a project. Public sector clients and the potential barrier of costs of implementation are likely to aid in limited adoption of the iContract in this scenario. However, a small scale pilot will likely be of a similar size and scope to the Weather Ledger and could therefore present opportunities to earlier implementation.

Scenario B: Blocktopia, is the most forward-thinking future of the four presented scenarios with the government being active in driving DLT and adopting it for many different public services, industry engaging on all levels from application development through to using the applications with autonomy, and society being largely trusting of the technology. This scenario represents a perfect ecosystem to support the development of DLT and SC applications and as such both the iContract and the Weather Ledger would likely fare well.

Under *Scenario C: GovChain*, the government is very active but aims to maintain control of DLT use through pushing private, permissioned platforms. This level of maintaining centrality sees larger organisations fare better than smaller ones and while society is trusting of the technology, there are concerns of authoritarianism emerging. The Weather Ledger would likely fare well in such a scenario given the positive impacts on efficiency and resources. The iContract, as a start-up could struggle to get a foothold, however, if supported by current standard form contracting bodies (e.g., JCT, NET, FIDIC), this controlled use of DLT could see it thrive.

In *Scenario D: Beyond the Hype*, DLT is not successful as a technology and its associated applications are, therefore, not successful either. Lack of support from government, industry and society means that both the iContract and the Weather Ledger would be unlikely to succeed.

Governance

The description of governance in van Rijswijk *et al.* (2019) includes legislation, regulatory frameworks and government supervision that contribute to the success and survival of an innovation. This study extends this component to include the overseeing, control and direction of an innovation.

The role of government was discussed more in the iContract focus group than the Weather Ledger focus group. This is not surprising given the different reach and impacts of the two applications and the finding that the Weather Ledger is aiming to work around current practices while the iContract is aiming to change them. iContract participants (iC2, iC3, iC4) felt the role of government was key to the application's success. From a client perspective, iC2 believes public owners "*could have a better chance*" as they are in a position to dictate how projects are managed. If this is supported by "*policy change"* it could be *"a significant driver of adoption within the private sector*" (iC3), much like BIM mandates around the world. However, such policy change requires support from other actors across the sector to be successful. The response from standard form contracting bodies such as the JCT and NEC could be "*be a major driver or inhibitor of uptake. As bodies, they have been consistently behind the curve when it comes to changes within the industry*" (iC3). These bodies, and others, would need to reconsider their current standard form contracts and work with governing bodies to understand what changes would be required to enable such change across the sector and be prepared to reinforce the potential benefits of doing so. The Weather Ledger participants took a different view of engaging with standard form contract bodies, which was seen as key to the success of the Weather Ledger and indeed other applications. It was suggested that coordinating across the sector could be an efficient and effective approach to realise benefits for the different organisations involved in developing DLT-/SC-based applications that aim to automate elements of standard form contracts. This could result in organisations "*getting their software out there more quickly*" (WL5) while the contracting bodies are "*getting their whole suite of contracts upgraded*" (WL5).

For the Weather Ledger, issues of governance were the main factor in complexity of implementation. The pilot project was funded by Innovate UK and with that came defined roles and responsibilities within the project team. However, participants discussed governance as a problem for achieving mainstream adoption because project actors did not have "*skin in the game*" (WL4). This suggests that those making the investment assume power and control over the project. "*Normally when you have a novel technology like this when clients demand that in their projects, the adoption is much easier, …it's an intervening strategy that helps adoption. You need more visionary clients*" (WL1).

Transparency in the process could be an attractive benefit to users where "*fighting corruption would be a good strategy to encourage policy makers to enforce such a solution*" (iC2), or to "*rebuild trust in cash flow through the supply chain in way that legislation hasn't*" (iC4). There are many benefits that can be realised by the sector but the level of PoCs to demonstrate them and action from those in positions to strongly encourage or enforce uptake of DLT-/SC-based systems will dictate how much change is achieved in the 5-year timeframe being considered here. If policy changes do not align sufficiently with the plans and objectives of applications such as the iContract and the Weather Ledger, it is acknowledged that "*a change in regulatory framework or a change in unions…could pop up and make a system difficult to implement in practice*" (iC4). In contrast, a regulatory framework was seen by WL3 as "*often needed to act as a pull. But it can also act as a push*" (WL3). Frameworks for DLT will not necessarily come from the construction sector (WL3), a point also raised by P4 during the interviews (see Section 4.3.4) but has the potential to be a driver for change.

It was mentioned several times that success of these technologies will be likely when there is enforcement through contracts. While the technologies are too immature at this point in time, five years into the future they may not be as DLT and SC platforms evolve. At this stage, it is unknown whether lack of a regulatory framework will help or hinder innovation of DLT/SC applications, but regulations are in development around the world as detailed by Cohen and Chen (2022), which shows acceptance from regulatory bodies that these technologies have a role to play the future.

Industry

This component refers to the extent of industry investment into R&D of a new innovation in terms of development and distribution of new applications (van Rijswijk *et al.*, 2019). This study includes receptiveness and willingness of the industry to embrace new innovations.

While elements of this paragraph can be attributed to governance, it also speaks to the industry component and how such DLT/SC technologies will be embraced by industry actors. It was considered whether the iContract would have the ability to shift the balance of power among actors. From the point of transparency, it was felt the application would not change the power balance, rather it would make it "*clear and apparent to the players*" through a more "*logical*" process (iC1). This ensures each actor knows "*what they're getting in for*" (iC1), "*And you know what everyone else is getting*" (iC2). Increasing transparency is typically discussed as an overall positive attribute of DLT but that main contractors are the ones unlikely to see it as beneficial given how they manage contracts to exert control over their supply chains. Main contractors would benefit from increased transparency in their supply chain but would likely not want to increase their own transparency for fear of explicitly revealing practices such as cash farming. "*There's so much competitive advantage to a contractor to have the information asymmetry*" (iC4) that main contractors are likely only to adopt the iContract through changing their mindset, finding an incentive to encourage adoption, or enforcement through the contract. However, if the main contractor is deploying its own application and "*forcing its supply chain to work in a certain way, increasing transparency, etc., it's very different than everyone forced by a higher power to use a specific solution [that's] mandated down*" (iC2). Ultimately, actors need to realise "*there's no value in that highly bespoke, highly adversarial contract process*" (iC4) and the iContract could be a driver for that through successful pilots to provide demonstration.

Discussions in the Weather Ledger focus group considered the benefits as attractors for actors. "*No one's going to sign up to a smart contract if it doesn't actually create an outcome that's better for them*" (WL5). The nature of the industry is resistance; "*Oh, we've already got a process for that, we don't need that, or I don't like the way this looks, you know, we're not going to use that tool*" (WL4). Even if benefits can be made explicit, there is still the challenge of changing mindsets where individuals and organisations are willing to trial new processes and new technologies such that "*finding the niche in the ecosystem to prove it, rather than the hardest spot might be the way to go*" (iC4). Construction often lags other industries in terms of technological advancements and typically "*look[s] at manufacturing to learn lessons*" (iC2). However, with DLT and SCs, "*in manufacturing it is as new to them as is in construction*" (iC7). Construction has the opportunity for first mover advantage here but the question of whether the sector will take it remains unanswered; lack of IR&D into construction (Li and Kassem, 2021a) could prevent this.

Often, money is a driver for adoption of new technologies either through increased profits or decreased costs. "*One of the things that unlocked [the Weather Ledger] pilot was money to innovate*" (WL4). Its pilot was successful; whether the sector will continue to invest with 'skin in the game' will determine its success to reach mainstream adoption. The results of the Weather Ledger pilot showed cost savings can be made, but the bigger finding was a better way to manage risk for the project. If better collection and management of data can be made and this translates to monetary values, "*the client can achieve a lower initial price of the contract*" (WL5) and therefore has competitive advantage. The proof-of-value demonstrated by the pilot gives tangible data points on which to make decisions about future investments for the industry: "*our device on site recorded about 18 millimetres more rain than the Met Office weather station did, which meant that our smart contract triggered a compensation event about eight [millimetres] above the threshold and the Met Office weather station was several [millimetres] below*" (WL5). As a PoC, there is the potential to apply the Weather Ledger software to other scenarios and obtain yet more data to demonstrate tangible benefits to the sector to encourage them to put said skin in the game.

An open challenge to consider is "*Who owns and operates the iContract after practical completion (i.e., during the defect notification period)?*" (iC6). The Hackitt Report (Hackitt, 2018) addresses this challenge in the context of the digital record suggesting this could be the dutyholder[8]. If the iContract is non-proprietary to any one actor in the project, it could occur that all relevant actors own and operate their own licenses of the software and project

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[8] Defined as: "Those key roles (whether fulfilled by individuals or organisations) that are assigned specific responsibilities at particular phases of the building life cycle" (Hackitt, 2018, p. 148).

data sits across the project organisations. Perhaps a new social structure ensues where no one owns the iContract and all actors are responsible for its operation.

Society

How society responds to, deliberates and chooses to adopt an innovation into day-to-day life is considered in this component on the basis that an innovation will be successful only if it aligns with existing systems and is accepted by society (van Rijswijk *et al.*, 2019).

Attention was directed to education and the skills required to enable these technologies with iC3 offering that "*Skills will be a major obstacle to rolling this out – construction is one of the least digitised sectors of the economy, and most firms lack the knowledge and skills to use these technologies effectively*" (iC3). Adding skills along with educating the workforce to the political agenda will be a driver to address the gap that will have an impact on a social level through facilitating acceptance of the technology and upskilling and educating the people who will use them day-to-day. WL3 agrees, suggesting "*case studies involving different partners or from different perspectives is also very powerful*". WL4 added that "*demonstration and education*" are the only ways this is going to be realistic, "*perhaps even have a demonstration worksite that's full of advanced digital tech*" (WL4). This approach would allow people to see the potential benefits and impacts these new technologies can have on their projects within and across organisations.

iC3 and iC7 both raised the point of cultural acceptance being a factor alongside addressing the skills gap in construction. This is contextualised by iC1 saying "*nobody's going to be comfortable jumping two feet first into a fully automated blockchain-based piece of software that's going to automatically make your contractual decisions for you*". An incremental approach will be more palatable starting with "*the low hanging fruit in terms of what contractual clauses are easily automated [and] probably lend themselves to a more logical way of thinking*" (iC1). If individuals and organisations in the sector can see the easy wins through digitisation/digitalisation, they are more likely to be open to exploring what else the technologies can do to improve efficiencies.

4.5 Summary

This chapter presented the results and analysis of the empirical data collected for this study. Interviews with 13 participants and three focus groups with 24 participants and made up the data collection activities. The first focus group that took place early in the research identified DLT as a socio-technical system, which guided development of research questions and the associated objectives for this study.

The insights from the interviews with industry provide a number of investigation avenues for field researchers and practitioners. Each of the challenges identified in the interviews is generic across the construction sector and while they need to be addressed at both individual, organisation and sector-wide level, without the intervention and drive through technological advancement, the likelihood is that change will be slow. It was stated that reform is required on several levels (e.g., procurement, payments, regulation) before the sector can advance. DLT, as also evidenced by the literature, is likely to form part of many proposed solutions to drive change in the construction sector through technologically led innovation.

Culture developed over many years has led to an adversarial nature in current practices where individuals and organisations are slow or even reluctant to change and collaborate. This stymies digital transformation of the sector and results in a high number of disputes, variations, cost overruns and delays. Potential DLT use cases discussed during the interviews to address this challenge include: tokenisation to incentivise collaboration through development of a reputation-based system (P10, P11); introduction of integrated project insurance to create a culture that promotes collaboration (P10); sharing data between organisations cryptographically to gain new insights into construction operations (P12); using the power of distributed ledgers to change human behaviours (P7, P10) where immutable recording of project activities provides incentives or enforcement to change; and better information management practices built on DLT to allow secure storage and exchange of data between parties (P2, P3, P4, P10). Changing culture is a challenging task and the introduction of DLT itself as any other innovation will create some collateral risks and ripples of uncertainty among the people affected by it. However, "*innovation forces change, while humans generally resist change. The pain of the change tends to be visible, while the benefits are usually diffuse and invisible*" (Manzi, 2012, p. 234). The identified use cases can be implemented as incremental changes to processes and working practices and can lead to positive effects on the sector that result in bigger impacts over time.

The industry focus groups served to understand the potential of two distinct DLT applications intended for real-world deployment in the construction sector—the iContract and the Weather Ledger. The iContract aims to digitalise the construction contract using intelligent contracts and the Weather Ledger aims to better manage risk of weather compensation events during physical construction. Participants from the UK and around the world provided expert opinion on what it might take to realise these applications considering the complexity, plausibility, challenges, opportunities, and potential benefits that can be exploited from their implementation. The focus groups centred on the future scenarios proposed by van Rijswijk *et al.* (2019) that considered two uncertainties of the role of government, and the predominant type of DLT (e.g., public, private, permissioned, unpermissioned). These uncertainties were contextualised by additional components of governance, industry and society. The analysis of the data collected at the focus groups established that each of these factors will play a role in how successful DLT- and SC-based applications will be in the sector. The findings from these research activities were used to develop roadmaps toward implementation, which are presented in the next chapter.

CHAPTER 5 | A Socio-Technical Framework to Guide Implementation and Value Realisation of Distributed Ledger Technologies (DLT) in the Construction Sector

5.1 Introduction

This chapter proposes a socio-technical framework to guide implementation and value realisation of DLT and SCs in the construction sector. It contributes to answering each of the research questions and their objectives as reiterated in Table 5.1.

Table 5.1: Research questions answered by the framework chapter

Research questions	Objectives
RQ1: What are the persistent challenges discussed in the context of DLT and SCs faced by the construction sector in light of the significant effort toward digitalisation over the last decade?	**1.1**: Identify the specific construction sector challenges that remain unresolved through a systematic literature review and interviews with industry experts. **1.2**: Create a taxonomy of construction sector challenges in the context of DLT and SCs to relate them to the different application categories of DLT and SCs for construction found within the literature.
RQ2: What role can DLT and SCs play alongside other technological innovations such as BIM and IoT in addressing the challenges faced by the construction industry?	**2.1**: Identify the construction sector applications to which DLT and SCs can be applied as proposed in literature and through consultation with academia and industry. **2.2**: Create a taxonomy of DLT and SC applications for the construction sector aligned with the construction sector challenges identified in RQ1. **2.3**: Establish which construction challenges have the potential to be addressed in part or in full by integration of DLT and SCs into the existing applications classified by the application taxonomy.
RQ3: How can a socio-technical approach support the construction sector in improving its readiness for the adoption of DLT and SCs by providing a systematic approach that guides the sector in identifying the steps required to add value and realise the benefits from integrating DLT and SCs into new and existing applications?	**3.1**: Identify dimensions of socio-technical systems theory to support analysis of the current state (without DLT and SCs) against the desired state (with DLT and SCs) of construction sector applications and identify the actor groups to be involved and/or affected by such applications along with their roles and responsibilities. **3.2**: Identify the requirements for readiness of the construction sector to adopt DLT and SCs in existing applications through consultation with academic and industry practitioners. **3.3**: Propose the steps required for achieving readiness of the construction sector to support development and implementation of DLT and SCs for new and existing applications.

The framework presented here is proposed to provide a systematic way of readying the construction sector ecosystem for the implementation of DLT and SCs across a myriad of applications. A visualisation of the framework is shown in Figure 5.1. It is the culmination of several models that each play a role in supporting meso and macro scale implementation of DLT- and SC-based applications in the sector. The models work together at different stages of readying the ecosystem to enable successful coevolution of the technological systems, processes and practices that are required for these technologies to succeed.

This extended socio-technical framework is made up of several artefacts:

- Taxonomy of Construction Sector Challenges
- Taxonomy of DLT and SC Applications for Construction
- DLT Four-Dimensional Model
- DLT Actors Model
- DLT Benefits Pathways
- DLT Meso Roadmap
- DLT Macro Roadmap

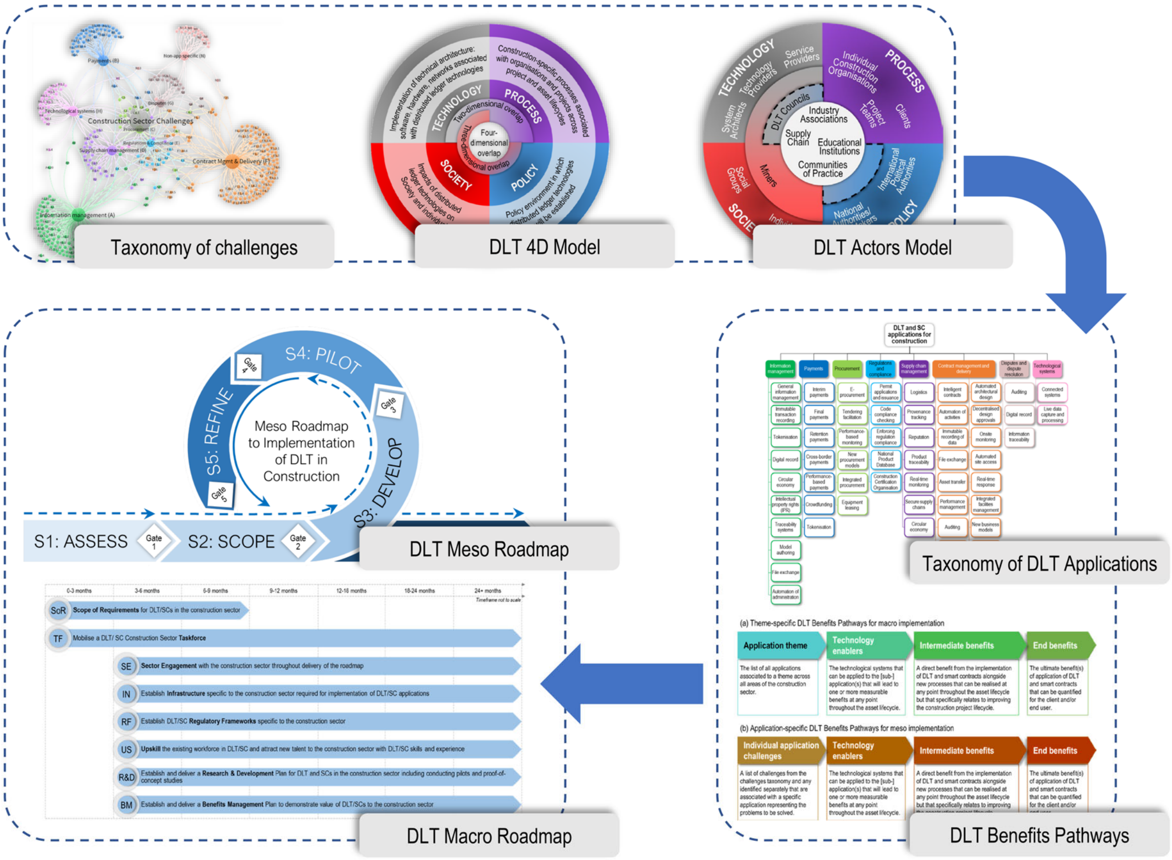


Figure 5.1: A socio-technical framework for implementation of DLT and SCs in the construction sector

When discussing DLT and SC applications in construction, the models are intended to improve understanding of the concepts involved. They represent knowledge constructs and foundations that are flexible, adaptable, and scalable, and can be used for a variety of investigations. Because of the growing recognition of the importance of the social element in technological solutions (Pazaitis *et al.*, 2017), the socio-technical perspective was adopted. Socio-technical systems theory is described in Chapter 2 (Section 2.2).

The following sections of this chapter will set out each model within the framework discussing how they were developed, what their purpose is, and who they are intended for. It will then move to discuss the contributions this framework can make to the construction sector.

5.2 Taxonomies to support implementation of DLT and SCs in construction

Taxonomies are the classification of subjects or concepts into a construct that is used to make sense of a specific area of investigation (Klavans and Boyack, 2017). They provide information on where a topic sits within the context of the taxonomy (Sujatha and Bandaru, 2011). According to Klavans and Boyak (2017), papers that present taxonomies with a minimum of 100 references are considered the gold standard of taxonomic subjects. This study incorporated data from over 150 papers for both the challenges and application taxonomies. Sujatha and Bandaru (2011) offer some advantages and disadvantages of constructing taxonomies manually as follows: they incorporate human decision and therefore high precision, and remove ambiguity; however, they are labour and resource intensive, and are difficult to scale. They can be used for the following activities: "*searching, re-purposing the content, unifying language across enterprise, future-proofing knowledge*" (Sujatha and Bandaru, 2011, p. 661).

This study proposes two taxonomies based on the literature reviewed in Chapter 2. The first classifies the myriad challenges facing the construction sector and the second classifies the research on applications of DLT and SCs in the sector. Table 5.2 provides details of how the elicitation techniques supported development of the taxonomies.

Table 5.2: Elicitation techniques that supported development of the taxonomies

Elicitation techniques	How the technique informed development of the construct
Systematic reviews 2017-19; 2019-21	• Both systematic reviews identified challenges for construction found in DLT-specific literature. These were classified across the eight application themes and put into the taxonomy of challenges. The many challenges making up the taxonomy can be seen in detail in Appendix D. • Applications of DLT and SCs in construction were identified and aligned to the eight themes and put into the taxonomy of applications.
Interviews 2018-19	• Challenges for construction were identified through interviews with industry practitioners and academics working in the field of construction. These were classified across the eight themes and put into the taxonomy of challenges. The many challenges making up the taxonomy can be seen in detail in Appendix D. • Identification of applications on which DLT and SCs could have an impact were also extracted from the interview data. These were classified across the eight themes and put into the taxonomy of applications.
Thematic analysis	• Thematic analysis was applied to the qualitative data extracted from the literature reviewed and the interviews conducted and mapped to the eight themes identified during the initial systematic review in 2017-2019.

5.2.1 Taxonomy of construction sector challenges in the context of DLT

It is not the purpose of this paper to thoroughly examine the challenges faced by the construction sector as they have been reported on many occasions, for example, through UK Government commissioned reports (Latham, 1994; Egan, 1998; see Wolstenholme, 2009; Farmer, 2016; Hackitt, 2018). However, the introduction of any new technological solution should be considered in the context of the problems it is attempting to solve or the system it is trying to improve; this is a widely accepted notion in innovation adoption studies as it affects adopters' perception of usefulness and the actual benefits of the new technological system (Rogers, 2003; Jeyaraj *et al.*, 2006; Ahmed and Kassem, 2018). Therefore, an extensive taxonomy of construction sector challenges discussed in DLT and SC research is presented. This means that these challenges are general to construction and not necessarily specific to applications that can be address by DLT and/or SC, just that they appeared in academic papers whose main theme was DLT and/or SCs in construction.

The data that make up the taxonomy were collected from qualitative review of the literature organised into nine themes through thematic analysis (eight themes corresponding to those in Chapter 2 and an additional theme for challenges that did not fit into those eight). The themes are A – information management; B – payments; C – procurement; D – supply chain management; E – regulations and compliance; F – contract management and delivery; G – disputes and dispute resolution; H – technological systems; and N – non-application specific challenges. The visualisation of the results in Figure 5.2 was created using VOSviewer (version 1.6.15), a freely available tool designed for visualising bibliometric networks.

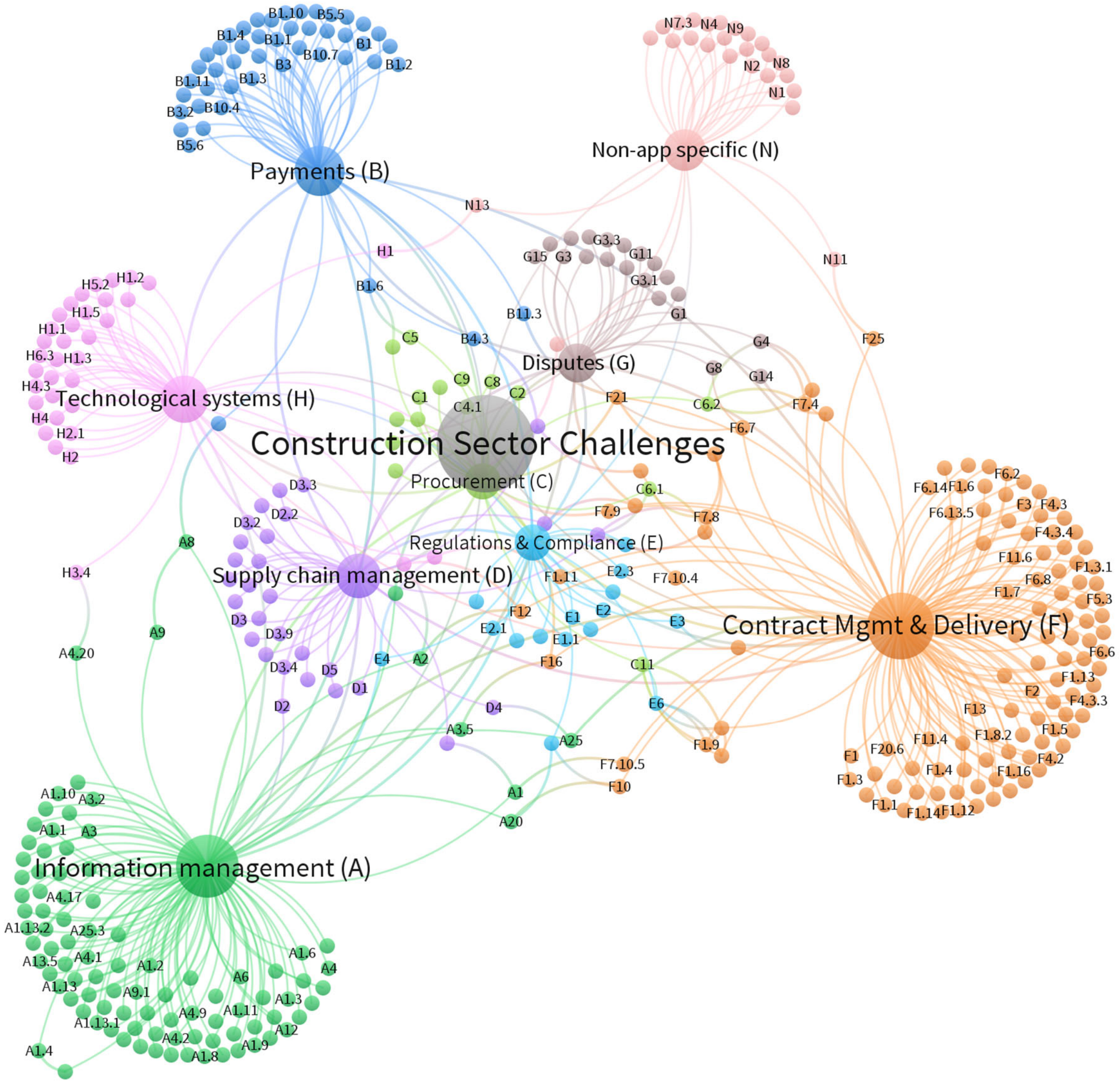


Figure 5.2: Taxonomy of construction sector challenges in the context of DLT research

Each cluster represents one of the nine themes, and each challenge is represented by a node that was given a unique code (e.g., H3.1). These codes correspond to the table of challenges supported by references in Appendix D and are discussed in the Literature Review in Chapter 2. From the central node representing the topic under consideration (construction sector challenges from DLT research) there are 419 items (challenges) with 597 links between the items. The links represent a challenge’s categorisation to a specific theme (e.g., cash flow is categorised under the theme of payments), and relationships between items (listed as “relationships” in Appendix D), where a relationship represents either the challenge appearing in more than one category (e.g., “an estimated 1/3 of construction projects are victims to counterfeiting and fraudulence” appearing in three themes: A20 – information management, E1.2 – regulations and compliance, and F10 – contract management and delivery) or a challenge having a relationship with or an impact on another challenge (e.g., F1.11: “scattered and fragmented construction management as a result of digital adoption” related to H6: “challenges with current IT systems”). Relationships were determined through analysis and categorisation of the data during the review process. The taxonomy has four levels where the nine themes listed above (A-H; N) represent level one with levels two to four representing individual challenges, some of which are broken down into smaller topics as shown in the table in Appendix D and indicated by the level of indent of an item.

The two largest themes are *contract management and delivery* (114 challenges) and *information management* (92 challenges). This is not surprising given the breadth of these themes that could be broken down into smaller themes (e.g., information management could be separated into information creation, information processing, information storage, information exchange, information models). However, given these aspects are so closely linked, separating them would result in a loss of context.

This taxonomy of challenges is designed to support researchers in understanding the current environment for the problems they are trying to solve. The approach to solving a problem is first to understand it in detail and then consider the potential tools to provide solutions. While this framework in its entirety is designed to support readying the ecosystem for DLT and SCs, its artefacts are multi-use. The taxonomy of challenges represents an analytical tool to support the problem solving process, which will later be used to consider whether DLT and/or SCs can form part of the solution. The taxonomy can support industry practitioners in a similar way to give them a deeper understanding of the sector and the challenges they are facing along with those challenges that may impact the solution at the periphery (i.e., those with relationships between items). It will be shown later that these challenges can be transposed on to the DLT Benefits Pathways that charts a path for solving the problems through application of several technologies to realise benefits for the sector.

5.2.2 Taxonomy of DLT and SC applications for construction

The taxonomy in Figure 5.3 represents a system of classification for the proposed applications of DLT and SCs in the construction sector. It is not representative of all possible applications regarding the topic; however, it presents those topics that were discussed in literature reviewed in this thesis. They were classified and mapped to the themes identified through thematic analysis. At this early stage in the research, there are two levels only. As research progresses, this will likely increase. The subtopics are the areas of application that received attention. And so, there are gaps in this taxonomy as it represents only what was in the literature. There will be new research papers in the coming years to add to this taxonomy, which will be updated as appropriate. Details of the specific applications are given in the Literature in Chapter 2 alongside the challenges (Section 2.3.4).

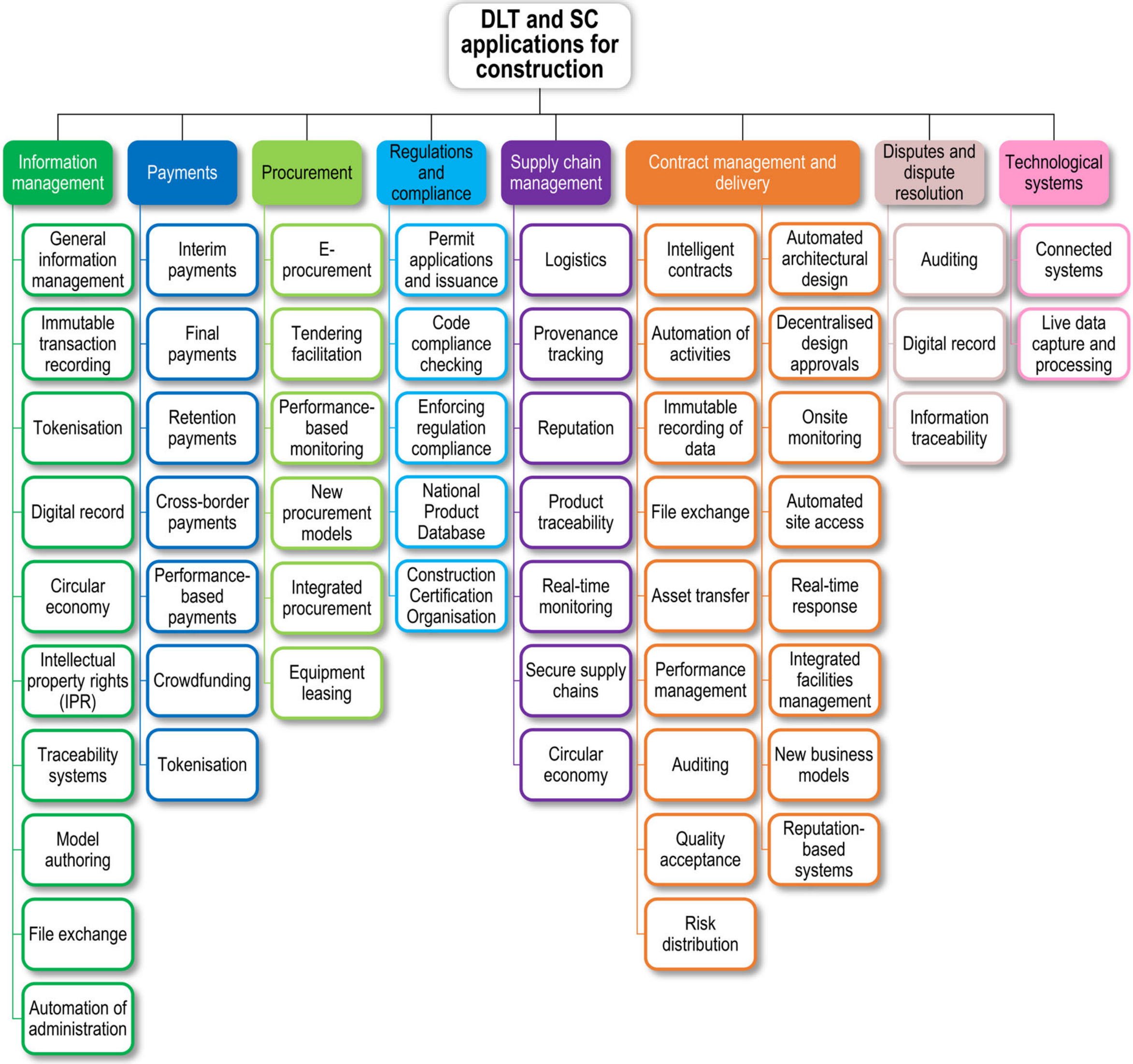


Figure 5.3: Taxonomy of DLT and SC applications for the construction sector

This taxonomy should be used in conjunction with the taxonomy of challenges to analyse a particular construction sector problem and then identify potential DLT-/SC-based applications that can provide solutions.

5.3 Four socio-technical dimensions

There are two conceptual models that utilise the four dimensions identified through analysing the challenges and opportunities for DLT and SCs in construction extracted from the initial SLR in Chapter 2. Table 5.3 details the different elicitation techniques that supported development of the DLT Four-Dimensional Model and the DLT Actors Model; both are presented forthwith.

While these models were developed based on construction- and built environment-specific literature, they can be used to evaluate other digital technologies in construction and other sectors. The socio-technical approach (discussed in Section 2.2) is widely used in many sectors and therefore the ability to extrapolate these models for other uses besides DLT

Table 5.3: Elicitation techniques that supported development of the DTL 4D Model and the DLT Actors Model

Elicitation techniques	How the technique informed development of the construct
Focus group 2018	• The first focus group identified DLT and SCs as socio-technical systems. This led to additional research on socio-technical systems theory (see Section 2.2) and the socio-technical approach was adopted for the remainder of the study.
Systematic review 2017-19	• The initial systematic review identified opportunities and challenges for DLT both specific to construction and generally that were classified into the four dimensions of technology, process, policy, society. These four dimensions made up the extended socio-technical framework underlying this study. • Identification of actor groups were also done through the initial systematic review that were classified across the four dimensions to make up the DLT Actors Model. • The initial identification of emerging applications of DLT and SCs in construction came from the initial review and were subsequently classified into resultant eight application themes that perpetuated through the thesis and into the taxonomies.
Interviews 2018-19	• The first interview that took place in April 2018 supported identification of challenges in construction and how DLT could support solutions to the challenges.
Thematic analysis	• Thematic analysis was applied to the qualitative data extracted from the literature reviewed and the interviews conducted that resulted in eight application themes to better understand the information obtained. These perpetuated throughout the study and formed the classification structure for the taxonomies to represent the state-of-the-art of DLT and SCs in construction.

and SCs increases their utility. They are discussed in this study purely from the construction perspective.

5.3.1 DLT Four-Dimensional Model

This conceptual model represents the four dimensions to be considered when discussing the application of DLT and SCs in the construction sector. The model and its four dimensions are shown in Figure 5.4. The model can identify potential areas of overlap across the four dimensions (i.e., the white area in the centre) as well as between two and/or three dimensions (i.e., the shaded areas surrounding the white area). This gives the model the ability to represent and capture interconnected knowledge across dimensions. This is critical to ensuring the model's longevity and adaptability for various purposes, especially in a rapidly evolving field like DLT.

The four dimensions of technology, process, policy and society were identified during the initial systematic literature review in 2017-2019 through categorising each of the challenges and opportunities extracted from the data. Table 2.5 and Table 2.6 in Section 2.3.2 show how each DLT challenge and opportunity was categorised across these dimensions. Findings from the first focus group (Section 4.2) that identified DLT as a socio-technical system formed the basis for identifying and defining the dimensions. It served as justification for extending the socio-technical standpoint to include policy and process on the basis that a new technological system must address elements other than society and technology.

5.3.1.1 Technology

The dimension of *technology* concerns the implementation of all technical aspects of the DLT environment, such as software, hardware, networks, and other infrastructure required for the system to function. Given the nascence of DLT and the lifecycle of new technologies generally, many of the challenges raised in Table 2.5 (Section 2.3.2) (e.g., interoperability, throughput, and latency) are expected to be resolved as new products and new versions of

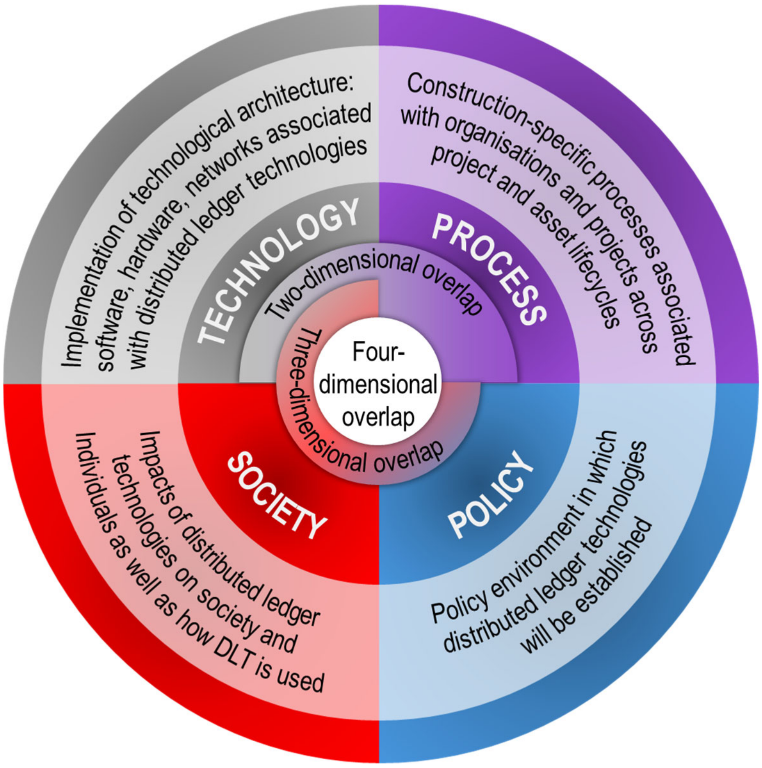


Figure 5.4: DLT Four-Dimensional Model

existing technologies are released. The use of unpermissioned or permissioned ledgers in the construction industry will be a key consideration. Scalability, security, privacy, integration with hardware (e.g., sensors), integration with software (e.g., IoT, APIs, interoperability, information models), and data frequency requirements (e.g., real-time, near-real-time, hourly, weekly, monthly) should be considered after taking the decision to adopt DLT for a proposed solution.

5.3.1.2 Policy

This dimension denotes the *policy* environment in which DLT will be implemented, which includes regulations, laws, policies, standards, and compliance. These areas are non-existent or are in development across most countries, see Cohen and Chen (2022) for an updated account of regulatory environments for blockchain globally. As many of the elements in this dimension are led by governments, they have a responsibility to thoroughly investigate the suitability of DLT and to ensure that the necessary regulatory and technological infrastructure is in place to allow it to thrive in the long run, facilitating its adoption and integration (e.g., with other smart technologies). The challenge will be to create a regulatory environment that encourages integration across services whilst overcoming interoperability issues and providing a manageable system that does not stifle innovation. Policy plans should include educating the general public about the benefits and operation of DLT as well as informing them about potential security and privacy issues in order for it to be a successful user-run system based on user-generated data. Furthermore, strong succession planning is required to train people with the appropriate skills to run the system, removing resourcing as a potential barrier to its implementation.

5.3.1.3 Process

The *process* dimension focuses on the practicalities of implementing DLT and SC technology and how individuals and organisations will embrace and use it. It entails: (1) comprehension of DLT implementation in procurement, design, construction, and facility operation and maintenance; and (2) capturing the possibilities and effects of DLT on underlying management processes throughout the project lifecycle. This dimension prompts individuals and organisations to consider how, when, and where DLT will be integrated into project and asset lifecycles; the extent to which existing processes and procedures will [need to] change as a result of its implementation; the changes required in organisational structures, business roles, business strategies, and business models to fully exploit the technology; and consider the changes as a result of regulation at the organisational, project, and supply chain levels to ensure compliance with both industry-wide regulatory frameworks and client requirements.

5.3.1.4 Society

The *society* dimension is concerned with the impact of DLT on society and its integration in the real world, which represents the social system in which the benefits will be realised. Such considerations are becoming more important due to the growing recognition of the social impacts of technological systems, such as the Cambridge Analytica data scandal (The Economist, 2018) and global policy changes such as the GDPR. What is uploaded into any system, including a blockchain, and how data are generated, collected, stored and processed is central, especially in terms of privacy and security. Given the high levels of energy consumption seen in distributed ledgers that use PoW protocols, environmental sustainability should be at the forefront of technological development. These aspects highlight the importance of addressing DLT as a socio-technical system, as the intersection between technology and its social impacts is clear. They must be considered together for any DLT application that promotes information sharing to avoid compromising on privacy and hindering collaboration between parties. For DLT applications in construction, the operational phase of assets will be the primary focus of this dimension, though all other phases (e.g., design and planning, procurement, construction) will also be relevant.

5.3.2 DLT Actors Model

The actors in each of the four dimensions representing the DLT domain in construction were identified by this model. Because new technological systems are complex, identifying and engaging with associated actors during the development and implementation phases ensures that any solution offered meets the needs of its users and beneficiaries. In the context of the construction industry, 16 different actors have been identified and mapped across the four dimensions in Figure 5.5, and their descriptions can be found in Table 5.4. Based on their involvement with DLT, each actor is made up of individuals, groups, or organisations. Several actors fit into more than one dimension.

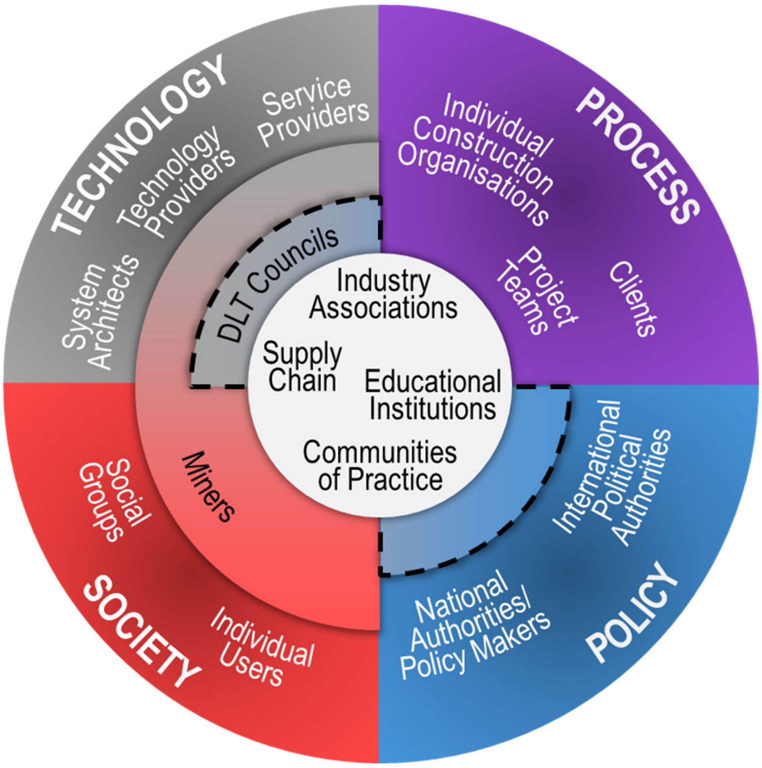


Figure 5.5: DLT Actors Model

This model can be used to allocate varying degrees of responsibility to the actors and to plan the complementary effort of various actors in the adoption and diffusion of DLT for construction applications. Assigning roles and responsibilities at various points during the adoption of DLT can be supported by using it to evaluate and benchmark the level of contribution needed from each actor. Three levels of contribution have been assigned to actors: ‘Primary’ actors—those who directly contribute to the development of technologies, standards, policies, and regulations and who have a say in how those technologies evolve over time, even after adoption; 'secondary' actors—those who will use the technology on a daily basis but will not necessarily contribute to its functionality; and 'supporting' actors—those who may contribute to data uploaded to the ledger or who have an interest in how they function but do not contribute to the running of the ledger nor use it commercially.

Three examples are provided to demonstrate how the model works. The *System Architect* is the person(s) responsible for creating the distributed ledger with a particular focus on software during the early stages of DLT development. The type of distributed ledger required will be determined by its intended use. Public ledgers have different requirements than private ledgers, especially in terms of security. The System Architect will oversee that requirements imposed by the client and/or application are met. They must be aware of regulations to ensure that any solution is compliant. *Individual Construction Organisations* are classified as secondary contributors. While they may use off-the-shelf technology as adoption of the technology grows and the options available become more diverse, in some cases they will be purveyors of new technological solutions based on the needs of their organisation. However, they will likely not be the direct developers of any new solution;

Table 5.4: Actors associated with DLT (Li et al., 2019a, p. 299)

Dimension	Actor	Description	Contribution
Technical	DLT System Architects	Individuals and organisations who develop DLT including programmers, coders, software developers, system engineers etc.	Primary
	Technology Providers	Individuals and organisations who develop hardware, software, networking architecture for DLT and those associated with enabling or interrelated technologies (e.g., IoT, sensors, drone technology).	Primary
	Service Providers	Companies involved in providing a technical service to organisations using DLT, particularly where private ledgers are used (e.g., consultants, insurance providers, dispute resolution firms).	Secondary
Political	National Authorities/ Policy Makers	State and local government authorities responsible for making policy, writing standards and setting regulations along with enforcing them.	Primary
	International Political Authorities	International groups working together to set international regulations for transactions that cross borders to promote international partnerships and to mitigate the possibility of fraud, corruption and other criminal activities.	Primary
Process	Individual Construction Organisations	Individual organisations operating in the construction industry including main architectural, engineering, contractor, sub-contractor and facilities management organisations.	Secondary
	Project Teams	Individuals across the supply chain who specifically form the project team who have access to the ledger and who have responsibility for producing information to the ledger or consuming information from the ledger.	Secondary
	Clients	Individuals or organisations, public and private, who commission construction projects with access to information on the ledger regarding their project.	Secondary
Social	Individual Users	Individuals who use DLT day-to-day either through performing transactions or by providing data to be uploaded to the ledger.	Supporting
	Social Groups	Groups of individuals with an interest in the impact of DLT at a societal level (e.g., regarding energy consumption, privacy, security, creation of a value-driven economy, ensuring societal needs are being met by technological solutions).	Supporting
Technical-Political overlap	DLT Councils	Stakeholder groups of DLT tasked with approving changes to software, data in the ledger and ensuring technology and operations comply with regulations and who have the power over how DLTs function in general.	Primary
Technical-Social overlap	Miners	Individual miners, mining pools and mining organisations operating as nodes and running the peer-to-peer network with an interest in the state of the technology and the level of energy required to run the network (in the case of Proof-of-Work).	Secondary
4D overlap	Industry Associations	Professional associations who represent the interests of individuals and organisations operating in the construction industry.	Supporting
	Supply Chain	Organisations that make up the supply chain for the construction industry that are: concerned with technical elements of the system regarding tracking and updating ledgers; impacted upon regarding international politics and regulations where supply chains cross borders; have a responsibility to operate in a sustainable manner; and who must follow processes as set by industry standards and clients.	Secondary
	Educational Institutions	Universities and other educational institutions conducting research in the field and developing programmes to train and upskill people in DLT.	Secondary
	Communities of Practice	Groups of individual practitioners with an interest in a specific area of DLT (e.g., interoperability, privacy, speed).	Supporting

instead, this will likely be contracted to the supply chain. *Social Groups* are classified as supporting contributors because of their interest in DLT but they do not necessarily have any influence over it other than the right to lobby authorities about how its use affects them day-to-day; they will not develop the technology nor use it commercially in the context of the construction sector, but they will be impacted by it.

5.3.3 Applying the models

The DLT Four-Dimensional Model was applied to the analyse the challenges and opportunities of DLT and SCs for construction. Its purpose is to improve understanding of the application of DLT and SCs in construction through considering where these challenges and opportunities lie in the model and highlight where an item might overlap more than one dimension. This should be used in combination with the DLT Actors Model that will assist in identifying the actor(s) with whom to consult when addressing a specific challenge or opportunity. These challenges and opportunities were identified in literature as part of the initial systematic review, the tables of which can be seen in Section 2.3.2. Both construction and non-construction specific items have been mapped. Figure 5.6 shows the challenges and Figure 5.7 shows the opportunities. Where there is a dotted line, this denotes items that overlap two dimensions that are not positioned next to one another in the model.

To demonstrate an example, taking *job security* in the challenges mapping, this sits across society and policy. It is a society challenge because it affects individuals in society as well as the workforce requirements, which is a matter that should be addressed from a policy perspective (i.e., policymakers should plan for job retention, reskilling and or welfare in the event of job displacement). The actors to consult on this challenge will be individual users (supporting contributors in the DLT Actors Model), and National Authorities/policymakers (primary contributors in the DLT Actors Model). *Faster processes* is an opportunity that overlaps society, technology and process. This is a society opportunity because it will have a benefit to users of DLT/SC based systems through offering better services through faster delivery; it is a technology opportunity because it can offer new technological advancements and the possibility of faster integrations between systems; and it is a process opportunity because processes can be speeded up through automation and system processing that can streamline existing processes and propose new business models. The actors to be consulted for this opportunity include each of the technology actors (system architects, technology providers, service providers); both actors from the society dimension (social groups, individual users); and each of the process actors (individual construction

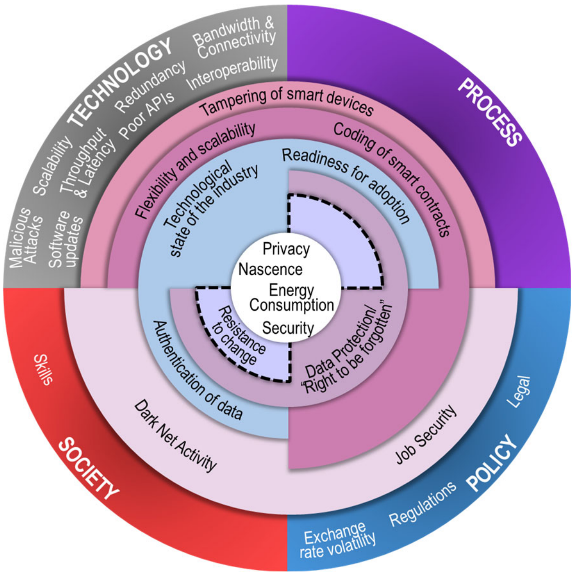


Figure 5.6: Challenges mapped across the DLT Four-Dimensional Model

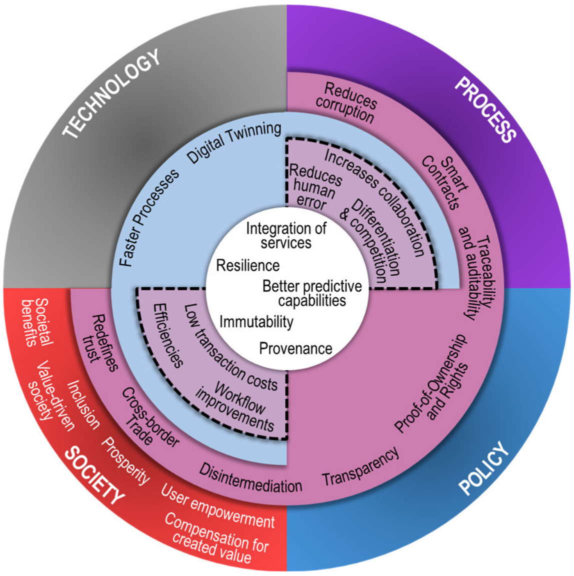


Figure 5.7: Opportunities mapped across the DLT Four-Dimensional Model

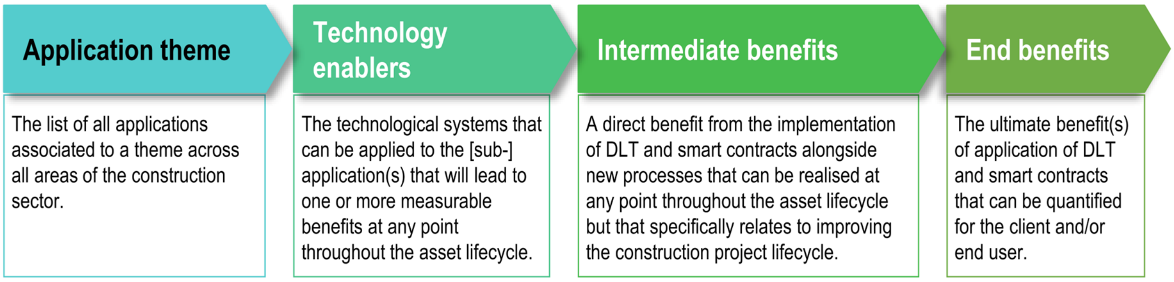
organisations, project teams, clients). This demonstrates the potential far reaching benefits that can be realised from a range of actors within the sector from a single opportunity.

5.4 DLT Benefits Pathways

The DLT Benefits Pathways are designed to describe ways in which the many construction sector challenges can be addressed by applications of DLT and identify the potential intermediate benefits and end benefits to the sector from such applications. This approach was chosen due to the clarity of seeing applications alongside proposed intermediate and end benefits. In the context of this study, the term ‘benefits’ applies to any measurable improvement (tangible and intangible) that results in providing a business advantage to any stakeholder involved in the project or results in a helpful or positive effect for users/occupants (Kassem *et al.*, 2020). In this study, an *intermediate benefit* refers to one that can be realised at any point in the asset lifecycle by any stakeholder involved in the project but that specifically relates to improving delivery of the project (e.g., streamlining workflows or guaranteeing cash flow to reduce insolvency of the supply chain). An *end benefit* is more holistic that impacts the project or its outcomes in its entirety (e.g., cost savings for the client/asset owner; environmental benefits from better building performance during operation). The study does not attempt to provide critical assessment of the benefits identified; this will be done in future research. Recognising there are barriers to adoption of DLT in construction, specific barriers and obstacles are discussed alongside individual DLT Benefits Pathways.

Two versions of the DLT Benefits Pathways are proposed for different scales of implementation. Figure 5.8(a) is proposed for general application themes to support macro scale implementation such as the themes identified through the literature review. Figure 5.8(b) is proposed for meso scale implementation and therefore individual applications. For the theme-specific DLT Benefits Pathways, in the *Application theme* box, a list of all the DLT and SC applications that are associated with a theme shall be listed. This is suitable for the macro scale to help the sector identify and understand the potential benefits of DLT and SCs for that specific theme. For application-specific DLT Benefits Pathways, the first box is used to identify all the *Individual application challenges* associated with the application pre-implementation of DLT/SCs. These challenges can be taken directly from the taxonomy of challenges and extended to include additional items as appropriate. The remaining three boxes of the DLT Benefits Pathways have the same function at both theme- and application-level. *Technology enablers* are those technologies that support the system in delivering the application. They include DLT and SCs along with existing/external systems and are defined in Table 5.5. Examples of both are given in the next sections. Intermediate and end benefits are defined above.

(a) Theme-specific DLT Benefits Pathways for macro implementation



(b) Application-specific DLT Benefits Pathways for meso implementation

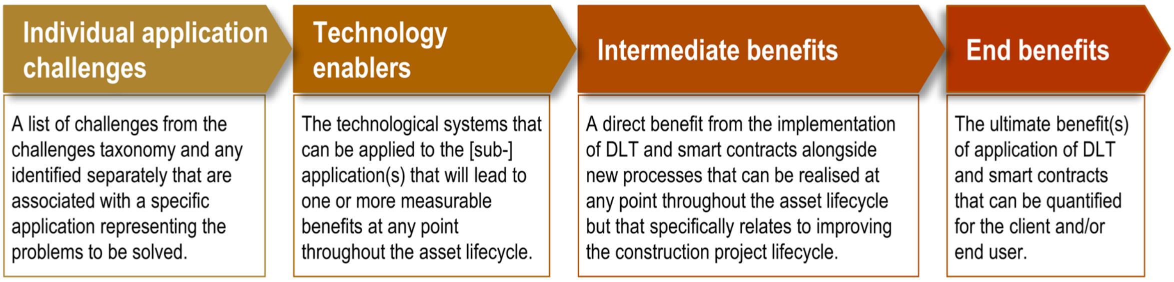


Figure 5.8: Defining DLT Benefits Pathways

Table 5.5: Technology enablers for DLT-based systems

Technology	Purposes
Distributed ledger	Recording transactions; proof-of-existence; proof-of-time.
SCs	Automating activities; executing pre-established rules; embedding funds for payment.
Internet of Things (IoT)	Comprising the perceptual layer (e.g., Wireless Sensor and Actuator Networks – WSAN, RFID, Zigbee, Bluetooth, etc.); the network layer (e.g., communication networks – satellite network, internet, mobile network, and communication protocols), the support layer (fog computing, cloud computing), and the application layer (IoT applications – e.g., onsite wearables, predictive maintenance).
Fiat exchange	Exchanging cryptocurrency or tokens into fiat currency and vice versa.
BIM technologies	E.g., modelling software, object libraries, common data environment (CDE), asset management tool.
Artificial intelligence (AI)	Automating activities (e.g., decision making).

The DLT Benefits Pathways consider benefits across the entire asset lifecycle from cradle-to-grave. This enables them to support concepts such as the circular economy (acknowledged as cradle-to-cradle in terms of the asset lifecycle) and information management that require data and information that flow across all phases of the asset lifecycle emphasising the need to create systems and processes that facilitate transition across phases, especially at handover from construction to operation. Table 5.6 details the different elicitation techniques that supported development of the DLT Benefits Pathways. In the same way the DLT Four-Dimensional Model and the DLT Actors Model can be extrapolated to other technologies and sectors, so too can the DLT Benefits Pathways; they were developed based on construction literature and data and they are applied here in a construction context.

5.4.1 Theme-specific DLT Benefits Pathways

DLT Benefits Pathways have been developed for each of the eight themes throughout this paper. Examples have been provided for information management and payments. The remaining six theme-specific DLT Benefits Pathways are included in Appendix E. The benefits pathways are described and supported with discussion based on academic research and industry practice (set out in the Literature Review Chapter) related to the

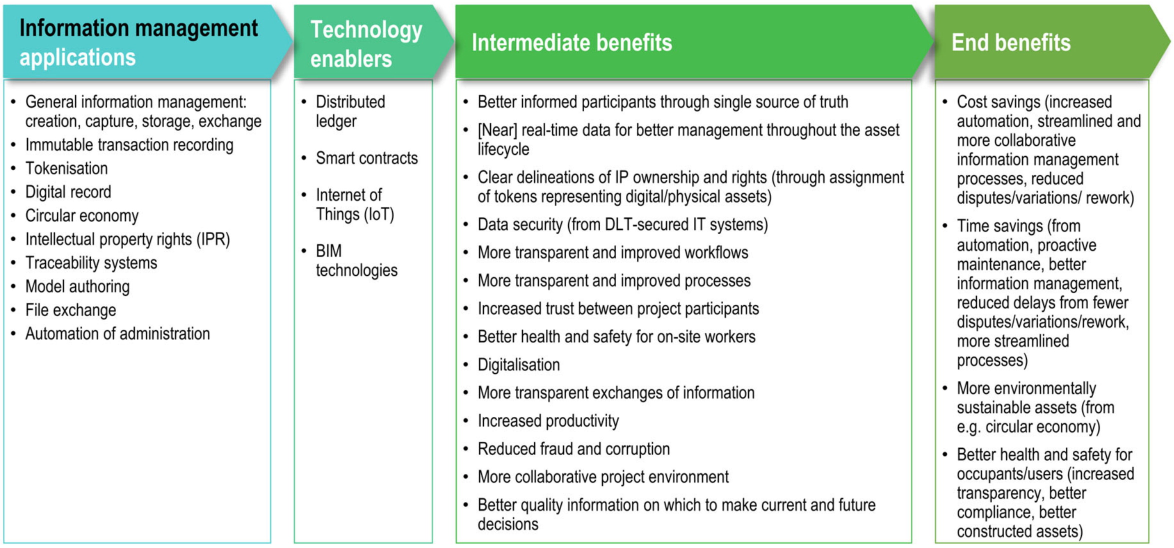
Table 5.6: Elicitation techniques that supported development of the DLT Benefits Pathways

Elicitation techniques	How the technique informed development of the construct
Systematic reviews 2017-19; 2019-2021	• Data from the systematic reviews across the applications of DLT and SCs in construction and the challenges to be solved by these applications were used to populate the DLT Benefits Pathways. • Benefits of applying these technologies to construction applications were identified and used to populate the DLT Benefits Pathways.
Interviews 2018-19	• Data from the interviews on applications of DLT and SCs in construction and construction challenges were used to populate the DLT Benefits Pathways. • Benefits of applying these technologies to construction applications were extracted from the data and used to populate the DLT Benefits Pathways.
Thematic analysis	• For consistency across the framework the eight application themes were applied to the DLT Benefits Pathways.
Interviews 2021	• Data from the consultation interviews specific to applications in development were used to populate the DLT Benefits Pathways. • These consultation interviews were also used to validate the DLT Benefits Pathways.

applications and associated benefits that can be realised through adoption and implementation of DLT and SCs at the macro scale.

DLT Benefits Pathways for information management

In Figure 5.9, the non-exhaustive list of information management applications, based on several technology enablers, leads to richer information management processes resulting in intermediate and end benefits for both project participants and occupants/users. Bringing different technologies together facilitates connection of thousands of devices from different manufacturers in the same building to one integrated ecosystem and protects it from potential malicious attacks through the inherent characteristics of DLT (Kinnaird and Geipel, 2018), namely, security. This acts as a precursor to improve information management practices driven by immutable recording and results in new offerings (e.g., the circular economy). Organised through analysis and interpretation of the literature, the *intermediate benefits* include streamlined workflows as a result of more reliable information exchange, transparent exchanges of information leading to increased trust between participants and data security of IoT based systems. The *end benefits* include cost and time efficiencies, more environmentally friendly built assets that perform better and are safer for occupants.



Information management applications

- General information management: creation, capture, storage, exchange
- Immutable transaction recording
- Tokenisation
- Digital record
- Circular economy
- Intellectual property rights (IPR)
- Traceability systems
- Model authoring
- File exchange
- Automation of administration

Technology enablers

- Distributed ledger
- Smart contracts
- Internet of Things (IoT)
- BIM technologies

Intermediate benefits

- Better informed participants through single source of truth
- [Near] real-time data for better management throughout the asset lifecycle
- Clear delineations of IP ownership and rights (through assignment of tokens representing digital/physical assets)
- Data security (from DLT-secured IT systems)
- More transparent and improved workflows
- More transparent and improved processes
- Increased trust between project participants
- Better health and safety for on-site workers
- Digitalisation
- More transparent exchanges of information
- Increased productivity
- Reduced fraud and corruption
- More collaborative project environment
- Better quality information on which to make current and future decisions

End benefits

- Cost savings (increased automation, streamlined and more collaborative information management processes, reduced disputes/variations/ rework)
- Time savings (from automation, proactive maintenance, better information management, reduced delays from fewer disputes/variations/rework, more streamlined processes)
- More environmentally sustainable assets (from e.g. circular economy)
- Better health and safety for occupants/users (increased transparency, better compliance, better constructed assets)

Figure 5.9: DLT Benefits Pathways for information management

The different applications working together provide access to an unprecedented amount of data produced during the lifecycle of a built asset. This level of integration would see BIM processes transition through phases that are a current barrier to its widespread adoption. For example, if information models are more reliable, use at construction sites and into facilities management could be more prevalent and result in a move toward effective digital twins. The current adversarial nature of the sector is a deterrent to sharing information, which means the level of information required for effective use of information models on construction sites and during operation is not reached. In a future that will be networked by myriad devices and systems, actors will be incentivised "*to maximize the transfer of information between parties*" (Mathews *et al.*, 2017, p. 2) to help this vision become a reality.

The challenges associated with ownership of data in information models is complex when multiple parties are involved in their creation, modification, management and storage. Through tokenisation, elements can be assigned a value and an owner to act as immutable, visible proof of ownership. In addition, rights as to who can do what with the associated data through clear delineations of IP written into SCs will provide transparency and confidence to the parties. The hashing function of DLT can then be deployed to document the changes made, when and by whom. These activities take place every day in construction projects and the element that causes a breakdown in communication, collaboration and/or trust is that these activities are not always explicitly distinguished. There is typically one client (that may be several individuals or organisations acting as one) and innumerable fragmented suppliers and contractors whose interests rarely align. This accounts for the complexity in construction contracts and the difficulty in explicitly defining roles, responsibilities and rights. If information management is controlled by SCs, there must be explicit rules of what the project participants must do thereunder. If those assigned tasks are tied to payment via the SC, this provides enforcement of the agreed terms for all participants. Initially, this change might be seen as a stick rather than a carrot but in time this would become business-as-usual thereby changing the view of the participants to one of receiving value for the work they produce. Kraken IM's Halcyon project claims to be a world-first in the delivery of a blockchain-based information management system able to "*supply, validate and approve engineering data*" that "*creates an immutable record of that data*" providing "*a permanent digital golden thread of the information, decisions and queries made during projects*" (Kraken IM, 2020). Commoditising information through tokenisation will incentivise project participants to share more readily if they receive something in return. However, what this approach should not do is reward those participants currently unwilling to share information that they are contractually obliged to do but do not for reasons of unclear IP rights or competitive advantage. Before this becomes reality, the client needs to be aware of exactly what they are paying for and entitled to under the terms of the contract but may not be receiving in the current environment. Another approach to this includes incentivising asset owners to share data about installed components (Li and Kassem, 2019b) on, for example, energy performance. If the owner is willing to provide the manufacturer with in-use data in return for something of value (e.g., discounts on future purchases, a better aftercare service, financial compensation) the manufacturer can improve their products and services based on real-world data.

The trigonal lattice framework by Koo *et al.,* (2019) for document management focuses on immutable tracing of information, particularly, materials, personnel and documents, which aims to make accessibility of that information quick and efficient. The authors highlight a challenge of the framework as having a unified coding system for construction items and resources. If such an application is coupled with the de-randomisation of GUIDs as in Xue and Lu (2020), this could create an effective information management system that is both traceable and transparent.

The circular economy could be one of the biggest recipients of better information management. It will be the driver to more sustainable choices (e.g., increased use of renewable resources; reduction in waste generated during physical construction). Sustainability is moving higher up the political agenda because of climate change from exploitation of the planet’s resources. Use of materials requires rethinking and a concerted effort from individuals and governments to become more sustainable. Disruption could be the driver to make these possibilities a reality. As part of the Construction Smart Contract Committee, Tata Steel, Arup, SAP and IBM are driving the circular economy by using blockchain to track the integrity of a steel I-beam throughout its life until it can be reused or recycled (Penzes, 2018). Data are tracked regarding chain of custody and details of materials from provenance for reuse and recycle at end-of-life.

Research on traceability and transparency in construction is scarce and no formal definition exists. The majority of traceability research is focused on supply chain and logistics resulting in definitions concerning provenance and chain of custody (Katenbayeva *et al.*, 2016). With reports such as the Hackitt Report (Hackitt, 2018) considering different aspects of the asset lifecycle, it has become apparent that traceability and transparency have a much wider reach and implications across the entire asset lifecycle, particularly with regards asset information. Traceability and transparency in the context of this study concerns information in respect of a built asset from design through construction, operation and end-of-life. It considers information about products, components and services and the ability to access that information when required with the confidence that is it of the right format and quality. When systems encompassing this are in place, it can lead to improved project management, support better decision-making and operational effectiveness; offer better procurement practices; have a faster response to health and safety issues; and result in more effective product recall. However, there are security and accuracy issues related to the use of substantial numbers of devices as oracles in terms of tampering and calibration (Wilson *et al.*, 2020). Privacy of data and information presents another problem, especially with the EU GDPR and similar regulations globally.

DLT Benefits Pathways for payments

The benefits of SC-based payments running on a DLT include faster payments through semi-automation, transparent sharing of payment-related information at a project level, facilitation of data confidentiality between contracting parties, a high degree of immutability (Das *et al.*, 2020), enhanced cost estimation in future projects based on reliable historical cost data (Abrishami and Elghaish, 2019), the ability to increase trust and "*greater enforceability of the contract*" (Perera *et al.*, 2020, p. 16), and security of payment to improve cash flow. Figure 5.10 sets out the DLT Benefits Pathways for payments.

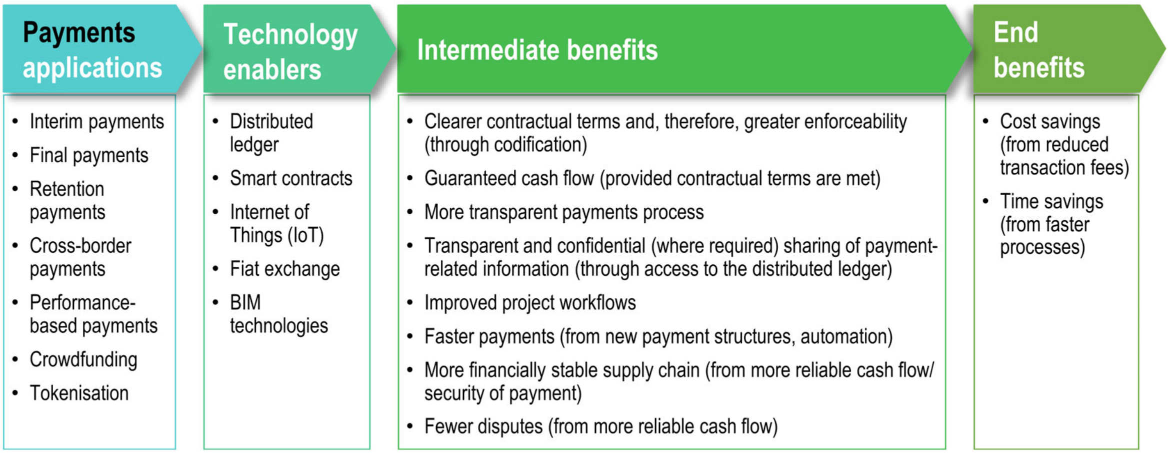


Figure 5.10: DLT Benefits Pathways for payments

While a guaranteed cash flow does not result directly in reduced cost to the project, it does have a financial benefit to the recipient who may otherwise be forced to borrow credit while the payment is being processed. In addition, it can prevent insolvency. Payments today can take up to 120 days; with funds embedded into SCs, payments can be made in minutes. However, it is not so simple to change the way payments are made. This requires clients to commit funds upfront to enable them to be embedded into an SC (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020) and requires main contractors to agree to a change in payment structure – direct from client to subcontractor through the SC as opposed to indirect from client to main contractor to subcontractor/supplier, which often may be several tiers long. The benefits to the client of this change is a more stable supply chain that is likely to perform better knowing they are guaranteed funds, so long as they meet the pre-agreed specifications. However, another SC payment issue concerns the privacy of transactions. Contractors interviewed in one study commented that use of such a system would make payments to the subcontractors visible to the employer, which should "*be kept private and should not be made available to the employer*" (Ahmadisheykhsarmast and Sonmez, 2020, p. 10). However, this could be seen as a failure of the current procurement and contract management system where the employer has a right to know how their money is being spent. On the other hand, Cheng *et al.* (2020) distinguish between the sensitive information within in a transaction (e.g., the amount paid) being private through encryption and non-sensitive information (e.g., payment date) being made public. Current procurement models and payment practices are at the centre of the sector's adversarial nature. Lack of transparency has been cited as a major challenge by many authors as seen throughout this paper. This is representative of the change required to procurement and payment practices across the sector.

For SCs to be used for payments, there needs to be some form of token to represent the value of what is being transferred. Currently, cryptocurrencies are not stable enough to be used mainstream and in the more secure DLT, such as the Bitcoin protocol which has yet to be hacked (Baldwin, 2020), scalability is not possible due to the design whereby each block takes approximately 10 minutes to validate. The use of tokens to be exchanged for fiat currency pose a possible solution but currency exchanges have been the victim of attacks (Selfkey, 2020), which currently represents a weakness in this application. The R3 Corda blockchain (a consortium of banks) could circumvent this. R3 Corda is a permissioned blockchain with the function of modularised consensus that allows transactions to be transmitted back and forth in fiat currencies (Elghaish *et al.*, 2020).

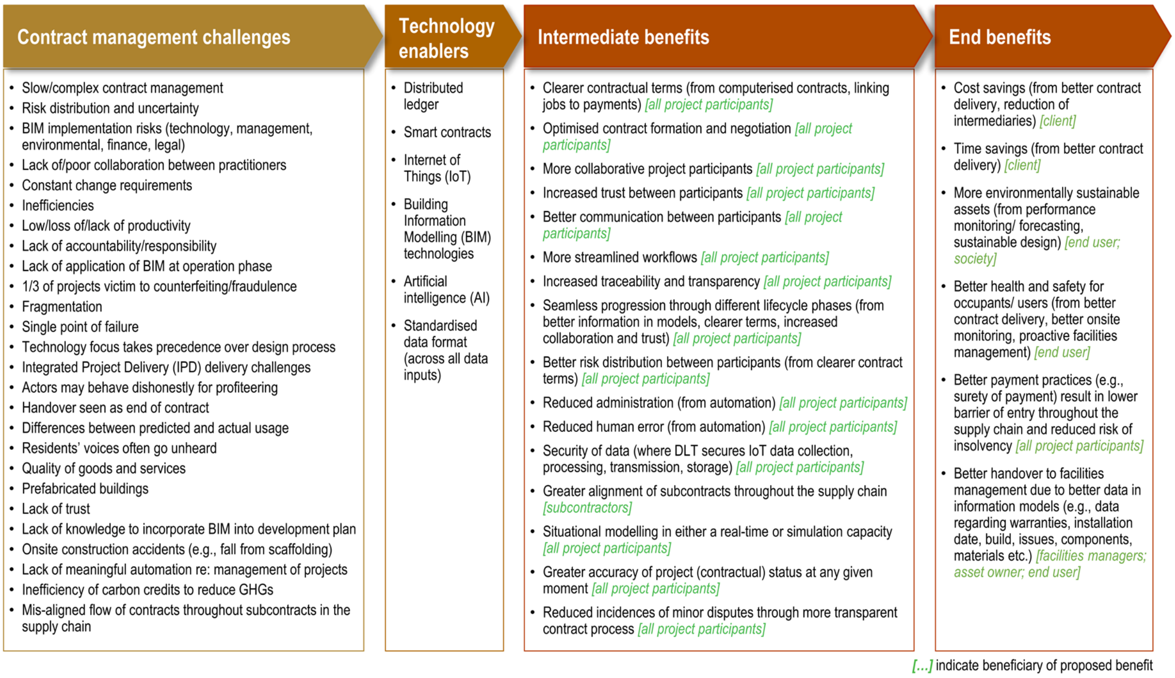
The direct to sub-contractor or supplier payment structure is similar to a PBA (Griffiths *et al.*, 2017). However, Brydon Wang (2018) believes SCs are a better option than PBAs due to lower transaction fees, automatic ledger recording, flexibility with regard to choice of procurement model, the ability to embed funds into SCs providing surety of payment (Cardeira, 2015; Ye *et al.*, 2018; Chong and Diamantopoulos, 2020), increased transparency of fiat payments triggered by SCs (Penzes, 2018), open to all tiers of contracts unlike PBAs that are restricted to payments to main contractors and top tier sub-contractors, and increased transparency through visibility of the ledger based on access rights allowing for commercial sensitivity of transactions. Ultimately, DLT has the potential to be a major disruptor to payment practices and will impact all parties in different ways.

5.4.2 Application-specific DLT Benefits Pathways

In advance of the industry focus groups (see Section 4.4), consultation interviews were conducted with people involved in the iContract and the Weather Ledger. In addition to preparing for the focus groups, these interviews were also used to validate the DLT Benefits Pathways specific to these applications. Details of the validation are given in Chapter 7.

DLT Benefits Pathways for the iContract

In Figure 5.11, the DLT Benefits Pathways for the iContract is shown. While the challenges presented in this DLT Benefits Pathways figure are not all specific to contract management, they have the potential to be solved, at least in part, by the addition of the iContract to the contract management process across the project lifecycle. A detailed description of the iContract is given in Section 4.4.6.1 but in brief, it aims to make the contracting process



Contract management challenges

- Slow/complex contract management
- Risk distribution and uncertainty
- BIM implementation risks (technology, management, environmental, finance, legal)
- Lack of/poor collaboration between practitioners
- Constant change requirements
- Inefficiencies
- Low/loss of/lack of productivity
- Lack of accountability/responsibility
- Lack of application of BIM at operation phase
- 1/3 of projects victim to counterfeiting/fraudulence
- Fragmentation
- Single point of failure
- Technology focus takes precedence over design process
- Integrated Project Delivery (IPD) delivery challenges
- Actors may behave dishonestly for profiteering
- Handover seen as end of contract
- Differences between predicted and actual usage
- Residents' voices often go unheard
- Quality of goods and services
- Prefabricated buildings
- Lack of trust
- Lack of knowledge to incorporate BIM into development plan
- Onsite construction accidents (e.g., fall from scaffolding)
- Lack of meaningful automation re: management of projects
- Inefficiency of carbon credits to reduce GHGs
- Mis-aligned flow of contracts throughout subcontracts in the supply chain

Technology enablers

- Distributed ledger
- Smart contracts
- Internet of Things (IoT)
- Building Information Modelling (BIM) technologies
- Artificial intelligence (AI)
- Standardised data format (across all data inputs)

Intermediate benefits

- Clearer contractual terms (from computerised contracts, linking jobs to payments) *[all project participants]*
- Optimised contract formation and negotiation *[all project participants]*
- More collaborative project participants *[all project participants]*
- Increased trust between participants *[all project participants]*
- Better communication between participants *[all project participants]*
- More streamlined workflows *[all project participants]*
- Increased traceability and transparency *[all project participants]*
- Seamless progression through different lifecycle phases (from better information in models, clearer terms, increased collaboration and trust) *[all project participants]*
- Better risk distribution between participants (from clearer contract terms) *[all project participants]*
- Reduced administration (from automation) *[all project participants]*
- Reduced human error (from automation) *[all project participants]*
- Security of data (where DLT secures IoT data collection, processing, transmission, storage) *[all project participants]*
- Greater alignment of subcontracts throughout the supply chain *[subcontractors]*
- Situational modelling in either a real-time or simulation capacity *[all project participants]*
- Greater accuracy of project (contractual) status at any given moment *[all project participants]*
- Reduced incidences of minor disputes through more transparent contract process *[all project participants]*

End benefits

- Cost savings (from better contract delivery, reduction of intermediaries) *[client]*
- Time savings (from better contract delivery) *[client]*
- More environmentally sustainable assets (from performance monitoring/ forecasting, sustainable design) *[end user; society]*
- Better health and safety for occupants/ users (from better contract delivery, better onsite monitoring, proactive facilities management) *[end user]*
- Better payment practices (e.g., surety of payment) result in lower barrier of entry throughout the supply chain and reduced risk of insolvency *[all project participants]*
- Better handover to facilities management due to better data in information models (e.g., data regarding warranties, installation date, build, issues, components, materials etc.) *[facilities managers; asset owner; end user]*

[...] indicate beneficiary of proposed benefit

Figure 5.11: DLT Benefits Pathways for the iContract

clearer, speed it up through automation and guide project delivery partners in providing data-driven decision-making. With a focus on better data collection, processing and management and integration with AI technologies, and unlike SCs that simply execute as programmed, the iContract is intended to offer data-driven solutions to project participants. It becomes clear that, if the application is delivered as intended in the coming years, the intermediate and end benefits offered in the figure above can bring efficiencies, increased productivity, better manage project risks, and deliver more sustainable assets.

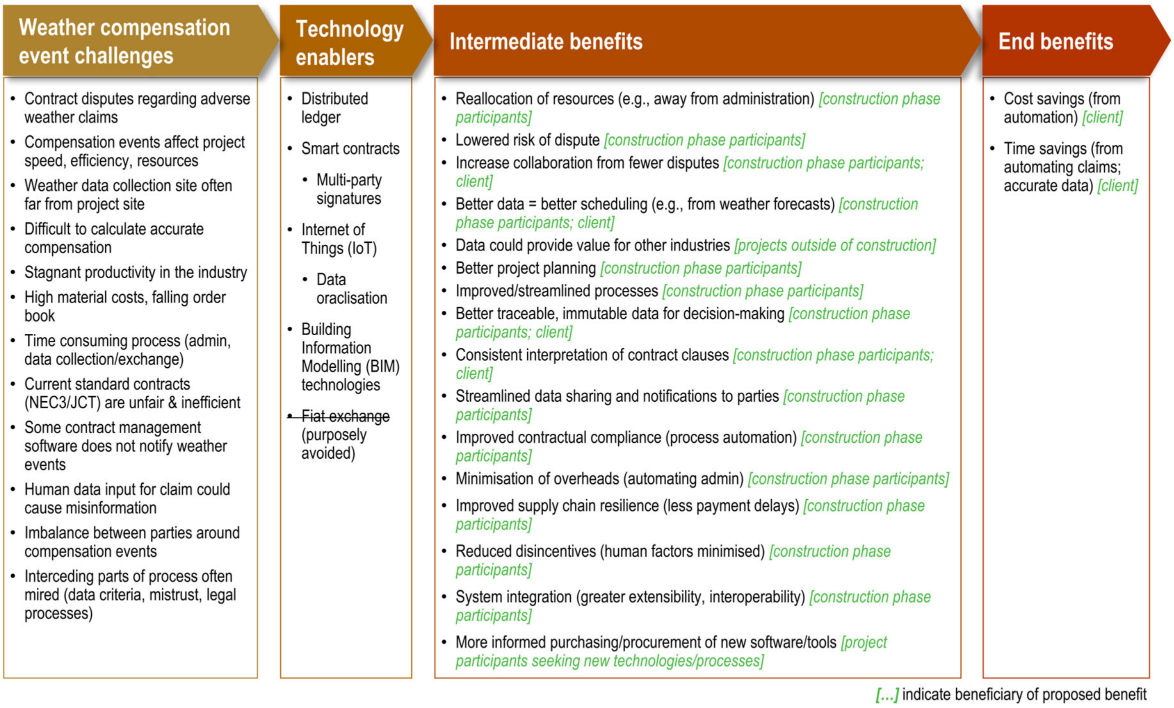
The actors in square backets in the intermediate and end benefits columns indicate the beneficiary(ies) of the benefit. This is intended to be a live artefact and will be developed and updated to provide more specific beneficiaries and additional items in each column as and when the iContract evolves in the coming years and new technological solutions become available.

DLT Benefits Pathways for the Weather Ledger

As highlighted in Chapter 4, the Weather Ledger aims to provide better data management to construction projects. Its DLT Benefits Pathways are shown in Figure 5.12. Given the application's proposed use is at the construction site, the beneficiaries of the intermediate benefits are restricted to actors involved in that stage of the project lifecycle. As the application develops and evolves, more detail can be added to the artefact in each column.

5.4.3 A review of the intermediate benefits

The intermediate benefits identified through the systematic review correspond to those that provide improvement to current practices of project delivery throughout the lifecycle of a built asset. This study does not attempt to quantify those benefits, such quantification will



Weather compensation event challenges

- Contract disputes regarding adverse weather claims
- Compensation events affect project speed, efficiency, resources
- Weather data collection site often far from project site
- Difficult to calculate accurate compensation
- Stagnant productivity in the industry
- High material costs, falling order book
- Time consuming process (admin, data collection/exchange)
- Current standard contracts (NEC3/JCT) are unfair & inefficient
- Some contract management software does not notify weather events
- Human data input for claim could cause misinformation
- Imbalance between parties around compensation events
- Interceding parts of process often mired (data criteria, mistrust, legal processes)

Technology enablers

- Distributed ledger
- Smart contracts
  - Multi-party signatures
- Internet of Things (IoT)
  - Data oraclisation
- Building Information Modelling (BIM) technologies
- ~~Fiat exchange~~ (purposely avoided)

Intermediate benefits

- Reallocation of resources (e.g., away from administration) *[construction phase participants]*
- Lowered risk of dispute *[construction phase participants]*
- Increase collaboration from fewer disputes *[construction phase participants; client]*
- Better data = better scheduling (e.g., from weather forecasts) *[construction phase participants; client]*
- Data could provide value for other industries *[projects outside of construction]*
- Better project planning *[construction phase participants]*
- Improved/streamlined processes *[construction phase participants]*
- Better traceable, immutable data for decision-making *[construction phase participants; client]*
- Consistent interpretation of contract clauses *[construction phase participants; client]*
- Streamlined data sharing and notifications to parties *[construction phase participants]*
- Improved contractual compliance (process automation) *[construction phase participants]*
- Minimisation of overheads (automating admin) *[construction phase participants]*
- Improved supply chain resilience (less payment delays) *[construction phase participants]*
- Reduced disincentives (human factors minimised) *[construction phase participants]*
- System integration (greater extensibility, interoperability) *[construction phase participants]*
- More informed purchasing/procurement of new software/tools *[project participants seeking new technologies/processes]*

End benefits

- Cost savings (from automation) *[client]*
- Time savings (from automating claims; accurate data) *[client]*

[...] indicate beneficiary of proposed benefit

Figure 5.12: DLT Benefits Pathways for the Weather Ledger

be made as DLT develops and more is known about the anticipated impact from real-world testing. At that point, the intermediate benefits can be used to support optioneering when considering investment options or process changes to applications that will require implementation of the technology enablers for their realisation, and to inform cost-benefit analyses that support the business case for investing in DLT and SCs. Each of the applications described in this paper can be used in silos. However, to do so could lead to increased challenges of interoperability and trust across applications and the sector. To achieve the greatest benefit from digitalisation through DLT and SCs, sector participants require an holistic approach about how best to develop and apply the different technological systems for the eight application areas identified across the DLT Benefits Pathways. To this end, interorganisational business models will help the sector align with the properties of DLT (Kifokeris and Koch, 2019c).

A birds-eye view of the intermediate benefits across the eight themes can be attributed to four aspects that DLT and SCs, integrated with other technology enablers, deliver. First, automation is facilitated by the technology enablers where DLT provides a secure environment for the applications to function, the SCs provide the rules for executing the automation of activities/tasks, IoT collects data for the SCs to be processed by edge/fog/cloud computing, BIM systems that supply and receive information for the involved scenario, and fiat exchanges that facilitate payment to participants based on their contribution and represented by tokens in return for verified and validated work. Automation of administrative activities means time and resources can be reallocated to delivery of value-adding activities for the project. Second, transparency becomes significantly increased, made possible through secure transfer, sharing and storage of information across all phases of the asset lifecycle. A higher level of transparency comes from (a) the ability to assign digital assets to individuals and organisations through tokenisation where a digital asset might represent a part of an information model indicating who designed it and who owns it, along with who owns the physical counterpart once commencement of the construction phase begins, continuing through to operations; and (b) the immutable recording of the transactions on the ledger that are visible based on the DLT's access rights. Automation of tasks and activities in the project drive clarity in contractual terms required for translation into SC code which in turn makes clear the roles and responsibilities of project participants. Third, further digitalisation in comparison to today's levels is achieved when DLT and SCs help derive additional value from other technological systems such as BIM technologies and IoT. Fourth, trust between participants is enhanced as a result of increased transparency due to participants being more likely to share data if they can prove what they own (e.g., through tokenisation). Using the technology enablers to make changes to current processes and practices will result in changes to human behaviour meaning participants will act more honestly if they know their contribution can be scrutinised through a digital record (Baucherel, 2020).

5.4.4 A review of the end benefits

The DLT Benefits Pathways showed that there are four end benefits that have implications for the adoption of DLT and SCs in construction. These are: cost savings, time savings, environmental benefits, and health and safety benefits. End benefits are achieved via several intermediate benefits being realised through the integration of several technology enablers in the use of the identified applications in this study. End benefits will be realised to the advantage of the owner and/or the asset's users/occupants.

Cost savings are acknowledged as a key driver in the decision to adopt new technologies (Ahmed and Kassem, 2018; Kassem *et al.*, 2020) including DLT (Clohessy and Acton, 2019). Improved cost performance can positively contribute to the challenges posed by current procurement models and sector practices, that force low margins across the project supply chain from contractors through subcontractors to suppliers, resulting in lack of trust and disincentivising collaboration (O'Reilly and Mathews, 2019). Cost savings are achieved from intermediate benefits such as automation, better information management practices, and reduced disputes, rework, and variations. An objective of adopting new IT systems is often the ability to reduce costs (Zhang and Dhaliwal, 2009).

Time savings can directly affect the level of cost savings on a project. From the applications reviewed, it appears automation is the main factor that will reduce time on projects (Hamledari and Fischer, 2021c) either from automating administration activities, facilitating faster exchanges of data, streamlining processes, or providing a new level of clarity in construction contracts. This end benefit is derived from intermediate benefits such as fewer variations, reduced rework, fewer disputes and/or shorter dispute resolution, and more proactive and effective maintenance. The ability to demonstrate a reduction in time for construction projects utilising a new technology in comparison with projects not using the technology will be an important factor in adoption decisions (Gao *et al.*, 2018).

From an environmental perspective, DLT contributes to increased sustainability by, for example, enabling strategies for use of more sustainable materials or the construction of built assets that consider the long-term effects of its footprint. Buildings that perform better for their owners and occupants will contribute not only to factors such as reducing greenhouse gas emissions from optimised energy usage but also to cost savings. Intermediate benefits such as better information management and changes to procurement processes can help realise circular economy initiatives that see reuse strategies for materials that are becoming scarce, and more streamlined supply chains will help to reduce waste. Sustainability is becoming a priority on political and economic agendas globally (United Nations, 2020) and while it may not be a deciding factor in the adoption of technology, in addition to cost and time savings, environmental benefits will be an aiding factor in the decision to adopt.

Health and safety is an important end benefit identified in the DLT Benefits Pathways. Events such as the Grenfell Tower fire in 2017 are forcing the sector to focus on health and safety of built assets. Weaknesses in regulation and compliance are identified as a key factor undermining safety, and attempts to drive change to prevent such events are ongoing (Hackitt, 2018). The applications of DLT and SCs have the potential to speed up the pace of change through forcing a new level of clarity in construction contracts, regulations and standards. Immutable recording of transactions that represent activities undertaken throughout the lifecycle of a built asset creates transparency of responsibilities and accountabilities. Leveraging technology for applications such as the National Product Database can create an environment for better compliance and, therefore, a safer, healthier environment for occupants and users. Intermediate benefits contributing to this end benefit include real-time access to information, increased collaboration, and a more compliant and competent sector. Several attempts to improve safety in construction through technology (e.g., BIM, wearable devices) have been made with limited impact seen to date (Nnaji *et al.*, 2019); however, with the adoption of DLT and SCs, these efforts could be enhanced.

The intermediate benefits and end benefits act as an aid in the observability of benefits for these new systems where observability refers to "*the degree to which the results of an innovation are visible to others*" (Rogers, 2003, p. 16).

5.5 Roadmaps to support implementation of DLT and SCs in construction

Society and its parts can be classified across different scales as indicated in Figure 5.13, where micro refers to individuals and their actions; meso considers organisations and groups that make up different parts of society; and macro represents the whole of society (Javaid *et al.*, 2019). As mentioned in the results in Chapter 4, the industry focus groups identified a need for two distinct roadmaps – one for macro scale implementation (the construction sector as a whole) and one for meso scale implementation (the DLT and SC applications being developed within the sector). The micro scale of the classification has been excluded from this study and will be considered in future research.

The meso scale is a relatively recent addition to the micro-macro scale proposed in Dopfer *et al.*'s (2004, p. 263) seminal study offering "*an analytical framework for evolutionary economics*". They established that the micro-macro framework was insufficient to explain the complex nature of economic evolution and therefore included an intermediary scale that can be used as a level to establish a system of rules for the micro and macro scales. Li (2012) partially disagrees with this approach adding that each scale requires a different set of rules. This intersection is where the proposed roadmaps presented in this section lie.

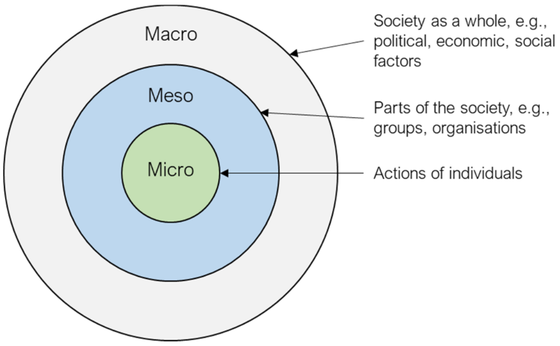


Figure 5.13: Micro-meso-macro scales (recreated from Javaid et al., 2019, p. 8)

Like each of the components of the socio-technical framework proposed in this thesis, they were developed from the perspective of the construction sector. Some components are specific to the sector (e.g., the taxonomies), but some components can be extrapolated to other sectors (e.g., DLT Benefits Pathways, DLT 4-D Model, DLT Actors Model). The roadmaps that follow can be generalisable to other sectors and technologies but would require some adaptation to ensure their applicability, for example, where the roadmaps refer to construction-specific regulations this could be changed to the relevant sector. The reason for this generalisability is that many technologies, while different in functionality, require integration with external systems and have a human element. The human element, the socio- part of the socio-technical system, makes up the main focus on the framework and the roadmaps – ensuring that the technologies developed and the ecosystem being readied are done so for the good of society and its individuals.

The macro scale roadmap is presented first, followed by the meso roadmap. Then, links between the two roadmaps are discussed. Table 5.7 below describes how each of the elicitation techniques contributed to the development of these roadmaps.

Table 5.7: Elicitation techniques that supported development of the DLT Roadmaps

Elicitation techniques	How the technique informed development of the construct
Systematic review 2019-21	• The data collected throughout the systematic review helped to understand the state-of-the-art of DLT and SC applications in construction and to identify the areas of importance for getting DLT and SC applications to market. While the industry focus groups were the main driver for development of the roadmaps, the systematic review provided an underlying appreciation for the challenges of implementing such applications.
Interviews 2021	• The consultation interviews with DLT application developers served to identify the level of support they might need in getting their applications to market. The interviews helped to structure the industry focus groups that followed to ensure they would be useful for the application developers and generate the right data to allow development of the roadmaps.
Focus group 2021	• The industry focus groups were the main data collection method applied to develop the roadmaps. The data collected were used to establish the route to implementation for applications of DLT and SCs at a meso scale and to establish what activities needed to take place at the macro scale to support that development.
Validation survey	• The validation survey was key to establish the suitability of the roadmaps developed following the industry focus groups. The survey served to validate the roadmaps functionality and whether they met their intended purpose, to check whether the data from the focus groups had been interpreted appropriately to make improvements, and to make further improvements to the roadmaps.

5.5.1 Macro Roadmap for Implementation of DLT in Construction

The purpose of the macro roadmap (Figure 5.14) is to support the sector in reaching a state of readiness to successfully implement DLT- and SC-based applications in construction. This roadmap is independent from, but works in conjunction with, the meso roadmap to support implementation of specific applications in the sector. It is driven by a Taskforce appointed by a National Authority and is made up of eight overarching actions that take place over a period of several years. The figures in the subsections below provide details of the tasks to be undertaken for each action and indicates the actor(s) responsible for driving the tasks. The primary actor may choose to delegate tasks to those best placed to carry out the work based on objectives and available resources. An indicative timeframe is given based on the need to ready the ecosystem in a timely manner coupled with the reality of the pace at which the sector moves to make positive change. A realistic timeframe that pushes the sector to challenge the status quo is proposed. Most activities are achievable in

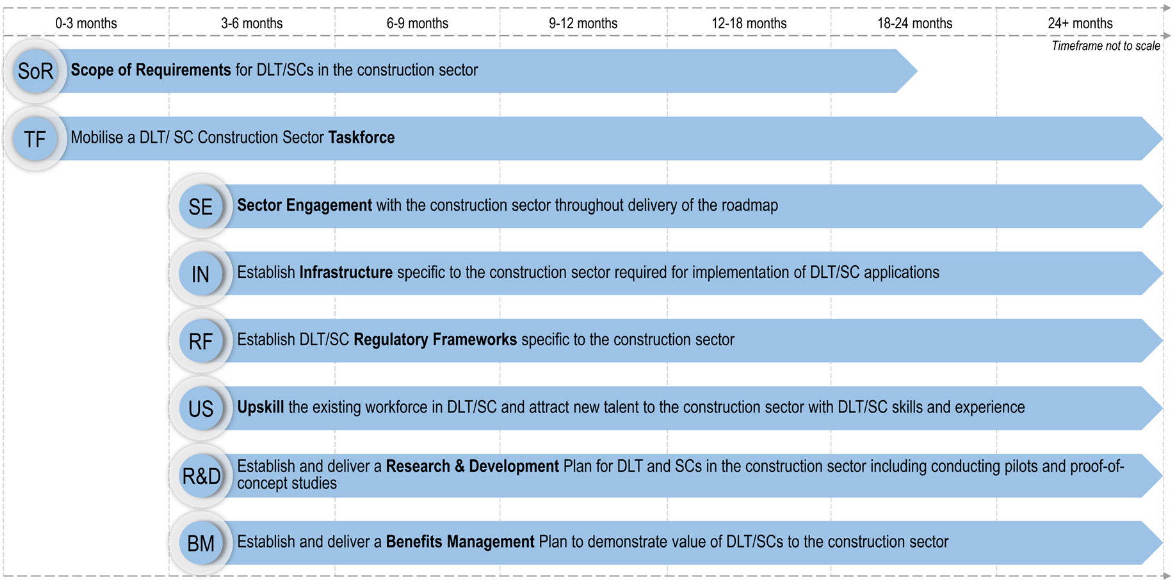


Figure 5.14: Macro roadmap to achieve readiness for DLT and SC applications in construction

the first two years with some tasks extending beyond the initial two year-period. This is a live artefact and as the roadmaps are enacted, funding is made available for its delivery, and a detailed delivery plan is established based on this roadmap, more detailed timeframes and indicative durations for tasks can be included. Indeed, it may be that the Taskforce would stagger the start date of the actions based on what was seen as priorities at the time. Appendix H indicates the evidence trail for each action in the macro roadmap based on outputs from the focus groups and supporting literature.

If should be noted that National Authorities around the world, who are the likely adopters of this roadmap, may have commenced their plan toward implementation of DLT and SCs in construction at the point the roadmap is adopted. It would be for them to assess those actions already underway and consider the extent to which this roadmap can support their efforts further.

Each action is set out below detailing the different tasks that should take place supported by an indicative timeframe, proposed actors responsible for delivering the task, the proposed tools (models discussed in previous subsections) that can support delivery of the tasks, and links between tasks within and across actions. While there are links between actions, they are designed to be delivered independently and therefore in parallel such that the National Authority can take the decision on which action is most important based on their timeframe and resources. However, defining the Scope of Requirements (SoR) and mobilising a DLT/SC Taskforce (TF) are two actions that should be delivered before the remaining six actions. Other than SoR and TF commencing first, the remaining actions have no hierarchy in terms of importance; they are all relevant and have a part to play in making adoption of DLT and SCs in construction a success.

Defining the Scope of Requirements (SoR)

One of the first actions in the macro roadmap is identifying the scope of requirements (SoR). The different tasks and their flow can be seen in Figure 5.15. This is arguably the most important action in the macro roadmap as it establishes what the National Authority wants to achieve from implementation of DLT and SCs into their construction sector. The SoR will be a vehicle to identify the needs of DLT-/SC-based systems and can be used to obtain funding streams; establish a Taskforce of personnel with the skills, knowledge and drive to champion the roadmap throughout its duration; align the roadmap with national strategies; set clear objectives and milestones; evaluate the potential value of DLT and SCs for their construction sector; and identify resource requirements to deliver the roadmap. The models presented earlier in this Chapter as part of the socio-technical framework can be utilised to inform the responsible persons of the challenges and opportunities associated with these technologies (Challenges and Applications taxonomies; DLT Benefits Pathways) as well as identify the actors with whom to engage (DLT Actors Model) and analyse the current systems and processes against the desire state (DLT Four-Dimensional Model).

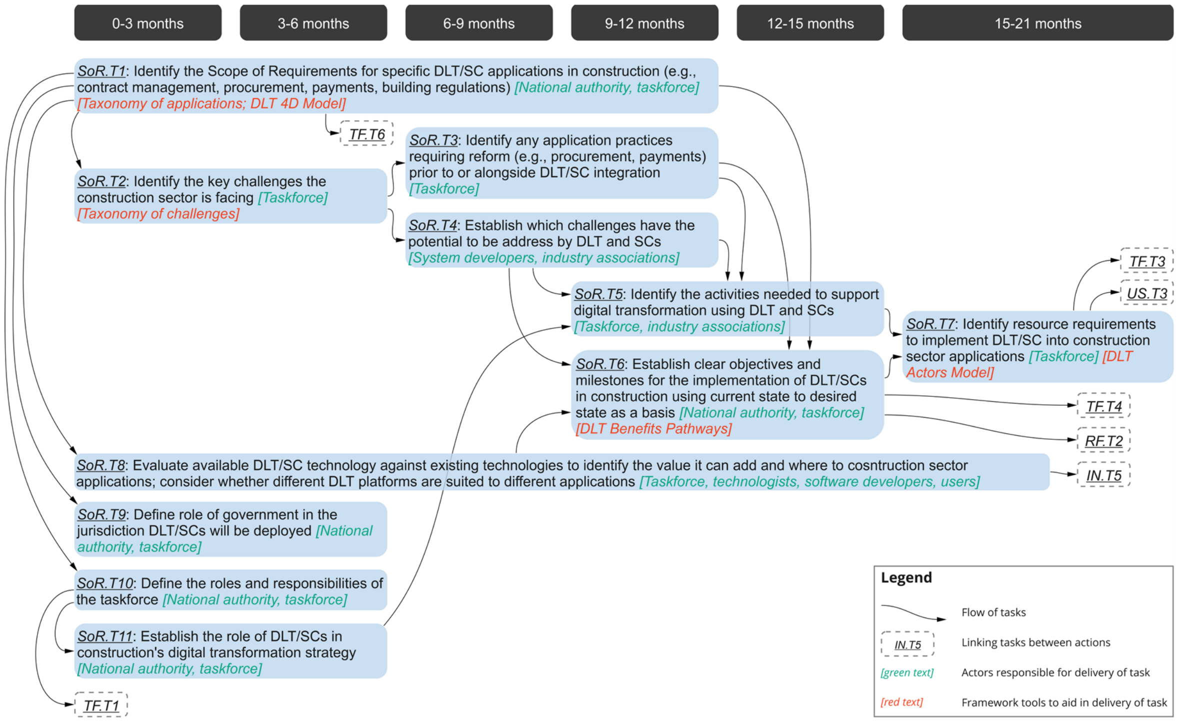


Figure 5.15: Define the Scope of Requirements (SoR)

Mobilise a DLT/SC Taskforce (TF)

The second action that will commence in parallel with the SoR is that of mobilising a Taskforce who will drive the remainder of the roadmap to a point where the sector is at a point of self-perpetuation (i.e., they no longer require organisation from a dedicated force to maintain momentum). The tasks within this action are shown in Figure 5.16. The Taskforce should be made up of representatives across the sector with a vested interest in its delivery and who will commit to being part of the Taskforce for its duration. The SoR action will aid in identifying who those individuals are and can be identified utilising the DLT Actors Model. The responsibilities of the Taskforce in the early stages will include securing commitment from actor groups for their participation for the roadmap's delivery, to identify and secure funding streams and to drive toward the point of adoption of DLT and SCs throughout the construction sector. They will be responsible for identifying specific use cases to demonstrate the potential benefits of the technologies and push for regulatory reform to account for these technologies.

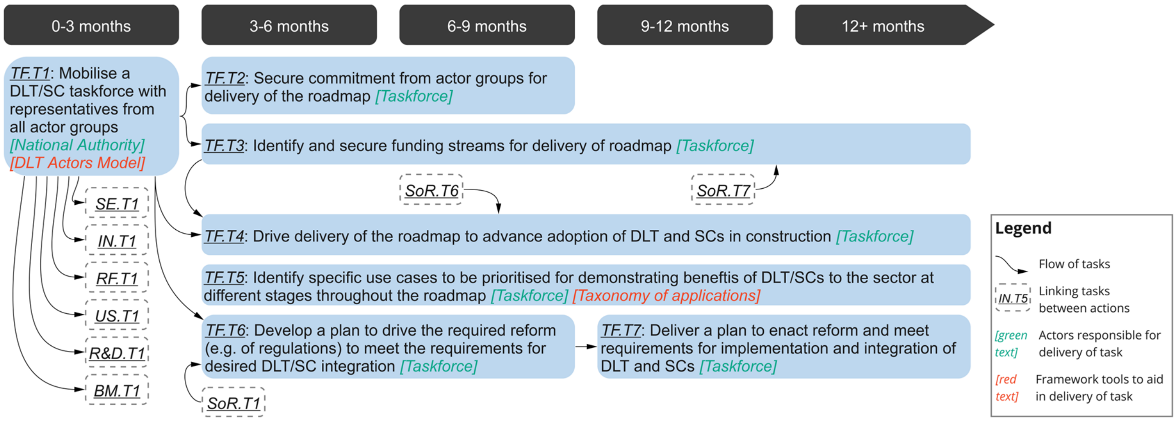


Figure 5.16: Mobilise a DLT/SC Taskforce

For many of the tasks across all the actions, the Taskforce is the responsible actor for its delivery. This may seem like over resourcing for the Taskforce. However, the actors responsible are not necessarily the individuals or groups who will undertake the activities directly, rather they are the actors accountable for ensuring the tasks are achieved and can delegate to the actor best placed to deliver the task based on skills and expertise.

Conduct Sector Engagement (SE)

The Sector engagement (SE) action shown in Figure 5.17 is central to the success of the roadmap in its entirety. Its focus is on engaging with all actors across the construction sector at relevant points throughout the roadmap's delivery. It involves identifying all the relevant actors with whom to engage, when and how. It can be supported by the DLT Actors Model and should run for the duration of the roadmap. It is directly linked to the Benefits Management (BM) action as this is how successes and 'lessons learned' of these technologies will be disseminated. Activities will include marketing, outreach, raising awareness, dissemination of results etc. and will also engage with meso projects where they form part of pilot and PoC studies that demonstrate benefits of these technologies in practice.

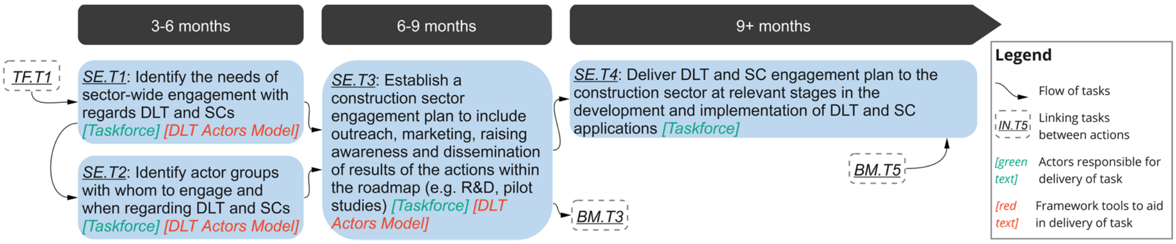


Figure 5.17: Conduct Sector Engagement (SE)

Establish DLT/SC Infrastructure (IN)

This action (Figure 5.18) revolves around establishing suitable infrastructure to support DLT and SCs in the construction sector at the macro scale to allow development and implementation of DLT and SC applications at the meso scale. Many start-ups and small and medium sized enterprises may have the creativity and innovation to develop such applications but may face barriers around ability to implement if suitable infrastructure is not in place (e.g., for reasons of lack of funds/resources, not being able to connect to networks or issues of interoperability). Equally, larger organisations may be deterred from developing DLT-/SC-based solutions in a sector that has low profit margins and little to no investment in R&D if costs to establish infrastructure to launch a solution prove prohibitive. Ensuring each of the different aspects of DLT/SC infrastructure are aligned is key such as ensuring standardised smart legal contracts are aligned to regulation as well as underlying DLT platforms. Such alignment will offer developers of DLT/SC applications the opportunity and encouragement to explore what these technologies can do.

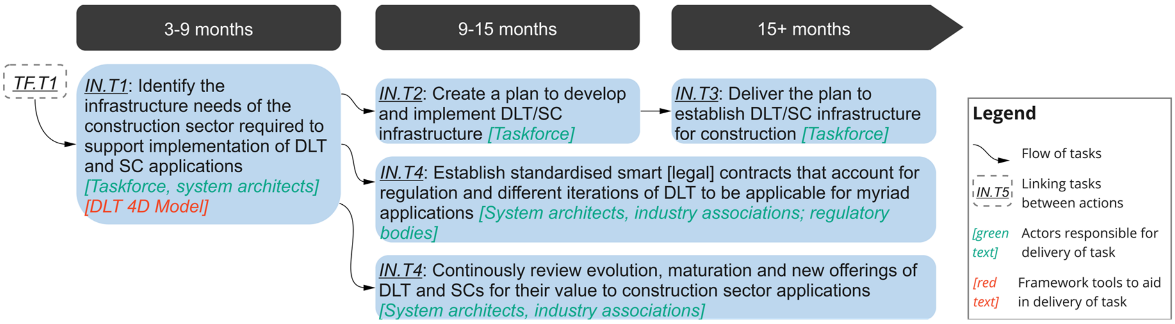


Figure 5.18: Establish DLT/SC Infrastructure (IN)

Establish DLT/SC Regulatory Frameworks (RF)

While many of the actions in the macro roadmap extend beyond 24 months, it is recognised the action to establish regulatory frameworks requires much more time to be delivered. Its tasks while few extend to 36 months and beyond accounting for the bureaucratic nature of such actions. The first task in this action shown in Figure 5.19 recommends setting up a sub-taskforce dedicated to establishment (or reform) of regulatory frameworks to incorporate DLT and SCs. As mentioned previously, at the point a National Authority chooses to adopt this roadmap, it may be that some actions have already commenced. In such a case, the National Authority should look to perform a gap analysis using the socio-technical framework to benchmark their implementation plan.

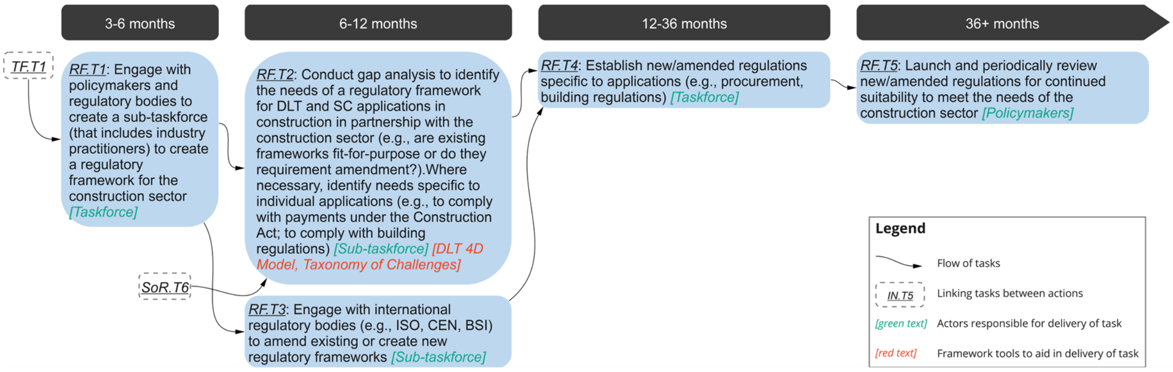


Figure 5.19: Establish DLT/SC Regulatory Frameworks (RF)

A gap analysis should be conducted to establish the requirements for amendment of existing regulations or creation of new regulations to be fit-for-purpose for DLT and SC applications in construction. They should consider compliance with, for example, payments under the Construction Act, building regulations and data protection. Engagement with regulatory bodies (e.g., ISO, CEN, BSI) will be essential as will engagement with standard form contracting bodies (e.g., JCT, NEC, FIDIC) that are central to the delivery of construction projects. Any amendments of new regulations should consider different applications (e.g., procurement, compliance) and once enacted should be periodically reviewed against new technological advancements, actual sector practices and health and safety requirements to ensure they remain fit-for-purpose.

Upskill the Workforce (US)

Understanding the requirements of applications in terms of their development, delivery and use will be a factor in their success. Upskilling the workforce with the right skills and experience will enable a sector that is ready to adopt DLT and SC-based applications. The action and its tasks can be seen in Figure 5.20. This action begins with development of educational frameworks and learning objectives to ensure the right skills are being established. In much the same way as infrastructure is required to succeed, so too are skills to ensure sufficient personnel to deploy and run the applications. This could be new entrants or reskilling of the existing workforce. The Taskforce will be responsible for securing funding to deliver this action as well as putting in place a plan for upskilling. The skills requirements will be identified through gap analysis and should be reviewed and updated periodically as new technologies are released for construction. Creation of materials and their delivery make up the final two tasks in this action and are intended to be delivered by established training and education institutions. Such training and education programmes could be delivered as professional training courses (e.g., continuing professional development), and as part of college and university programmes – first integrated into existing courses (e.g., construction management) and later as dedicated programmes (e.g., digital construction).

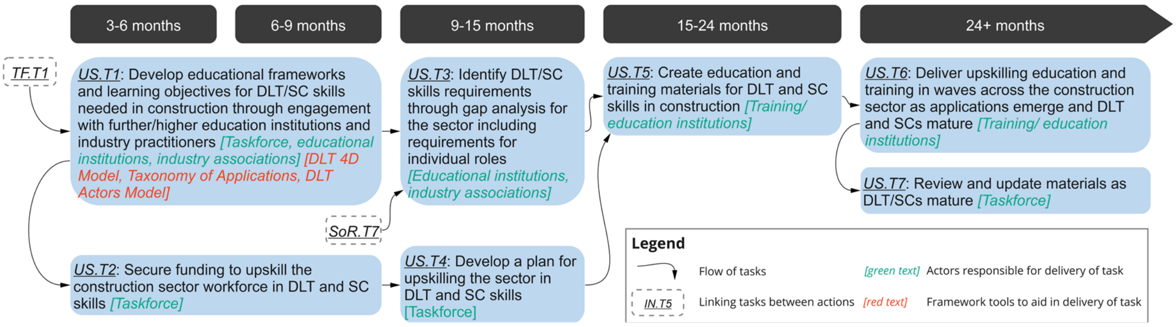


Figure 5.20: Upskill the Workforce (US)

Conduct Research & Development (R&D)

As mentioned previously in this thesis, R&D activities in the construction sector have been substantially lacking, especially when compared to other sectors such as manufacturing, aerospace and automotive. This action (Figure 5.21) aims to rectify that by establishing a robust R&D strategy for the construction sector and in particular R&D into DLT and SC technologies. The first task aims to identify the areas of R&D for DLT and SCs that are most important to meet the needs of digital transformation for the sector. This task utilises the challenges and applications taxonomies and engages with industry and research institutions to identify where the needs are. From this, a plan to encourage more R&D activity in the sector is developed and a plan to attract and obtain funding streams for its delivery is established. Such funding should not just come from public bodies; there should be emphasis on industry and academia funding too to ensure vested interests will result in realised applications.

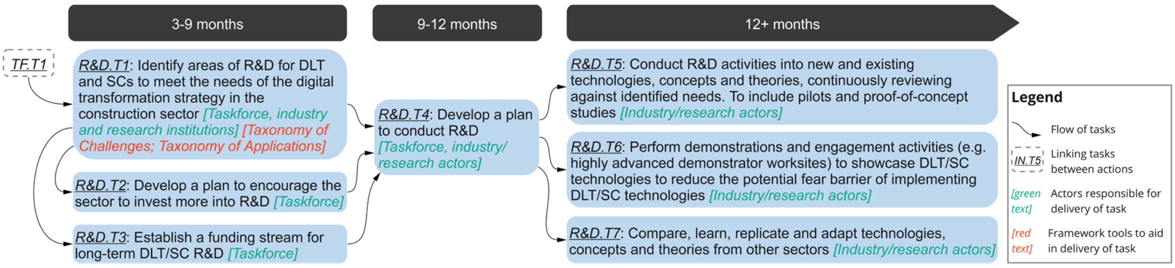


Figure 5.21: Conduct Research & Development (R&D)

This action will integrate with meso roadmap activities where meso projects can form part of the R&D plan to conduct pilot and PoC studies. This action should constantly review the state-of-the-art for available and emerging technologies, concepts and theories as well as looking to other sectors who typically advance faster than construction. In addition, this action will engage with both the Sector Engagement (SE) and Benefits Management (BM) actions as the research and associated results will be valuable to the sector generally to maintain momentum of the roadmap and to demonstrate the realised benefits to the sector.

Manage Sector-wide Benefits (BM)

The benefits management action (Figure 5.22) will be central to measuring the success of DLT and SC applications in construction. The process of benefits management includes the identification, planning, measurement and tracking of benefits from initiation to the point of the last benefit being realised. In the context of macro adoption of DLT and SCs in construction, the last benefit may not be seen for many years. However, the SoR action will establish objectives and milestones, benefits of which will be a part, and the Taskforce will decide which of the benefits are to be subjected to the benefits management action. As with many parts of this roadmap, the Benefits Management Plan will be a live artefact that is reviewed, updated and used as a benchmark against which to monitor progress of macro implementation.

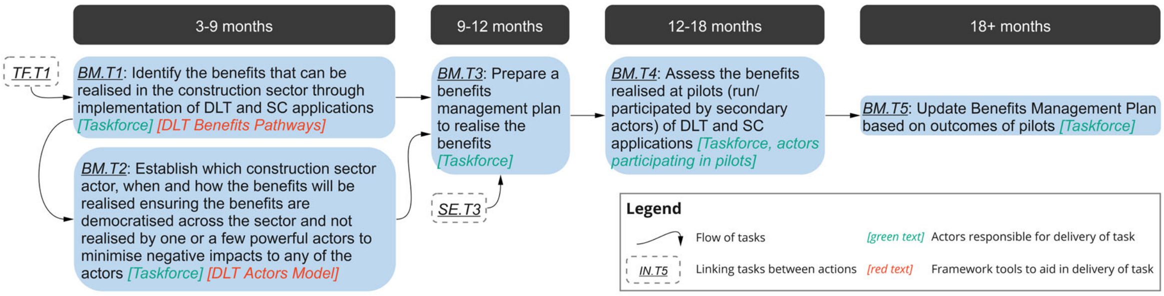


Figure 5.22: Manage Sector-wide Benefits (BM)

Part of identifying and measuring benefits will include identification of the actor(s) who will receive the benefit, how and when. Key to the success of DLT and SCs, particularly in the early stages of adoption, will be to ensure benefits are democratised and not skewed to any one or few powerful actors. This will mitigate any potential negative impacts and behaviours from actors who may not be in favour of change. A robust Benefits Management Plan will ensure benefits continue to be monitored and updated throughout the duration of the roadmap and beyond where appropriate. Interaction is required with the Sector Engagement action that will be responsible for disseminating information about benefits that will act as a driver for engagement from the sector with the roadmap generally.

5.5.2 Meso Roadmap for Implementation of DLT in Construction

The purpose of the meso roadmap (Figure 5.23) is to support the development and implementation of DLT and SC applications for the construction sector, where an application represents a current or new technological system with the ability to be integrated with DLT and SCs. This roadmap is designed to be independent from the macro roadmap. However, there are elements of the macro roadmap that could impact the success of a new DLT/SC application in construction, for example, the availability of skills required to deliver and/or run the new system, the regulatory environment surrounding it or the macro support to pilots and PoC studies (i.e., through funding for development or establishing DLT/SC infrastructure that will facilitate implementation). More details on the links between the two roadmaps are presented in Section 5.5.3. Appendix I indicates the evidence trail for each stage in the meso roadmap based on outputs from the workshops and literature. The six stages shown in Figure 5.23 demonstrates the progressive and agile nature of the roadmap. At the end of each stage is a decision gate to support the taskforce in making a formal decision on whether to progress to the next stage or to reject the implementation of DLT and/or SCs into the new system. This provides an exit strategy in case of demonstrated lack of value or engagement from the industry users. The meso roadmap is not supported by an indicative timeframe as each application will differ in time and resource requirements to progress through the stages depending on its objectives, its interactions with other systems and processes and the actor groups involved in its implementation. This roadmap is not intended to be a methodology for meso development and implementation of DLT-

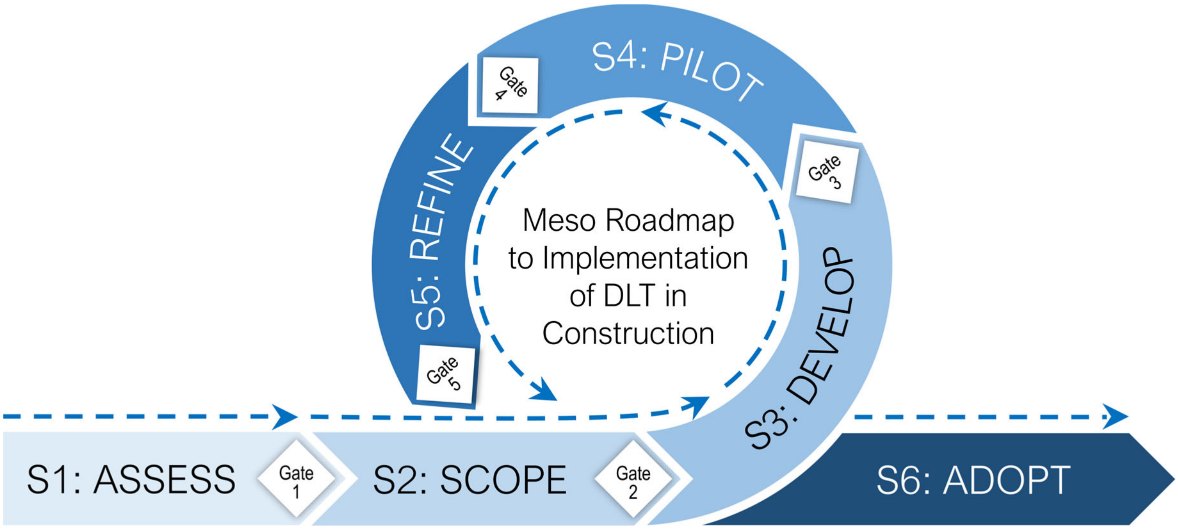
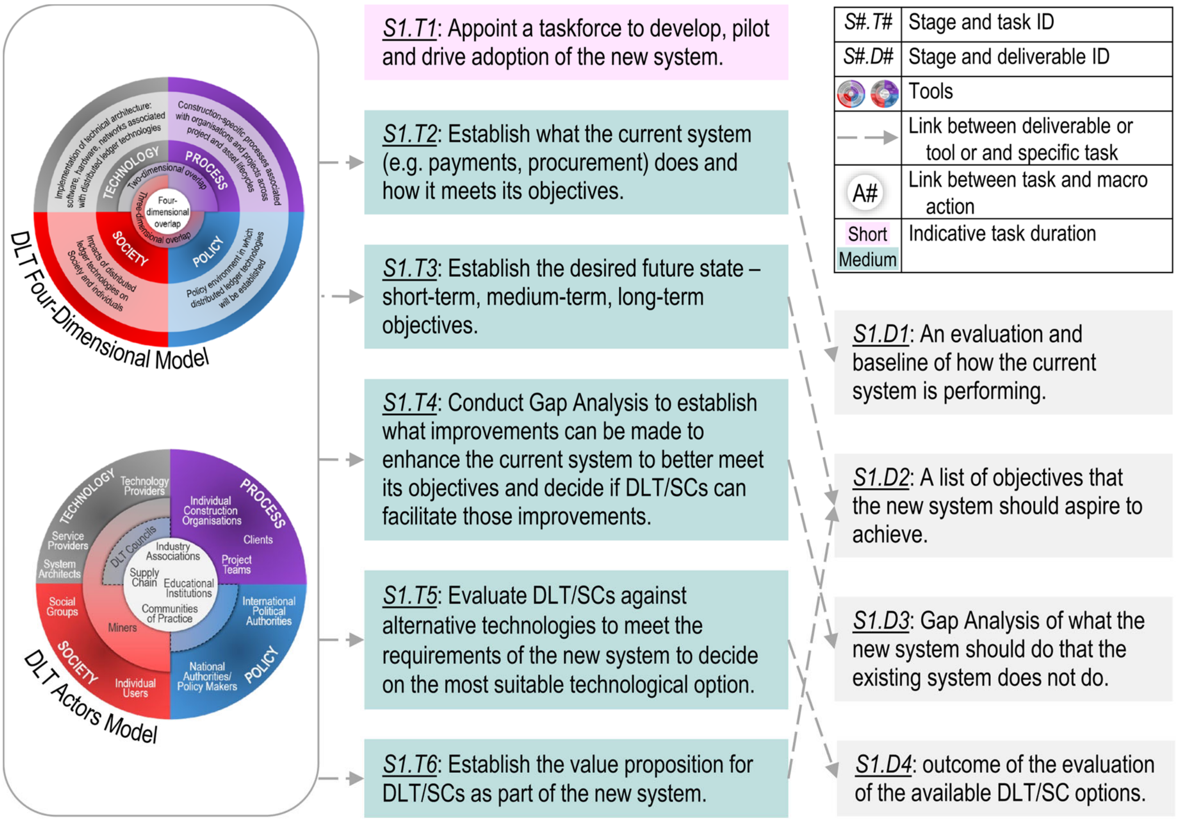


Figure 5.23: Meso roadmap for implementation of DLT and SC applications in construction

/SC-based applications nor is it prescriptive in the sense that all stages and tasks must be followed. Rather, it is designed to be adaptable to the owners of the application to perform those actions applicable to the application and the circumstances surrounding it. This roadmap will be beneficial for start-ups looking to enter the space of digital construction with new applications, as well as governments and institutions looking to exploit new technologies, advance the sector from within, and consider how they can improve business models.

Stage 1: Assess

The first stage in the meso roadmap (Figure 5.24) involves assessing the current system and its associated processes and practices. It considers how effective the system is in meeting the needs of the construction sector and how to deal with the sector's nuances (e.g., one-off projects, high fragmentation) that make it unique to all other sectors such as automotive and manufacturing. This provides those intent on improving a system with the detailed knowledge of the challenges of the existing system (e.g., payments, supply chain management, contract management and delivery as discussed in the Literature Review in Chapter 2). In addition, it identifies which elements of the system currently work well such that problems can be solved and opportunities can be exploited in the new iteration. This stage has a specific focus on evaluating the existing DLT and SC technologies available alongside evaluating alternative technologies to support application developers in choosing the best solution for the new system, recognising that DLT and SCs may not be the best option at a certain point in time.



S1.T1: Appoint a taskforce to develop, pilot and drive adoption of the new system.

S1.T2: Establish what the current system (e.g. payments, procurement) does and how it meets its objectives.

S1.T3: Establish the desired future state – short-term, medium-term, long-term objectives.

S1.T4: Conduct Gap Analysis to establish what improvements can be made to enhance the current system to better meet its objectives and decide if DLT/SCs can facilitate those improvements.

S1.T5: Evaluate DLT/SCs against alternative technologies to meet the requirements of the new system to decide on the most suitable technological option.

S1.T6: Establish the value proposition for DLT/SCs as part of the new system.

S#.T#	Stage and task ID
S#.D#	Stage and deliverable ID
◎ ◎	Tools
- - →	Link between deliverable or tool or and specific task
A#	Link between task and macro action
Short Medium	Indicative task duration

S1.D1: An evaluation and baseline of how the current system is performing.

S1.D2: A list of objectives that the new system should aspire to achieve.

S1.D3: Gap Analysis of what the new system should do that the existing system does not do.

S1.D4: outcome of the evaluation of the available DLT/SC options.

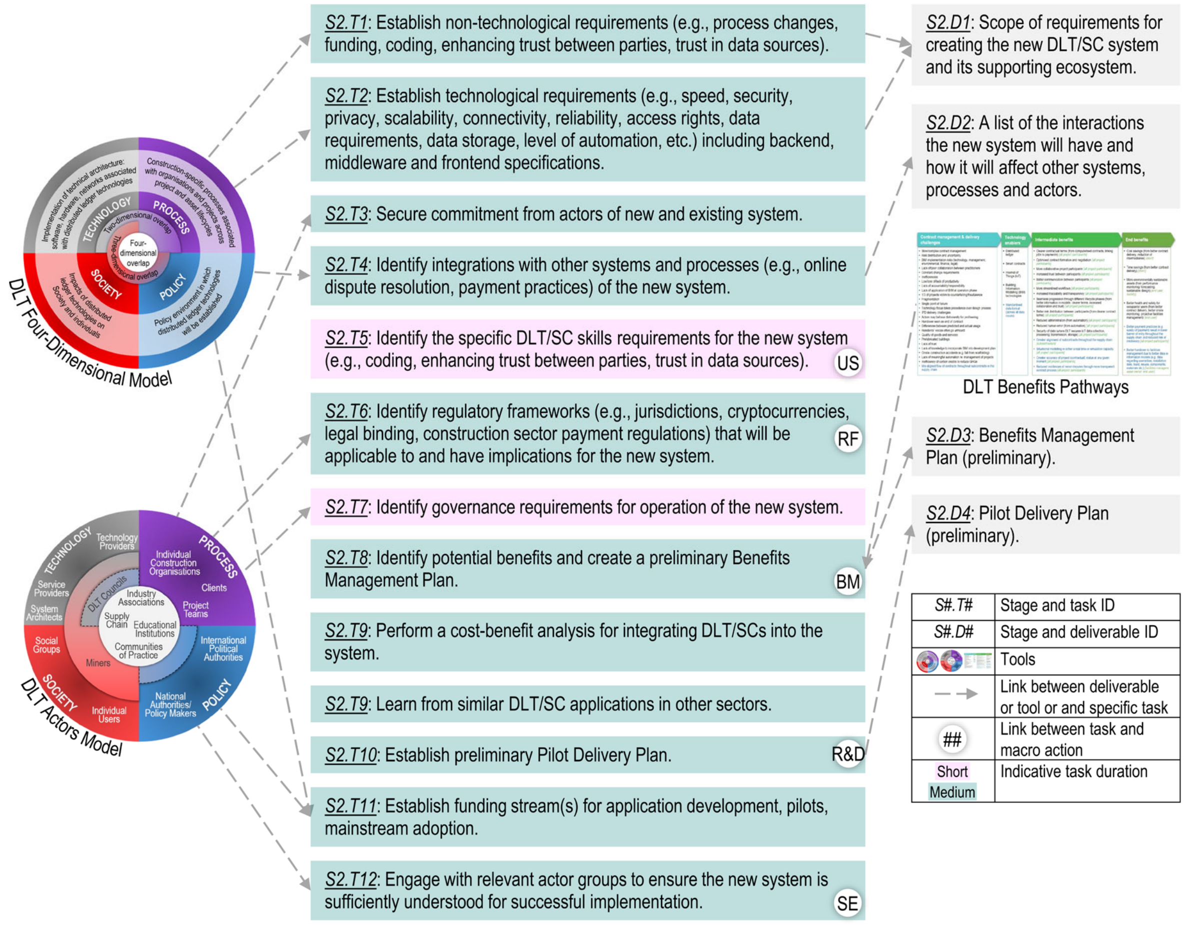
Figure 5.24: Stage 1: Assess of the meso roadmap

This stage utilises the DLT Four-Dimensional Model and the DLT Actors Model to support the assessment by analysing the system from different perspectives and considering the different actor groups who interact with it and/or are affected by it. The deliverables (S1.D1 to S1.D4 in Figure 5.24) will support decision making in terms of continuing onto the next stage. Tying this and all stages together is the appointment of a taskforce at the beginning of the process to drive development and implementation of the application throughout the roadmap. It is intended that the taskforce is made up of individuals with a vested interest in the application and its success and those who can commit to participating at all stages of the roadmap. The individuals making up the taskforce could be, for example, application developers; construction project clients in the role of championing a new application; main contractors in the role of implementer of a new application; industry associations as drivers of R&D; policymakers; or public sector representative as champions for a new innovation. The final task in Stage 1 considers the value proposition of the application being developed. This should consider both existing, emerging and future technologies entering construction (e.g., 5G, DfMA) to ensure the new application utilises the most appropriate technologies, considers developments and approaches in different regions, and the changes needed for different parts of the world.

Stage 2: Scope

Once a decision has been made to move forward with developing a new DLT-/SC-based system, the next stage (Figure 5.25) entails scoping what the new system will do, who it will be used by, how they will be impacted by it and how it will change current processes and linked systems. For example, if the plan is to automate payments, this might link to but be separate from procurement. This stage will support developers in identifying all the interactions with the improved system and establish what changes, if any, are required outside of the new system. Much of the work involved in developing and implementing a new system needs to be done upfront to ensure its best chance of success once financial commitment has been made. On this basis, stages 2 and 3 require significant effort from the application developers.

This stage utilises the DLT Four-Dimensional Model and the DLT Actors Model to analyse the needs of the system and consider its interactions with different actors. It also utilises the DLT Benefits Pathways tool to provide justification to develop the new system, which considers the challenges the application is attempting to solve, highlights the different technology enablers for the new system and documents the intended intermediate and end benefits that can be realised and by whom from implementing the new system. These benefits can act as a benchmark against which to monitor progress and success of the application at the pilot stage, early adoption and mainstream adoption. The circles (e.g., US in Stage 2, Task 5 – S2.T5) indicate links to actions in the macro roadmap. For example, S2.T5 is linked to US (upskilling the workforce in the macro roadmap). Where S2.T5



S2.T1: Establish non-technological requirements (e.g., process changes, funding, coding, enhancing trust between parties, trust in data sources).

S2.T2: Establish technological requirements (e.g., speed, security, privacy, scalability, connectivity, reliability, access rights, data requirements, data storage, level of automation, etc.) including backend, middleware and frontend specifications.

S2.T3: Secure commitment from actors of new and existing system.

S2.T4: Identify integrations with other systems and processes (e.g., online dispute resolution, payment practices) of the new system.

S2.T5: Identify the specific DLT/SC skills requirements for the new system (e.g., coding, enhancing trust between parties, trust in data sources).

S2.T6: Identify regulatory frameworks (e.g., jurisdictions, cryptocurrencies, legal binding, construction sector payment regulations) that will be applicable to and have implications for the new system.

S2.T7: Identify governance requirements for operation of the new system.

S2.T8: Identify potential benefits and create a preliminary Benefits Management Plan.

S2.T9: Perform a cost-benefit analysis for integrating DLT/SCs into the system.

S2.T9: Learn from similar DLT/SC applications in other sectors.

S2.T10: Establish preliminary Pilot Delivery Plan.

S2.T11: Establish funding stream(s) for application development, pilots, mainstream adoption.

S2.T12: Engage with relevant actor groups to ensure the new system is sufficiently understood for successful implementation.

S2.D1: Scope of requirements for creating the new DLT/SC system and its supporting ecosystem.

S2.D2: A list of the interactions the new system will have and how it will affect other systems, processes and actors.

S2.D3: Benefits Management Plan (preliminary).

S2.D4: Pilot Delivery Plan (preliminary).

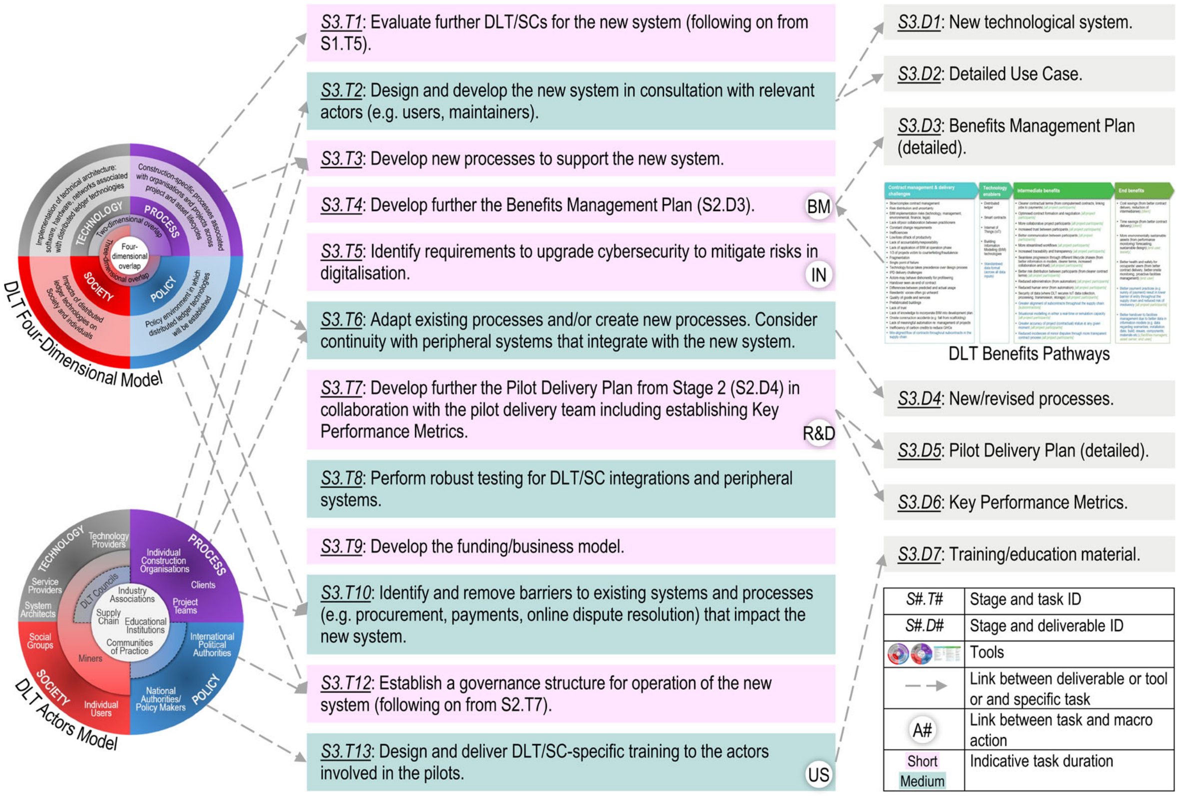
S#.T#	Stage and task ID
S#.D#	Stage and deliverable ID
	Tools
– →	Link between deliverable or tool or and specific task
##	Link between task and macro action
Short Medium	Indicative task duration

Figure 5.25: Stage 2: Scope of the meso roadmap

considers identification of the specific skills required for the new application, the work being done under the macro roadmap could be a benefit to meso implementation through helping to deliver the skills required by training and educating the existing workforce, or it could work inversely where the meso roadmap informs the macro roadmap of the required skills for the sector.

Stage 3: Develop

The third stage of the meso roadmap (Figure 5.26) takes the application developer through development of the technological system whilst also considering important aspects that should be addressed, for example, compliance with regulations (or developing a system that can be adapted to comply with regulations if they are likely to be enacted later than the launch of the new system), or robust planning for pilot studies. Benefits management is an important part of this step. Here, the DLT Benefits Pathways tool can act as a baseline accounting for what was identified in Stage 2 and any additional benefits identified in this stage. Another part of this stage is to develop a detailed use case for the application. Use cases consider all uses of a technological system, intended and unintended, to support the development process and ensure that the system can respond *as it will be used* by the users rather than *as it was intended* by the designer as there are often variations between the two. At the end of this stage, everything should be in place to support delivery of the



S3.T1: Evaluate further DLT/SCs for the new system (following on from S1.T5).

S3.T2: Design and develop the new system in consultation with relevant actors (e.g. users, maintainers).

S3.T3: Develop new processes to support the new system.

S3.T4: Develop further the Benefits Management Plan (S2.D3). BM

S3.T5: Identify requirements to upgrade cybersecurity to mitigate risks in digitalisation. IN

S3.T6: Adapt existing processes and/or create new processes. Consider continuity with peripheral systems that integrate with the new system.

S3.T7: Develop further the Pilot Delivery Plan from Stage 2 (S2.D4) in collaboration with the pilot delivery team including establishing Key Performance Metrics. R&D

S3.T8: Perform robust testing for DLT/SC integrations and peripheral systems.

S3.T9: Develop the funding/business model.

S3.T10: Identify and remove barriers to existing systems and processes (e.g. procurement, payments, online dispute resolution) that impact the new system.

S3.T12: Establish a governance structure for operation of the new system (following on from S2.T7).

S3.T13: Design and deliver DLT/SC-specific training to the actors involved in the pilots. US

S3.D1: New technological system.

S3.D2: Detailed Use Case.

S3.D3: Benefits Management Plan (detailed).

S3.D4: New/revised processes.

S3.D5: Pilot Delivery Plan (detailed).

S3.D6: Key Performance Metrics.

S3.D7: Training/education material.

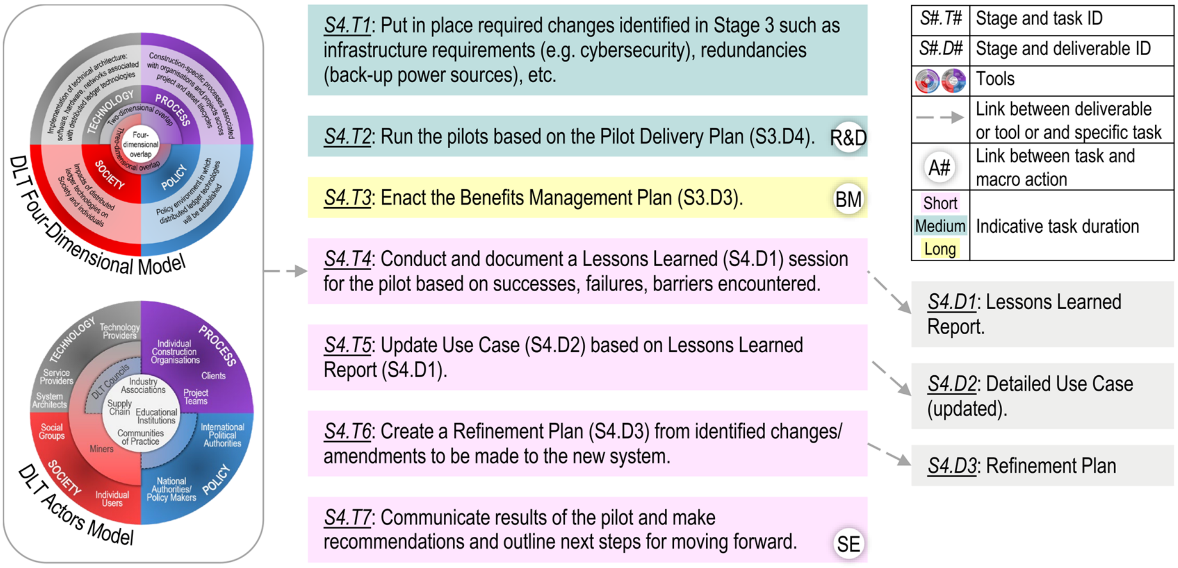
S#.T#	Stage and task ID
S#.D#	Stage and deliverable ID
	Tools
⟶	Link between deliverable or tool or and specific task
A#	Link between task and macro action
Short Medium	Indicative task duration

Figure 5.26: Stage 3: Develop of the meso roadmap

pilot studies in Stage 4. The current iteration of the new DLT-/SC-based system should have sufficient functionality that allows the aims and objectives of the pilot studies to be achieved. This stage is the start of the agile process within the roadmap where develop, pilot and refine allow iterations to reach a satisfactory standard before adoption.

Stage 4: Pilot

The pilot stage (Figure 5.27) of the meso roadmap is critical to the success of a new system as it is the first opportunity to observe how the intended system will operate, it will demonstrate real benefits, identify potential problems and highlight how it is actually used by the users. A new technology brings with it uncertainty. Pilot studies can help alleviate some of the uncertainty by testing how a new technology will perform as part of a new system and provide justification for its deployment based on the results. It should be noted, however, that success at pilot does not automatically translate into success at mainstream adoption (Pal *et al.*, 2008). However, the evaluation criteria chosen carefully at Stage 3 should provide the application developers with the best data to equip them with the best chance of success at mainstream adoption. Lessons learned is incorporated into the pilot activities enabling a plan to be put in place to maximise success and mitigate any potential problems that may impact adoption of the system.



S4.T1: Put in place required changes identified in Stage 3 such as infrastructure requirements (e.g. cybersecurity), redundancies (back-up power sources), etc.

S4.T2: Run the pilots based on the Pilot Delivery Plan (S3.D4). R&D

S4.T3: Enact the Benefits Management Plan (S3.D3). BM

S4.T4: Conduct and document a Lessons Learned (S4.D1) session for the pilot based on successes, failures, barriers encountered.

S4.T5: Update Use Case (S4.D2) based on Lessons Learned Report (S4.D1).

S4.T6: Create a Refinement Plan (S4.D3) from identified changes/ amendments to be made to the new system.

S4.T7: Communicate results of the pilot and make recommendations and outline next steps for moving forward. SE

S4.D1: Lessons Learned Report.

S4.D2: Detailed Use Case (updated).

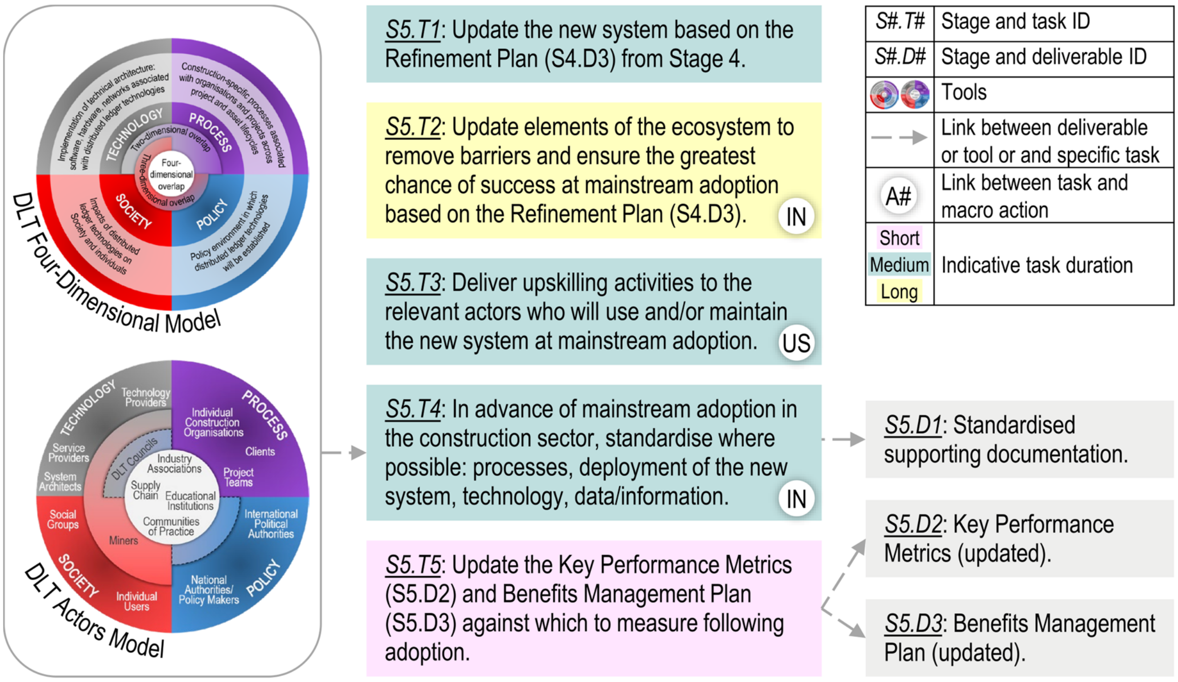
S4.D3: Refinement Plan

S#.T#	Stage and task ID
S#.D#	Stage and deliverable ID
●●	Tools
- - →	Link between deliverable or tool or and specific task
A#	Link between task and macro action
Short Medium Long	Indicative task duration

Figure 5.27: Stage 4: Pilot of the meso roadmap

Stage 5: Refine

Following the pilot stage, the application developer should focus on learning from the experiences gained during the pilots and implement any changes to refine the system (Figure 5.28) and its associated processes prior to mainstream adoption. The level of effort required by this will depend on the size and reach of the application and the required level of changes to the new system before the launch. At this stage, there should be development of a full suite of supporting documentation setting out detailed processes, governance, and guidance associated with the new system. Key Performance Metrics that will be used to measure future success of the application are devised and the Benefits Management Plan maintained to ensure focus is kept on ensuring the application is as successful as possible and diffusion of the system is managed.



S5.T1: Update the new system based on the Refinement Plan (S4.D3) from Stage 4.

S5.T2: Update elements of the ecosystem to remove barriers and ensure the greatest chance of success at mainstream adoption based on the Refinement Plan (S4.D3). IN

S5.T3: Deliver upskilling activities to the relevant actors who will use and/or maintain the new system at mainstream adoption. US

S5.T4: In advance of mainstream adoption in the construction sector, standardise where possible: processes, deployment of the new system, technology, data/information. IN

S5.T5: Update the Key Performance Metrics (S5.D2) and Benefits Management Plan (S5.D3) against which to measure following adoption.

S5.D1: Standardised supporting documentation.

S5.D2: Key Performance Metrics (updated).

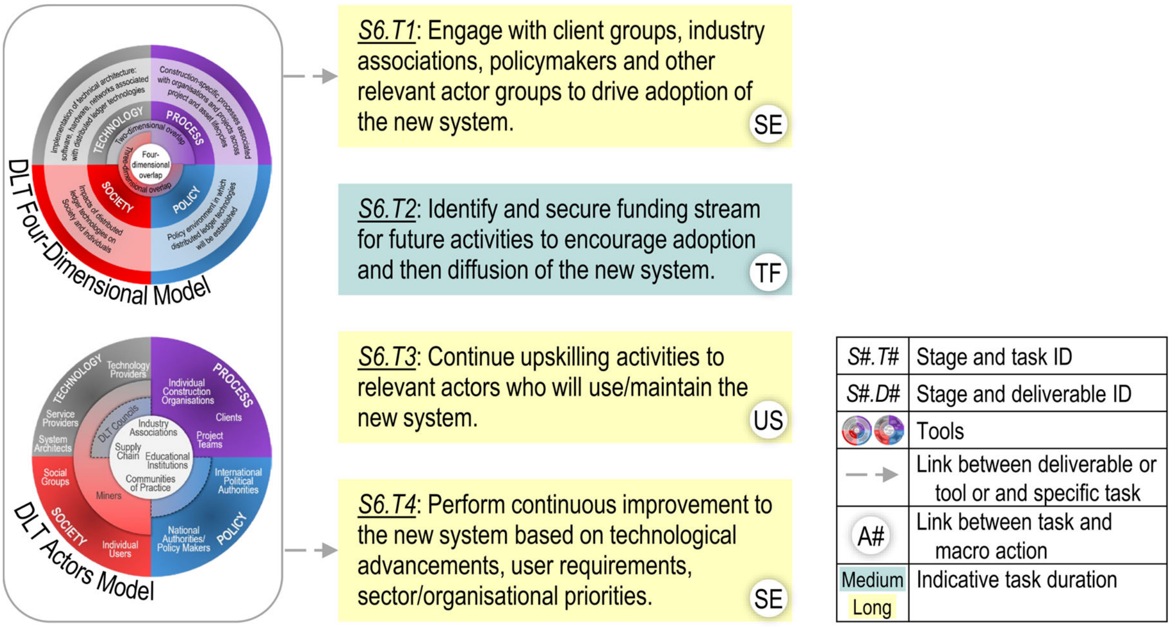
S5.D3: Benefits Management Plan (updated).

S#.T#	Stage and task ID
S#.D#	Stage and deliverable ID
●●	Tools
- - →	Link between deliverable or tool or and specific task
A#	Link between task and macro action
Short Medium Long	Indicative task duration

Figure 5.28: Stage 5: Refine of the meso roadmap

Stage 6: Adopt

The final stage of the roadmap (Figure 5.29) sees mainstream adoption of the new system into the construction sector. This roadmap refers to early adoption of the new system and advises that as the application reaches this stage further effort is put into creating a diffusion roadmap to manage the adoption and continuous improvement indefinitely. Attention may need to be given to funding adoption and diffusion of the system as well as providing training to ensure there are sufficient resources with the skills to run it. Depending on the scale of the application, policymakers may be effective in driving adoption through, for example, requirements for applications to be used on publicly funded projects (either through a mandate or as a contractual clause in a contract). For non-publicly funded projects, engagement with clients will be key in the early stages of adoption to get their buy-in.



S6.T1: Engage with client groups, industry associations, policymakers and other relevant actor groups to drive adoption of the new system. SE

S6.T2: Identify and secure funding stream for future activities to encourage adoption and then diffusion of the new system. TF

S6.T3: Continue upskilling activities to relevant actors who will use/maintain the new system. US

S6.T4: Perform continuous improvement to the new system based on technological advancements, user requirements, sector/organisational priorities. SE

S#.T#	Stage and task ID
S#.D#	Stage and deliverable ID
● ●	Tools
– – →	Link between deliverable or tool or and specific task
A#	Link between task and macro action
Medium Long	Indicative task duration

Figure 5.29: Stage 6 of the meso roadmap

5.5.3 Linking the meso and macro roadmaps

These roadmaps provide actions that could help the construction sector progress toward a state of higher digitalisation through implementation of DLT and SCs. They can be used by researchers and industry practitioners in the development of new applications and strategies for advancing the sector. The two roadmaps are intended to be used separately from one another, however, there are links between them. A challenge raised in literature is that of decoupling between practice and policy where there is misalignment between the two (Zomer *et al.*, 2020). The links between the two roadmaps discussed in this section show how the roadmaps aim to avoid such decoupling.

SoR: Define the Scope of Requirements

Part of understanding the SoR will to be understand what activity is ongoing with new application developments at a meso scale to be able to support the sector on the areas covered by the macro roadmap.

TF: Mobilise a DLT/SC Taskforce

A macro-scale taskforce representative of the sector should have members who are connected with DLT/SC application developers. The role of the macro taskforce will be to support creation of an ecosystem to provide the sector with the best chance of successful implementation. To know what the sector needs, the macro taskforce must regularly engage with application developers and the wider sector and have an awareness of the meso scale roadmap.

SE: Conduct Sector Engagement

A large part of driving adoption of DLT and SC applications in construction will depend on perception of the people in the sector and their willingness to change the tools and processes in use today. A macro level engagement plan will inform the sector that could result in application developers and organisations at the meso level to be encouraged to engage with projects and pilots to explore the use of DLT and SCs.

IN: Establish DLT/SC Infrastructure

Putting in place the infrastructure to support DLT and SC applications in the sector will have a significant impact on the ability of start-ups and construction organisations to explore the feasibility and implementation of DLT and SC applications at the meso scale.

RF: Establish DLT/SC Regulatory Frameworks

An application would be subject to complying with regulations and an application developer may indeed be part of a working group to establish new regulations but, ultimately, it would be for National (and International) Authorities to establish new regulations. Those involved in application development (e.g., through the meso roadmap) will need to be aware of activities taking place at a macro scale.

US: Upskill the Construction Sector Workforce

Upskilling the workforce (and bringing in new entrants) is a macro concern for the sector given the projected workforce requirements in the coming years (Clark, 2021). This is, therefore, a challenge for national governments to address through creation of an education and upskilling programme to retrain the existing workforce and incentivise new entrants to join the sector. From the meso perspective, application owners (whether they be application developers, main contractors etc.) will require suitably skilled personnel to use and maintain new DLT-/SC-based systems. The sector currently lacks DLT/SC skills; therefore, the application owners will be responsible for acquiring or training personnel with the skills to run the system. Application owners could tap into government upskilling programmes to obtain the required skills.

R&D: Conduct Research & Development

It is recognised that R&D in construction is significantly lacking (Li *et al.*, 2019a) as a result of ingrained practices and low profit margins. A Weather Ledger focus group participant highlighted the Aerospace Technology Initiative, which is funded by industry participants based on the size of the organisation and match funded by government. The aerospace sector can bid for funding to conduct R&D without having to wait for calls from the likes of Horizon Europe or Innovate UK. Such an initiative could have a significant impact on the construction sector, driven by government at the macro scale for the benefit of the sector as a whole and individual organisations/ projects to drive development of applications at the meso level. Regardless of how, it is essential that R&D is increased across the sector. This represents a direct link between the macro and meso roadmaps. The taskforce will not conduct pilots and PoCs themselves, rather they will support and possibly fund the development of meso scale applications. The results of such pilots and PoCs will then be used to demonstrate the value of DLT and SCs for the construction sector. Demonstrating value at an enterprise scale as well as a project and sector scale will encourage individuals and organisations to engage.

BM: Establish a Benefits Management Plan
Benefits will be derived from the meso level applications that implement DLT and SCs. They will be identified from the pilot studies, case studies and real-world applications throughout the construction sector. They will form a basis for the macro Taskforce to convince the sector of the actual benefits that can be realised by individuals, organisations and projects.

5.6 Summary

Throughout this chapter, the artefacts (shown in Figure 5.1) developed through rigorous elicitation techniques (the results of which can be seen in Chapters 2 and 4) are presented. They make up the socio-technical framework to guide implementation and value realisation of DLT and SCs in the construction sector. The Taxonomy of Challenges, the Taxonomy of DLT Applications, the DLT Four-Dimensional Model, the DLT Actors Model and the DLT Benefits Pathways are analytical tools to help individuals, organisations and the sector better understand the current environment we are in and establish the place we want to get to based on the current state-of-the-art of DLT and SCs in the construction sector. The DLT Meso and Macro Roadmaps lay the foundations for getting us there. The models can be used independently from the roadmaps; however, the roadmaps are best supported by integration with the models throughout the different stages of development. There is emphasis on DLT and SCs as socio-technical systems, but it recognises that society and technology are not the only dimensions that should be considered when implementing a new technological system; process and policy also play a role. These additions allow one to consider the entire ecosystem where the technological system will have impact to ensure its benefit for all actors across all stages of the construction project lifecycle—cradle-to-cradle in the emerging reality of the circular economy. The taxonomies, benefits pathways and roadmaps are live artefacts that should be reviewed and updated as advances are made and new technological offerings and processes emerge. They allow users of the models and roadmaps to adapt them to suit their needs recognising that different applications and organisations may have different needs. This offers applicability to use outside of construction sector applications, for example, in other sectors and for other technologies.

CHAPTER 6 | Validation and Impact

6.1 Introduction

This chapter sets out the activities undertaken to validate the artefacts within the framework as part of this thesis. It also discusses the impact that has been seen by the research conducted by this study and published in peer-reviewed journals. Validation satisfies the *Evaluation* element of the design science research methodology (DSRM) as depicted in Figure 3.3. First, validation of artefacts generally is discussed, then validation and impact of the different artefacts that make up the framework are taken in turn.

6.2 Validation of artefacts

Following the DSRM, evaluation is a key facet to test the effectiveness of the developed artefacts. Validation is a process that aims to evidence the validity of what has been produced, and to confirm it can solve the problem(s) it intended to solve (Shaw, 2003; Olsina *et al.*, 2020). From a body of research reviewed by Shaw (2003, p. 7), it was reported that validation activities "*based on analysis and real-world experience*" were most successful. On this basis, peer review validation of the artefacts was the choice of measurement in terms of their suitability for their intended purpose acknowledging that further, continuous evaluation will take place as the framework is implemented in the real-world. Given the proposed use of the framework presented in this thesis, that is to support implementation of two nascent technologies, and the durations of the proposed roadmaps within the framework, validation through real-world application was not possible. However, validation based on real-world experience of participants was. In time, as the framework is implemented in the real-world, evaluation of its effectiveness can be measured, and it can be updated as appropriate. Indeed, Gonzalez and Sol (2012) explain that the cycles in DSR are open-ended due to the fact that artefacts are continuously modified to suit the needs of the environment to which they are intended to serve, which often brings new opportunities and/or gaps to fill.

6.3 Validation of the Taxonomies

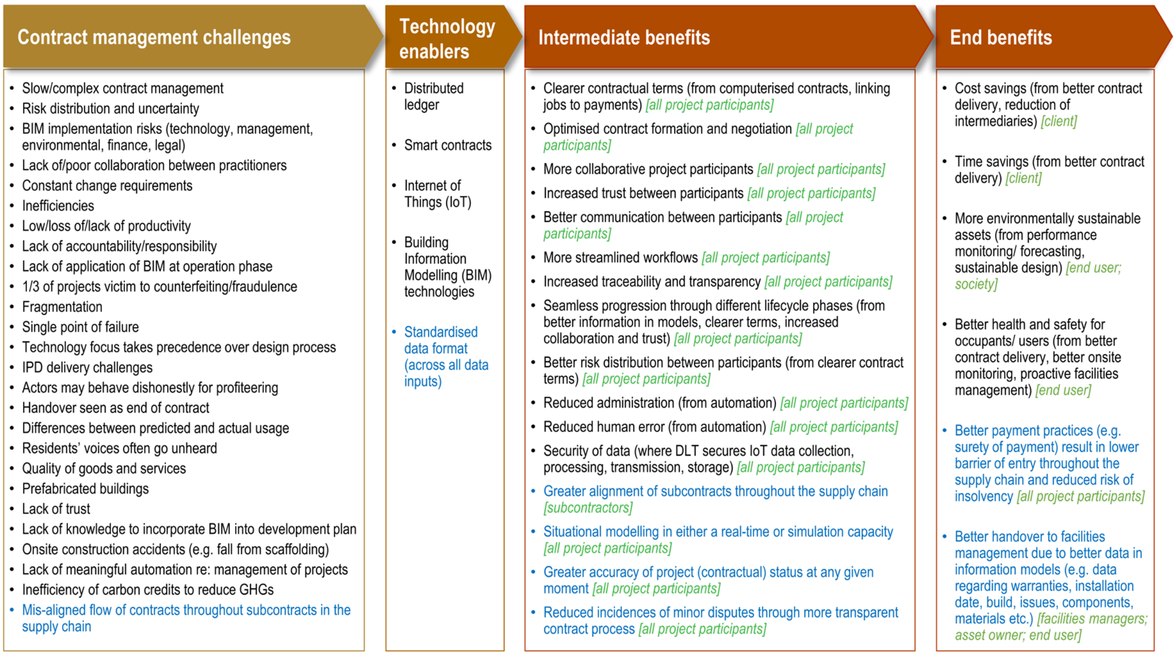
While the Taxonomy of Challenges and the Taxonomy of DLT and SC Applications have not received formal review, the data that made up the taxonomies and the classification therein were peer reviewed for a top tier academic journal Automation in Construction. The paper, Li and Kassem (2021b), went through three rounds of review and was accepted following addressing comments from reviewers.

6.4 Impact of the 4D Models

The DLT Four-Dimensional Model and the DLT Actors Models were peer reviewed when submitted to Automation in Construction. The paper, Li *et al.* (2019a), was accepted after one round of review, no comments were made on the models nor were changes requested to what was presented in the manuscript. Since publication, the paper and its proposal of DLT as a socio-technical system has had substantial impact on the topic of blockchain and DLT for construction. It had attracted almost 400 citations in the four years since publication and Section 7.2 below discussion how the socio-technical approach was adopted by other researchers in the field. To the best knowledge of the author, none of the almost 400 citations refutes any of the proposed ideas and concepts.

6.5 Validation of the DLT Benefits Pathways

During the consultation interviews (Section 4.4), the DLT Benefits Pathways were validated. Application owners were sent DLT Benefits Pathways for their application and asked to review it prior to the consultation interview taking place. During the consultation, the artefact was discussed with the application owners and updated based on their feedback. The application-specific DLT Benefits Pathways shown in Figure 6.1 and Figure 6.2 indicate the changes suggested by the application owners. Both application owners felt their respective DLT Benefits Pathways were beneficial to support business cases for moving forward with application developments and to use as a baseline against which to monitor progress and success of the application.



Contract management challenges

- Slow/complex contract management
- Risk distribution and uncertainty
- BIM implementation risks (technology, management, environmental, finance, legal)
- Lack of/poor collaboration between practitioners
- Constant change requirements
- Inefficiencies
- Low/loss of/lack of productivity
- Lack of accountability/responsibility
- Lack of application of BIM at operation phase
- 1/3 of projects victim to counterfeiting/fraudulence
- Fragmentation
- Single point of failure
- Technology focus takes precedence over design process
- IPD delivery challenges
- Actors may behave dishonestly for profiteering
- Handover seen as end of contract
- Differences between predicted and actual usage
- Residents' voices often go unheard
- Quality of goods and services
- Prefabricated buildings
- Lack of trust
- Lack of knowledge to incorporate BIM into development plan
- Onsite construction accidents (e.g. fall from scaffolding)
- Lack of meaningful automation re: management of projects
- Inefficiency of carbon credits to reduce GHGs
- Mis-aligned flow of contracts throughout subcontracts in the supply chain

Technology enablers

- Distributed ledger
- Smart contracts
- Internet of Things (IoT)
- Building Information Modelling (BIM) technologies
- Standardised data format (across all data inputs)

Intermediate benefits

- Clearer contractual terms (from computerised contracts, linking jobs to payments) *[all project participants]*
- Optimised contract formation and negotiation *[all project participants]*
- More collaborative project participants *[all project participants]*
- Increased trust between participants *[all project participants]*
- Better communication between participants *[all project participants]*
- More streamlined workflows *[all project participants]*
- Increased traceability and transparency *[all project participants]*
- Seamless progression through different lifecycle phases (from better information in models, clearer terms, increased collaboration and trust) *[all project participants]*
- Better risk distribution between participants (from clearer contract terms) *[all project participants]*
- Reduced administration (from automation) *[all project participants]*
- Reduced human error (from automation) *[all project participants]*
- Security of data (where DLT secures IoT data collection, processing, transmission, storage) *[all project participants]*
- Greater alignment of subcontracts throughout the supply chain *[subcontractors]*
- Situational modelling in either a real-time or simulation capacity *[all project participants]*
- Greater accuracy of project (contractual) status at any given moment *[all project participants]*
- Reduced incidences of minor disputes through more transparent contract process *[all project participants]*

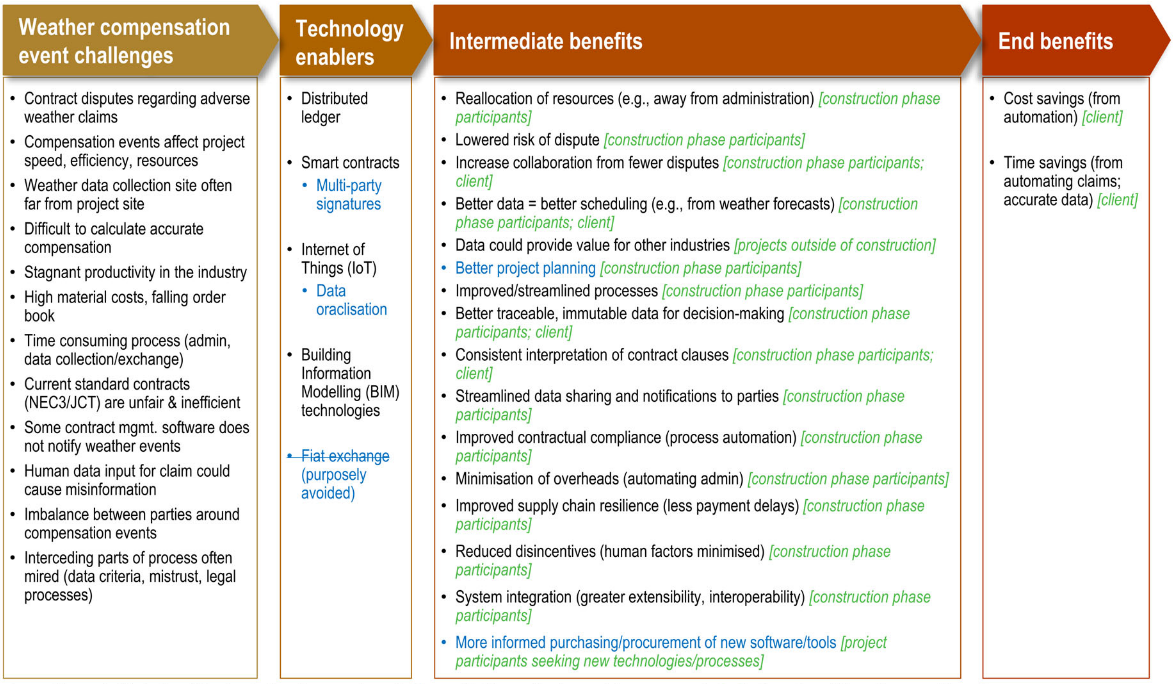
End benefits

- Cost savings (from better contract delivery, reduction of intermediaries) *[client]*
- Time savings (from better contract delivery) *[client]*
- More environmentally sustainable assets (from performance monitoring/ forecasting, sustainable design) *[end user; society]*
- Better health and safety for occupants/ users (from better contract delivery, better onsite monitoring, proactive facilities management) *[end user]*
- Better payment practices (e.g. surety of payment) result in lower barrier of entry throughout the supply chain and reduced risk of insolvency *[all project participants]*
- Better handover to facilities management due to better data in information models (e.g. data regarding warranties, installation date, build, issues, components, materials etc.) *[facilities managers; asset owner; end user]*

Legend: items in **black**, from extensive literature review; items in **blue**, added by application owner; actors in ***[…]*** indicate beneficiary of proposed benefit

Figure 6.1: DLT Benefits Pathways for the iContract showing application owner additions

The DLT Benefits Pathways for the iContract (introduced in Section 5.4.2) are shown in Figure 6.1. The contract management challenges in black (all but the last bullet point in the first column) were taken directly from the challenges taxonomy in Section 5.2.1. The final bullet, *mis-aligned flow of contracts throughout subcontracts in the supply chain*, was added by the developer of the iContract who felt this was possibly the biggest challenge of all for contract management in the construction sector. The addition of a standardised data format



Weather compensation event challenges

- Contract disputes regarding adverse weather claims
- Compensation events affect project speed, efficiency, resources
- Weather data collection site often far from project site
- Difficult to calculate accurate compensation
- Stagnant productivity in the industry
- High material costs, falling order book
- Time consuming process (admin, data collection/exchange)
- Current standard contracts (NEC3/JCT) are unfair & inefficient
- Some contract mgmt. software does not notify weather events
- Human data input for claim could cause misinformation
- Imbalance between parties around compensation events
- Interceding parts of process often mired (data criteria, mistrust, legal processes)

Technology enablers

- Distributed ledger
- Smart contracts
  - Multi-party signatures
- Internet of Things (IoT)
  - Data oraclisation
- Building Information Modelling (BIM) technologies
- ~~Fiat exchange~~ (purposely avoided)

Intermediate benefits

- Reallocation of resources (e.g., away from administration) [construction phase participants]
- Lowered risk of dispute [construction phase participants]
- Increase collaboration from fewer disputes [construction phase participants; client]
- Better data = better scheduling (e.g., from weather forecasts) [construction phase participants; client]
- Data could provide value for other industries [projects outside of construction]
- Better project planning [construction phase participants]
- Improved/streamlined processes [construction phase participants]
- Better traceable, immutable data for decision-making [construction phase participants; client]
- Consistent interpretation of contract clauses [construction phase participants; client]
- Streamlined data sharing and notifications to parties [construction phase participants]
- Improved contractual compliance (process automation) [construction phase participants]
- Minimisation of overheads (automating admin) [construction phase participants]
- Improved supply chain resilience (less payment delays) [construction phase participants]
- Reduced disincentives (human factors minimised) [construction phase participants]
- System integration (greater extensibility, interoperability) [construction phase participants]
- More informed purchasing/procurement of new software/tools [project participants seeking new technologies/processes]

End benefits

- Cost savings (from automation) [client]
- Time savings (from automating claims; accurate data) [client]

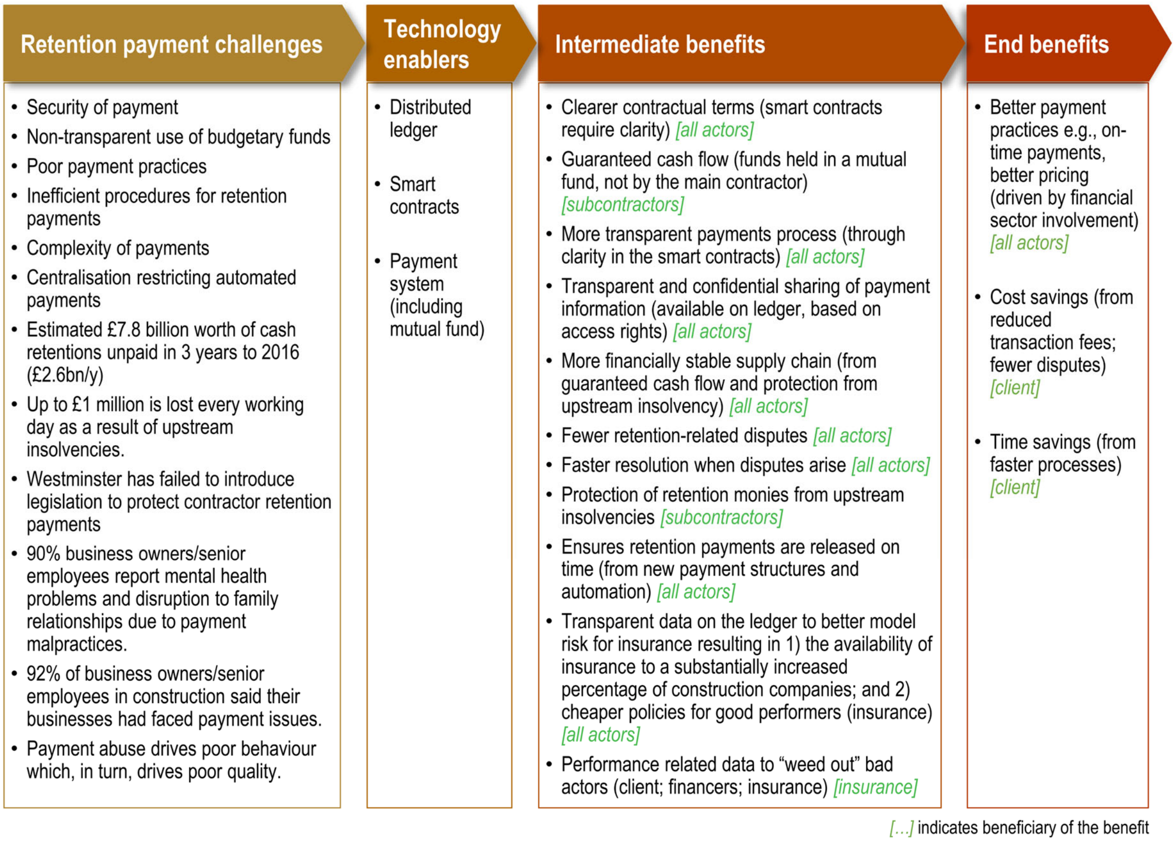
Legend: items in **black**, from Weather Ledger literature; items in **blue**, added by application participants; actors in **[…]** indicate beneficiary of proposed benefit

Figure 6.2: DLT Benefits Pathways for the Weather Ledger showing application owner additions

was added to the technology enablers alongside DLT, SCs, IoT and BIM technologies. Again, it was felt that this enabler was in fact the most important of all for the iContract to be successful. Four intermediate benefits and two end benefits were added to those already identified from literature that were discussed in the Literature Review in Chapter 2 alongside the applications identified.

No additional challenges were added to the DLT Benefits Pathways in Figure 6.2 for the Weather Ledger (introduced in Section 5.4.2), however, there were additions to the technology enablers based on experience from the pilot studies. Multi-party signatures were a challenge for the project where multiple parties were involved in the pilot project, and each was required to sign off on the SCs in the application. They added specificity to the use of IoT sensors on the pilot site acting as oracles where many IoT-based sensors on the sites were key to collection of data. The point of processing was discussed with the application owners where fog and cloud computing were options for data processing at the site but with the power challenges for the data collection devices arising from the pilots, this is something that should be considered at the point of roll-out for the application and on a case-by-case basis. As discussed in the results Section 4.4.6.2, *fiat exchange* was purposefully avoided by the Weather Ledger. Two additional intermediate benefits were added to the artefact, again, based on the results of the pilot studies of better project planning and more informed purchasing/procurement of software/tools. All other items were drawn from literature and Weather Wedger reports.

A third DLT Benefits Pathway was developed for a blockchain-based application, the Retention Deposit Clearing House, in development for managing retention deposits and payments for construction projects. The application was intended to be a third application for the industry focus groups. However, challenges with commitment from participants to attend the focus group meant it was not able to go ahead. Despite this, DLT Benefits Pathways were developed for the application, as shown in Figure 6.3. The application owner felt it was a useful construct and had no other items to add to any column.



Retention payment challenges

- Security of payment
- Non-transparent use of budgetary funds
- Poor payment practices
- Inefficient procedures for retention payments
- Complexity of payments
- Centralisation restricting automated payments
- Estimated £7.8 billion worth of cash retentions unpaid in 3 years to 2016 (£2.6bn/y)
- Up to £1 million is lost every working day as a result of upstream insolvencies.
- Westminster has failed to introduce legislation to protect contractor retention payments
- 90% business owners/senior employees report mental health problems and disruption to family relationships due to payment malpractices.
- 92% of business owners/senior employees in construction said their businesses had faced payment issues.
- Payment abuse drives poor behaviour which, in turn, drives poor quality.

Technology enablers

- Distributed ledger
- Smart contracts
- Payment system (including mutual fund)

Intermediate benefits

- Clearer contractual terms (smart contracts require clarity) *[all actors]*
- Guaranteed cash flow (funds held in a mutual fund, not by the main contractor) *[subcontractors]*
- More transparent payments process (through clarity in the smart contracts) *[all actors]*
- Transparent and confidential sharing of payment information (available on ledger, based on access rights) *[all actors]*
- More financially stable supply chain (from guaranteed cash flow and protection from upstream insolvency) *[all actors]*
- Fewer retention-related disputes *[all actors]*
- Faster resolution when disputes arise *[all actors]*
- Protection of retention monies from upstream insolvencies *[subcontractors]*
- Ensures retention payments are released on time (from new payment structures and automation) *[all actors]*
- Transparent data on the ledger to better model risk for insurance resulting in 1) the availability of insurance to a substantially increased percentage of construction companies; and 2) cheaper policies for good performers (insurance) *[all actors]*
- Performance related data to "weed out" bad actors (client; financers; insurance) *[insurance]*

End benefits

- Better payment practices e.g., on-time payments, better pricing (driven by financial sector involvement) *[all actors]*
- Cost savings (from reduced transaction fees; fewer disputes) *[client]*
- Time savings (from faster processes) *[client]*

[…] indicates beneficiary of the benefit

Figure 6.3: DLT Benefits Pathways for construction project retentions payments

Based on feedback from the three application owners, no changes to the structure of the DLT Benefits Pathways as an artefact were required; each felt the intended purpose of the artefact was clear and concise and allowed for easy visualisation of what their application was attempting to achieve. They saw value in the artefact to support business justifications for moving forward with a DLT-/SC-based application and to demonstrate the potential of their applications to stakeholders.

6.6 Validation of the roadmaps

Siau and Rossi (2011) describe empirical evaluation as a method for evaluating systems analysis and design, of which survey is a method for collecting said empirical data. Respondents are engaged for their experience to gather attitudes, impressions, opinions and beliefs using a questionnaire. Validation of the meso and macro roadmaps took the form of peer review via an online survey. Following analysis of the focus group transcripts and written contributions of the participants (on e-post-it notes via the online collaborative whiteboard), the two roadmaps were developed and sent to focus group participants along with other industry practitioners and academics for validation. The final roadmaps are presented in Section 5.5. An online survey was created that consisted of one 5-minute video, three multiple-choice questions and one open question for comments for each roadmap. The questions can be seen in Appendix J. An online survey was used to perform the validation to reach people without geographical limitations and so respondents could participate at their convenience. Typeform, an online survey platform that allowed participants to complete the survey via an internet browser was chosen. The survey was live for 28 days between 9th November and 7th December 2021.

Three metrics were used to validate the roadmaps focusing on *clarity* (how easily understood the roadmap was), *accuracy* (how representative the roadmap was for its intended purpose), and *usefulness* (how useful respondents think the roadmap will be to fulfil its intended purpose). These metrics have previously been used for validation of a study assessing five models for macro BIM adoption (Kassem and Succar, 2017). Participants were invited via email to complete the survey with a follow up email sent 16-days later. Responses were anonymous unless the respondent chose to leave an email address should further clarification be required on their written responses to the open question. The criteria for the 65 participants invited to complete the survey were as follows:

- an attendee of one of the two industry focus groups; OR
- an academic, industry practitioner or government representative with experience in the construction sector; and
- knowledge of DLT and SCs; and
- knowledge of the challenges facing the construction sector.

Purposive sampling was applied to select the participants from within the researcher's network to ensure these criteria were met. Purposive sampling is the intentional selection of respondents based on their ability to directly contribute to the research questions (Clark *et al.*, 2021). The response rate for the survey was 54% (35 responses).

A Likert scale was chosen to measure respondents' views of the roadmaps. The Likert scale was conceived in 1932 to measure human attitude in a scientific manner (Joshi *et al.*, 2015). Its simplicity of use and flexibility in choosing a scale led to it being a popular quantitative tool for measuring attitudes of respondents (Chyung *et al.*, 2017). Likert scales offer standardised data based on formalised definitions that support researchers in their analysis, comparison among datasets and aggregation of data (Muller, 2013). In choosing the number of points in a Likert scale, there does not appear to be a specific number that provides the optimum results (Chang, 1994). It has been shown that scales with a midpoint, where the midpoint should represent a neutral position, can prompt respondents to choose the midpoint even if they do not necessarily have a neutral stance (Chyung *et al.*, 2017). On this basis, the multiple-choice questions were asked using four options to avoid central tendency bias, that is the inclination of participants to opt for a response closer to the centre than either endpoint of a scale (Douven, 2018). According to Chyung *et al.* (2017), where there is potential for respondents to misuse a midpoint, it should be omitted or the number of anchors (choices) in the scale should be increased. In this instance, the choice to omit the midpoint was taken to make the scale simple for respondents to choose their response quickly and therefore mitigate the risk of losing respondents before they completed the survey. To mitigate the risk that respondents interpret the question differently (Chang, 1994), this study phrased questions to provide a succinct, simple definition of the three metrics of clarity, accuracy and usefulness.

The results of the survey can be seen in Table 6.1 and Table 6.2. Both roadmaps received positive scores across all three metrics. For the macro roadmap, *clarity* scored 89% across very easy and somewhat easy regarding ease of understanding; *accuracy* scored 94% across very representative and somewhat representative regarding how representative the roadmap was for its intended purpose; and *usefulness* scored 89% across very useful and somewhat useful in its ability to meet its intended purpose. For the meso roadmap, *clarity* scored 86% across very easy and somewhat easy regarding ease of understanding; *accuracy* scored 97% across very representative and somewhat representative regarding how representative the roadmap was for its intended purpose; and *usefulness* scored 94% across very useful and somewhat useful in its ability to meet its intended purpose, 65% of whom thought it was very useful. These scores demonstrate that the roadmaps are perceived to have moderate to high levels of clarity, accuracy and usefulness.

Table 6.1: Results of validation of the macro roadmap

Clarity	%	Accuracy	%	Usefulness	%
Very easy	**45.71**	Very representative	42.86	Very useful	42.86
Somewhat easy	42.86	Somewhat representative	**51.43**	Somewhat useful	**45.71**
Somewhat difficult	11.43	Marginally representative	5.71	Marginally useful	11.43
Very Difficult	0.00	Not at all representative	0.00	Not at all useful	0.00

Table 6.2: Results of validation of the meso roadmap

Clarity	%	Accuracy	%	Usefulness	%
Very easy	**48.57**	Very representative	**48.57**	Very useful	**65.71**
Somewhat easy	37.14	Somewhat representative	**48.57**	Somewhat useful	28.57
Somewhat difficult	14.29	Marginally representative	2.86	Marginally useful	5.71
Very Difficult	0.00	Not at all representative	0.00	Not at all useful	0.00

To support these scores, respondents were offered the opportunity to provide comments based on what they had seen in the videos. The macro roadmap received 28 written comments; the meso roadmap received 27 responses. They can be seen in Appendix K along with notes on how the comments were addressed and incorporated into the final versions of the roadmaps.

Feedback in favour of the macro roadmap drew comments including: “*I agree with the list of actions*”; “*It’s an excellent backdrop for things to consider when transitioning from theory to testing*”; and “*This is a very good framework that identifies key themes and actions and* *would be a good basis for developing a programme of work in this area*". This is promising and suggests the roadmap is a good building block on which to move forward with regards macro adoption of DLT and SCs in construction.

Feedback from the respondents that prompted revisions to the macro roadmap can be seen in Appendix K along with details of how the comments were addressed and/or incorporated into the final version. A summary of the changes made include:

- More detail provided on the tasks.
- Renaming of actions to remove numbers that gave the impression of priority or order in which actions should be tackled.
- Inclusion of arrows to show order and relationships between tasks within and across actions.
- Broadened the timeframe for Scope of Requirements and included identification of challenges.
- Inclusion of evaluation of DLT/SC technologies that originally appeared in the meso roadmap only.
- A comment was made during the validation activity that *Taskforce* was oversubscribed in terms of tasks to which they were assigned. However, while the task is assigned to them, it reflects their responsibility to ensure a task is delivered, which they may choose to delegate to an actor best suited to do so. Ultimately, the responsibility lies with the Taskforce to ensure the task is delivered and how but by whom it is delivered is up to them to take on or to delegate.

Feedback in favour of the meso roadmap drew comments including: "*I think it looks great!*"; "*It comes across as a roadmap for a disruptive 'startup' venture. The route to the pilot 'proof of concept' is direct. This will initiate change rather than seek permission for change which is the right road to take*"; "*It seems a well-defined roadmap*"; and "*Easy to understand. Clear line between stages and the introduction of gates means there are objectives to be met before moving on the next state*".

Feedback from the respondents that prompted revisions to the meso roadmap can be seen in Appendix K along with details of how the comments were addressed and/or incorporated into the final version presented in this thesis. A summary of the changes made include:

- Adapted to incorporate an agile flow of stages that allows for interaction of the development and testing stages.
- Inclusion of identification of value proposition in Stage 1.
- Inclusion of a cost-benefit analysis task is Stage 2.
- Reinforcement of the technological development tasks in the roadmap where the majority were focused on the social elements of the socio-technical artefact.
- Clearer and/or more detailed explanation of the stages and tasks were given in the

Framework Chapter. The challenge for the validation survey was to provide enough detail to explain the roadmap but not too much so as to overwhelm the participants.

6.7 Summary

This chapter has outlined the validation activities undertaken to validate the artefacts developed for this research and the impact the research has had on the community. First, the concept of validation of artefacts was discussed. Then, the activities for validation of the different artefacts that make up the socio-technical framework presented in this thesis were given. The taxonomies were validated through peer review. The DLT Four-Dimensional Model and the DLT Actors Model were also validated through peer-review of a top-tier journal. The DLT Benefits Pathways were validated during consultation interviews that took place with DLT application owners. Finally, the macro and meso roadmaps were validated through peer-review using an online survey.

CHAPTER 7 | Discussion

7.1 Introduction

This chapter discusses the findings and explains the contributions to knowledge for the research presented in this thesis. It does this by considering the body of literature on the subject and outlines how the research questions (in Table 7.1, reiterated from Section 1.6) have been answered. It separates the discussions and contributions to knowledge into two streams by first considering the socio-technical framework in its entirety and then examining the contributions of its individual framework. This is followed by recommendations informed by this thesis and ends with a summary of the chapter.

Table 7.1: Research questions

Research questions	Objectives
RQ1: What are the persistent challenges discussed in the context of DLT and SCs faced by the construction sector in light of the significant effort toward digitalisation over the last decade?	**1.1**: Identify the specific construction sector challenges that remain unresolved through a systematic literature review and interviews with industry experts. **1.2**: Create a taxonomy of construction sector challenges in the context of DLT and SCs to relate them to the different application categories of DLT and SCs for construction found within the literature.
RQ2: What role can DLT and SCs play alongside other technological innovations such as BIM and IoT in addressing the challenges faced by the construction industry?	**2.1**: Identify the construction sector applications to which DLT and SCs can be applied as proposed in literature and through consultation with academia and industry. **2.2**: Create a taxonomy of DLT and SC applications for the construction sector aligned with the construction sector challenges identified in RQ1. **2.3**: Establish which construction challenges have the potential to be addressed in part or in full by integration of DLT and SCs into the existing applications classified by the application taxonomy.
RQ3: How can a socio-technical approach support the construction sector in improving its readiness for the adoption of DLT and SCs by providing a systematic approach that guides the sector in identifying the steps required to add value and realise the benefits from integrating DLT and SCs into new and existing applications?	**3.1**: Identify dimensions of socio-technical systems theory to support analysis of the current state (without DLT and SCs) against the desired state (with DLT and SCs) of construction sector applications and identify the actor groups to be involved and/or affected by such applications along with their roles and responsibilities. **3.2**: Identify the requirements for readiness of the construction sector to adopt DLT and SCs in existing applications through consultation with academic and industry practitioners. **3.3**: Propose the steps required for achieving readiness of the construction sector to support development and implementation of DLT and SCs for new and existing applications.

7.2 Contributions of the socio-technical framework

It has often been observed that the construction sector is slow to digitalise (Perera *et al.*, 2020), lacks trust (Cheng *et al.*, 2020), is resistant to change (McNamara and Sepasgozar, 2020) and has an unwillingness to collaborate or share information (Goh *et al.*, 2019). DLTs such as blockchain and associated SCs have been discussed in literature for some years as technologies with the potential to support the sector's technological advancement and solve challenges such as those around trust and collaboration.

The aim of this research was to explore the potential of these technologies and their ability to address these challenges through proposing a socio-technical framework to guide the construction sector in reaching a state of readiness to adopt DLT and SC applications and begin realising the benefits they could bring. The socio-technical approach was adopted during the early stages of the research, namely, through the initial literature review commencing in late 2017 and the focus group that took place in January 2018. These activities helped develop and shape the aim, research questions and associated objectives as shown in Table 7.1. The aim was achieved by developing conceptual constructs as presented in Chapter 5 based on data collection and analysis of empirical investigations. The socio-technical approach formed the basis for RQ3 and specified the need to identify ways in which DLT and SCs can unlock benefits for the sector as part of technological solutions to the myriad challenges it faces.

The socio-technical framework proposed in this thesis is the first of its kind for implementation of blockchain in the construction sector; and, to the best knowledge of the author, no other socio-technical framework for blockchain in construction is available in the public domain. There are, however, several socio-technical frameworks for construction-related industries that provide validity to the socio-technical approach in addressing construction sector challenges.

A framework focusing on zero carbon buildings is proposed by Pan and Ning (2015) that sets technical systems within regulation, society and geographic contexts. The technical context considers targets for reducing carbon, a definition and scope of zero carbon buildings, measurement of carbon emissions and renewable energy reliance. Similar to the framework proposed in this thesis, the finding of Pan and Ning's research highlights that technology alone is insufficient to address the target of zero carbon and identifies human behaviours as lacking in policies. Shin (2014) presents a framework that conceptualises the IoT as a socio-technical system built around environmental, social, content and technical aspects. Its focus is on developing a human-centred IoT that emphasises the design process rather than the final version of the IoT being in a state of. This framework alludes more to the strategy of developing the IoT in contrast to the socio-technical framework presented in this thesis, which aims to provide practical constructs that can be applied by the sector and individual application developers to advance DLT and SC implementation rather than simply consider how it should be approached. A framework to identify key aspects and interactions for building regulatory systems takes a socio-technical approach by Meacham and van Straalen (2018) aiming to better facilitate regulatory change through characterisation and implementation of risk metrics in building regulations. The socio-technical system considers "*technical and legal basis (legal and regulatory environment), acceptance and implementation (market environment), and decision-making (interaction environment)*" (Meacham and van Straalen, 2018, p. 453). Their framework is more prescriptive than the others offering several steps to facilitate regulatory change based on risk. This aligns to the framework in this thesis but lacks the level of detail in comparison.

In addition, several authors consider the socio-technical perspective as key to answering questions about the future of blockchain use cases such as Hunhevicz *et al.* (2021) who posed several socio-technical questions for the future of a self-owning house. Sigalov *et al.* (2021) consider a framework for blockchain-based SCs as a socio-technical system. Van

Groesen and Pauwels (2022) consider the construction sector to be ready for a socio-technical shift that DLT and SCs can bring. And Kifokeris *et al.* (2020) apply sociomateriality to their research, which is a socio-technical approach that considers the inseparability of the social and material aspects of digital innovations.

7.2.1 Practical implications of the framework

In the same way that Geels (2004) highlights the importance of production, diffusion and use of technology in the development of socio-technical systems, the framework presented in this thesis is a construct that engages multiple stakeholders throughout the journey to implementation from production to diffusion and use of DLT and SC applications in construction. This approach aims to actively involve stakeholders that is key to the success of new technological systems (Pan and Ning, 2015).

An underlying assumption of the digital revolution, or Industry 4.0, is that automation will displace the need for human interaction in the workplace. However, Kolade and Owoseni (2022) argue that the need for human interaction will not disappear, rather how humans interact with technology will change when using products and services or undertaking tasks. This highlights the importance of the human (social) element of developing DLT- and SC-based systems and the framework places emphasis on the social aspect of the systems at the centre. While three of the four dimensions in the framework (process, policy, society) are distinct, each of them encompasses a social element. Whether from the perspective of how organisations will integrate systems into existing processes (process) and how humans interact with them, to how governments will address issues such as skills (policy) that links directly to the people who will implement, operate and/or use the systems, or a more explicit social aspect that considers how individuals might accept these new technologies (society).

From the literature review, the first focus group and the interviews, it was confirmed that trust is one of the biggest challenges in the construction sector. DLT is proposed by many as a way to solve the problem of trust through, for example, a change in business models (Srećković and Windsperger, 2019), increasing willingness to collaborate (San *et al.*, 2019), or protecting IP (Belle, 2017). The framework enables users to evaluate their trust position using the taxonomy of challenges and identify routes to change their position through using the taxonomy of applications and the DLT Benefits Pathways. The roadmaps allow them to achieve the change either through engagement at the macro scale or through development of an application at the meso scale. Some other major challenges in construction include information asymmetry (Cerić, 2019), payments practices (Ahmadisheykhsarmast and Sonmez, 2020) and contract management (McNamara and Sepasgozar, 2018) that illustrate areas of the sector that have the potential to be improved substantially by integrating DLT and SCs into current applications or the creation of new ones. The framework aims to provide a flexible set of tools to encourage the sector to create an ecosystem ready to support these applications as well as provide guidance in the development of applications. Focusing on all four of the dimensions in the framework (technology, process, policy, society) was shown to help in ensuring any system meets the needs of its users and therefore offers a greater chance of success at the point of adoption.

7.3 Contributions of the framework components

Aligning the framework components to the research questions, the taxonomy of challenges is a response to RQ1; the taxonomy of applications is a response to RQ2; and the remaining components align with RQ3.

7.3.1 Taxonomies

Given the outputs for RQ1 and RQ2 are similar, they are discussed together here. Data for the taxonomies were drawn from literature related to DLT and SCs and can be seen in Chapter 2 and Appendix B. Visualisations of the taxonomies are presented in Chapter 5. Taxonomies offer several benefits (Fouche, 2006; Klavans and Boyack, 2017) including organised and meaningful categorisation of data and information to support understanding of a specific area of investigation; they make the retrieval of information simple and quick through better structuring of information as well as showing those items closely linked to a specific area of interest; they offer a way to remove unimportant information that may not be relevant to the user offering streamlined results significant to their interests; and they can improve the quality of information and facilitation of information sharing. The two taxonomies proposed in this thesis are linked to the themes identified through the literature review to provide coverage across the entire construction sector and categorised into meaningful application themes. This categorisation of data into themes ensures such quick and simple retrieval of information.

It is important to note that these taxonomies are live artefacts that can be periodically updated to reflect the real-world situation of the sector.

The taxonomy of challenges is representative of those that have persisted in the construction sector for many years. Several studies discuss the challenges of the sector, for example, in cloud computing (Bello *et al.*, 2021), AI (Abioye *et al.*, 2021) and circular economy (Hossain *et al.*, 2020) but none has been directed towards the application of DLT and SCs. When extracting the data from the body of literature reviewed, it was found that many papers did not always specify which sector challenge they were attempting to solve with the application of DLT and SCs and while this was sometimes obvious it was not always made explicit by the authors. This presents a limitation to the taxonomy such that it is not specific to the domain of DLT and SCs, however, this makes its utilisation more widespread and applicable to many areas of the construction sector and a broader range of researchers and practitioners. The detailed taxonomy of challenges makes three contributions: (1) the links from one challenge category to others in the taxonomy demonstrate the need for holistic and integrated approaches to addressing the challenges identified recognising that changes in silos could compound issues with current practices rather than result in a more joined-up sector; (2) as these new technological systems are adopted, the taxonomy can be used as a baseline for the sector's challenges against which to review any impact made; and (3) other researchers in the field can use the taxonomy as a point of departure for understanding the environment surrounding their area of interest.

The taxonomy of applications is an emerging construct that will be expanded over time as DLT and SCs develop into useable technological systems, their proposed and real-world application in the sector expands, and PoCs demonstrate more of what is and is not possible with their integration. In its current iteration, it presents a snapshot of what is drawing attention in the academic community. It allows researchers and practitioners to search for information pertinent to their interests and identify gaps in the taxonomy where they may want to focus their efforts.

7.3.2 Four-dimensional models

An early iteration of the framework that encompassed only the DLT Four-Dimensional Model and the DLT Actors Model was published in *Automation in Construction* (Li *et al.*, 2019a) and has attracted over 390 citations to-date. The models have since drawn attention from the academic community in support of their ability to help understand the potentials of DLT in construction along with the wider socio-technical approach discussed in Section 7.2 above. Examples include Msawil *et al.* (2022) who apply the four dimensions to evaluate the challenges of construction contract administration (CCA) in a paper that considers the extent to which blockchain can improve CCA, and Hunhevicz and Hall (2020b) who suggest using the framework to evaluate use cases and their relationship to participants that they highlighted as a gap in the literature when considering design options of DLT.

These two models assimilate the results of the literature review into multi-dimensional conceptual models that formed the basis of implementation of DLT and SCs in construction. Like each of the models that make up the framework, they can be used independently or in combination depending on the desired outcome of the user. The DLT Four-Dimensional Model's elements (technology, process, policy, society) in combination with the DLT Actors Model offer simple yet effective constructs with which to analyse as-is situations and develop desired future states. Their emphasis, like with all elements of the framework, is to prioritise the consideration of social integrations alongside technology to ensure useful systems that truly benefit society.

7.3.3 DLT Benefits Pathways

Qualitative review and analysis of the data conducted for this thesis showed that DLT and SCs have the potential to support digitalisation of the sector and realise several benefits that can bring about the change it needs to advance. The taxonomy of challenges provides an holistic view of current practices across many facets of the construction sector. This allowed creation of the DLT Benefits Pathways where drawing of clear benefits was possible and showed the impact these new technological systems could have on the sector in solving some of these challenges. This component of the framework directly addresses the aspect of value realisation in RQ3.

An inductive approach was applied by extrapolating the challenges identified in RQ1 along with emerging applications of DLT and SCs in RQ2 to develop the DLT Benefits Pathway. Fifty-seven application areas across the eight application themes were identified from the literature and represented by the taxonomy of applications. The DLT Benefits Pathways organise and link together the challenges, enabling technologies, and the intermediate and end benefits for the application themes (macro) and specific applications (meso). This construct acts as an aid in the observability of benefits for this new system where observability refers to "*the degree to which the results of an innovation are visible to others*" (Rogers, 2003, p. 16).

Almost all studies reviewed for this thesis discussed some sort of benefit for the applications proposed, though none formalised identification and a route to measurement of the benefits in the way the DLT Benefits Pathways aims to do. A study outside of construction developed impact pathways for blockchain in the supply chain centred on the four variables of market mechanisms, plausibility checks, SCs and tokenisation, and peer-to-peer trust (Köhler *et al.*, 2021). The emphasis of these pathways is on social and environmental impact to demonstrate how outputs of blockchain can influence the outcomes of the mechanisms that result in some positive impact. The study claims to show "*how such implementations can create positive impact*" (Köhler *et al.*, 2021, p. 11), which takes us a step further to realising the benefits of DLT and SCs in the same way the DLT Benefits Pathways aims to provide a useful construct to enable individuals and organisations to see explicitly how DLT and SCs could add value.

The DLT Benefits Pathways can support industry practitioners in their decision-making on whether to invest time, resources and effort into exploration of DLT and SCs. They can be used by (1) *technology developers* interested in investing in DLT systems to develop a value proposition for their technological investments; (2) *policymakers*, to encourage the adoption of such systems through the development of supporting rules, regulations and standards; (3) *construction organisations* (clients/owners, architects, engineers, contractors, facility managers), as a basis for business cases to invest time and effort in exploration of DLT and SCs for the sector. The pathways can be used to compare alternative investment options informing the quantification of the opportunity cost of each; and (4) *researchers*, to investigate suitable performance measures and supporting empirical evidence for such benefits. They can act as a baseline to observe the extent to which the proclaimed benefits have been achieved. In addition, they can support development of readiness measurement models to assess the readiness of the ecosystem for implementation of DLT and SCs and to perform gap analysis. The current challenges raised around the emerging applications and the current state of the construction sector provide a realistic view on where to start investigations.

Two important implications from the DLT Benefits Pathways are: (1) they revealed that DLT and SCs in construction applications are not standalone technologies but are always accompanied by other digital technologies and systems, on which realisation of their benefits is often reliant; and (2) the discussion of the DLT Benefits Pathways exposed the fact that technological systems alone, including those comprising DLT and SCs as part of the pathways' enabling systems, are not enough to unlock the change and positive impact included in the pathways.

7.3.4 DLT macro and meso roadmaps

The roadmaps were intended to be a driving force for implementation and the likelihood of this was confirmed by those involved in the validation activity (see Appendix K). While they come last in their order of presentation, they could in fact be the first point of interaction for a macro entity intending to explore DLT and SCs for a market or sector and the same for a meso entity looking to develop or adapt an application with DLT and/or SCs.

Research into DLT and SC applications in construction has increased substantially in previous years. However, much is focused on the creation of frameworks and PoC studies with only one study demonstrating application in the real world (Kochovski and Stankovski, 2021). Indeed, even the Weather Ledger pilots were conducted as shadow running projects rather than deployed to the project directly. There is a lack of specificity in current research, which limits the extent to which benefits can be evaluated in terms of the degree to which the benefit can be achieved versus the cost of implementation and the ease or difficulty of achieving a specific benefit; this will be key to encouraging adoption.

It was shown in Chapter 4 (Section 4.4.3) that there are no suitable roadmaps to support implementation of DLT and SCs into construction, either in construction or from other sectors. The roadmaps presented here contribute to advancing the construction sector's efforts to digitalise through DLT and SCs by providing progressive actions to support their development and implementation to real-world construction projects. Through consideration of two DLT/SC applications, the Weather Ledger and the iContract, and in consultation with industry practitioners and academics, two roadmaps were developed that will commence the journey to a higher state of digitalisation for the construction sector. It is hoped that the gap will be filled with advancing the research to pilot studies with improved definition and specificity of the proposed use cases. A direct link to the roadmaps can aid in increasing the number of PoCs and real-world application.

The challenges of regulation and compliance have been discussed several times throughout this thesis (Allison and Warren, 2019; Li *et al.*, 2020; McNamara, 2020). For DLT and SCs, the challenge will be integrating them into existing policy that is already plagued with issues of non-compliance in the sector. The myriad of DLT and SC applications that are in development or will be in the near future resemble the dot-com era of the internet in the late 1990s. Some applications (e.g., the Weather Ledger) will emerge in and around current practices; other applications (e.g., the iContract) will aim to challenge current practices. The former will likely face fewer barriers to entry than the latter. Regardless of which level of disruption an application aims to achieve, the roadmaps proposed in this thesis aim to support their development by encouraging engagement with macro implementation efforts that will create a suitable ecosystem at a meso level. Such links between the two could minimise the potential of policy-practice decoupling (Bromley and Powell, 2012; Zomer *et al.*, 2020) provided both macro and meso actors are prepared to engage and collaborate. This is captured in the guidance that National Authorities appoint a Taskforce representative of the entire sector with an emphasis on those who will be expected to implement and comply with policy. This is in line with Quezada *et al.* (2016) who are of the view that governments at all levels (national, state, local) play an important role in the success of innovations.

It is intended that these roadmaps are regularly reviewed as more research is conducted into construction-specific applications and learning is transferred from the implementations and benefits these technologies bring to other sectors.

7.4 Summary

The research and findings of this study provide a springboard from which to move forward in the field of DLT and SCs for construction. This study makes several contributions to knowledge in the field of DLT and SC implementation. First, it proposes a socio-technical framework that incorporates four dimensions of technology, process, policy and society to aid in addressing the difficulties of adopting a multifaceted innovation such as DLT into a complex industry structure like construction. It considers how the systems will be used to de-risk adoption thereby increasing their likelihood of successful implementation. The framework encourages researchers to test, critique and advance the theory associated with DLT and SC implementation in construction. By using the framework as a whole, the current position of the sector can be evaluated and improved either through supporting development and implementation for macro readiness or through advancing individual applications at a meso level. The framework can support a plan to reach a desired position with the addition of that which DLT and SCs can bring.

The individual components of the framework can be used individually or in combination with others depending on the objective of the user(s). Each element should be treated as a live artefact to be updated as the sector and the technologies within it evolve. Taxonomies present a clear and concise way to obtain information specific to the needs of the user. The taxonomy of challenges represents the persistent challenges across the sector while the taxonomy of applications represents the current state-of-the-art of the sector with respect to DLT and SCs. The four-dimensional models offer a socio-technical approach to analysing the current environment and to identify the actor groups with whom to engage in understanding how to address the challenges of the sector through creation of new value using DLT and SCs. The DLT Benefits Pathways offers a structured approach to visualise the challenges of the sector, establish which technologies can support their resolution and identify the potential intermediate and end benefits that can be realised from DLT and SC applications. Finally, the roadmaps provide a progressive route to support readiness of the ecosystem to adopt DLT and SC applications at a macro scale while offering guidance on a route to market at a meso scale. The linking of the macro and meso roadmap can aid in the prevention of policy-practice decoupling where they both support one another to achieve the goals of the sector.

Recommendations are made for the sector in how to move forward with implementation of DLT and SCs.

CHAPTER 8 | Conclusion

8.1 Introduction

Some of the biggest challenges faced by construction revolve around trust, collaboration and resistance to change. Findings from this study call for reform of the sector across culture, payments and regulations to address some of these challenges. Since 2015, attentions have been directed toward the potential of distributed ledger technologies (DLT) such as blockchain and smart contracts (SCs) to explore whether they can form part of the solution to many of the challenges. This thesis contributes to the field by conducting an exploratory study into the extent to which DLT and SCs can bring about a step-change in the sector's advancement.

Immutability, traceability and transparency of DLT—characteristics that lead to better accountability, auditability, and less bureaucracy—have the potential to change how the construction sector operates in order to exploit technological advances and bring it in line with other sectors like automotive, manufacturing, and logistics. This will enable the sector to manage resources more effectively while lowering costs, project durations, and payment disputes. Many of the issues will be resolved as DLT and SCs evolve and mature, and opportunities to exploit their benefits will increase. To overcome the issues that plague the construction sector, it must be adaptable and open to the possibilities that DLT and SCs can offer. It must be understood, though, that DLT and SCs are not a panacea in and of themselves and should be used in conjunction with advancements in the policy, process, and social dimensions as outlined in the proposed framework. Only in this way, on the path to a 'smart' vision of the future, can the construction sector exploit the potential of ongoing DLT applications and other digital developments in the wider built environment.

This final chapter of the thesis brings together the study to demonstrate how the research can support the implementation of DLT and SCs in the construction sector. First, the chapter shows how the research questions were answered. Then, it provides details of the contributions to knowledge made by the study before offering recommendations, explaining the limitations and discussing future directions for further research.

8.2 Addressing the research questions

Three research questions (RQs) and associated objectives were established to meet the aim of proposing a socio-technical framework to guide the construction sector in reaching a state of readiness to adopt DLT and SC applications. How the research questions were answered in this thesis are discussed. The socio-technical approach was established in the early stages of the research through an initial systematic literature review looking at DLT and SCs across the built environment and through an exploratory focus group. These activities informed development of the RQs and objectives guiding the research thereafter.

8.2.1 Research question 1

Research question 1 (RQ1) focused on understanding the persistent challenges of the construction sector that have been reported on over the last 30 years (e.g., in Latham, 1994; Egan, 1998; Wolstenholme, 2009; Farmer, 2016; Hackitt, 2018). There were two associated objectives for RQ1: identify the unresolved challenges through systematic literature review and interviews with industry practitioners, and to create a taxonomy of those challenges that can later be related to the different applications of DLT and SCs for construction. The taxonomy of construction sector challenges is presented in Chapter 5; the data from which it was developed is presented as part of Chapter 2.

To answer this RQ, the body of literature specific to DLT and SCs was reviewed, and the challenges of the sector extracted. The challenges presented do not necessarily represent all the challenges of the construction sector; they represent those discussed in research discussing DLT and SCs. Equally, the challenges are not necessarily related to DLT and SCs, but they may correspond to the proposed applications for DLT and SCs that could solve them, in part or in full. This is because some authors highlighted challenges when introducing their papers by setting out the general state of the construction sector before going on to offer insights for DLT and SCs in construction; some related the challenges to the applications under discussion, others did not.

Through thematic analysis, eight themes of challenges (and later applications) were found to characterise the empirical investigations for this thesis. These eight themes are information management, payments, procurement, supply chain management, contract management and delivery, regulation and compliance, disputes and dispute resolution, and technological systems. As a prominent methodology for managing construction projects, it was found that Building Information Modelling (BIM) was inherent across each of these themes and was not, therefore, given its own theme. It is acknowledged that BIM provided a precursor to this study in that it is seen as the main expression of digital innovation in construction and is prominent across the asset lifecycle. It and its characteristics formed the basis of the keyword selection for conducting the literature review that underpinned this research.

8.2.2 Research question 2

The second RQ asked what role DLT and SCs can play alongside other technological innovations such as BIM and the Internet of Things (IoT) in addressing the challenges faced by the construction sector. The three associated objectives aimed to identify the construction sector applications to which DLT and SCs can be applied as proposed in literature and through consultation with academia and industry; to create a taxonomy of DLT and SC applications for the construction sector aligned with the construction sector challenges identified in RQ1; and to establish which construction challenges have the potential to be addressed in part or in full by integration of DLT and SCs into the existing applications classified by the application taxonomy.

Each of the elicitation techniques employed for this study made a finding that DLT and SCs are not standalone technologies to solve the challenges of the construction sector. Each use case and application of DLT and SCs involved some integration with other technological systems such as BIM, IoT, AI, ML etc. So, to answer RQ2, the role they play is to form part of a wider technological solution to adapt existing systems or to develop new systems based on the new functionality they bring. In addition, and in light of the socio-technical approach adopted for this study, it was found that technology alone is insufficient to solve the construction sector's challenges. Analysis of the data extracted from the literature review identified four dimensions that made up a socio-technical framework under which to establish new and updated systems, processes and policies for the sector. The four dimensions—technology, process, policy, society—address different but equally important aspects of developing and implementing new technological systems in the construction sector.

The taxonomy can be used to demonstrate the level of interest in DLT and SCs across the eight themes that encompass the majority of construction sector operations. In its current iteration, the taxonomy as a live artefact has a low level of granularity with two levels – the application theme and the application areas below that theme. For example, the application theme *disputes and dispute resolution* (level 1 granularity) has three areas of application – auditing, digital record, information traceability (level 2 granularity). As the technologies evolve and new applications are established, this level of granularity will increase. In its current iteration, the applications taxonomy offers a system of classification that can define where applications sit within construction sector operations and how they relate to the myriad challenges as set out in the challenges taxonomy.

It was found to be too early in the trajectory of these technologies to meet objective three for RQ2, which was to establish which challenges can be solved by DLT and SCs. Given the limited application of DLT- and SC-based applications, there are no empirical data that can be used to evidence the extent of this. As research advances in the field, this objective will be revisited. However, through development of the DLT Benefits Pathways that can be used at a macro scale (e.g., an application theme) or at a meso scale (e.g., a specific application), the challenges associated with a theme or application can be identified from the taxonomy of challenges, technology enablers can be identified (i.e., all those technologies that will integrate to form a technological system), and intermediate and end benefits can be identified. This offers a baseline of challenges and proposed benefits that can be measured against as challenges are solved and benefits are realised.

8.2.3 Research question 3

The third research question centred on understanding how a socio-technical approach to

DLT and SCs can support the construction sector in improving its readiness for their adoption. To answer this RQ, a systematic approach to guide the sector in identifying the steps required to add value and realise the benefits from integrating DLT and SCs into new and existing applications was taken. This RQ was rooted in the Design Science Research Methodology (DSRM) (Peffers *et al.*, 2007) that encompasses activities to identify problems and motivations, defines objectives and solutions, designs and develops appropriate artefacts, demonstrates use of the artefacts, evaluates them and then communicates them to the world. Following this methodology resulted in a socio-technical framework to support implementation of DLT and SCs into construction.

The first objective involved identifying appropriate dimensions of socio-technical systems theory that would support analysis of the current state of the sector and establish the goals for the future state. Grounded in theory from Geels (2004), Trist and Bamforth (1951) and Baxter and Sommerville (2011) and supported by findings from the first focus group and literature review, the identified dimensions became technology, process, policy and society. These were integrated into the DLT Four-Dimensional Model and the DLT Actors Model with which to identify the actor groups to be involved and/or affected by DLT/SC applications along with their roles and responsibilities. The second objective aimed to identify the requirements for readying the ecosystem to enable smooth transition of these technologies into the sector. This was achieved by engaging with sector academics and practitioners to better understand how the sector functions and what it needs to advance. Two applications destined for real-world application were analysed to support this understanding. The results from this empirical investigation addressed the third objective, which was to propose the steps required for achieving readiness of the construction sector to support development and implementation of DLT and SCs for existing applications. This took the form of two roadmaps, one for macro implementation and one for meso implementation of DLT and SC applications for construction.

8.3 Contributions to knowledge

The contributions to knowledge of this thesis are offered in detail in the Chapter 7. They are summarised here.

Contributions to knowledge of the socio-technical framework:

- To the best of the author’s knowledge, the framework is the first to take a socio-technical approach to the implementation of DLT and SCs in construction. The importance of a socio-technical approach places equal focus on society *and* technology with the implementation of new technological systems that will facilitate their success and specified the need to identify ways in which DLT and SCs can unlock benefits for the sector to the myriad challenges it faces.
- The framework encourages active involvement of stakeholders through considering

the social aspects of a technological system alongside technical aspects. This socio-technical approach is growing in importance with the realisation that engaging with users of the system is central to its success.

- The framework can be used to evaluate the position of an organisation (or group) looking to develop DLT- or SC-based applications at the meso scale or to evaluate the position of the sector with regard to how it wants to incorporate these technologies into its existing systems and processes at the macro scale. The framework offers a progressive approach that considers four dimensions of technology, process, policy and society at every stage of developing and implementing an application.
- The framework aims to provide a flexible set of tools to encourage the sector to create an ecosystem ready to support these applications as well as provide guidance in the development of applications. Focusing on all four of the dimensions in the framework (technology, process, policy, society) was shown to help in ensuring any system meets the needs of its users and therefore offers a greater chance of success at the point of adoption.
- Some of the research presented in this thesis has been published in journal articles (see (Li *et al.*, 2019a) and (Li and Kassem, 2021b)) and had substantial impact on the research community with the papers attracting over 450 citations to date.

Contributions to knowledge of the framework components:

- The taxonomy of construction sector challenges and the taxonomy of DLT and SC applications for construction offer retrieval of information that is organised and classified into meaningful themes enabling a user to quickly locate the information relevant to their needs. They offer a comprehensive picture of the state of the sector with regard to the challenges it faces, and the applications proposed to solve them. They can act as a baseline for the sector against which to measure success of solutions and act as a point of departure for researchers with an interest in the field.
- The DLT Four-Dimensional Model and the DLT Actors Model offer analytical tools centred on the four dimensions (technology, process, policy, society) to support identification of challenges and opportunities for the sector and specific applications and identification of the stakeholders with whom to engage and who will be affected by implementation of the application. They can be used to evaluate the as-is situation and establish details of the desired future state. The DLT Four-Dimensional Model has been applied to Msawil *et al.*. (2022) to evaluate the challenges of construction contract administration (CCA).
- The DLT Benefits Pathways artefact offers a robust construct that maps out the

challenges (identified from the taxonomy of challenges) associated with an application theme or a specific application, establishes the technology enablers needed to realise the application, and identifies the intermediate and end benefits that can be realised from such applications. This artefact can also act as a baseline against which to measure success as well as support business cases to justify investment in the exploration of DLT and SCs for organisations and institutions.

- The DLT Macro and Meso Roadmaps offer progressive guidelines that aim to support the sector in achieving a state of readiness at the macro scale to implement DLT and SC applications at the meso scale. The two roadmaps are independent from one another but have links to support each other in achieving their objectives. Focusing on the two scales acknowledges the different requirements to guide implementation of DLT and SCs at a sector-wide scale and the application scale. They were developed alongside industry practitioners to offer valuable constructs to meet the sectors needs in readying the ecosystem for implementation of DLT- and SC-based applications. This approach aims to limit the risk of policy-practice decoupling by emphasising the need to create and adapt policy in line with sector practices where they facilitate rather than provide a barrier to advancement.

8.4 Recommendations

Based on the research presented in this thesis, several recommendations are being made to the sector to move forward in considering the adoption and implementation of DLT and SCs for construction.

- Policymakers should engage with all parts of the sector to understand the needs of the sector and align them with the needs of society. These needs should be incorporated into the Scope of Requirements as proposed by the macro roadmap to set objectives for plans to ready the sector for implementation of DLT and SCs. Taking a socio-technical approach will provide the sector with the best chance of success by considering all dimensions related to construction sector operations.

- Given the pace of change of technological innovation, longevity and planned obsolescence should be considered when proposing applications that combine several digital technologies (e.g., DLT, SCs, BIM, IoT) that are intended for use across the lifecycle of built assets. This is especially relevant given the traditionally slow pace of change within the construction sector generally.

- Review of existing regulatory frameworks should be made to ensure they are fit-for-purpose along with consideration of how DLT and SCs might fit into them. Applications developed prior to regulatory frameworks being revised should be created with adaptability in mind so they can respond quickly to any new regulations.

- User acceptance of DLT and SCs will be central to their successful adoption. Any development should incorporate engagement with all relevant actor groups (identified using the DLT Actors Model) with a robust engagement plan established (as indicated in the macro and meso roadmaps) to minimise any resistance to change and to ensure any system implemented is developed in collaboration with its user(s).

- Any benefits to be realised from DLT and SC integration should be democratised meaning benefits should not be realised by any one actor to the detriment of others and, where possible, they should be equitably distributed. This should be a central facet of the Benefits Management Plan established within the macro roadmap.

- Proof-of-concepts and real-world application of DLT and SCs are essential to demonstrate tangible results of the new systems. Partnerships between public bodies, academia and industry will drive R&D. Openness of benefits realised as well as challenges faced will both demonstrate their usefulness to the sector and allow emerging applications to learn from previous experiences. Learning from other sectors will also support advancement of these technologies within construction. The roadmaps will guide the sector at both the macro and meso scales to realise these levels of development.

- Focusing on the gaps identified in the literature will allow the sector to explore more of the potential applications and benefits of DLT and SCs. These gaps were identified as: the role of DLT and SCs in digital twins; the role of NFTs; focus on integration of DLT and SCs across the entire project lifecycle and as part of holistic systems (e.g., CognitiveBIM by Tagliabue *et al.*, 2019) rather than just the specific DLT/SC element; consider how developments in other sectors such as supply chain and logistics and fintech will impact construction sector operations; and the challenges of IoT that could impact on the successful integration of DLT and SCs.

8.5 Limitations of the study

While this study followed a robust exploratory methodology and employed Design Science Research to propose a socio-technical framework rooted in empirical investigations, inevitably, there are limitations. There are risks to the validity of both the developed constructs and the tools used to develop them. *Construct validity* is the degree to which operationalisations in research accurately reflect the theoretical constructs they are intended to reflect, or the likelihood that a study's findings are accurate and free of bias (Alves *et al.*, 2010). The *internal* and *external validity* of the constructs are both significantly influenced by the *instrument's validity*. The elicitation techniques (instruments) outlined in Chapter 3 were used to collect data from a range of sources to create appropriate constructs to support the study’s aim. When properly applied to thoughtfully crafted research questions, these elicitation techniques can significantly increase the construct's validity. Their meticulous execution in accordance with the procedures outlined in the methodology and results chapters ensured internal validity of the process as far as was possible by removing biases in the selection of papers and interpretation of the data (Zhou *et al.*, 2016). Until the artefacts proposed in this thesis can be applied and tested in the real world, the extent of their applicability remains to be seen.

There is a limitation relating to the sample chosen for data collection. With regards the literature review, the 153 papers reviewed for this study under the systematic literature review plus the 29 additional papers reviewed in the following period were collected based on preconceived selection criteria. There is a chance noteworthy studies could have been omitted from the search results during the screening process. However, given the papers were collected over a period of five years from Google Scholar, Scopus and ResearchGate as well as monitoring social media for new sources, there is a high degree of confidence the impact of this will be minimal. With regards the interviews, a sample of 13 could be considered low to make generalisations of the sector. However, at the time the interviews took place (2018-2019), knowledge of DLT and SCs in construction was limited and finding more participants with the required level of knowledge and expertise was not possible. The data collected through this method were designed to complement the findings from the literature review. In addition, by the time the last few interviews took place, it was felt the point of saturation had been reached where no new information was being obtained from the participants. Regarding the focus groups conducted to support development of the roadmaps, two could be considered insufficient to collect enough data on which to develop useful constructs. However, supplemented by findings from the literature and interviews, the consultative approach taken with application owners, and engagement with individuals across the sector and academia to validate the resultant roadmaps, the outputs offered in this study make contributions to the field and can be further developed into valuable, usable artefacts.

Another limitation of the research is concerned with researcher bias. Biases were addressed in the scrutiny of the data collected for this study, which consisted of a structured data extraction and analysis process that is replicable and provided meaningful results for the intended audience. While an interpretive philosophy was adopted for this study to consider subjective experiences of the participants, an objective approach was taken to analyse the data collected. Removing one’s personal experiences from the process resulted in the more objective viewpoint. Moreover, the researcher did not have a background in construction prior to undertaking this research and therefore did not have preconceived ideas of the workings of the sector that could have aided in bias. Upon reflection of the study in its entirety, it came from a starting point of Building Information Modelling (BIM) as a basis for how projects are conducted in construction. The supervision team both had extensive knowledge and experience in this field; this has had substantial influence on how the study was framed. Many of the initial search terms for the literature review were framed around the challenges of the construction sector from a BIM perspective and elements of adoption and implementation were influenced by BIM-based research. While this is not necessarily a negative to the study, it has impacted its output and consideration would need to be given to how the socio-technical framework proposed in this thesis can be extrapolated to parts of the construction industry that are not rooted in BIM.

External validity refers to generalisability of the findings. The aim of the research was to pinpoint the specificity of the work done on DLT and SCs in the construction sector while also making broad generalisations about what that means for its future. The results can be considered generalisable to the current state-of-the-art of research on DLT and SCs in construction given the scope and the rigorous research instruments used to identify and analyse the majority of the available studies on the subject. Due to the relationship between identified applications and technological advancement, there is still a risk associated with generalisation that is related to the relevance of results in the future. However, using the protocols described in this paper, researchers in the future will be able to duplicate the research.

8.6 Future work

The framework presented in this thesis is a step toward tried and tested conceptualisations of social phenomena in the field of DLT and SCs. To reach this point, there are several avenues for future work. Each of the artefacts that make up the framework are intended to be live and updated periodically to reflect the state-of-the-art of DLT and SCs in the construction sector at a point in time. The framework will be developed through demonstration, evaluation, and design and development as the technologies under investigation evolve and mature ensuring that it remains relevant and up to date. To add further utility to the framework, it is intended that metrics to assess the readiness of the sector are developed to support implementation of DLT and SCs across a variety of use cases. This will support users of the framework in conducting a gap analysis of where they are in terms of development to where they want to get to in terms of adoption and implementation. This approach will support recommendations in achieving the desired level of readiness across the sector.

The taxonomies presented in this thesis can be further developed into ontologies. Transforming the classification and hierarchy offered by the taxonomic structures into ontologies would increase their usefulness by adding a layer of knowledge to the relationships between the themes and adding axioms to define them.

There are three areas for further investigation related to the DLT Benefits Pathways. First, to critically assess the benefits from the DLT Benefits Pathways aligned to specific applications as they develop, are tested and then deployed to real-world projects. Second, to understand whether DLT and SCs would integrate with the current ecosystem of processes, standards and technologies adopted within the construction sector, or whether they would exert an innovation-led change of current processes and regulations. And third, to understand if and how the existing technologies will coevolve to enable the applications of DLT and SCs in construction.

The roadmaps have several areas for further investigation that includes adding detailed dates and durations to the macro roadmap actions. To do this, partnership with a National Authority tasked with exploring DLT and SCs would be beneficial along with working with them to refine the macro roadmap into a construct that accounts for any activities already started and/or completed and identify any additional activities that would support implementation of DLT and SCs. Adding dates to the meso roadmap would be beneficial as individual applications follow its stages and should be applicable to the application in development. Consideration of how implementation of the roadmaps will be funded and by whom should be made. Inclusion of a micro roadmap that focuses on enterprise level implementation would add value to the sector and close the loop for the different scales of adoption. For both roadmaps, the addition of socio-technical indicators for each task would add value to those implementing it and would bring into play the DLT Four-Dimensional Models to identify actors, challenges and opportunities of the application. This is in response to a comment from the validation survey. Another comment suggested inclusion of ‘worked’ examples of the roadmaps in actions that would provide guidance in how they should be used. At a meso level, this would be effective if done in partnership with an application such as the Weather Ledger or the iContract that already have plans in place for implementation.

Some open challenges were identified from the research that could be explored in the future that included consideration of governance structures, particularly around who makes the decision on the level of decentralisation of DLT for applications. In a decentralised system, thought should be given to who owns and operates, for example, the iContract after practical completion of a construction project (e.g., during the Defects Notification Period).

Appendices

Appendix A: Summary of literature reviewed

Reference	Publication Type	Research method(s)	Paper content	DLT Conceptualised
(Abrishami and Elghaish, 2019)	Conference	Lit. review; framework	Smart contract-automated payments.	Hyperledger Fabric
(Ahmad and El-Sayegh, 2021)	Book section	Insight	Discusses how blockchain can help increase productivity in construction with a specific focus on the UAE.	N/A
(Ahmadisheykhsarmast and Sonmez, 2018)	Conference	Insight	Smart contract-automated payments.	N/A
(Ahmadisheykhsarmast and Sonmez, 2020)	Journal	PoC simulation; case study	Smart contract-based progress payments.	Ethereum
(Ahmadisheykhsarmast *et al.*, 2020)	Book section	PoC simulation; case study	Smart contract-based retention payments.	Ethereum
(Akbarieh *et al.*, 2020)	Conference	Framework	A framework to revalorise building materials at end of life based on building as a material bank (BAMB).	Blockchain
(Aleksandrova *et al.*, 2019)	Conference	Insight; framework	Recording exchanges of a BIM project.	Blockchain
(Badi *et al.*, 2020)	Journal	Questionnaire	Analysis of smart contracts for construction applications using TOE framework.	N/A
(Baek *et al.*, 2020)	Conference	Framework	Blockchain-based verification for adequacy of scaffolding onsite.	Hyperledger Fabric
(Barima, 2017)	Book section	Insight	Procurement; payments.	N/A
(Belle, 2017)	Conference	Insight	General applications.	N/A
(Bindra *et al.*, 2019)	Conference	Framework	Automated building access.	Blockchain
(Blumberg, 2019)	Conference	Framework	Installation of components manufactured off-site.	Hyperledger Fabric
(Blumberg, 2021)	Book section	Framework	Installation of off-site manufactured components with approvals facilitated by smart contracts.	Hyperledger Fabric
(Brydon Wang, 2018)	Journal	Insight; case study	Automated payments via smart contracts.	N/A
(Bukunova and Bukunov, 2019)	Conference	Insight	Blockchain to secure data in decentralised, multi-party BIM projects	N/A
(Calvetti *et al.*, 2020)	Journal	Framework	A framework addressing GDPR with regards workforce performance monitoring onsite.	Blockchain
(Cardeira, 2015)	Conference	Insight	Embedding funds into smart contracts.	N/A
(Cardeira, 2017)	Conference	Insight	Data transfer (BIM file exported as XML to be read by smart contracts).	N/A
(Cerić, 2019)	Conference	Framework	Minimisation of information asymmetry.	Blockchain
(Cheng *et al.*, 2020)	Conference	PoC simulation	Confidential data exchange using public key encryption and user authentication between two parties.	Ethereum
(Chong and Diamantopoulos, 2020)	Journal	Lit. review; case study; questionnaire	Security of payment by embedding funds into smart contracts.	Hyperledger Fabric
(Cooper, 2018)	Industry report	Workshops	General applications.	N/A
(Copeland and Bilec, 2020)	Journal	Framework	Integration of geospatial mapping, BIM and blockchain to facilitate the concept of buildings as material banks (BAMB) for circular economy.	N/A
(Dakhli *et al.*, 2019)	Journal	Insight; case study	Cost reduction achieved by elimination of intermediaries.	Blockchain
(Darabseh and Martins, 2020)	Journal	Lit. review	General applications.	N/A
(Das *et al.*, 2020)	Journal	Framework; PoC simulation	Semi-automatic interim payments.	Public blockchain
(Das *et al.*, 2021a)	Conference	Framework	Unified, decentralised document management system.	Blockchain
(Das *et al.*, 2021b)	Journal	Lit. review; framework	Critical evaluation of data encryption and blockchain to facilitate security in collaborative BIM platforms.	Blockchain
(De La Peña and Papadonikolaki, 2019)	Conference	Interviews	Enhanced trust using IoT and blockchain to secure data and mitigate information asymmetry.	N/A
(Di Giuda *et al.*, 2020b)	Book section	Insight	Blockchain and smart contracts to aid BIM processes and contract execution throughout the building lifecycle.	N/A

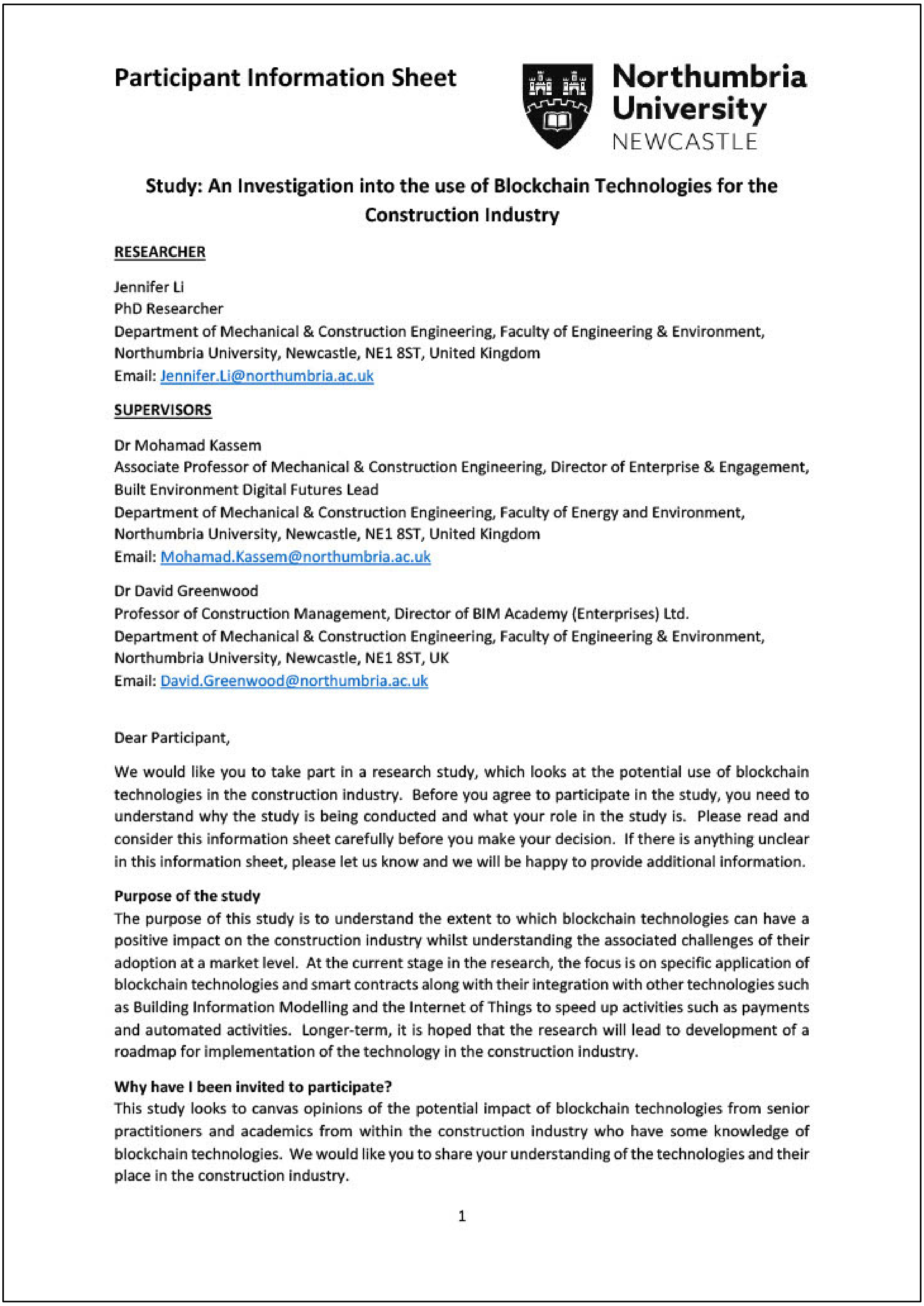
Reference	Publication Type	Research method(s)	Paper content	DLT Conceptualised
(Di Giuda *et al.*, 2020a)	conference	Framework	BIM, DLT and automated payments for the design phase of construction projects.	Blockchain
(Dounas and Lombardi, 2018)	Conference	PoC simulation	Integration of CAD/BIM and blockchain at design phase.	DAOstack, Ethereum
(Dounas and Lombardi, 2019)	Conference	Framework	Decentralised architectural design with tokens as voting rights for reputation and stake.	DAOstack, Ethereum
(Dounas *et al.*, 2019)	Conference	PoC prototype	Consensus mechanism for collaboration in BIM design optimisation.	Ethereum
(Dounas *et al.*, 2020a)	Conference	Framework; PoC simulation	Decentralised BIM architecture.	Ethereum
(Dounas *et al.*, 2020b)	Journal	PoC prototype	Incentivising architectural design with BIM and Ethereum to allow for interoperability between digital tools.	Ethereum
(Dounas *et al.*, 2021)	Conference	PoC prototype	Non-fungible tokens for facilitate the circular economy starting with architectural design.	Ethereum
(Elghaish *et al.*, 2020)	Journal	PoC simulation	Payments: automated payments for integrated project delivery (IPD).	Hyperledger Fabric
(Erri Pradeep *et al.*, 2019)	Conference	Lit. review; insight	Blockchain to improve BIM workflows.	N/A
(Erri Pradeep *et al.*, 2021)	Journal	Prototype	Data privacy, corruption, integrity and longevity issues are addressed by blockchain and tested by simulation.	Ethereum
(Faraji, 2019)	Conference	Questionnaire (Delphi)	Contract administration and risk balancing using smart contracts and blockchain.	Ethereum
(Fiore *et al.*, 2020)	Book section	Insight	The role of blockchain and smart contracts in material passports, and advancing BIM through reliable data.	N/A
(Fitriawijaya *et al.*, 2019)	Conference	PoC simulation	Smart contracts integrated with BIM data to track goods through the supply chain.	Ethereum
(Ganter and Lützkendorf, 2019)	Conference	Insight	Storage of an information model on the blockchain to avoid data loss.	N/A
(Götz *et al.*, 2020)	Journal	Lit. review; survey; framework	Three pillars of functionality, interoperability and "integrability" as enablers of digital twins in construction based on blockchain.	N/A
(Graham, 2019)	Grey literature	Insight	Insights into blockchain's potential for construction.	N/A
(Greenwald, 2020)	Journal	Insight	Several examples of real-world start-ups for blockchain in construction.	N/A
(Gunasekara *et al.*, 2021)	Journal	Framework; survey	The ability of blockchain and smart contracts to facilitate e-procurement for facilities management.	Blockchain
(Hamledari and Fischer, 2021b)	Technical report	Simulations based on real-world data	Comparative analysis on the ability of blockchain and smart contracts to increase visibility of the construction supply chain with regards payments.	Ethereum
(Hamledari and Fischer, 2021c)	Journal	Case study	Automating payments by disintermediating the payment supply chain using and smart contracts.	Ethereum
(Hamledari and Fischer, 2021d)	Journal	Simulations based on real-world data	Integration of crypto assets to facilitate supply chain payments based on blockchain.	Ethereum
(Hargaden *et al.*, 2019)	Conference	Insight	General applications.	N/A
(Harty, 2019)	Book	Insight	General applications.	N/A
(Heiskanen, 2017)	Journal	Insight	General applications.	N/A
(Hijazi *et al.*, 2019a)	Conference	Lit. review; insight	General applications.	N/A
(Hijazi *et al.*, 2019b)	Conference	Lit. review; framework	Proposed architecture to integrate BIM and blockchain.	Blockchain
(Hultgren and Pajala, 2018)	Master's thesis	Lit. review; case study; interviews	Supply chain transparency and material traceability.	N/A
(Hunhevicz and Hall, 2020b)	Journal	Framework	Decision framework to match DLT design options with desired use case characteristics.	N/A
(Hunhevicz *et al.*, 2020a)	Conference	Insight	Blockchain for IPD governance and organisational structures for digitising processes and incentive mechanisms.	Blockchain
(Jagannathan and Prasad, 2018)	Conference	Framework	Smart contract-based payment structure to speed up payments in disputes.	N/A
(2021)	Journal	Lit. review	Literature review on the benefits of blockchain for supply chain management.	
(Kifokeris and Koch, 2019c)	Conference	Lit. review; insight	Analysed digital business models for Swedish construction supply chain firms.	N/A
(Kifokeris and Koch, 2020)	Journal	Lit. review; interviews;	Proposed a digital business model for the Swedish construction supply chain.	Blockchain

Reference	Publication Type	Research method(s)	Paper content	DLT Conceptualised
		framework		
(Kinnaird and Geipel, 2018)	Industry report	Insight; workshops	General applications across construction and the built environment.	Blockchain
(Kochovski and Stankovski, 2021)	Journal	Real-world application	Results of a Horizon 2020 project converting a traditional construction site to a smart site - DECENTER, a fog computing and brokerage platform.	Blockchain
(Koo *et al.*, 2019)	Conference	Framework; case study	Enhance accuracy, effectiveness, transparency and risk allocation of quality assurance.	Blockchain
(Kuperberg and Geipel, 2021)	Conference	Lit. review	Evaluation of literature on DLT in the construction sector.	N/A
(Lamb, 2018)	Industry report	Insight	Benefits, barriers and maturity of smart contracts.	N/A
(Lanko *et al.*, 2018)	Conference	Insight; case study	RFID tags to trace concrete through the supply chain from extraction to construction site.	N/A
(Lee *et al.*, 2021)	Journal	Framework, case study	An integrated framework for digital twin and blockchain demonstrated by a pre-fabricated installation project.	Microsoft's Azure
(Lemeš and Lemeš, 2020)	Conference	Insight	Advantages and disadvantages of distributed CAD environments.	N/A
(Lemeš, 2020)	Book section	Insight	Exploration of how blockchain can be used in distributed CAD environments.	N/A
(Li and Kassem, 2019a)	Conference	Framework	Implementation roadmap for blockchain in construction.	N/A
(Li and Kassem, 2019b)	Conference	Interviews	General applications.	N/A
(Li *et al.*, 2019a)	Journal	Lit. review; framework	Socio-technical framework incorporating technical, social, process and policy dimensions.	N/A
(Li *et al.*, 2019b)	Conference	Framework	Automation: smart contracts to automate installation tasks during the construction phase.	Blockchain
(Li *et al.*, 2020)	Conference	Framework	Automated maintenance and repairs integrating BIM, IoT, DAO.	Blockchain
(Li *et al.*, 2021a)	Journal	Simulation	Intelligent platform based on cyber-physical systems, IoT, BIM and blockchain for smart product-service systems innovation in prefabricated housing construction.	Blockchain
(Li *et al.*, 2021b)	Journal	Simulation	Integration of blockchain, BIM, big data and artificial intelligence to guarantee completeness/accuracy of data.	Blockchain
(Li *et al.*, 2021c)	Journal	Framework; prototype	Two-layer Adaptive Blockchain-based Supervision (TABS) model for supervision of off-site modular housing production (OMHP) to address problems that the pandemic highlighted with regards travel restrictions.	Hyperledger Fabric
(Liu *et al.*, 2021)	Journal	Lit. review	Several applications discussed across BIM, blockchain, sustainable design, operations.	N/A
(Liu *et al.*, 2019)	Journal	Framework	Framework that supports reuse of materials based on provenance to support sustainability.	Blockchain
(Lokshina *et al.*, 2019)	Workshop	Framework	Integration BIM, IoT and blockchain in the system design of a smart building.	Blockchain
(Lombardi *et al.*, 2020)	Conference	Simulation	Validation of collective decision making by voting for architectural design facilitated by a DAO.	Ethereum
(Luo *et al.*, 2019)	Conference	Framework	Payments: smart contract-triggered interim payments on a permissioned blockchain.	Blockchain
(Maciel, 2020)	Book section	Insight	General applications and considerations of DLT.	N/A
(Mason and Escott, 2018)	Conference	Questionnaire	Stakeholder perceptions of smart contracts for construction.	N/A
(Mason, 2017)	Journal	Lit. review; insight	Intelligent contracts as an extension to BIM to semi-automate contractual performance.	N/A
(Mason, 2019)	Journal	Insight; case study	Considers if smart contracts complement BIM or negate its need.	N/A
(Mason, 2021)	Book	Insight	In-depth review of smart contracts and the contracting process for construction.	N/A
(Mathews *et al.*, 2017)	Conference	Insight	The extent to which blockchain can affect trust in construction.	N/A
(McMeel and Sims, 2021)	Industry report	Workshops	A token economy for trading construction waste, smart contracts for payments and materials procurement.	N/A
(McNamara, 2020)	Book section	Insight	Impacts of intelligent contracts on construction.	N/A
McNam(McNamara and Sepasgozar, 2018)	Conference	Interviews	Assessment of potential for intelligent contracts based on industry perceptions of BIM and traditional	N/A

Reference	Publication Type	Research method(s)	Paper content	DLT Conceptualised
			contracts.	
(McNamara and Sepasgozar, 2020)	Journal	Lit. review; interviews; framework	Framework to assess readiness of construction for intelligent contracts.	N/A
(McNamara and Sepasgozar, 2021)	Journal	Lit. review; framework	Review of 46 papers; a tri-dimensional iContract model is presented: systems and processes; organisational behaviour; and environmental factors.	N/A
(MEED Mashreq Construction Partnership, 2019)	Industry report	Insight	General applications.	N/A
(Morvai, 2018)	Grey Literature	Insight	Decentralised project delivery system.	N/A
(Nanayakkara *et al.*, 2019a)	Conference	Lit. review	General applications.	N/A
(Nanayakkara *et al.*, 2019b)	Conference	Workshops	Ranks blockchain and smart contract characteristics.	N/A
(Nanayakkara *et al.*, 2021)	Journal	Questionnaire	Highlights key construction supply chain issues; offers potential blockchain solutions to payment issues.	N/A
(Nawari and Ravindran, 2019a)	Journal	Lit. review; framework	Speeding up the building permit process in post-disaster events.	Hyperledger Fabric
(Nawari, 2021)	Conference	Framework	Expansion of existing BIM workflows by incorporating DLT.	Hyperledger Fabric
(Nguyen *et al.*, 2019)	Industry report	Insight	General applications across cities, energy, property, transport, water.	N/A
(Norta *et al.*, 2020)	Grey literature	Framework	Decentralised platform for supply chain and project management.	N/A
(O'Reilly and Mathews, 2019)	Conference	PoC simulation	Incentivisation to design better than net zero energy buildings with BIM and digital twin.	Custom blockchain
(Oliveira Júnior *et al.*, 2020)	Conference	Framework	Information validation system incorporating IoT, BIM and smart contracts to increase the confidence of information flows in projects.	Blockchain
(Park *et al.*, 2020)	Conference	Framework	Automation of quality control events, tasks, activities using image recognition technology, image matching, IoT sensors and blockchain to secure and verify the data.	Hyperledger Fabric
(Pattini *et al.*, 2020)	Conference	Framework	Optimisation and assurance of transparent information flow through phases of a BIM project.	Blockchain
(Pellegrini *et al.*, 2020)	Journal	Case study	Increases the amount of data stored across the lifecycle of a materials in built asset to reduce construction waste by supporting circular economy principles and designing in reuse/recycle strategies in BIM projects.	N/A
(Penzes, 2018)	Industry report	Insight	General applications plus real-world examples.	Blockchain
(Perera *et al.*, 2020)	Journal	Lit. review	Extensive review of DLT; general applications – construction and non-construction.	
(Perera *et al.*, 2021)	Grey literature	Insight	Discusses e-procurement to mitigate human error, disputes, save costs, efficient and effective process.	N/A
(Pishdad-Bozorgi *et al.*, 2020)	Journal	Insight; questionnaire; interviews	Three scenarios for blockchain in information management.	Blockchain
(Qian and Papadonikolaki, 2020)	Journal	Interviews	Effects of blockchain and smart contracts on different levels of trust.	N/A
(Raslan *et al.*, 2020a)	Conference	Framework	Integration of asset information models, BIM and blockchain	Blockchain
(Rodrigo *et al.*, 2020)	Journal	Lit. review; interviews	Blockchain-based embodied carbon estimating in construction supply chains.	N/A
(San *et al.*, 2019)	Conference	Lit. review; framework	General applications and implications of private blockchains in construction.	Blockchain
(Shahrayini *et al.*, 2021)	Conference	Framework	Frameworks considering how blockchain can integrate with IoT & BIM to enhance efficiency in supply chains.	N/A
(Shemov *et al.*, 2020)	Journal	Lit. review; framework	A framework to prevent malicious attacks during supply chain activities.	Hyperledger Fabric
(Sheng *et al.*, 2020b)	Conference	Framework; case study	Semi-automating the business logic of quality management.	Hyperledger Fabric
(Sheng *et al.*, 2020a)	Journal	Framework; case study	Quality information management system to record project's product state, organisation state, process state.	Hyperledger Fabric

Reference	Publication Type	Research method(s)	Paper content	DLT Conceptualised
(Shojaei, 2019)	Journal	Framework; case study	Blockchain-based information system to enhance environmental sustainability practices.	Hyperledger Fabric
(Shojaei *et al.*, 2020)	Conference	Framework	Transaction recording as BIM project progresses; smart contracts link physical asset and information model.	Hyperledger Fabric
(Shojaei *et al.*, 2021)	Journal	Case study;	Facilitation of circular economy principles on production, installation, use and salvage of a HVAC unit.	Hyperledger Fabric
(Shojaei, 2019)	Conference	Insight	General applications.	N/A
(Singh and Ashuri, 2019)	Conference	Framework	Validated BIM data to resolve disputes in design development.	Blockchain
(Siountri *et al.*, 2020)	Journal	Framework	Secure storage and access to data integrating BIM, IoT, blockchain for a smart museum.	Blockchain
(Srećković and Windsperger, 2019)	Conference	Framework	Transformation of the value chain through DAOs as new organisational models.	Blockchain
(Srećković *et al.*, 2020)	Workshop	Framework	Smart contract-based design approvals based on analysis and process modelling of a BIM workflow at design.	Blockchain
(Suliyanti and Sari, 2021)	Journal	Simulation	Demonstration of how information exchange can be secured on a blockchain for a BIM project.	Hyperledger Fabric
(Tagliabue *et al.*, 2019)	Conference	Framework	Optimisation of in-use phase of CognitiveBIM asset based on user-behaviour.	N/A
(Tezel *et al.*, 2021)	Journal	Lit. review; focus groups, workshop, prototype	Three applications are modelled, prototyped and validated with industry and academia, namely, project bank accounts, reverse-auction tendering and asset tokenisation.	Ethereum
(Turk and Klinc, 2017)	Journal	Insight	Four scenarios for integrating blockchain into BIM.	Blockchain
(Villegas-Ch *et al.*, 2020)	Journal	Framework	Blockchain-based secure data layer in P2P, IoT-networked university campus operations.	Private blockchain
(Wang *et al.*, 2017)	Journal	Insight	Notarisation-, transaction-, provenance-related applications.	N/A
(Wang *et al.*, 2020)	Journal	Framework; PoC simulation	Real-time information management to increase supply chain efficiency.	Hyperledger Fabric
(Wilson *et al.*, 2020)	Workshop	Framework	Proposal of a product-level traceability system offering open research avenues.	N/A
(Woo *et al.*, 2020)	Conference	Framework	Transformation of carbon credit documentation into smart contracts for semi-automated credit acquisition that supports constructors in meeting environmental obligations.	Hyperledger Fabric
(Xiong *et al.*, 2019)	Journal	Framework; PoC simulation	Protection of private keys from attack in construction supply chains.	Blockchain
(2021)	Journal	Lit. review	Systematic review of smart contracts for procurement in various industries.	N/A
(Xue and Lu, 2020)	Journal	Framework; case study	Minimising information redundancy through logging changes rather than entire models, running a basic blockchain on a website.	Blockchain
(Yang *et al.*, 2020)	Journal	Lit. review; case study	Process, benefits, challenges of adopting private and public blockchains in construction.	Hyperledger Fabric; Ethereum
(Ye and König, 2021)	Conference	Framework	Automated billing in 5D BIM projects based on quantity take-off and bill of quantities.	Blockchain
(Ye *et al.*, 2018)	Conference	Insight	Exploration of interrelations between BIM, IoT and blockchain.	N/A
(Ye *et al.*, 2020)	Conference	PoC simulation	BIM Contract Container (BCC) - as a basis for automatic payment transactions.	Blockchain
(Zhang *et al.*, 2020)	Journal	Framework	Hybrid architecture with dual storage to improve quality traceability in prefab. Buildings.	Hybrid blockchain
(Zheng *et al.*, 2019)	Journal	Framework	Authenticated, traceable and secure historical BIM data.	Public and private blockchain
(Zhong *et al.*, 2020)	Journal	Framework; PoC simulation	Improved information sharing and enhanced trust to assure quality management.	Hyperledger Fabric
(Zuberi, 2021)	Diploma thesis	PoC prototype	Smart contract-led facilities management to resolve issues and recurrent maintenance.	Ethereum

Appendix B: Sample Participant Information Sheet and Consent Form for Interviews



Participant Information Sheet

Northumbria University
NEWCASTLE

Study: An Investigation into the use of Blockchain Technologies for the Construction Industry

RESEARCHER

Jennifer Li
PhD Researcher
Department of Mechanical & Construction Engineering, Faculty of Engineering & Environment,
Northumbria University, Newcastle, NE1 8ST, United Kingdom
Email: Jennifer.Li@northumbria.ac.uk

SUPERVISORS

Dr Mohamad Kassem
Associate Professor of Mechanical & Construction Engineering, Director of Enterprise & Engagement,
Built Environment Digital Futures Lead
Department of Mechanical & Construction Engineering, Faculty of Energy and Environment,
Northumbria University, Newcastle, NE1 8ST, United Kingdom
Email: Mohamad.Kassem@northumbria.ac.uk

Dr David Greenwood
Professor of Construction Management, Director of BIM Academy (Enterprises) Ltd.
Department of Mechanical & Construction Engineering, Faculty of Engineering & Environment,
Northumbria University, Newcastle, NE1 8ST, UK
Email: David.Greenwood@northumbria.ac.uk

Dear Participant,

We would like you to take part in a research study, which looks at the potential use of blockchain technologies in the construction industry. Before you agree to participate in the study, you need to understand why the study is being conducted and what your role in the study is. Please read and consider this information sheet carefully before you make your decision. If there is anything unclear in this information sheet, please let us know and we will be happy to provide additional information.

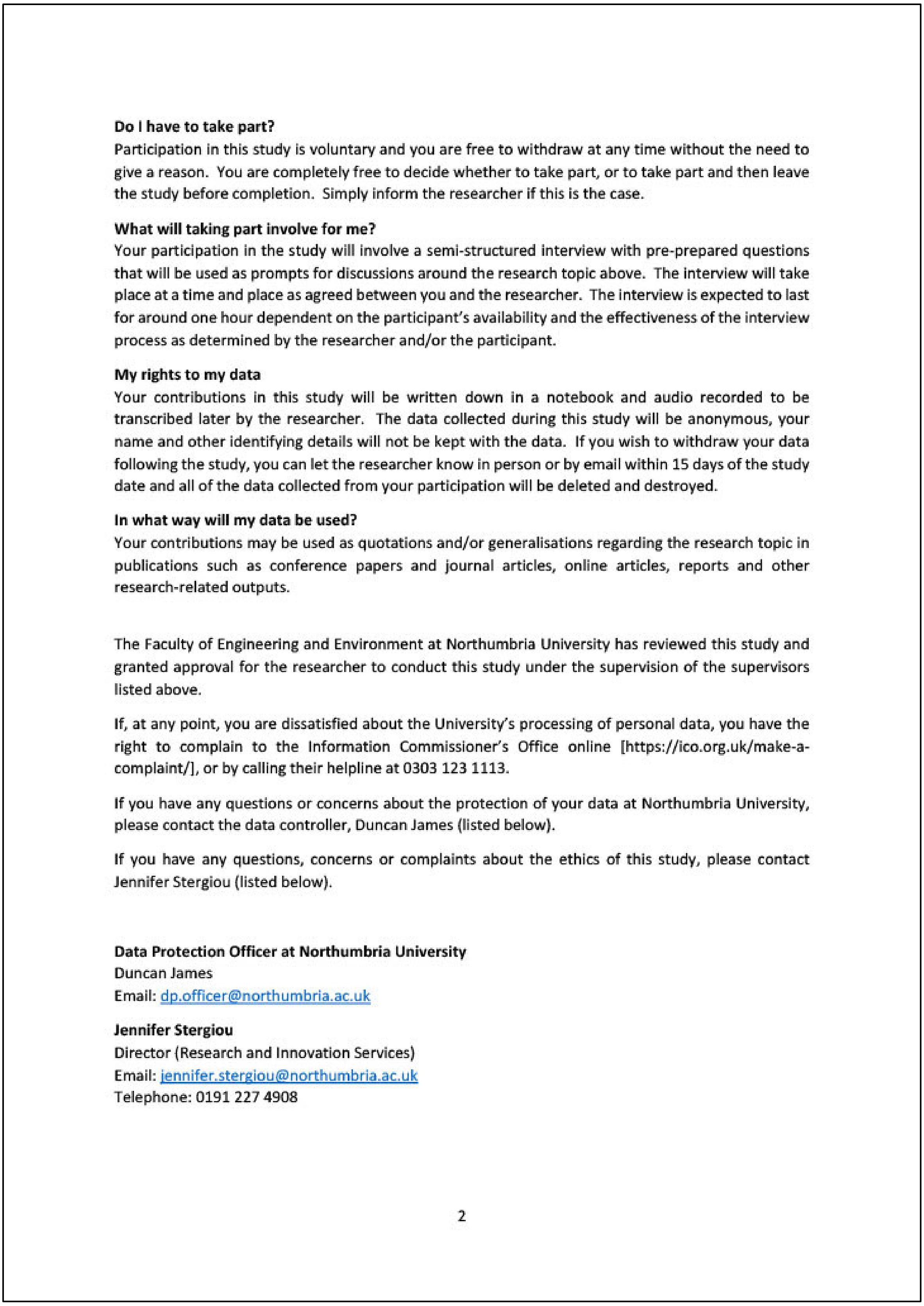
Purpose of the study

The purpose of this study is to understand the extent to which blockchain technologies can have a positive impact on the construction industry whilst understanding the associated challenges of their adoption at a market level. At the current stage in the research, the focus is on specific application of blockchain technologies and smart contracts along with their integration with other technologies such as Building Information Modelling and the Internet of Things to speed up activities such as payments and automated activities. Longer-term, it is hoped that the research will lead to development of a roadmap for implementation of the technology in the construction industry.

Why have I been invited to participate?

This study looks to canvas opinions of the potential impact of blockchain technologies from senior practitioners and academics from within the construction industry who have some knowledge of blockchain technologies. We would like you to share your understanding of the technologies and their place in the construction industry.

1



Do I have to take part?

Participation in this study is voluntary and you are free to withdraw at any time without the need to give a reason. You are completely free to decide whether to take part, or to take part and then leave the study before completion. Simply inform the researcher if this is the case.

What will taking part involve for me?

Your participation in the study will involve a semi-structured interview with pre-prepared questions that will be used as prompts for discussions around the research topic above. The interview will take place at a time and place as agreed between you and the researcher. The interview is expected to last for around one hour dependent on the participant's availability and the effectiveness of the interview process as determined by the researcher and/or the participant.

My rights to my data

Your contributions in this study will be written down in a notebook and audio recorded to be transcribed later by the researcher. The data collected during this study will be anonymous, your name and other identifying details will not be kept with the data. If you wish to withdraw your data following the study, you can let the researcher know in person or by email within 15 days of the study date and all of the data collected from your participation will be deleted and destroyed.

In what way will my data be used?

Your contributions may be used as quotations and/or generalisations regarding the research topic in publications such as conference papers and journal articles, online articles, reports and other research-related outputs.

The Faculty of Engineering and Environment at Northumbria University has reviewed this study and granted approval for the researcher to conduct this study under the supervision of the supervisors listed above.

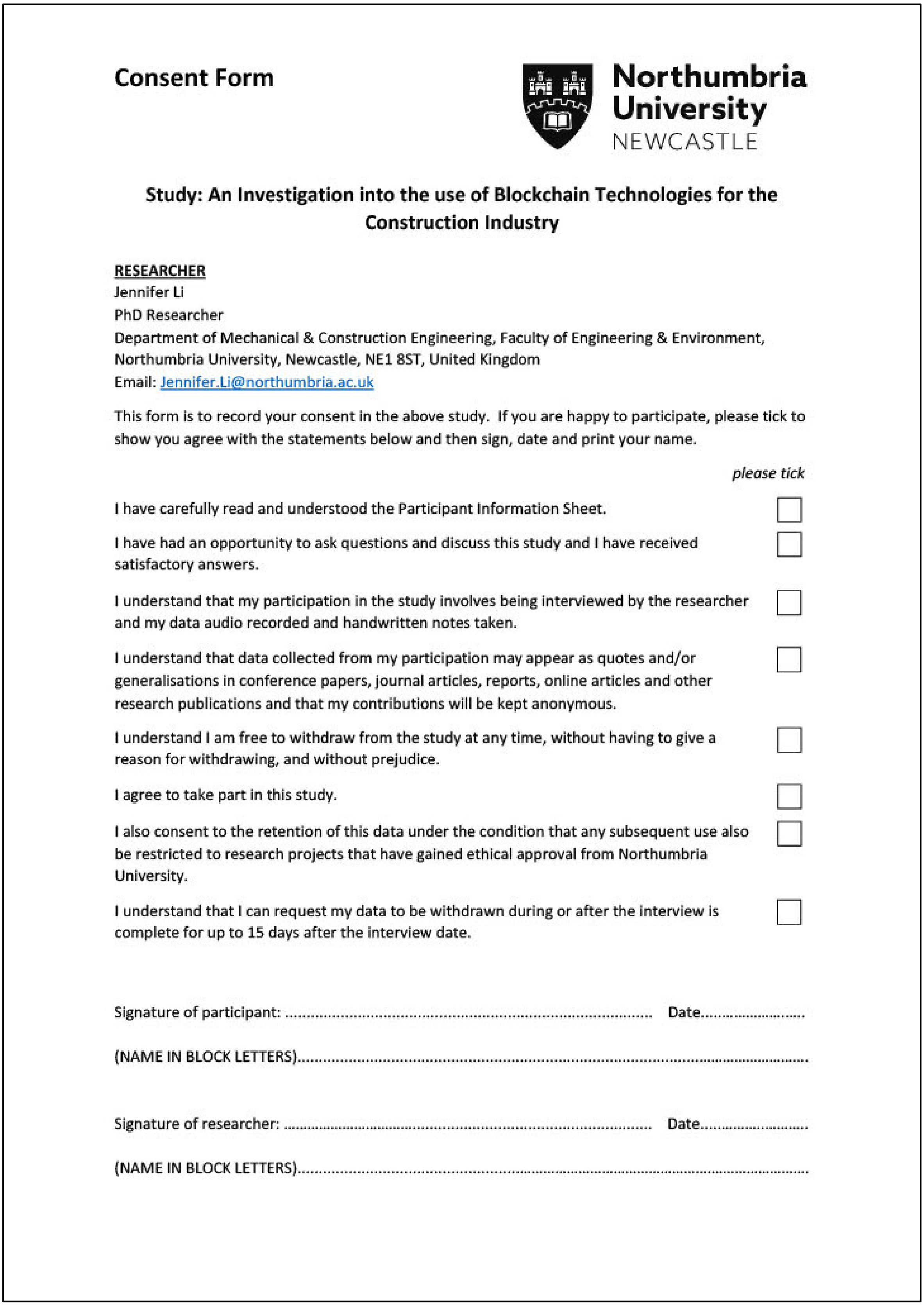
If, at any point, you are dissatisfied about the University's processing of personal data, you have the right to complain to the Information Commissioner's Office online [https://ico.org.uk/make-a-complaint/], or by calling their helpline at 0303 123 1113.

If you have any questions or concerns about the protection of your data at Northumbria University, please contact the data controller, Duncan James (listed below).

If you have any questions, concerns or complaints about the ethics of this study, please contact Jennifer Stergiou (listed below).

Data Protection Officer at Northumbria University
Duncan James
Email: dp.officer@northumbria.ac.uk

Jennifer Stergiou
Director (Research and Innovation Services)
Email: jennifer.stergiou@northumbria.ac.uk
Telephone: 0191 227 4908



Consent Form

Northumbria University
NEWCASTLE

Study: An Investigation into the use of Blockchain Technologies for the Construction Industry

RESEARCHER
Jennifer Li
PhD Researcher
Department of Mechanical & Construction Engineering, Faculty of Engineering & Environment,
Northumbria University, Newcastle, NE1 8ST, United Kingdom
Email: Jennifer.Li@northumbria.ac.uk

This form is to record your consent in the above study. If you are happy to participate, please tick to show you agree with the statements below and then sign, date and print your name.

	please tick
I have carefully read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	☐
I understand that my participation in the study involves being interviewed by the researcher and my data audio recorded and handwritten notes taken.	☐
I understand that data collected from my participation may appear as quotes and/or generalisations in conference papers, journal articles, reports, online articles and other research publications and that my contributions will be kept anonymous.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐
I also consent to the retention of this data under the condition that any subsequent use also be restricted to research projects that have gained ethical approval from Northumbria University.	☐
I understand that I can request my data to be withdrawn during or after the interview is complete for up to 15 days after the interview date.	☐

Signature of participant: .... Date...........................

(NAME IN BLOCK LETTERS)..

Signature of researcher: .... Date...........................

(NAME IN BLOCK LETTERS)..

Appendix C: Plausible future for the iContract and Weather Ledger in 2026

Scenario A: Dual Reality (passive government; predominantly public/unpermissioned DLT)

	What the future looks like in 2026 (van Rijswijk *et al.*, 2019)	**iContract**	**Weather Ledger**
Governance	▪ Government did not engage with DLT. ▪ They failed to adapt legislation & regulations. ▪ Society is becoming automated but government is isolated from this. ▪ Private political parties hold referenda; government does not know what to do with the results.	Lack of government support for DLT applications impacted the early adoption of the iContract in the construction sector. It is not widely used for government contracts as they did not mandate the use of digital contracts nor do they actively encourage DLT adoption. Those that do use the iContract are the forward-thinking contractors who see the benefit of reduced transaction fees and automated administration. This allows for reallocation of resources to value-adding activities and therefore increases efficiencies and productivity.	Given the government's lack of support for DLT, it was difficult to form a governance structure for the Weather Ledger where all parties were happy to engage equally. And with lower than expected results, there was no government impetus to explore it further.
Industry	▪ Industry heavily invested in DLT. ▪ They developed their own regulations and standards. ▪ Regulations and standards support international trade using cryptocurrencies. ▪ Enterprises must covert cryptocurrencies to fiat currency for taxation.	Industry's appetite for DLT to drive digitalisation is seeing more and more applications being used at all stages of the project lifecycle. Such applications include wearable devices and exoskeletons to ensure health and safety on site; and automated building management services to monitor energy usage and occupant behaviour. Interest in the iContract is growing steadily, particularly as it can integrate these new technologies into project management and information models, but many top tiers of the supply chain are still weary of replacing the traditional construction contract while the lower tiers are pushing for their use based on proven benefits to payment practices seen from DLT applications in other industries.	Despite lack of government support, development of the Weather Ledger continued, driven by the innovators of the sector. Once contractors began to see the benefit of automating weather compensation events through reduced administration and more accurate data, more and more were happy to implement the Weather Ledger on large projects.
Society	▪ Limited trust and acceptance of DLT. ▪ Companies focus on innovation over privacy/reliability. ▪ Quantum computing poses a threat to DLT encryption. ▪ Reluctance toward smart contracts due to structural uncertainty, lack of regulations and standards. ▪ Lack of DLT adoption from authorities resulted in private identity bureaus disassociated from authorities. ▪ General public is reluctant to use DLT for large transactions (e.g. house purchases) leaving intermediaries with a market to serve.	Lack of appetite for DLT leaves society sceptical of the iContract being built on it with the issues that have been seen in privacy and reliability over technological advancement. The platforms that do not focus on these issues are causing delays in adoption of the iContract as a result of the caution that is required in construction projects. Main contractors are vigilant in maintaining privacy, lack of which threatens to publicise their commercial sensitivities.	Given the lack of trust and acceptance of DLT generally, it was difficult to create a suite of integrated applications to improve construction sector practices. Organisations are reluctant to opt for automated payments given the issues of reliability and are uncomfortable handing over control of finances to code. Several applications built of DLT are available based on the proof-of-value demonstrated by the Weather Ledger but the joined up thinking across applications is missing.

Scenario B: Blocktopia (active government; predominantly public/unpermissioned DLT)

	What the future looks like in 2026 (van Rijswijk *et al.*, 2019)	**iContract**	**Weather Ledger**
Governance	▪ Digital citizenship is reality - anyone can become a digital citizen and create and operate a digital business in the region. ▪ Obtaining a digital passport requires attestation by the government. ▪ Individuals hold self-sovereign identity wallets giving them control over their own data and gains trust from external parties that the data correspond with the administration of the government. ▪ Government responded quickly to DLT adapting legislation and regulation to support digital transactions. ▪ They actively engage to remove barriers to decentralised systems and hold a favourable position in society.	Government is in favour of the iContract particularly because it is built on a DLT. The benefits of digitalisation are widely acknowledged and the reduction in disputes and increased productivity from streamlined workflows meaning the client receives better value for money. Adoption of the iContract is steadily increasing throughout the construction sector with project participants seeing the value in better information management (e.g., creation, processing, exchange, storage). Government construction strategy focuses on the upskilling and digitalisation at all levels.	The Weather Ledger was a driving factor for the government to invest heavily in research and development of DLT. This led to them creating a government-owned blockchain that allowed them to receive the benefits of DLT whilst still maintaining a level of control over society. Governance of DLT was dictated by government; this resulted in limited innovation, particularly around distribution of power. The Weather Ledger is used on projects with construction durations of over 6 months and has proven to reduce the number of disputes on projects.
Industry	▪ Start-ups drove the DLT revolution seeing rapid improvements in energy consumption, scalability and security. ▪ Open source is the de facto standard. ▪ Trade of intellectual property on DLT runs safely and efficiently. ▪ All information exchange is clear and transparent negating the need for intermediaries (e.g., notaries). ▪ Public services (e.g., land registry) move to public blockchains.	Industry is driving many new applications to advance the construction sector, many of which are built on DLT architecture. It welcomes the iContract as it makes drafting and negotiating contracts a much simpler, faster process. New plugins for the iContract are being developed regularly that add further value to the project and ensure much richer information is passed on to the operations phase. Adoption is increasing quickly given the transparency brought about by the iContract which is even supported by main contracts are they find ways to increase efficiencies and productivity.	The rise of private/permissioned DLT made construction project participants more comfortable with engaging in DLT-based applications that allowed them to maintain privacy of data. The Weather Ledger is used on all large projects and other applications are seeing increasing success. The sector is becoming more streamlined, but it is still the large contractors and financial institutions who dictate terms of business and largely control the finances of projects.
Society	▪ DLT provide fast, reliable, decentralised services for transacting between strangers. ▪ DLT is widely trusted and accepted by society. ▪ It is expected that everyone manages their [personal] business through DLT. ▪ This level of adoption weakens the less technologically savvy. ▪ Presented as infallible but several cases of lost identities/possessions have arisen.	Society welcomes the new age of digitalisation, which has been proven to drive compliance and reduce costs while offering better value for money for the taxpayer. The concern that users of the iContract might struggle with digitalisation of processes was unfounded due to the simple, intuitive nature of the APIs and the proliferation of smartphones, tablets and smart glasses throughout society. A few members of society who have struggled with digitalisation are the outliers as natural attrition takes hold and the younger generations begin to rise through the ranks.	The regulations and standards around DLT meant that society was confident DLT-based applications were in its interests. They are starting to see better constructed buildings that are safer and more complaint but that are also more sensitive to their needs and comfort.

Scenario C: GovChain (active government; predominantly private/permissioned DLT)

	What the future looks like in 2026 (van Rijswijk *et al.*, 2019)	**iContract**	**Weather Ledger**
Governance	▪ Government retrained personnel, created field labs and collaborated with start-ups to keep pace with DLT. ▪ Many processes are harmonised and streamlined. ▪ Private/permissioned platforms are preferred to give access to citizens whilst maintaining governmental control. ▪ Legislation and regulation have been adapted; evidence on a blockchain is considered admissible. ▪ Government is actively working to protect citizens from tech giants. ▪ The information position of authorities is much improved and welcomed by citizens who trust authorities over commercial entities.	Publicly funded projects were the first to pilot the iContract and it quickly became legislation to employ digital contracts on construction projects. Publicly funded projects are restricted to the government's proprietary DLT which occasionally halts digital advancement and adoption. However, the government is open to technological development with regards DLT applications to ensure they maintain their advantage to digitalise faster than it has in the past. The Hackitt Report's digital record to provide the golden thread of information is now being realised through DLT and the iContract supports that through the trusted data collected throughout the project.	Early pilots like the Weather Ledger demonstrated to government the value that DLT could bring to all sectors despite the limited results that were shown. They began to work closely with the construction sector to identify what support was needed to create an ecosystem right for DLT-based applications. The Weather Ledger became a departure point for automation of elements of contracts and there is good integration across the different applications. Government created standards that ensured interoperability and organisations began the see the value in collaboration.
Industry	▪ As a result of lower transaction costs, faster transactions and increased security, established institutions (e.g. banks, insurers) employ DLT to optimise processes and supply chains. ▪ Different DLTs prevail in different sectors/industries. ▪ DLT is used to automate processes for the powerful elites rather than transforming ingrained structures.	Financers and public clients are insistent on the use of DLT to allow them to have a better picture of how well a contractor performs based on historical data. Good performers are happy with this and get more favourable terms for borrowing finance and bad performers are forced into behaving with more integrity. Unfortunately, large software providers have cornered the market for digital contracts and made them proprietary to their systems making it difficult for smaller enterprises and start-ups to enter the market. As a start-up, the iContract sometimes struggles to compete with these large software providers.	Many options for DLT became available following several successful pilots of new DLT-based applications, particularly as they were open source. Industry was very open to implementing the Weather Ledger as soon as they saw cost savings from data collection and processing. The Weather Ledger quickly expanded to include IoT data collection for health, safety and progress reporting which led to fewer disputes.
Society	▪ Trust and acceptance are high given the government's proactivity. ▪ Concerns about authoritarianism are increasing due to restrictions placed on citizens regarding freedom and consumerism. ▪ E-voting was implemented in 2021 providing 100% reliability and the highest ever turnout and reduced costs. ▪ Law firms employ smart lawyers who provide certifications that smart contracts comply with laws and regulations.	Citizens are much more confident in construction of new built assets given the implementation of the digital record. However, there are concerns about their privacy now that the information is available to the government. Existing building stock is taking some time catching up with regards compilation of compliant digital records, but citizens are confident that renovations are suitably compliant due to the iContract that links to standards and legislation.	Payment applications based on DLT developed quickly and integrated with Apple Pay and Google Pay etc. which meant society generally had good experience of their funds and data being kept safe and secure. DLT applications are accepted generally and individuals easily adapted to having their data collected knowing they have better control over it. Initially, construction workers were uncomfortable with their every move being tracked and immutably recorded but ultimately, it resulted in safer construction sites and people behaving with more honesty and compliance.

Scenario D: Beyond the Hype (passive government; predominantly private/permissioned DLT)

	What the future looks like in 2026 (van Rijswijk *et al.*, 2019)	**iContract**	**Weather Ledger**
Governance	▪ Government did not engage in DLT not foreseeing its potential disruptive capability, top managers did not see its urgency. ▪ Cyber-attacks increase diverting money away from innovation investment. ▪ Concerns increased of quantum computing proving problematic for DLTs robustness and safety. ▪ Financial institutions and well-organised employers' organisations successfully lobbied against DLT.	Government is not in favour of the iContract and digital contracts generally due to the increased threat and incidences of cyber-attacks. Without this support, the iContract has struggled to gain traction in the sector due to the costs of implementation and lack of interest from financers and main contractors.	The results of the Weather Ledger pilot was not enough to sway government toward further exploration of DLT applications. This, and other applications have struggled to gain traction in a sector that remains resistant to change and that is occupied with security against cyber-attacks. This has resulted in stagnant digitalisation.
Industry	▪ Lack of government interest and support deterred innovation and use of DLT generally. ▪ Reputational damage caused by energy consumption of the Bitcoin blockchain in the face of the climate emergency. ▪ Due to lack of innovation, solutions to energy consumption and scalability did not arise ▪ DLT champions in the late 2010s laughed it off by 2025.	Industry has continued to fail to digitalise and pushes against the use of the iContract and other digital contracts to maintain the status quo. Digitalisation generally has lagged further putting construction last behind that of agriculture. Industry is exploring quantum-based DLT platforms in an attempt to compete with the threat of quantum hacking but progress is slow.	There is lack of interest of the sector to explore DLT applications, especially as many are still trying to adapt to BIM practices.
Society	▪ A referendum that took place in 2020 via blockchain that guaranteed voter anonymity was later found to be traceable further dampening society's interest in DLT. ▪ Issues around privacy and energy consumption were too much to sway public opinion toward the adoption and diffusion of DLT.	Society is wary of applications built on DLT and significant digitalisation that encroaches on their privacy such as IoT. There is reluctance to adopt the iContract due to the disruptive changes it will cause to current construction processes and individuals not trusting in its ability to digitalise onsite activities.	Society does not accept any of the benefits of DLT given their experience with voting. There is general distain which means organisations attempting to implement DLT-based applications are wasting time and resources.

Appendix D: Taxonomy of construction sector challenges from DLT in construction research

Construction sector challenges in the context of DLT research	ID	Relationships
Information Management	A	B,C,D,D2,E, E4, F,G,H
Information sharing/exchange	A1	D2.3, F7.10.5
Parties provide minimum information required (Nawari and Ravindran, 2019a)	A1.1	
No incentive to share information (Pattini *et al.*, 2020)	A1.2	
Reluctance to share information (Penzes, 2018; Ye *et al.*, 2018; Li and Kassem, 2019b; Kiu *et al.*, 2020; McNamara, 2020)	A1.3	
Lack of real-time information sharing (Wang *et al.*, 2020)	A1.4	A1.5
Growing need for real-time information sharing (Ye and König, 2021)	A1.5	A1.4
Lack of/poor information sharing/exchange (Cerić, 2019; De La Peña and Papadonikolaki, 2019; Li and Kassem, 2019b; Raslan *et al.*, 2020a)	A1.6	
Lack of an effective coordinative information platform (Xiong *et al.*, 2019)	A1.7	
Lack of reliable/accessible information management (Shojaei *et al.*, 2019; Raslan *et al.*, 2020a)	A1.8	
Poor communication and collaborative information sharing (Yang *et al.*, 2020)	A1.9	
Ineffective information transmission (Xiong *et al.*, 2019)	A1.10	
Ineffective information management causes poor communication (Cerić, 2019)	A1.11	
Challenges of information sharing due to lack of trust, and absence of a guarantee for data privacy (Pishdad-Bozorgi *et al.*, 2020)	A1.12	
Chronology and frequency of information exchange in BIM (Pradeep *et al.*, 2020)	A1.13	
Results in unclear liability (Pradeep *et al.*, 2020)	A1.13.1	
Information is vulnerable to unethical modification (Pradeep *et al.*, 2020)	A1.13.2	
Leads to misuse of information (Pradeep *et al.*, 2020)	A1.13.3	
Single point of failure (Mathews *et al.*, 2017)	A2	F12, H5.8
Information management post-construction/at operation	A3	
Issues in sharing data/information during asset management (Wang *et al.*, 2017)	A3.1	
Incomplete documentation post-construction (Goh *et al.*, 2019)	A3.2	
Lack of application of BIM at the operation phase as a result of poor information quality (Li *et al.*, 2020)	A3.3	
Poor information management can affect occupant safety (Wilson *et al.*, 2020)	A3.4	
Low quality data sets at the end of construction projects (Hunhevicz *et al.*, 2020b)	A3.5	F16
As a result of poor documentation (Hunhevicz *et al.*, 2020b)	A3.5.1	
As a result of difficulty in finding the data (Hunhevicz *et al.*, 2020b)	A3.5.2	
As a result of low reliability of the information (Hunhevicz *et al.*, 2020b)	A3.5.3	
Reconstruction of data sets is expensive and time consuming (Hunhevicz *et al.*, 2020b)	A3.5.4	
Information inconsistency and transformation between project handover and FM team for in-use phase (Raslan *et al.*, 2020a)	A3.6	
Information models	A4	
Single version of information models dependent on trust between parties (Dounas *et al.*, 2019)	A4.1	
Single version of information models dependent on infrastructure on which the database runs (Dounas *et al.*, 2019)	A4.2	
Model reuse and adoption strategies (Liu *et al.*, 2019)	A4.3	
Model ownership (Turk and Klinc, 2017; Ye *et al.*, 2018; Dounas and Lombardi, 2019; Erri Pradeep *et al.*, 2019; Mason, 2019)	A4.4	
Collective authorship (Dounas and Lombardi, 2019)	A4.5	
Data ownership (Mathews *et al.*, 2017; Ganter and Lützkendorf, 2019; Suliyanti and Sari, 2019; Kiu *et al.*, 2020)	A4.6	
Tracking modifications rights (Turk and Klinc, 2017)	A4.7	
Inability to effectively track changes (Zheng *et al.*, 2019)	A4.8	
Unauthorised viewing/editing (Erri Pradeep *et al.*, 2019)	A4.9	
Distribution rights (Turk and Klinc, 2017)	A4.10	
Liability for changes/errors (Turk and Klinc, 2017)	A4.11	
Copyright protection (Turk and Klinc, 2017)	A4.12	
Inability to verify if information has been authorised by issuing party (Kinnaird and Geipel, 2018)	A4.13	
Intellectual Property (IP) rights (Mason, 2017; McNamara and Sepasgozar, 2018; Ye *et al.*, 2018; Erri Pradeep *et al.*, 2019; Liu *et al.*, 2019; Tezel *et al.*, 2020)	A4.14	
Safeguarding IP protection (Turk and Klinc, 2017; Nawari, 2021)	A4.15	
Risk allocation/distribution (Faraji, 2019; Hargaden *et al.*, 2019)	A4.16	
Distributed design decisions (Turk and Klinc, 2017)	A4.17	
Confidentiality of data (Turk and Klinc, 2017)	A4.18	
Lack of content in information models for use at construction sites (Li *et al.*, 2020)	A4.19	

Construction sector challenges in the context of DLT research	ID	Relationships
Decentralisation and openness of information models due to uncertainties, security challenges and vulnerabilities (Siountri *et al.*, 2020)	A4.20	H3.4
Nature of current practices results in information models becoming fragmented over time (Dounas *et al.*, 2020b)	A4.21	
Security of information/data (San *et al.*, 2019; Singh and Ashuri, 2019; Lemeš and Lemeš, 2020; Villegas-Ch *et al.*, 2020)	A5	
Cyber security (Liu *et al.*, 2019)	A6	
Data privacy (Tezel *et al.*, 2020)	A7	
Information/data fragmentation (Hijazi *et al.*, 2019a; Sharma and Kumar, 2020)	A8	A9, B11.1
Information/data asymmetry (Cerić, 2019; Ganter and Lützkendorf, 2019; Maciel, 2020; Pattini *et al.*, 2020; Shemov *et al.*, 2020)	A9	A8
As a result of disintegrated document management systems between project participants (Kiu *et al.*, 2020)	A9.1	
Stakeholders may behave adversely by providing information asymmetry caused by lack of integration (Pishdad-Bozorgi *et al.*, 2020)	A9.2	
Information gaps between participants (Zhong *et al.*, 2020)	A10	
Information redundancies (Fitriawijaya *et al.*, 2019)	A11	
Data veracity/reliability of data (Salama and Salama, 2019)	A12	
Lack of confidence in authenticity and integrity of project data (Sheng *et al.*, 2020a)	A12.1	
Current information management system/practices	A13	
Time consuming (Heiskanen, 2017; Erri Pradeep *et al.*, 2019; Xiong *et al.*, 2019)	A13.1	
Expensive (Xiong *et al.*, 2019)	A13.2	
Not resistant to alteration/tampering (Zhong *et al.*, 2020)	A13.3	
Often results in information wastage due to geographical dispersion (Xiong *et al.*, 2019)	A13.4	
Often results in information wastage due to high numbers of participants (Xiong *et al.*, 2019)	A13.5	
Poor quality of current information management practices (Hunhevicz and Hall, 2020b)	A13.6	
Non-conformances are inaccurately documented or not documented at all which makes pinpointing the party at fault difficult (Sheng *et al.*, 2020a)	A14	
Issues with data storage of current/historical projects (Perera *et al.*, 2020; Raslan *et al.*, 2020a)	A15	
Record keeping is poor (Li *et al.*, 2020)	A16	
Trust is negatively influenced by traditional methods of information sharing (Di Giuda *et al.*, 2020b)	A17	
Trust and networking costs are barriers to information and digital collaboration (Belle, 2017)	A18	
High cost of intermediaries that do not add value to the construction project (e.g. duplication of information entry) (Heiskanen, 2017)	A19	
An estimated 1/3 of construction projects are victims to counterfeiting and fraudulence (Wilson *et al.*, 2020)	A20	E1.2, F10
EIRs/BEPs often misunderstood/underestimated (Maciel, 2020)	A21	
Elision of information and responsibility of agents for it (Dounas *et al.*, 2020a)	A22	
Knowledge management is dysfunctional as a result of the majority of data going unused in construction (Norta *et al.*, 2020)	A24	
Traceability and transparency	A25	D4, F
Low/lack of transparency (Penzes, 2018; Nanayakkara *et al.*, 2019b; Shojaei *et al.*, 2019; Hunhevicz and Hall, 2020a; Yang *et al.*, 2020; Zhong *et al.*, 2020)	A25.1	
Low trust between parties (Nanayakkara *et al.*, 2019b)	A25.1.1	
Issues with security of deliverables (Nanayakkara *et al.*, 2019b)	A25.1.2	
Inability to track products re: quality, condition monitoring (Sivula *et al.*, 2018)	A25.1.3	
Difficult to pinpoint the cause of poor-quality work, goods, etc. (Zhong *et al.*, 2020)	A25.1.4	
Leads to distrust (Zhong *et al.*, 2020)	A25.1.5	
Leads to reluctance to collaborate (Zhong *et al.*, 2020)	A25.1.6	
Compounds issues of efficiency and productivity (Zhong *et al.*, 2020)	A25.1.7	
Limited digitalisation leading to inefficient traceability (Hultgren and Pajala, 2018)	A25.2	H3
Traceability as a BIM-related concern (Hargaden *et al.*, 2019)	A25.3	
Difficulties in traceability and comparison of exchange of massive files (Xue and Lu, 2020)	A25.4	
Lack of traceability	A25.5	
Lack of traceability in construct[196]ion supply chains (Wilson *et al.*, 2020)	A25.5.1	
Not wanting to share commercially sensitive data (Wilson *et al.*, 2020)	A25.5.2	
Not receiving direct benefit from the data shared (Wilson *et al.*, 2020)	A25.5.3	
Potential for transfer/uncovering liability (Wilson *et al.*, 2020)	A25.5.4	
Lack of accountability (Yang *et al.*, 2020)	A25.6	
Payments	**B**	A,C,D,E,F,G,H
Security of Payment (SoP)	B1	
Affecting cash flow (Cardeira, 2015; Jagannathan and Prasad, 2018; Abrishami and Elghaish, 2019; Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020; Perera *et al.*, 2020; Shemov *et al.*, 2020)	B1.1	

Construction sector challenges in the context of DLT research	ID	Relationships
Payment uncertainties/delays/non-payment (Cardeira, 2015; Wang *et al.*, 2017; Ahmadisheykhsarmast and Sonmez, 2018; Ye *et al.*, 2018; Ahmadisheykhsarmast and Sonmez, 2020; Jagannathan and Prasad, 2018; Abrishami and Elghaish, 2019; Nanayakkara *et al.*, 2019a; Li *et al.*, 2019a; Nanayakkara *et al.*, 2019b; Perera *et al.*, 2020; Shemov *et al.*, 2020; Badi *et al.*, 2020; Chong and Diamantopoulos, 2020; Das *et al.*, 2020)	B1.2	
Causing increased costs (Ahmadisheykhsarmast and Sonmez, 2020; Badi *et al.*, 2020)	B1.3	
Causing delivery delays (Badi *et al.*, 2020; Chong and Diamantopoulos, 2020)	B1.4	
Causing contractual disputes (Chong and Diamantopoulos, 2020)	B1.5	
Causing opportunistic and adversarial relationships between the parties (Badi *et al.*, 2020)	B1.6	C5, C6
Reducing performance/adversely affecting the outcomes of the project (Ahmadisheykhsarmast and Sonmez, 2020; Badi *et al.*, 2020)	B1.7	
Resulting in insolvency or bankruptcy (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020)	B1.8	
Inconsistent payment terms (Yang *et al.*, 2020)	B1.9	
Disputes on withheld payments (Ahmadisheykhsarmast and Sonmez, 2020; Yang *et al.*, 2020)	B1.10	
Disputes on cash flow arrangements (Ahmadisheykhsarmast and Sonmez, 2020; Yang *et al.*, 2020)	B1.11	
Quality fraud (Yang *et al.*, 2020)	B1.12	
Data authenticity (Yang *et al.*, 2020)	B1.13	
Non-transparent use of budgetary funds (Brydon Wang, 2018)	B2	
Financial management of Integrated Project Delivery (IPD) (Elghaish *et al.*, 2020)	B3	
Management of financial transactions in Integrated Project Delivery (IPD) projects (Elghaish *et al.*, 2020)	B3.1	
Inconsistency of accounting between owner parties and non-owner parties (Elghaish *et al.*, 2020)	B3.2	
Disintegration of economic flows (Kifokeris and Koch, 2019a)	B4	
Payment structure through main contractor (Mason, 2019)	B4.1	
Main contract withholding or failing to make payments (Wang *et al.*, 2017; Brydon Wang, 2018)	B4.2	
Decoupling of payments for transport and delivery services, and logistics solutions and services (Kifokeris and Koch, 2019a, 2019c)	B4.3	D3.7
Payment practices	B5	
Poor payment practices (Li and Kassem, 2019b; McNamara, 2020)	B5.1	
Create distrust between contracting parties (Hamledari and Fischer, 2021a)	B5.1.1	
Unfair payment practices (Das *et al.*, 2020)	B5.2	
Outdated payment practices (O'Reilly and Mathews, 2019)	B5.3	
Current practices rely on human-centred workflows resulting in late or non-payments (Hamledari and Fischer, 2021c)	B5.4	
Current practices are time consuming (Hamledari and Fischer, 2021b, 2021a)	B5.5	
Current practices are information intensive (Hamledari and Fischer, 2021a)	B5.6	
Current practices are heavily intermediated (Hamledari and Fischer, 2021a)	B5.7	
Inefficient procedures for retentions payments that can take up to 60 days after initiation of the process (Ahmadisheykhsarmast *et al.*, 2020)	B6	
Financial fragility (Brydon Wang, 2018; Li *et al.*, 2019a)	B7	
Expensive cost of finance (Nanayakkara *et al.*, 2019b)	B8	
Complexity of payments (Altay and Motawa, 2020)	B9	
Limited use of Project Bank Accounts (PBAs)	B10	
High implementation costs (Ahmadisheykhsarmast and Sonmez, 2020)	B10.1	
Loss of cash flow benefits (Ahmadisheykhsarmast and Sonmez, 2020)	B10.2	
Requirement for staff training (Ahmadisheykhsarmast and Sonmez, 2020)	B10.3	
Not in line with company policy (Ahmadisheykhsarmast and Sonmez, 2020)	B10.4	
Resistance from main contractors to adopt PBAs for reasons of cash flow (Ahmadisheykhsarmast and Sonmez, 2020)	B10.5	
Administrative demands from PBAs (Ahmadisheykhsarmast and Sonmez, 2020)	B10.6	
PBAs are complex in nature (Ahmadisheykhsarmast and Sonmez, 2020)	B10.7	
Centralisation restricts automation of payments (Hamledari and Fischer, 2021c)	B11	
Centralised and siloed methods of data capture prevent single source of truth (payment related) due to product flow (progress updates) and cash flow (payments) requiring verification as a result of data fragmentation (Hamledari and Fischer, 2021c)	B11.1	A8
Centralisation skews the concentration of power creating bottlenecks that can slow down payment processes (Hamledari and Fischer, 2021c)	B11.2	
Lack of trust makes it impossible to automate payments as parties constantly need to validate and verify facts (Hamledari and Fischer, 2021c)	B11.3	F21
Procurement	**C**	A,B,D,E,F,F16, F21,G,H
Problems with the current procurement process (Mason and Escott, 2018)	C1	

Construction sector challenges in the context of DLT research	ID	Relationships
Lowest tender wins model (Harty, 2019; O'Reilly and Mathews, 2019)	C2	
Lump-sum and lowest tender procurement are the main issues in building trust (Shemov *et al.*, 2020)	C3	
Low profit margins (Barima, 2017; Li *et al.*, 2019a; Ye and König, 2021)	C4	
Low profit margins as a result of low digitalisation (Ye *et al.*, 2020)	C4.1	H3
Adversarial pricing (Li *et al.*, 2019a)	C5	B1.6
Adversarial relationships between parties (Hargaden *et al.*, 2019; Luo *et al.*, 2019)	C6	B1.6
Inability to maintain long-term, trusting relationships (Pattini *et al.*, 2020)	C6.1	D1.1, F7.8, F11.2
Actors may behave dishonestly in the face of profiteering (Zhong *et al.*, 2020)	C6.2	F7.4, F15, G4
Requirement to build more for less (Li *et al.*, 2019a)	C7	
Increase of capital expenditure through private investment (Li *et al.*, 2019a)	C8	
Front-loaded process with delayed benefit to the client (Maciel, 2020)	C9	
Clients do not request BIM (Belle, 2017)	C10	
Unclear roles and responsibilities (Li *et al.*, 2020)	C11	F1.9, F4.1
BIM's inability to impact procurement (Perera *et al.*, 2020)	C12	
Supply Chain Management	**D**	A,B,C,E,F,G,H
Supply chain at "ad hoc" level (Hijazi *et al.*, 2019b)	D1	
Fragmentation between stakeholders due to one-off teams (Hijazi *et al.*, 2019a)	D1.1	C6.1, F7.8, F11.2
Fragmentation of project delivery due to fragmented supply chain (Shojaei *et al.*, 2020)	D1.2	
Supply chain data	D2	A
Unclear/lack of provenance data (Shojaei *et al.*, 2019)	D2.1	
Unclear/lack of supply chain data (e.g. chain of custody) (Shojaei *et al.*, 2019)	D2.2	
Clients do not actively participate in construction supply chain information flows (Kifokeris and Koch, 2020)	D2.3	A1
Disintegrated information flows due to fragmentation across project phases or the number of stakeholders (Pishdad-Bozorgi *et al.*, 2020)	D2.4	
Logistics	D3	
Disintegration of material flows (Kifokeris and Koch, 2019a)	D3.1	
Congestion onsite due to lack of coordination (Kifokeris and Koch, 2019a)	D3.2	
Inflexible transportation options (e.g. having to rent a whole truck when only half is needed) (Lanko *et al.*, 2018)	D3.3	
Inefficiencies in storage/delivery of materials/equipment/components (Lanko *et al.*, 2018)	D3.4	
Onsite delivery delays (Lanko *et al.*, 2018; Kifokeris and Koch, 2019a)	D3.5	
Inability to track products (e.g. quality, condition) (Sivula *et al.*, 2018)	D3.6	
Decoupling of payments for transport and delivery services, and logistics solutions and services (Kifokeris and Koch, 2019a, 2019c)	D3.7	B4.3, F1.2
Complex supply chain coordination (Kifokeris and Koch, 2019a)	D3.8	
Area disposition plans (e.g. drawings based material and storage management plans) are static (Kifokeris and Koch, 2020)	D3.9	
Inefficient regulation of delivery entries at construction site (Kifokeris and Koch, 2020)	D3.10	
Supply chain fragmentation (Ye *et al.*, 2018; Kifokeris and Koch, 2019b; Nawari and Ravindran, 2019a; Perera *et al.*, 2020; Sharma and Kumar, 2020; Shemov *et al.*, 2020)	D4	A25
Lack of/poor collaboration (Ye *et al.*, 2018; Li *et al.*, 2019b)	D4.1	F4
Lack of transparency (Wang *et al.*, 2017; Ye *et al.*, 2018; Perera *et al.*, 2020)	D4.2	
Lack of traceability (Wang *et al.*, 2017; Ye *et al.*, 2018)	D4.3	
Lack of trust (Ye *et al.*, 2018; Shemov *et al.*, 2020)	D4.4	
Highly fragmented supply chains with undifferentiated products and services and limited capabilities for investments in new technologies (Norta *et al.*, 2020)	D4.5	
Fragmentation leads to low productivity, cost and time overruns due to change orders, inadequate design specifications; liability claims, conflicts, disputes (Pishdad-Bozorgi *et al.*, 2020)	D4.6	
Complex supply chains (Nanayakkara *et al.*, 2019b; Perera *et al.*, 2020; Tezel *et al.*, 2020)	D5	
Lack of supply chain continuity (Nanayakkara *et al.*, 2019a)	D5.1	
Conflicting interests of supply chain participants (Wang *et al.*, 2017; Shemov *et al.*, 2020)	D6	
Long supply chains for DfMA and industrialised construction (Xue and Lu, 2020)	D7	
Regulations and Compliance	**E**	A,B,C,D,F,G,H
Poor regulatory environment for product assurance (Allison and Warren, 2019)	E1	
Product testing, labelling, marketing is opaque and insufficient (Li *et al.*, 2020)	E1.1	
An estimated 1/3 of construction projects are victims to counterfeiting and fraudulence (Wilson *et al.*, 2020)	E1.2	A20, F10
Poor regulation and compliance (McNamara, 2020)	E2	
Lack of enforcement of regulations and compliance (Li and Kassem, 2019b)	E2.1	
Ignorance around regulations and compliance (Li *et al.*, 2019a)	E2.2	
Inadequate regulatory oversight (Li *et al.*, 2019a)	E2.3	
Regulatory gap (Pattini *et al.*, 2020)	E2.4	

Construction sector challenges in the context of DLT research	ID	Relationships
Failure to comply with legislative and contractual obligations (Brydon Wang, 2018)	E2.5	
Weak compliance processes (Li *et al.*, 2020)	E2.6	
Regulations and guidance are ambiguous and inconsistent (Li *et al.*, 2020)	E2.7	
Lengthy permit application process (Graham, 2019; Nawari and Ravindran, 2019a)	E3	F7.1
Slow to establish standards for digital cooperation (Belle, 2017)	E4	A, H6
Lack of standardised guides for IFC (Xue and Lu, 2020)	E5	
Competence across the system is patchy (Li *et al.*, 2020)	E6	C11, F1.9, F4.1, F8.1
Contract management and delivery	**F**	A,A25,B,C,D,E, G,H
Slow/complex contract management (Ye *et al.*, 2018; Faraji, 2019; Luo *et al.*, 2019; McNamara and Sepasgozar, 2020; Shojaei *et al.*, 2020)	F1	
Poor coordination (Fitriawijaya *et al.*, 2019)	F1.1	
Supply chain inconsistencies between design and construction workflows (Hijazi *et al.*, 2019a)	F1.2	D3.7
Distrust in construction contracts (Mason, 2017; Wang *et al.*, 2017)	F1.3	
Distrust between contracting parties leading to employment of third parties (Das *et al.*, 2021a)	F1.3.1	
Onerous nature of administering construction contracts (McNamara and Sepasgozar, 2018, 2020)	F1.4	
Complexity leads to change orders and disputes (Shojaei *et al.*, 2020)	F1.5	
Ineffective management (Ye *et al.*, 2018)	F1.6	
Complex project delivery, typically over cost and schedule (Maciel, 2020)	F1.7	
Issues in construction management processes (Perera *et al.*, 2020)	F1.8	
Result in poor trust (Perera *et al.*, 2020)	F1.8.1	
Result in poor information sharing (Perera *et al.*, 2020)	F1.8.2	
Result in poor process management (Perera *et al.*, 2020)	F1.8.3	
Issues of allocating responsibilities and liabilities due to overlaps in roles and obligations (Nawari, 2021)	F1.9	C11, E6, F4.1, F8.1
Legal issues/uncertainties (Turk and Klinc, 2017; Hargaden *et al.*, 2019)	F1.10	
Scattered and fragmented construction management as a result of digital adoption (Zhong *et al.*, 2020)	F1.11	H6
Trust and transparency an issue in BIM collaboration (Kiu *et al.*, 2020)	F1.12	
Current collaboration systems are outdated and inappropriately assembled (Norta *et al.*, 2020)	F1.13	
Interrelated processes, sub-processes and involved stakeholders (Norta *et al.*, 2020)	F1.14	
Lack of complete specifications for processes and sub-processes and uniformity of materials, work and teams resulting in uncertainty (Norta *et al.*, 2020)	F1.15	
Structure of the industry is tightly coupled individual projects with loosely coupled permanent works that foster short-term thinking to the detriment of long-term innovation and learning (Norta *et al.*, 2020)	F1.16	
Risk distribution and uncertainty (Nawari, 2021)	F2	
BIM implementation risks (technical, management, environmental, financial, legal) (Liu *et al.*, 2019)	F3	
Lack of/poor collaboration between practitioners (Kiu *et al.*, 2020)	F4	D4.1, G
Unclear roles and responsibilities (Li *et al.*, 2020)	F4.1	C11, E6, F1.9, F8.1
Issues preventing collaboration	F4.2	
Lack of traceability (Goh *et al.*, 2019)	F4.2.1	
Inability to comply or demonstrate compliance (Goh *et al.*, 2019)	F4.2.2	
Lack of flexibility (Goh *et al.*, 2019)	F4.2.3	
Poor stakeholder relationships (Goh *et al.*, 2019)	F4.2.4	
Suboptimal coordination between stakeholders (Maciel, 2020)	F4.3	
Lost productivity (Maciel, 2020)	F4.3.1	
Rework (Maciel, 2020)	F4.3.2	
Delays (Maciel, 2020)	F4.3.3	
Increased fees (Maciel, 2020)	F4.3.4	
Constant change of requirements (Wang *et al.*, 2017)	F5	
Collective responsibility and insurance arrangements (Mason, 2017)	F5.1	
Inappropriate verification mechanism for approval of milestones (Chaveesuk *et al.*, 2020)	F5.2	
Early problems propagated through project to affect completion date (Shemov *et al.*, 2020)	F5.3	
Increasing complexity of construction projects (Ye and König, 2021)	F5.4	
Confrontational contractual relationships (Zhong *et al.*, 2020)	F5.5	
Inefficiencies	F6	
Paper-based processes take time to administer (Hargaden *et al.*, 2019; Kiu *et al.*, 2020)	F6.1	
Time wastage (Morvai, 2018; Sharma and Kumar, 2020; Yang *et al.*, 2020)	F6.2	

Construction sector challenges in the context of DLT research	ID	Relationships
Money wastage (Morvai, 2018; Sharma and Kumar, 2020; Yang *et al.*, 2020)	F6.3	
Cost overruns (Prasad and Koner, 2019)	F6.3.1	
High cost of intermediaries that do not add value to the construction project (e.g. idle workers/machinery) (Dakhli *et al.*, 2019)	F6.3.2	
Resource waste (Ye *et al.*, 2018; Fitriawijaya *et al.*, 2019)	F6.4	
Inconsistent/ambiguous construction contracts (McNamara and Sepasgozar, 2018)	F6.5	
Large amounts of administration work prone to human error (Nanayakkara *et al.*, 2019a)	F6.6	
Delays to construction projects (Prasad and Koner, 2019)	F6.7	
Inadequate design specifications (Sharma and Kumar, 2020)	F6.8	
Inefficient project governance (Penzes, 2018)	F6.9	
Poor quality of works (Chaveesuk *et al.*, 2020)	F6.10	
Project participants may cut corners then deflect blame (Zhong *et al.*, 2020)	F6.10.1	
Nonconformance as a product of poor quality (Sheng *et al.*, 2020a)	F6.10.2	
Little coordination between project participants (design architects, contractors, vendors) (Sharma and Kumar, 2020)	F6.11	
Significant cost to verifying/re-entering data for management & operations (Wilson *et al.*, 2020)	F6.12	
Discontinuity across design, manufacturing, transportation, storage, site work, assemblage (Xue and Lu, 2020; Yang *et al.*, 2020)	F6.13	
Fragmentation (Xue and Lu, 2020)	F6.13.1	
Escalating costs (Xue and Lu, 2020)	F6.13.2	
Severe delays (Xue and Lu, 2020)	F6.13.3	
Limited productivity (Xue and Lu, 2020)	F6.13.4	
Inferior quality (Xue and Lu, 2020)	F6.13.5	
Design exploration and design validation happen in professional silos (Dounas *et al.*, 2020a)	F6.14	
Loss of/low/lack of productivity (Mathews *et al.*, 2017; Ye *et al.*, 2018; Penzes, 2018; Graham, 2019; Shojaei, 2019; Shojaei *et al.*, 2019; Li and Kassem, 2019b; Li *et al.*, 2019a; Lokshina *et al.*, 2019; Hunhevicz and Hall, 2020a; Siountri *et al.*, 2020; McNamara, 2020; Pattini *et al.*, 2020; Sharma and Kumar, 2020; Ye and König, 2021)	F7	
Regulation (e.g. applying for permits) (Graham, 2019)	F7.1	E3
Time wastage (e.g. waiting for materials/equipment) (Graham, 2019)	F7.2	
No uniform design for buildings (Graham, 2019)	F7.3	
Profiteering drives up cost (Graham, 2019)	F7.4	C6.2, F15, G4
Poor project control (Penzes, 2018; Chaveesuk *et al.*, 2020)	F7.5	
Poor coordination (Fitriawijaya *et al.*, 2019)	F7.6	
Managing geographically dispersed teams (Hargaden *et al.*, 2019)	F7.7	
Managing geographically dispersed teams on product design (Lemeš, 2020)	F7.7.1	
Teams disband at the end of projects (Xue and Lu, 2020)	F7.8	C6.1, D1.1, F11.2, F11.3.1
Low productivity as a result of low digitalisation (Ye *et al.*, 2020)	F7.9	H3
Poor quality rework (Park *et al.*, 2020)	F7.10	
Affects productivity and performance (Park *et al.*, 2020)	F7.10.1	
Results in increase costs of materials, time, labour (Park *et al.*, 2020)	F7.10.2	
Cause of accidents (Park *et al.*, 2020)	F7.10.3	
Non-conformance with quality standards and specifications (Park *et al.*, 2020)	F7.10.4	E
Manual observation and recording of non-conformance/defects take time and is subject to human error when re-entering data and can result in omission of data (Park *et al.*, 2020)	F7.10.5	A1
Lack of accountability/responsibility (Penzes, 2018; Hargaden *et al.*, 2019; Liu *et al.*, 2019; Zhong *et al.*, 2020)	F8	
BIM integration concept blurs level of responsibility between different project team members & trust in collaboration (Liu *et al.*, 2019)	F8.1	C11, E6, F1.9, F4.1
Lack of application of BIM at the operation phase (Li *et al.*, 2020)	F9	
An estimated 1/3 of construction projects are victims to counterfeiting and fraudulence (Wilson *et al.*, 2020)	F10	A20, E1.2
Fragmentation (Barima, 2017; Kinnaird and Geipel, 2018; McNamara and Sepasgozar, 2018; Kifokeris and Koch, 2019a; Shojaei, 2019; Shojaei *et al.*, 2019; Hamma-Adama *et al.*, 2020; Hunhevicz and Hall, 2020b; Wang *et al.*, 2020; Yang *et al.*, 2020)	F11	
Vertical fragmentation (between project phases) (Hunhevicz and Hall, 2020b)	F11.1	
Longitudinal fragmentation (when teams disband at the end of projects) (Hunhevicz and Hall, 2020b)	F11.2	C6.1, D1.1, F7.8, F11.3.1
Structural fragmentation (Li *et al.*, 2019a; Norta *et al.*, 2020)	F11.3	
Fragmented project organisational structure due to short contractual relationships resulting in lack of trust (Cheng *et al.*, 2020)	F11.3.1	F7.8, F11.2, F21
Leadership fragmentation (Li *et al.*, 2019a)	F11.4	
Organisational fragmentation (Maciel, 2020)	F11.5	

Construction sector challenges in the context of DLT research	**ID**	**Relationships**
Process/procedural fragmentation (Pattini *et al.*, 2020)	F11.6	
Lack of trust as a result of fragmented cooperation (Qian and Papadonikolaki, 2020)	F11.7	
Single point of failure (Mathews *et al.*, 2017)	F12	A2, H5.4
Technology focus takes precedence over design process (Dounas *et al.*, 2020a)	F13	
IPD delivery challenges (Elghaish *et al.*, 2020)	F14	
Actors may behave dishonestly in the face of profiteering (Zhong *et al.*, 2020)	F15	C6.2, F7.4, G4
Handover seen as end of contract (Harty, 2019)	F16	A3.5, C
Differences between predicted and actual usage (Tagliabue *et al.*, 2019)	F17	
Residents voices often go unheard (Li *et al.*, 2020)	F18	
Quality of goods and services (Nanayakkara *et al.*, 2019b)	F19	
Prefabricated buildings	F20	
High initial costs (Zhang *et al.*, 2020)	F20.1	
Lack of standard norms (Zhang *et al.*, 2020)	F20.2	
Shortage of skilled labour (Zhang *et al.*, 2020)	F20.3	
Immature supply chain (Zhang *et al.*, 2020)	F20.4	
Liability disputes (Zhang *et al.*, 2020)	F20.5	G14
Delivery delays (Zhang *et al.*, 2020)	F20.6	
Cost increases (Zhang *et al.*, 2020)	F20.7	
Schedule delays (Zhang *et al.*, 2020)	F20.8	
Construction accidents onsite (Zhang *et al.*, 2020)	F20.9	
Public concerns (Zhang *et al.*, 2020)	F20.10	
Supply chains more complex for prefab buildings than for traditional buildings (Zhang *et al.*, 2020)	F20.11	
Lack of trust (Penzes, 2018; De La Peña and Papadonikolaki, 2019; Goh *et al.*, 2019; Nanayakkara *et al.*, 2019a; Cheng *et al.*, 2020; Zhong *et al.*, 2020; Hunhevicz and Hall, 2020b; Kiu *et al.*, 2020; Qian and Papadonikolaki, 2020; Shojaei *et al.*, 2020; Tezel *et al.*, 2020)	F21	B11.3, C, F11.3.1
Little attention has been given to construction suppliers' relationship management (CSRM) designed to foster trust between parties (Pishdad-Bozorgi *et al.*, 2020)	F21.1	
Lack of knowledge to incorporate BIM into development plan (Belle, 2017)	F22	
Onsite construction accidents, specifically, falling from scaffolding (Baek *et al.*, 2020)	F23	
Lack of meaningful automation with regards management of construction projects (Norta *et al.*, 2020)	F24	
Inefficiency of carbon credits to reduce greenhouse gas emissions (Woo *et al.*, 2020)	F25	N11
Disputes	**G**	A,B,C,D,E,F, F4,F6.7 H
Litigation around data ownership (Harty, 2019)	G1	
Lengthy dispute resolution process (Jagannathan and Prasad, 2018; McNamara and Sepasgozar, 2018)	G2	
Contractual disputes (Chaveesuk *et al.*, 2020; Hamma-Adama *et al.*, 2020)	G3	
Ambiguities in the terms of the contracts (Shojaei *et al.*, 2020)	G3.1	
Horizontal fragmentation (between trade-by-trade competitive bidding) (Hunhevicz and Hall, 2020a)	G3.2	
Stipulations over agreed protocols (Wang *et al.*, 2017)	G3.3	
Actors may behave dishonestly in the face of profiteering (Zhong *et al.*, 2020)	G4	C6.2, F7.4, F15
Legal disputes preventing evolution of the industry (Morvai, 2018)	G5	
Late/delayed payment disputes (Goh *et al.*, 2019)	G6	
Quality/fraud disputes (Yang *et al.*, 2020)	G7	
Late delivery of work (Shojaei *et al.*, 2020)	G7.1	
Underperforming delivery of work (Shojaei *et al.*, 2020)	G7.2	
Specification disputes (Chaveesuk *et al.*, 2020)	G8	F6.7
Lack of an effective communication channel (Goh *et al.*, 2019)	G9	
Lack of corrective information sharing on site (Goh *et al.*, 2019)	G10	
Poor document control systems (Goh *et al.*, 2019)	G11	
Disputes leading to lack of collaboration (Goh *et al.*, 2019)	G12	
Conflict disputes (Sharma and Kumar, 2020)	G13	
Liability claims (Sharma and Kumar, 2020)	G14	F20.5
Disputes as a result of slow/complex contract management (Shojaei *et al.*, 2020)	G15	
Technological systems	**H**	A,B,C,D,E,F,G
Interoperability	H1	N13
Interoperability issues between building components (Bindra *et al.*, 2019)	H1.1	
Interoperability issues between software programmes (Cardeira, 2017; Wang *et al.*, 2017, 2020; Kinnaird and Geipel, 2018; Bukunova and Bukunov, 2019; Erri Pradeep *et al.*, 2019; Salama and Salama, 2019)	H1.2	
Software interoperability leads to poor coordination between clients and contractors (Ye *et*	H1.2.1	

Construction sector challenges in the context of DLT research	ID	Relationships
al., 2020)		
Interoperability issues between software programmes at handover (Salama and Salama, 2019)	H1.3	
Interoperability issues between actors' systems (Wang *et al.*, 2017; Kifokeris and Koch, 2019a)	H1.4	
Interoperability issues with current document management systems (Kiu *et al.*, 2020)	H1.5	
Interoperability issues with different software and tools when project team members need to collaborate on the same BIM models (Norta *et al.*, 2020)	H1.6	
Centralised systems (Kiu *et al.*, 2020)	H2	
Central IoT systems vulnerable to attack (Ye *et al.*, 2018)	H2.1	
Insufficient digitalisation/slow to digitalise (Barima, 2017; Belle, 2017; Ye *et al.*, 2018; Nawari and Ravindran, 2019a; Shojaei *et al.*, 2019; Goh *et al.*, 2019; Hijazi *et al.*, 2019a; Li *et al.*, 2019b; Lokshina *et al.*, 2019; Altay and Motawa, 2020; Norta *et al.*, 2020; Perera *et al.*, 2020; Siountri *et al.*, 2020; Kiu *et al.*, 2020; McNamara, 2020; McNamara and Sepasgozar, 2020; Ye and König, 2021)	H3	A25.2, C4.1, F7.9, N3
Fragmentation (Rodrigo *et al.*, 2020)	H3.1	
Lack of replication (Rodrigo *et al.*, 2020)	H3.2	
Transience (Rodrigo *et al.*, 2020)	H3.3	
Lack of planning for decentralisation through BIM (Siountri *et al.*, 2020)	H3.4	A4.20
Fragmentation of BIM processes (Dounas *et al.*, 2020b)	H3.5	
Vulnerabilities of cloud platforms (Turk and Klinc, 2017; Das *et al.*, 2021a)	H4	
Security attacks related to data loss (Cheng *et al.*, 2020; Das *et al.*, 2021a)	H4.1	
Denial of Service (DoS) access (Cheng *et al.*, 2020; Das *et al.*, 2021a)	H4.2	
Partial control over sensitive data (Das *et al.*, 2021a)	H4.3	
Data corruption (Cheng *et al.*, 2020)	H4.4	
Information security (Lemeš, 2020)	H4.5	
BIM Platforms	H5	
Data security (Shi *et al.*, 2021)	H5.1	
Lack of transparency (Shi *et al.*, 2021)	H5.2	
Security issues in BIM-IoT architecture (Siountri *et al.*, 2020)	H5.3	
Central BIM platform represents single point of failure (Kiu *et al.*, 2020)	H5.4	A2, F12
Challenges with current IT systems	H6	E4, F1.11
Cannot ensure security (Zhong *et al.*, 2020)	H6.1	
Cannot ensure traceability (Zhong *et al.*, 2020)	H6.2	
Cannot ensure transparency of quality information (Zhong *et al.*, 2020)	H6.3	
Decentralised/loosely coupled network (Hunhevicz and Hall, 2020b)	H6.4	
Lack of integration methods that foster BIM adoption (Elghaish *et al.*, 2020)	H6.5	
Lack of onsite mobile technology (Li *et al.*, 2020)	H6.6	
Insufficient resilience of software platforms (Nawari, 2021)	H6.7	
Privacy issues in software agents (Nawari, 2021)	H6.8	
Third party dependence on software agents (Nawari, 2021)	H6.9	
Non-application specific challenges	**N**	
Inadequacies in the leading BIM protocol (Mason, 2017)	N1	
Adversarial nature of the industry (McNamara and Sepasgozar, 2018; O'Reilly and Mathews, 2019)	N2	
Change resistant industry (Li and Kassem, 2019a; Lokshina *et al.*, 2019; Shojaei *et al.*, 2019, 2020; McNamara and Sepasgozar, 2020; Norta *et al.*, 2020; Pattini *et al.*, 2020; Sharma and Kumar, 2020; Shemov *et al.*, 2020)	N3	H3
Urbanisation (Nguyen *et al.*, 2019)	N4	
Lack of investment in R&D (Li *et al.*, 2019a)	N5	
Results in limited collaboration and a labour-productivity decline (Norta *et al.*, 2020)	N5.1	
Lack of senior management support (Li and Kassem, 2019a)	N6	
Cost of implementation of BIM (Li and Kassem, 2019a)	N7	
Return on Investment of BIM is unclear (Belle, 2017)	N7.1	
Difficult to justify the extra overheads of BIM (Maciel, 2020)	N7.2	
Lack of tangible benefits (Li and Kassem, 2019a)	N7.3	
Scale of culture change required (Li and Kassem, 2019a)	N8	
Poor industry image (Li *et al.*, 2019a)	N9	
Aging workforce (Li *et al.*, 2019a)	N10	
Sustainability (Hunhevicz and Hall, 2020a)	N11	F25
Highly project-based industry (Maciel, 2020)	N12	
Lack of universal use (Li and Kassem, 2019a)	N13	H1
Training and education	N14	
Lack of trained personnel (Li *et al.*, 2020)	N14.1	
Lack of experience within the workforce of applying BIM processes (Li and Kassem, 2019a)	N14.2	
Lack of training/education around BIM requirements (Maciel, 2020)	N14.3	

Construction sector challenges in the context of DLT research	**ID**	**Relationships**
ITC illiteracy of workforce (Li and Kassem, 2019a)	N14.4	
Ambiguity of what the BIM spectrum might mean (Dounas *et al.*, 2020a)	N15	
Reluctance to adopt BIM as a result of fear or legal consequences in the case of low performance (Norta *et al.*, 2020)	N16	
Diffidence - denying the need for process change where BIM is presented as an already good fit and monodisciplinary (Dounas *et al.*, 2020a)	N17	
Take, make, waste model contributes 40% of CO2 emissions worldwide (Copeland and Bilec, 2020)	N18	

Appendix E: Theme-Specific DLT Benefits Pathways

DLT Benefits Pathways for procurement

Procurement activities do not happen independently; there are myriad activities connected to them from requirements elicitation through to end-of-life pursuits. Poor decisions taken in the early stages of a construction project can have lasting, negative effects later in the asset lifecycle. Procurement is a highly strategic issue that can be supported by technological systems to help achieve savings such as reduced time, transaction costs and transposition error (Mathews *et al.*, 2017). DLT has the ability to facilitate the automation of trust providing identity, reputability, price guarantee, an immutable record, and automated invoicing (Nguyen *et al.*, 2019).

Figure 0.1 highlights the procurement applications and potential associated benefits that can be affected by DLT in different ways to affect procurement. A move toward e-procurement has been investigated previously (Ciribini *et al.*, 2015) indicating computerisation of the procurement process can be cascaded through subsequent phases allowing requirements and performance data to be tracked throughout the asset lifecycle. SCs would be coded following rules for procurement (e.g., the Official Journal of the European Union (OJEU) process), the administrative activities would be significantly reduced through automation where there is no need to wait for human interaction, and the process would be significantly more transparent as SCs require clarity. These applications take a more holistic approach to procurement's role in the construction process by linking procurement to subsequent phases of the asset lifecycle to measure performance during construction and operation that results in payments when works are completed satisfactorily. This creates *integrated procurement* where it becomes more than just a milestone in a project. If performance management is connected to procurement objectives and monitored through, for example, IoT-based sensors, participants are likely to see faster validation of work and faster payments for work complete. To enable this pathway, advancement in its supporting technological systems (e.g., BIM, IoT, SCs) and sector

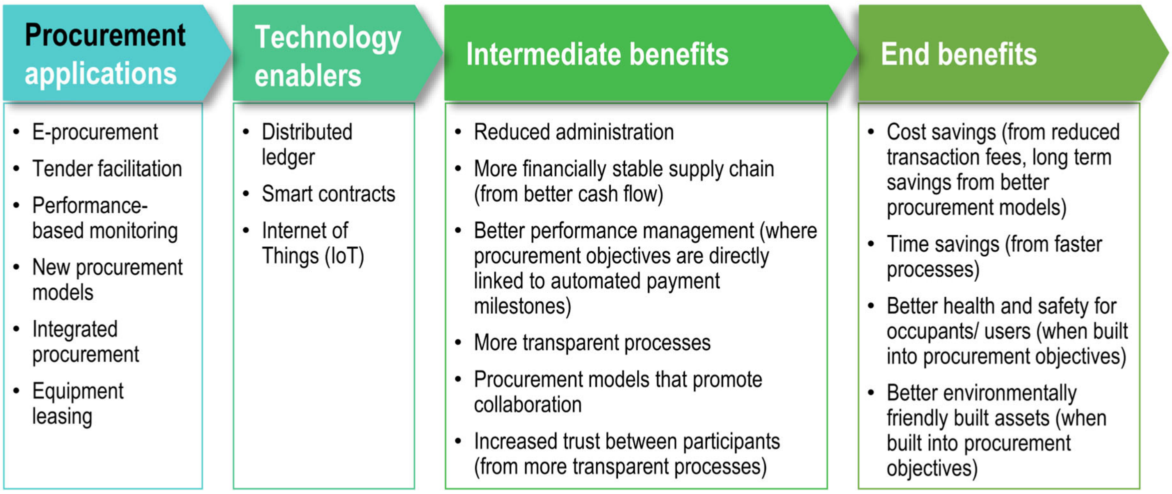


Figure 0.1: DLT Benefits Pathways for procurement

reform of procurement practices are necessary. To realise value according to the proposed pathway interoperability, integration and adoption of enabling technologies (e.g., BIM, IoT, SCs) require significant improvement. However, these must be accompanied by sector reform. As Hunhevicz and Hall (2020b, p. 1) state, "*technology implementation should be treated as means to an end to address the fundamental problems of the construction industry*". Procurement practices require reform and a move toward value-for-money procurement models that look at whole lifecycle costing rather than the lowest cost. And while health and safety of built assets are statutory requirements, building health and safety objectives into procurement and linking them directly to payments will likely result in increased health and safety for the asset's occupants and/or users. In addition, consideration of the implementation costs and activities required to realise an ecosystem capable of delivering the suggested benefits must be given. The combination of BIM and DLT creates an opportunity to streamline procurement models and improve collaboration. This will result in disintermediation of third parties so heavily embedded in current practices to give greater control to the client over transparency of cost, time and scope (McNamara and Sepasgozar, 2020).

DLT Benefits Pathways for SCM

Global supply chain activities are already utilising DLT. TradeLens, an initiative by global shipping company Maersk in collaboration with IBM, claims to be a neutral supply chain platform built on blockchain technology with the purpose of facilitating collaboration, information sharing and innovation on a global scale (TradeLens, 2020). By December 2019, TradeLens was publishing more than 2 million events per day in a global network of over 175 supply chain organisations (Link-wills, 2020). While construction supply chains are nowhere near as advanced yet, it is likely that construction materials are already being shipped and published on TradeLens or will be in the near future. This is in line with an interviewee in Li and Kassem (2019b) who believes DLT development in construction will likely be driven by other sectors such as finance and supply chain logistics.

To realise the intermediate benefits highlighted in Figure 0.2, digitalisation of integrated systems across organisations through employing the technology enablers can increase efficiency and lower transaction costs making supply chains more agile (Kifokeris and Koch, 2019a). Given the progress of TradeLens, the construction sector has a real-world application from which to learn as it moves toward a DLT-based solution. It is expected that there will be long negotiations and a need to address issues of cyber security and integration with existing systems before implementation begins (Kifokeris and Koch, 2019a). Ultimately, it is expected that this move will result in more reliable data, increased procurement efficiency, consistent reporting across the supply chain, and the ability to trace products through the supply chain (Ye *et al.*, 2018). Perera *et al.,* (2020) state that construction supply chains are currently independent from information models and workflows, which has an

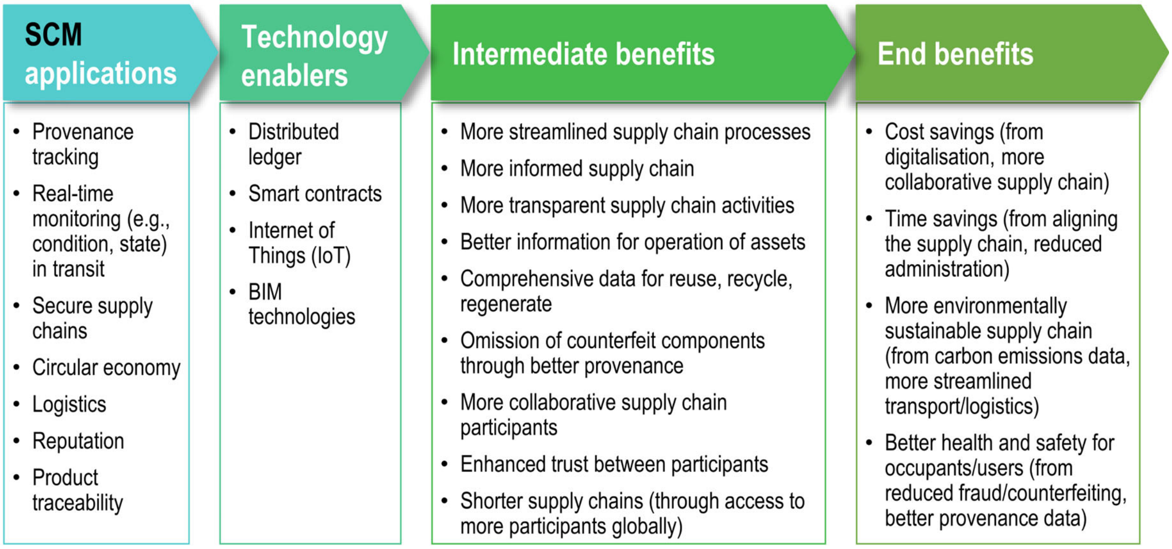


Figure 0.2: DLT Benefits Pathways for supply chain management

impact on the quality of the final asset. Integration of the two, through DLT, will make the whole building process more streamlined and ensure reliable data across the asset lifecycle. The addition of SCs will provide measurable benefits and a more transparent economic environment whilst maintaining security of the supply chain offering more protection to cargo owners and carriers, and reducing trust and information barriers between participants resulting in less disputes (Lanko *et al.*, 2018). Digitalisation of current processes will increase speed and aid in better procurement choices and decision-making such as through decentralised e-marketplaces (e.g., as in Li *et al.*, 2020) ensuring the best people and organisations are selected for the job rather than contracts being awarded to familiar individuals or teams (Kinnaird and Geipel, 2018).

The appetite to adopt blockchain was investigated by Sivula *et al.,* (2018) based on an interview with executives from one Finnish construction company. Five areas show promise as follows: providing extended customer value; cryptocurrency-based logistics model; transparency between the actors; enhanced service network; and digital ledger system of the building or infrastructure. In a roundtable discussion of upstream construction supply chain practitioners, the top ranking benefits of blockchain and SCs for construction supply chains included: efficiency, trust, fairness, security, transparency, accountability, compliance and standardisation (Nanayakkara *et al.*, 2019b). While these attributes can be supported by many scholars, the approach to the workshop was an assumption that the two technologies would ‘do good’ through the question posed: “*What are the most appealing factors for you in the use of Blockchain and SCs considering its possibility of use in the construction supply chain?*” (Nanayakkara *et al.*, 2019b, p. 6). There was an omission of the limitations or risks of such. Other authors state limitations as: high cost of implementation that requires supply chain participants to invest in IoT devices and supporting infrastructure for edge/fog computing; throughput and latency of current DLT such as the bitcoin blockchain that takes 10 minutes to confirm a transaction and approximately an hour for it to be considered secure (Shemov *et al.*, 2020); digital signatures of transactions do not provide veracity of the data (Kinnaird and Geipel, 2018); and reluctance of the sector to change (Lokshina *et al.*, 2019; Pattini *et al.*, 2020; Sharma and Kumar, 2020).

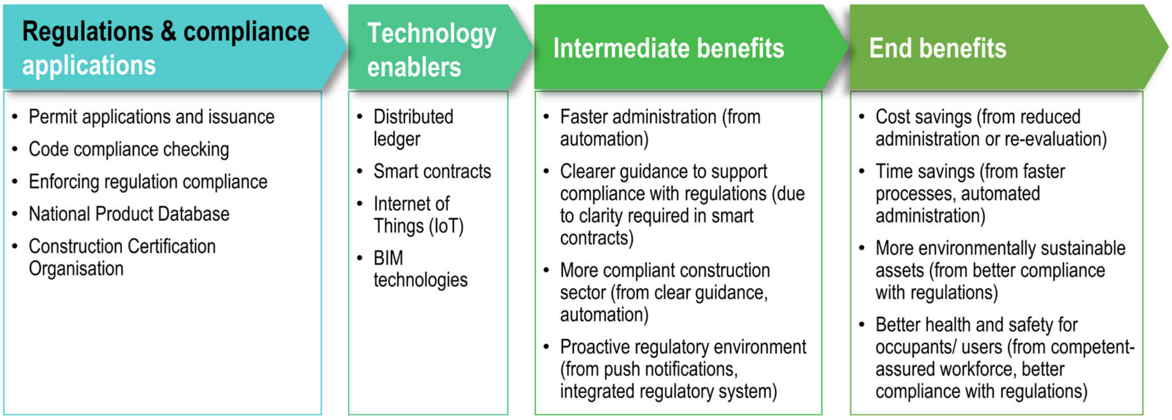
It is clear that DLT and SCs have the ability to ensure integrity and validity of the SCM process (Kifokeris and Koch, 2019c) offering many intermediate and end benefits as in Figure 0.2 but much is needed before this can be realised. However, realignment of processes, sufficiently skilled resources and digital integration of business models are required (Tezel *et al.*, 2020).

DLT Benefits Pathways for regulations and compliance

Regulations exist for the protection of individuals and the environment. The UK's Building Regulations 2010, for example, is designed to secure "*the health, safety, welfare and convenience of persons in and about buildings, furthering the conservation of fuel and power, preventing waste, undue consumption, misuse or contamination of water, furthering the protection or enhancement of the environment, and facilitating sustainable development*" (Department for Communities and Local Govenment, 2010, p. 1).

While there is limited progress in the discussion of the application of DLT to regulations and compliance discussed in literature, with the exception of Nawari and Ravindran (2019a), it is an area that has substantial impact on the construction sector due to the complexities of construction contracts and the health and safety implications on individuals. DLT and SCs can streamline compliance processes through automation and increase their transparency. However, before SCs can be programmed and deployed, it is important to clarify what is required and when.

The MEED Mashreq Construction Partnership (2019) raises the issue of updating legislation and commonly used suites of contracts (e.g., FIDIC), especially with regards the risk profile associated with DLT on projects, ensuring parties are held to account in the event of flaws in the project. An empirical study by Salama and Salama (2019) in the United Arab Emirates (UAE) found the role of governments is a critical success factor for the adoption of DLT, particularly with demonstrating their commitment to digital transformation. Wilson *et al.,* (2020) consider a shift in traceability systems from one where traceability activities are reactive with regards demonstrating compliance with regulations to one where participants begin to receive additional benefits over and above compliance and start to derive additional business value. This brings the possibility of participants volunteering information based on incentives related to reduced costs, enhanced collaboration and reduced complexity of construction projects. These intermediate benefits will drive the end benefits to ensure better value for money for the client/owner through compliance from the outset requiring less rework/variations and a safer built environment for occupants/users.



Regulations & compliance applications

- Permit applications and issuance
- Code compliance checking
- Enforcing regulation compliance
- National Product Database
- Construction Certification Organisation

Technology enablers

- Distributed ledger
- Smart contracts
- Internet of Things (IoT)
- BIM technologies

Intermediate benefits

- Faster administration (from automation)
- Clearer guidance to support compliance with regulations (due to clarity required in smart contracts)
- More compliant construction sector (from clear guidance, automation)
- Proactive regulatory environment (from push notifications, integrated regulatory system)

End benefits

- Cost savings (from reduced administration or re-evaluation)
- Time savings (from faster processes, automated administration)
- More environmentally sustainable assets (from better compliance with regulations)
- Better health and safety for occupants/ users (from competent-assured workforce, better compliance with regulations)

Figure 0.3: DLT Benefits Pathways for regulations and compliance

The Benefits Pathways highlighted in Figure 0.3 demonstrate the possibilities for the sector in becoming better at compliance with regulations. The sector is currently reactive, but it can be proactive. The challenge is that, unlike manufacturing or automotive, construction projects are unique and while elements can be replicated from one project to the next, client's requirements or site conditions will always offer something different for each and every project. Creating regulations for a sector that is not standardised is a challenge. Several technological systems and multiple processes need to coevolve according to a market-level unified and coordinated roadmap focused on improving regulation and compliance in order to allow the intermediate and end benefits to be realised.

DLT Benefits Pathways for construction management and delivery

With BIM came the promise of an industry transformation (McNamara and Sepasgozar, 2018) and while its impact can be seen through leaps in, for example, model authoring, design coordination and clash detection, its mission of a collaborative, digitalised sector is yet to be realised. A large proportion of the problems of project delivery can be attributed to the contract. Current contracts are complex and though there are suites of standardised contracts such as the New Engineering Contract (NEC) or the Joint Contracts Tribunal (JCT), there is none that has yet been successful in providing the level of required clarity and transparency to consistently deliver successful contracts. The construction contract establishes what must be done throughout a project but leaves room for interpretation that is often the cause of disputes. DLT and SCs have the potential to bring important efficiencies in contract management (Wang *et al.*, 2017). It will force the transformation of contract clauses into explicit computational language moving away from the descriptive language used today (Pattini *et al.*, 2020).

Several of the applications in Figure 0.4 require a number of the technology enablers working together to deliver the proposed intermediate and end benefits. For example, IoT-equipped devices can monitor temperature in an operational building with the collected data processed at the point of collection via edge, fog or cloud computing. The DLT would secure transmission of the data and SCs would execute based on the processed data. If the

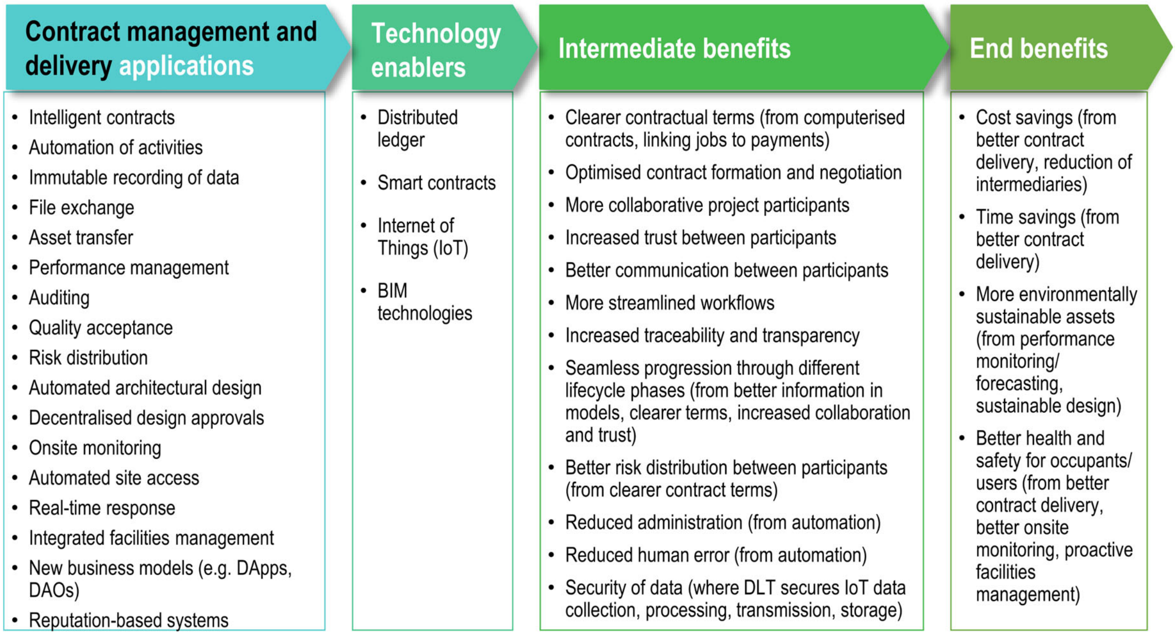


Figure 0.4: DLT Benefits Pathways for contract management and delivery

building was too cold or too warm, thermostats would be automatically adjusted up or down to increase occupants' comfort levels. This in turn results in better energy performance and reduces carbon emissions. The data and response to the data are immutably recorded on the ledger which can be used for predictive maintenance and auditing and increases traceability and transparency of the process. Harty (2019) believes such a structure would result in new income sources, better sustainability and better building performance that in turn becomes an incentive to the parties.

The level of clarity required to populate SCs and intelligent contracts would offer a substantial level of disruption to current practice. Automation would reduce administration and associated costs; security of payment would provide a new level of confidence to subcontractors and suppliers; transparency in the contract would drive parties to collaborate and reduce or more evenly distribute risk (McNamara and Sepasgozar, 2018). A semi-automated approach would leave the door open for human interaction for elements that require verification that is not yet automatable (McNamara, 2020). The question remains as to whether this would also allow the current level of disputes to perpetuate.

The Accord Project (2020) is an open source, collaborative initiative that aims to develop an ecosystem for smart legal contracts to provide a common format for smart agreements, facilitating reuse and sharing of agreement templates, that are technology agnostic across any infrastructure (e.g., cloud, blockchain, IoT). It is hoped that initiatives such as this can support standardisation of SCs and help realise their implementation into construction. The Weather Ledger (Digital Catapult, 2020), an Innovate UK project led by EHAB Limited and supported by Clyde & Co, Connected Places Catapult, Digital Catapult, Ferrovial Corporation UK and BAM Nuttall, aims to use a distributed ledger, SCs and IoT devices to automate compensation events related to weather on two real-world construction sites. The

IoT devices collect data, SCs process the data and act upon it, and the ledger secures the system and provides immutable transparency. The system will automate the process of a compensation claim if a once-in-a-ten-year weather event occurs. The project will act as a trial to demonstrate use of DLT and SCs in construction for an event that does not have challenges of GDPR and the SCs would execute based on simple governance rules.

Improvements to information management (discussed in Section 2.3.4.1) would propagate through to improve contract management and delivery. It would make transition across project phases smoother as a result of more complete information sets and clarity from automated contracts. Rogers (2018) emphasises the importance of adopting BIM in facilities management but caveats that with the fact the construction sector has not significantly progressed in this area. This reiterates the point that technology is only one part of the solution; processes and attitudes to the way construction contracts are delivered also require change. Salama and Salama (2019) indicate several challenges to the use of blockchain and BIM in facilities management including identifying cost-benefit, security, quality control and governments' role in establishing constraints for information and interaction. They contrast these challenges with enablers of the technology that support improvement of efficiency and productivity, availability of data, and governments' commitment to digital transformation.

DLT Benefits Pathways for disputes and dispute resolution

There are two aspects of dispute resolution discussed in this paper: (1) avoidance or reduction of disputes, which relies on the quality of information collected, clarity of roles and responsibilities etc.; and (2) the process of dispute resolution that can be made easier, faster, and cheaper through the use of DLT and SCs in comparison to current practices. The former is alluded to in other sections (e.g., information management in Section 2.3.4.1) and the latter is discussed in this section. In the event that disputes are not avoided, Figure 0.5 shows two technology enablers are required in dispute resolution; the immutable ledger of transactions that provides the evidence to be scrutinised to resolve a dispute, and SCs to perform automated administrative tasks. The data on the ledger would be created using different technological systems such as modelling software or IoT, but when it comes to

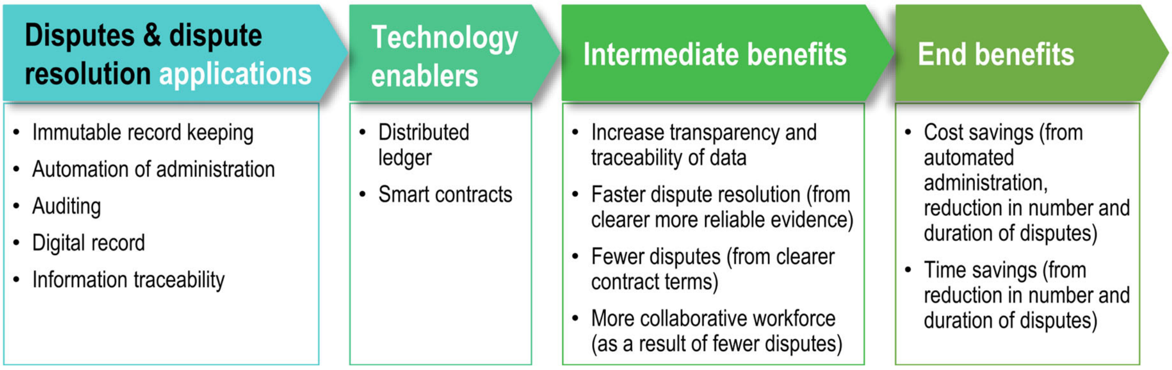


Figure 0.5: DLT Benefits Pathways for disputes and dispute resolution

dispute resolution, it relies on the data already collected. To demonstrate dispute resolution on blockchain in practice, Penzes (2018) highlighted the benefits achieved when IBM Global Financing transferred around 2.9 million transaction records to a blockchain resulting in a reduction in time of 75% on 25,000 disputes. This equated to a 40% saving on legal and administrative costs. The ledger of records increased visibility of transactions for all 4,000 participants in real time. This level of transparency and traceability provides accountability and enhances quality of services across the lifecycle of the asset.

The impact of visibility that DLT and SCs bring could have profound effects on the construction sector including a more "*logical and rigid contract system*" (McNamara and Sepasgozar, 2020, p. 442) that applications such as the iContract offer. The inflexibility of intelligent contracts removes the space that allows for disputes and reduces the power of the higher tier contractors to squeeze their sub-contractors and suppliers as a result of low profit margins and ineffective procurement models. However, the creation of such an inflexible contract would require precise anticipation of every eventuality in a contract clause that would require substantial coding to achieve the level of detail required and be very expensive to create and be checked by all parties involved.

The infrastructure for a blockchain-based dispute management system does not yet exist. However, in a landmark case in China in 2018 (*Hangzhou Huatai Media Culture Media Co., Ltd. V. Shenzhen Daotong Technology Development Co., Ltd.* (2018) Zhe 0192 No. 81), a court ruled evidence that had been stored on a blockchain to be legally admissible. The plaintiff discovered copyright infringement on a website, captured a screenshot of the infringement and associated source code and uploaded them to the Factom blockchain and the Bitcoin blockchain. The presence on the blockchain provided veracity of the data that it was in fact copyright infringement (Tsai Lee & Chen Patent Attorneys & Attorneys at Law, 2018). In such cases, evidence uploaded to a distributed ledger could save valuable time that would be taken to get something physically notarized – costs are much lower, evidence is saved almost instantly and the above case has set a precedent for evidence in the future (Vivien Chan & Co, 2020). While this may only be the case in China, it is likely to become the case in many other countries in the near future. Individuals and organisations do not have to wait for a fully integrated ecosystem to begin realising the benefits of DLT as a way to prove something at a point in time.

Kinnaird and Geipel (2018) believe blockchain-based transactions will significantly increase transparency when work is delivered, and files are securely exchanged due to immutability and timestamping. They add that this increases trust between participants which would then reduce corruption and inefficiencies of contractual disputes.

DLT Benefits Pathways for technological systems

Technology is only a set of tools; it is the processes and data that are associated with the technology that derive value. The problem of interoperability will only be solved entirely if software vendors are incentivised to create interoperable systems. Thinking needs to move away from one of intellectual property and competitive advantage toward a mindset of value that can be derived from collaboration. Dounas *et al.,* (2019) have begun exploration of a translation mechanism for transferring the underlying BIM logic from one proprietary programme to another and results thus far are promising (Dounas *et al.*, 2020b), they have yet to test the interoperability between visual scripting platforms and BIM.

The benefits of such systems include the reduction of bottlenecks due to distribution and security against malware of malicious users (Cooper, 2018). De La Peña and Papadonikolaki (2019) found that IoT in a blockchain system contributed to the evolvement of trust through the ability to access information in real time and without the requirement of technical prowess. It is said that the only technology with the power to unlock the full potential of the IoT is blockchain (O'Reilly and Mathews, 2019). Blockchain-supported IoT systems can offer automated data transmission leading to "*efficient quality management, dispute resolution, [supply chain] SC traceability, transparency, security, reduction of information asymmetries, stakeholder involvement, faster responses and efficient decision-making*" (De La Peña and Papadonikolaki, 2019, p. 9). The current state-of-the-art of DLT suffers from scalability issues, the energy required to process a blockchain but also the numerous devices and connectivity between them, the legalities of coded contracts, and responsibilities in the event of failure or error (Cooper, 2018). And while the level of adoption of IoT in construction is greater than that of DLT, there still remains a dearth of real-world case studies applying IoT to construction projects (McNamara, 2020). Despite the fact that DLT is still at its early stage of development regarding construction applications, the sheer volume of studies investigating DLT in construction is an indication that it is very likely to become mainstream, but there is a time lag of several years before this is realised. On that basis, the forward-thinking applications regarding connected systems have time to coevolve to ensure they converge at the right time to achieve maximum benefits for the sector, such as those indicated in Figure 0.6.

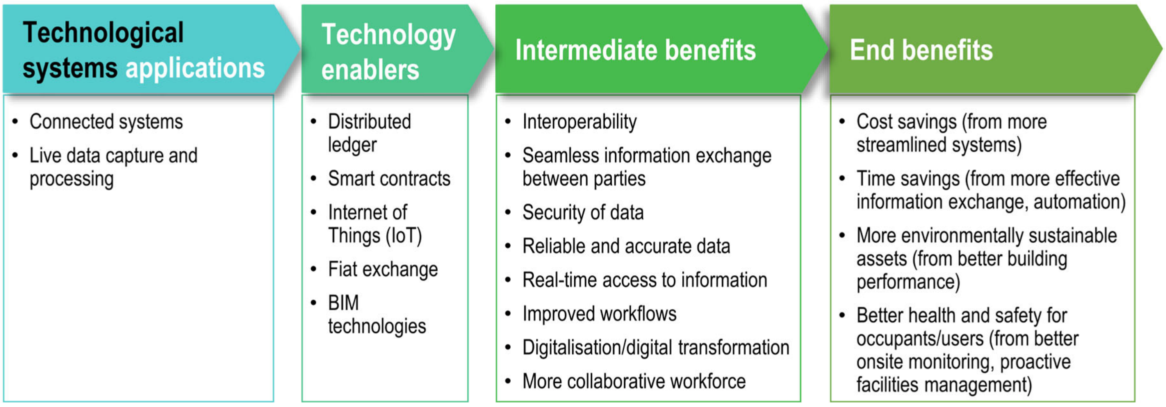


Figure 0.6: DLT Benefits Pathways for technological systems

Appendix F: iContract focus group data

Code	Theme	Quotes
iCA	Challenges to standard form contracts	1. “it's good to not reinvent the wheel every single time” (iC4) 2. “successful approach would be first to replicate current processes using a new solution” (iC1) 3. “a lot of the contracts actually need to be completely reassessed” (iC4) 4. “bespoking contracts and inventing endless z clauses that [parties] write into their own contract terms” (iC2) is what drives inefficiencies and waste in construction projects and “as a general rule of thumb, we don't really want to see people fiddling with the more standard terms and conditions; it doesn't help anybody” (iC2) 5. “if you create business-as-usual, you're going to get more resistance to the adoption of the technology because business-as-usual is a non-trust sort of relationship. … Thinking through how people might use this [technology] to preserve current status quo versus how can you avoid that?” (iC3)
iCB	Functionality of the iContract	1. The iContract is proposed as Software-as-a-Service (SaaS) intended to be “a tool that you would use on a daily basis… letting people know how they should be acting” (iC6) 2. “the iContract will draw on data that it was scanned in at x date, the concrete was x strength, and party y and party z contributed to that under the work breakdown structure as part of the schedule and that's where the payments would kind of go through a waterfall” (iC6) 3. “technologies are driving better behaviours in project management…the plans have to be more real because [the parties] know they're going to be measured against them. If people know they're going to get paid off their plans, then they'll put a lot more effort into the accuracy of their plan. It drives more of a proactive behaviour to monitor what you're doing to plan better” (iC4) 4. There will be “a landscape of this contract technology. Some are specialised in recording deliveries to site; some may be specialised in defect or quality control on sites” (iC5) 5. The iContract is “capturing snapshots of these information flows and this is built around the information lifecycle, the data lifecycle, and just plugging into it. As if there's a platform for information exchange and iContract becomes the contractual layer connecting it” (iC1) 6. “technology tends to augment either positive or negative behaviour by human beings, but it will never solve the problems and it will never generate positive outcomes … if the industry is not committed to changing its approach, changing its culture, and focusing on delivering value and performing better, then all of these initiatives and technologies will fail to have the impact that they could, because people will find ways and means of obstructing them” (iC2)
iCC	Transparency	1. “it's a demand for a greater transparency” (iC6) 2. “the potential kind of project that this may go to is a project that is already looking to ‘how can we increase transparency?’” (iC6) 3. “if you can find a team already [working toward transparency], and you already have some collaborative flows between them, and they need to speed things up and make them more transparent, because they already agreed on transparency. So this type of solution will come. ‘Okay, I can help you make this transparency work’, rather than convince people to be transparent, and then give them the solution for transparency.” (iC1) 4. “you're talking about transparency, which is very valid. You're making the process more logical, making people actually understand the risks they are exposed to” (iC6) 5. “if it's a large organisation, implementing its own Ethereum solution, forcing its supply chain to work in a certain way, increasing transparency, etc, you know, it's very different than everyone forced by a higher power to use a specific solution mandated down” (iC1) 6. “there's such low levels of trust in the construction industry. It's a non-trust based piece, do you deliberately design a piece of technology that rebuilds or enforces transparency and therefore trust? And creates that certainty about what has to be delivered and when and what you'll get paid? Or is it going to be like business-as-usual, because if you create business-as-usual, you're going to get more resistance to the adoption of the technology. Because business-as-usual, is a non-trust, sort of relationship. Like making the last payment, something that parties do is, ‘We'll get to the final payment, and then I'll change the rules of the game, and you don't get your last 10% and so you'll lose money on the job’. Thinking through how people might use this to preserve current status quo versus how can you avoid that?” (iC3) 7. “simplicity and transparency are very, very good starting points. So is the assurance of payment that I'm assuming sort of sits at the heart of the blockchain pieces but if there was still someone who's got to press the button about whether or not you get paid, and there's a subjective element sitting in the contract behind it, you might not get the shift that you want. The other thing that's bouncing around is that people think all risk sits inside a contract. And that's not the case at all. So, just the choice of which contract you choose to use and the capacity to deliver the nature of the human behaviour pieces that sit behind a successful project, you can't write this stuff into contracts, the decision making ability. So, I suppose if what you're trying to do is take a contract and embed in a more transparent system, logical decision making, more assurance around cash flow, and putting them into a system that simpler then it's certainly better than the status quo.” (iC3) 8. “if you can have the system drive more upfront planning and organisation and transparency, then that in itself is clearly identified as an ongoing, recurring issue in the industry” (iC3)
iCD	Considerations for the iContract	1. “if a government is already a coercive government or prescriptive government implements this, it's very different to that being implemented horizontally in a market” (iC1) 2. “one of the biggest challenges is having a central source of truth that lasts throughout the whole project lifecycle, having a uniformity of data format, having standardisation of data” (iC6) 3. iC1 commented that the challenge of realising the iContract is at the “process layer, not at the data [layer]”

Code	Theme	Quotes
iCE	Benefits	1. “I think not only with iContract, but with all innovation in construction, is this issue of democratising the benefit. So it doesn't matter how attractive the technology or innovation you go with to the project parties, if it's not beneficial for everyone, they say, “What's in it for me?” … the technology has to offer some form of democratised benefit to facilitate its adoption” (iC5) 2. “simplicity and transparency are very, very good starting points” (iC3)
iCF	Possible projects for the iContract	1. “Real binary things or process. So if you've gotten any situations or certain things having to be done that can be automated. So you've got concrete sensors, releasing payment, when it reaches a certain strength there's no reason now why you can't do that when it comes to software contracting” … “So things like, say, you've got the NEC contract, and you've got set tangible durations for responding in certain points in time, you know, like, that's quite good. I think you could automate aspects of that, if you haven't met these criteria, then, you know, you can't realise the benefits or you lose your rights under the contract. If you've got things like concrete sensors, then you want to release the payment when the concrete's reached a certain strength. I think you can do that. I don't see any reason why, I mean, mechanically, with technology, I think you can do that. I can see why it wouldn't happen as part of people and process. But I think it's I think it's definitely plausible.” (iC4) 2. “One where the contractor is trying to drive efficiency in its downstream supply chain, and it has a lot of control in that scenario, or otherwise, in an alliance / collaborative scenario where the financial motivators have been where the overall best for project motivations have been shifted to the point that you actually have owner and contractor buy-in to run in an iContract model. As opposed to a traditional, where we're at loggerheads, master-slave type relationship” (iC3) – iC8 in agreement … 3. “And the reason I'm saying that, I think is one of the complexities is that in a traditional [design and construct] D&C hard dollar contract model, there's so much competitive advantage to a contractor to have the information asymmetry, then they'll be reluctant to what do they get in return for having all of this information? Now, there'll be a point where it will all be there and a clever owner might force them to lose that power. But finding the niche in the ecosystem to prove it, rather than the hardest spot might be the way to go.” (iC3)
iCG	Complexity	1. “The whole industry has got so many parts that you don't know what's going to pop up down the track, a change in regulatory framework or a change in unions or any number of things could pop up and make a system difficult to implement in practice” (iC3) 2. “I don’t think technology is the barrier, it's going to be the people and the system and changing it” (iC3) 3. “regulatory frameworks works, you know, are the least susceptible to change like these that these are the last two to change” (iC1) 4. “My worry is the length of supply chains and the nature of supply chains” (iC8)
iCH	Plausibility	1. “very plausible within five years in isolated instances.” (iC8) 2. “I think it's plausible.” (iC4) 3. “I think trying to do a whole contract is challenging.” (iC4) 4. “if you're dealing with terms like, in the opinion of the engineer, I think that might that would cause immense problems” (iC8)
iCI	Prerequisites	Pilot 1. “Different types of works under different types of contract - main contract, subcontracts, employment contracts?” (iC4) 2. “I think the pilot project should target a project team that already advanced in collaborative thinking – for example, a team that is either part of an integrated supply chain, and/or are implementing Integrated Project Delivery or similar. This will provide some usability data while neutralising some of the other aspects that increase complexity beyond the target 5 years.” (iC1) 3. “This is required to develop/define potential benefit metrics” (iC7) 4. “Needs to systematically identify and enable clear use cases/applications, ensure all enablers are in place; a clear list of performance measures /KPI to be measured.” (iC5) 5. “I don't think one pilot is going to cut it” (iC4) 6. “A successful pilot will require a client and a prime contractor to be willing to test this on a project/range of projects in a portfolio.” (iC2)
		Mainstream adoption 5. “Cost…” (iC4) 6. “Scaled and proven benefits/value” (iC4) 7. “Reliability of/trust in new system. Level of complexity” (iC5) 8. “Acceptance of Project Bank Account or Trust” (iC6)
		Technology 9. “Uniformity of data (Standardisation) Or translator service 3rd party IPAAS” (iC6) 10. “Focus on mobility and ease of use to improve adoption of the solution. If this can be connected to RFID or QRCODES, then adoption may be facilitated due to ease of use” (iC1)
		Process 11. “Who owns and operates the iContract after practical completion (i.e., during the defect notification period)?” (iC7) 12. “Do contract clauses need to be re-written? Are they ready to be "Smart"?” (iC4) 13. “Who creates and then who administers the SC?” (iC4)
		Policy 14. “The main policy challenge would be encouraging government clients to adopt this; this would be a significant driver of adoption within the private sector. The improving the efficiency and visibility of contractual terms would encourage Government to do this.” (iC2) 15. “One of the main benefits of such a solution is the increase in transparency. So focusing on this as one

Code	Theme	Quotes
		method of fighting corruption would be a good strategy to encourage policy makers to enforce such a solution” (iC1) 16. “Has potential to rebuild trust in cash flow through the supply chain in way that legislation hasn’t” (iC3)
		Society 17. “Will it be used to abuse end of the supply chain - commodify trade contractors (the Uber dilemma)” (iC3) 18. “How do we build peoples trust?” (iC4)
iCJ	External factors	Policy 1. “Reaction of JCT/NEC to this will be a major driver or inhibitor of uptake. As bodies, they have been consistently behind the curve when it comes to changes within the industry.” (iC2) 2. “Skills will be a major obstacle to rolling this out - construction is one of the least digitised sectors of the economy, and most firms lack the knowledge and skills to use these technologies effectively.” (iC2) 3. “Demand for greater transparency of process – audibility of government projects” (iC6) 4. “Do contracts/clauses need to be re-written/revamped?” (iC4) – see section on standard form contracts. 5. “Could it address quality issues in construction – e.g., products used with traceability and accountability” (iC3) 6. “Improve cash flow across industry and overcome issues that flow from this. Be an ongoing policy issue for government through security of payment legislation” (iC3)
		Technology 7. “Faster transactions. Cheaper than manual administration.” (iC4) 8. “Adaptability of standard forms into new forms of code? Especially if it's an alteration to the standard form.” (iC4) 9. “Integration & interoperability” (iC4) 10. “Technologies automating specific parts (a subset) of the contracts are more likely (standard forms often get modified).” (iC5)
		Society 11. “Audit – especially for taxpayers” (iC4) 12. “You won't know it's in the "blockchain", you just do it!” (iC4) 13. “Skills for developing iContracts and cultural acceptance” (iC5) 14. “GDPR is not a major issue – I don't see this creating more complications than other forms of digitisation. Cyber security is more of an issue – overall, this is poor in the sector, and unless it improves, all digital initiatives will be undermined.” (iC2) 15. “How will the role of project managers change - what will that professional body seek to influence?” (iC3)
iCK	Internal factors	Process 1. “New processes will be hard to embed unless supply chains do become more structured and long term. One option might be to focus on the offsite manufacturing firms in the industry as a starting point - they probably have smaller supply chains and more structured ones.” (iC2) 2. “Is it behaving correctly? Who can check the code/flow?” (iC4) 3. “quality and completeness of supporting artefacts (e.g., project schedules). But also SC drives proactive behaviours for better planning.” (iC5) 4. Discussion on vertical integration starting with iC1 (p. 21, 1:11:30 to p. 22, 1:15:04) 5. Also discussion on looking to manufacturing to learn from them: Mohamad, “in manufacturing is as new to them as is in construction. So it's the same level of newness and looking at the supply chain automation, as well, using some SC was in supply chain. And it's you look at the conversation is really recent 2019-2020, it's new as well, on the other side” (iC5)
		Technology 6. “Compatibility (integration with internal workflows or technologies)/benefits of technology. It would also depend on acceptance of other enabling technologies (QR codes, and other IoTs)” (iC5) 7. “Always easier to buy in systems like this as a service, i.e., if I were a firm, I would want a turnkey solution for the process, even if I had to train my staff how to use it.” (iC2) 8. “Where do you buy? How do you pay – SaaS?” (iC4)
		[Organisational] policy 9. “The main challenge is that organisations will need to be prepared to make an investment in the use of this technology, i.e., it is about a decision to move to using iContracts at scale, not a one-off experiment. This makes the case harder to make.” (iC2) 10. “What is the relationship with H&S systems and rules. Can it build efficiency or does it add complexity” (iC3)
		Society 11. “How can the technology be gamed to shift risk down the contract chain?? cf can it build trust.” (iC3) 12. “Shift in teams from the bidding team to the delivery team. Standardisation might assist that transition, but how could delivery team resist the iContract” (iC3) 13. “there's such low levels of trust in the construction industry? It's a non-trust based piece, do you deliberately design a piece of technology that rebuilds or enforces transparency and therefore trust? and creates that certainty about what has to be delivered and when and what you'll get paid? Or is it going to be like business as usual, because if you create business as usual, you're going to get more resistance to the adoption of the technology. Because business as usual, as a non-trust, sort of relationship. I mean, like making the last payment, will this, you know, if something that parties do is we'll get to the final payment, and then I'll change the rules of the game, and you don't get your last 10%. And so you'll lose money on the job? how, thinking through how people might use this to preserve current status quo versus, you know, how can you avoid that?” (iC3) 14. “simplicity and transparency are very, very good starting points. So is the assurance of payment that I'm

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		assuming sort of sits at the heart of the blockchain pieces but if there was still someone who's got to press the button about whether or not you get paid, and there's a subjective element sitting in the contract behind it, you might not get the shift that you want. The other thing that's bouncing around is that people think all risk sits inside a contract. And that's not the case at all. So, you know, just the choice of, you know, which contract you choose to use and the capacity to deliver the nature of the human behaviour pieces that sit behind a successful project, you can't write this stuff into contracts. The decision making ability, so I suppose if what you're trying to do is take a contract and embed in a more transparent system, logical decision making, more assurance around cash flow, and putting them into a system that simpler than, it's certainly better than the status quo" (iC3)
iCL	Risks	1. "Early implementation failure (> bad news) that would hinder the whole thing." (iC5) 2. "Integrating this with other initiatives e.g., skills and cyber security will be a huge challenge, but is critical to making this benefit the whole supply chain." (iC2) 3. "Coding – does it reflect the clause? (iC4) 4. "Errors. Ownership/operation of the platform" (iC7) 5. "Is there a risk with using the technology on too complex a project first." (iC3) 6. "As mentioned in the document circulated: rubbish in, will be a lot of rubbish out!" (iC1)
iCM	Opportunities	1. "Drive a culture of 'better info' in the industry" (iC5) 2. "Immutability. Clause execution enforcement" (iC7) 3. "Is there an opportunity for funding bodies to require the use of an iContract in order to minimise corruption?" (iC3) 4. "Big opportunities are greater transparency and accountability, helping avoid disputes and increasing efficiency within supply chains." (iC2) 5. "A solution similar to the one discussed provides an opportunity to discuss multiple interconnected topics." (iC1) 6. "Cash flow and faster payments" (iC4) 7. "Drive proactive planning" (iC4) 8. "Improve transparency" (iC4) 9. "Data not documents... improve efficiencies through automation" (iC4) 10. "Stability of payment throughout supply chain" (iC6)
iCN	Limitations	1. "Does not resolve the key issues in the industry - the need for more collaboration, better risk management etc. So it is dependent on other initiatives to achieve maximum impact." (iC2) 2. "Reliant on sophistication of data available in any given project" (iC6) 3. "Need for flexibility in the code/written contract" (iC6) 4. "Will the lawyers trust the iContract" (iC3) 5. "Understanding Cost / Value" (iC4) 6. "Who is going to create? Who is going to administer?" (iC4) 7. "Can it be applied to all clauses?" (iC4) 8. "unlikely to achieve full automation of contract" (iC5) 9. "The level of knowledge needed - across domains - to implement the solution is quite high. This requires a lot of explaining, simplifying and demonstrating before stakeholders understand the need and see the opportunities it opens." (iC1) 10. "Skill shortages to operate iContract, storage of data after practical completion of a project" (iC7)
iCO	Open challenges	1. "The low level of digital skills in the industry is a key challenge; so is making the culture more open and transparent." (iC2)
iCP	Actions to achieve implementation	Technology 1. "data standardisation - especially for data exchange" (iC7) 2. "Standardisation of data across project lifecycle" (iC6) 3. "Integration with other technology - reality capture or sensors for automated actions, etc." (iC4) 4. "a successful pilot" (iC3)
		Process 5. "promote the idea at strategic level, support implementation (skills, pilots, etc.)" (iC5) 6. "Visualize the operation of clauses/provisions" (iC7) 7. "Review of the standard forms - are they ready to be "smart"" (iC4) 8. "promote use of standard forms of contracts" (iC5)
		Policy 9. "promote use of standard forms of contracts" (iC5) 10. "Championed by government / client" (iC4) 11. "Adoption of better data standards. sharing in the industry" (iC3) 12. "Securing organisational commitment to move to a system where digital supply chain management - whether contracts, payments or in relation to quality and performance is digitised." (iC2)
		Society 13. "evidence that the new process improved cash flows and reduced disputes" (iC3) 14. "Do they need to know it's a smart contract?" (iC4)
		General 15. "Value proposition" (iC4) 16. "Training - technical and awareness" (iC4) 17. "Credible evaluation of the likely economic benefits, and also how these can be increased by linking initiatives e.g., iContract plus quality management." (iC2)

Appendix G: Weather Ledger focus group data

Code	Theme	Quotes
WLA	Weather Ledger offerings	1. Ultra-local weather readings 2. Are current parameters appropriate? Once in a 10 year weather event – is that a good/fair measure in any case? 3. Discussion around parametric insurance – prevention of risk is a different mindset to what the insurances companies are looking at the moment. The different mindset could result in more time for the contractors on site to respond to predictions in weather events that allow them to better plan and mitigate risks that might occur so that's potentially very attractive to insurance companies. 4. "the main thing that we discovered wasn't that DLT is solving anything, it's actually that by having more shared access to information, whether that's client, contractor, insurer as well, and having better models and information, it prevents a lot of the risks that might lead to a compensation event even happening. And then the DLT is kind of your failsafe last ditch effort in the event that something does go wrong. Ideally, we want to we want to avoid costs as much as possible"
WLB	Challenges with weather compensation	1. "And ultimately, that the tools or things that are in place today to deal with weather risk aren't that sophisticated" 2. "Currently, there isn't that much, I guess, knowledge about what the actual price of weather risk really is people are sort of pricing it on a gut feel" 3. Current MET office weather data is not stored on a blockchain, "they just have records and they are sitting there"… "weather is being broadcast in the internet, and they normally have a source, but maybe that's, that's not in the blockchain. And therefore, it's not a resilient option" 4. Weather data is often far from the construction site so the data is not "local" as it can be up to 100 miles away. 5. "insurance sector generally is quite slow to move"
WLC	From other industries	1. Regarding government working with industry to develop regulatory frameworks: "I guess we've seen that kind of stuff happen in the banking space with open banking, and more recently, the legal space, there's a lot x sandbox. So traditionally, this kind of industry has been slow to kind of move in that direction, but Fingers crossed construction could be one of those." 2. "if you look at the at ATI, the Aerospace Technology Institute, where we also do some work, funded by big aerospace companies, and then matched by government, so that it becomes a pot that aerospace projects can get into, and they have a kind of like in a innovate, like, format. So they run on the innovate rules. And they put out competitions, just like innovate, but it's specific for aerospace industry challenges. So if construction were to adopt something similar, where they're paying for their own benefit, so the larger people put in more, the smaller people put in less, but it sets aside a pot that government matches against, you know, that that could potentially lead to better structured research in in the construction sector. Other rather than waiting for the next construction led call coming out of innovate, for example, that's, you know, that's just it." – how do you get construction to buy-in when there's such low levels of R&D investment and such low profit margins?
WLD	Considerations for the Weather Ledger	1. "what happens to a contract after there's been some sort of dispute. And once it's resolved, how does the outcome of that actually ended up back on chain again? So how do you kind of update the state or do some kind of compensation transaction to get the state of the DLT back to what everybody agrees is what it should be. And that's not something that's easy to do, or will be resolved overnight, I would think but it's, it is something that we're kind of looking at and thinking could be relevant here" 2. Potential for the Weather Ledger: "the data is gold thing has reached the construction industry, and everyone wants to try to get more visibility. And so that, you know, that's, if that can continue to happen, then then there's huge opportunity to use that data to create smart agreements. Yeah, I think maybe that's what a number of these are about sort of, you know, now that one thing, or that now that there's a number of things being developed? That will only sort of increase as more data is made available?" 3. "first instance was when there were issues with the IoT devices, not being able to draw enough power in some cases. So we put in a backup, we put in a backup data source, which is written into the amendment as well. So both you have if you're going to deploy it as an IoT device on site, you would then also have a backup source. Even if you have are just using another source, you probably would have another backup. I guess, it's I don't know if our common break is written into the amendment, or probably as long as there isn't a contamination of both your data sources, where you can always just still default to those data sources and, and discuss them" 4. "the good thing is, like we identified earlier, it's not not massively complex. And within the NEC, at least as sort of timing constraints provided for how when when you have to make these notices, as if, right now, it's instantaneous. So if we were to find an error, relatively quickly, there would still be time to fulfil the traditional process. Probably" 5. Consideration for digitalisation: "getting the young people are getting young, project managers who are coming through the system, aware of what's on the horizon. So that's maybe a university or training thing. But they're not going to be decision makers. They're not going to have power to actually enact or make decisions for many years. So you do have to hit the top of the food chain at some point." 6. Considerations for any application (?): "how do we engage NEC, JCT, fidic, etc, on some of these things? Because I imagine and know, clearly that lots of people are thinking and developing different parts of this. Is there a way to coordinate better, so that it's not just lots of different entities building different things. And there's some sort of Confluence. And maybe those are the organisations to sort of help enable that. Because then, by partnering with all of the groups who are developing these things, we're to partner with them. And in theory, there's the benefit to them in that, you know, they're getting their whole suite of contracts upgraded, and then there's a benefit entities, whoever they may be, to get, you know, getting

Code	Theme	Quotes
		their software out there more quickly.”
WLE	Benefits	1. “the majority of the cost savings come if the client can achieve a lower initial price of the contract and if the contractor can increase their chance of winning their bid. You know, they're like, from a cost saving perspective, as we found in the grant costs are nothing to sort of jump out of bed for in terms of the savings that they actually make, because ultimately, weather compensation events aren't the most common, they may be in the top 15, or 20. So from that perspective, it's all about probably differentiation and competitive advantage for the contractor. And then, you know, the potential to have a reduced price.”
WLF	Complexity	1. The main issue around complexity is of the governance structure. The Weather Ledger pilot had a several organisations involved and most were willing to participate as necessary but this was backed by Innovate UK funding so the participants did not have “skin in the game”.
WLG	Plausibility	1. The application for the Weather Ledger already exists and the pilot project shows it works. However, there were issues with deploying the application directly to the project so it was ran as a simulation but with real-world data collected by IoT weather sensors on site. The app will continue to be developed so by the time we reach 2025 it will be integrable into existing systems. Given the scope of the project and the small area of focus, it is very plausible that this application be adopted by the sector.
WLH	Prerequisites	Pilots 1. “Grant was a shadow run - now to actually have decisions being made by the contracts.” – post-it 2. “Adding and trialling additional clauses or conditions” – post-it 3. “Payment release after stages are confirmed to be complete” – post-it 4. “Money?? - E.g ATI model?” – post-it 5. Actual pilot – the weather data “wasn't recognised by the clients in those conversations” – the pilot was “shadow running” so the data collected on the construction sites was not recognised by the clients.
		Mainstream adoption 6. “Money?? - E.g ATI model?” – post-it 7. “Integration with Digital Twin platforms” – post-it 8. “Closer collaboration with NEC, JCT, FIDIC etc.” – post-it
		Technology 9. “Robust IoT devices for on-site deployment, with appropriate battery life, connectivity, etc” – post-it 10. “Leverage AI/ML” – post-it 11. “Trust in technology” – post-it 12. “Open Banking for automated payments” – post-it 13. “Standard tested and trusted legal clause implementations” – post-it 14. “Trusted data 'supply chain' from IoT device into ledger - legal backing or testing for oraclised data” – post-it
		Process 1. “Trusted data 'supply chain' from IoT device into ledger - legal backing or testing for oraclised data” – post-it 2. “Better weather modelling to enable more accurate pricing (Enhanced Planner)” – post-it 3. “Legal & commercial teams briefed so they can use the tool for pricing at bid stage” – post-it 4. “Standardised deployment of sensors” – post-it 5. “Lightweight governance model for managing or working through collaborative digital infrastructure” – post-it
		Policy 1. “Suitable regulatory frameworks” – post-it 2. “having a suitable regulatory framework is often needed to act as a pull. But it can also act as a push” 3. “I think DLT frameworks will come to generally not just for the construction industry, but I think in order for this particular application and construction, I'd be surprised if someone wasn't working on a regulatory framework to help with that push and pull system.” 4. “Legal testbeds or trial cases for SCs” – post-it 5. “Trust in the data sources and providers” – post-it 6. “Improved Online Dispute Resolution” – post-it
		Society 1. “Education around the technology/usage” – post-it 2. “Enhanced sustainability through more efficient working and resource allocation” – post-it
WLI	Internal/ External factors	Technology 1. “Business model for deploying and managing IoT sensors in the field - are these brought in by the construction companies and the ledger is the infrastructure?” – post-it 2. “If Met Office begins to offer hyperlocal weather service” – post-it 3. “Greater interoperability of data - to contribute to other facets of SCs” – post-it
		Process 4. “Site workers being happy with IoT devices - will they be maintained correctly? Who will be responsible?” – post-it 5. “Confidence in the technology - knowing THAT it works, not caring HOW it works (think about email on your phone - everyone uses it)” – post-it 6. “Insurers being part of this” – post-it 7. “Lawyers being part of this” – post-it
		Policy 8. “Legality of SCs” – post-it 9. “Skill of planners in weather modelling” – post-it
		Society

Code	Theme	Quotes
		10. “Technical literacy and adaptability of relevant parties (e.g., project managers) to use new digital tooling” – post-it
WLJ	Risks	1. “Ends up creating a more complex process (even if that is a better risk process)” – post-it 2. “No one's gonna sign up to a smart contract, if it doesn't actually create an outcome that's better for them. And to create a better outcome, we need to do some work upfront to actually calculate probabilities of events different, you know, we can't just rely on the one in 10 year, because actually doesn't, isn't that suitable for actually managing weather risk is fine for being a standard clause in a contract? So, you know, the product we're building is a risk management tool, it's not a DLT tool. So our objective is to manage risk better. And that may result in you know, the DLT being more a complicated process, it might have a much, much better result. It might be simpler. That depends on how comfortable people within the commercial team are and taking some of those decisions, which affect the risk profile of a project. And you know, could in theory, have hundreds of 1000s of pounds worth of sort of difference from what the current method results in? That makes sense?” 3. “Challenger enters market with part of offering e.g., IoT devices brought on site by construction companies, offered by Met Office” – post-it 4. “Legal or process barriers in way of enabling full-service offering (end-to-end: weather-> ledger-> SC-> payments)” – post-it 5. “Defective readings” – post-it 6. “Clients may not pay for the tool - resulting in lower uptake from contractors” – post-it 7. “Accurate cost benefit or creation and maintenance” – post-it
WLK	Opportunities	1. “Greater transparency” – post-it 2. “New functionalities to enhance Smart Legal Contracts” – post-it 3. “Cost savings, improved profitability, workers only on site when able to work” – post-it 4. “Wedge to get more advanced tech to enter construction” – post-it 5. “Possibility of new value propositions” – post-it 6. “Reduced operation and dispute costs” – post-it 7. “Just starting point for greater use of SCs” – post-it
WLL	Limitations	1. “Potentially replaceable for site future toolkits” – post-it 2. “"Not invented here"”– post-it 3. “when someone says, “Oh, we've already got a process for that. We don't need that, or I don't like the way this looks, you know, we're not gonna use that tool.” So just very human, very petty human factors” 4. “Luddites” – post-it 5. “How do you get companies to agree to or operate shared digital infrastructure” – post-it 6. “Complexity of implementing legal agreements and clauses as currently written” – post-it 7. “Digitisation effort needed” – post-it 8. “Contractors make money from subjectivity... Will they act against their own interest?” – post-it 9. “ultimately, whether it's right or wrong, people see their ability to fight over a claim as a way to make more money. And clearly, this, you know, you have to set a line in the sand with a smart contract. This is your risk threshold, and this is the price of your risk. Are people willing to actually do that, even if, you know, a model tells them with, you know, objective data, this is the probability of impacts, and this is the costings that you're putting in is the potential waterfall of impacts. They might just still say, Well, I don't want to sign up to that, because we feel that we could argue for more, even if the case isn't true, as Chris did, you know, often when they're making a claim, they'll only get 80% of that claim at best. So even even if there is almost to do with the perception of their ability to be able to fight for more money, rather than necessarily, you know, having a easier outcome. So, yeah, again, it's like an entrenched, I guess, attitude.”
WLM	Actions	Technology 1. “Head-to-head testing of smart legal contract frameworks” – post-it 2. “EHAB - keep making the tech better!” – post-it 3. “Sustainable and predicable cost of execution (not subject to high gas/oracle costs)” – post-it
		Process 4. “Clients to demand use of ledger” – post-it 5. “Just thinking that normally when you have like a novel technology like these when they when clients demand that in their projects, the adoption is much easier.” … “it's not a kind of final. Final strategy, but it's a it's a intervening strategy that helps adoption. you need more visionary clients” 6. “I guess that the, you know, the contractor pitching it to the client and sort of convincing them is definitely really appealing in contract tickers, you could argue that that helps differentiate them and their bid and you know a lot of things. Yeah, I'm sure you could argue around that. I think that's still a bit more difficult route from the sense of how do you make it diffuse quickly? That being said, Maybe if we're just talking about early diffusion and adoption, then that will be where it will come from.” 7. “Clients awareness/buy-in is key” – post-it 8. “Partnerships that empower consultants + lawyers of clients to get benefit from putting SCs in place” – post-it 9. “Clients to have more awareness of weather exposure” – post-it 10. “Contractors to have more awareness of weather exposure” – post-it 11. “The implementation of this process cannot cause delays to the project start” – post-it
		Policy 12. “Law society for smart legal contracts to give comfort to sector” – post-it 13. “Commissioning groups / government clients need to ask for digitised worksites” – post-it 14. “blessing of JCT/NEC” – post-it

Code	Theme	Quotes
		15. “Heads of major firms to embrace digital technologies and/or experimental mindset” – post-it 16. “Government backing of interactions between ledger-based systems and financial infrastructure (i.e., ledgers posting transaction requests to banks)” – post-it 17. “ISO/BSI work on smart legal contracts” – post-it 18. “does this need to be tested in a legal context? Is a ruling needed?” – post-it
		Society 19. “Demand for more accountability from construction sector on sustainability, proving events on site” – post-it 20. “if you can minimise workers on site or equipment call to site or equipment used, when actually it's not able to be used, you know, more effective, efficient project scheduling is less fuel burned, less dust kicked up, you know, all of this, all of these knock on effects in terms of local pollution sustainability, that everyone's more and more concerned about, of course, it doesn't talk to the longevity of the project, or the materials used the sort of bigger sustainability aspect, but it does contribute in a small way to informing the informing, you know, both the clients and the and the local people that this project's being done correctly” 21. “More willingness to take up advanced digital technologies” – post-it 22. “its demonstration and education, those the only ways that we think it's going to be realistic is perhaps even have a demonstration worksite, You know, that's, that's full of advanced digital tech, where people are invited to come and have a play, have a look and get over the fear barrier, you know, the fud barrier.” 23. “A green agenda” – post-it 24. “just saying that as a society action, you know the greenwash should be should be presented, that the green is strategy and how those makes construction more sustainable, etc.” 25. “the construction industry needs to accept more transparency” – post-it
		General 26. “Education/exposure to benefits to help with willingness” – post-it 27. “I think it has to be across all levels. There's multiple players involved in different sectors if you include legal and insurance as well. So I think it has to be across multiple levels and considering different sectors. And in terms of what education, someone's already put case studies, which I think is a great idea. Case studies, involving different partners or from different perspectives is also very powerful.” 28. “Digital community / DLT community / IoT community need to let policy makers know this tech exists and should be used!” – post-it 29. “National advanced construction demonstrator sites to showcase advanced technologies and overcome FUD” – post-it 30. “More case studies to highlight benefits” – post-it 31. “how do you price a smart contract?” – post-it

Appendix H: Evidence for the macro roadmap

The codes in the following table correlate to the codes in Appendices F, G and K unless otherwise indicated by an academic reference.

Action	Evidence
Scope of Requirements (SoR)	Macro validation comment 24 (Appendix K)
Taskforce (TF)	iCD; iCD.1; WLM.16; (Garcia and Bray, 1997, p. 18); (Ahmad *et al.*, 2013)
Sector Engagement (SE)	iCJ.1; iCP.5; iCP10; iCP.14-15; iCP.17; WLH.26-27; WLL; WLM.12-16; WLM.22-24; WLM.26
Regulatory frameworks (RF)	iCG; iCI.14-16; iCP.11; WLM.17
Infrastructure (IN)	Macro validation comment 3 (Appendix K)
Upskilling (US)	iCJ.2
Research & Development (R&D)	WLM.1-3; WLM.22
Benefits Management (BM)	iCI.5-8; iCP.13; iCP.15; iCP.17

Appendix I: Evidence for the meso roadmap

The codes in the following table correlate to the codes in Appendices F and G unless otherwise indicated by an academic reference.

Stage 1: Assess		
Tasks	**Focus group quote / academic reference**	**Actor responsible**
S1.A1	(Garcia and Bray, 1997, p. 18)	Primary: system architect, or innovation leader
S1.A2	iCA.2	Primary: Taskforce, current system owner. Secondary: users
S1.A2.1	(Glass, 1997, p. 91)	
S1.A2.2	iCA; iCI.12; iCJ.4	
S1.A2.3	---	
S1.A2.4	---	
S1.A2.5	iCA; WLB	
S1.A3	iCB	Primary: Taskforce. Secondary: users
S1.A4	iCB	Primary: Taskforce
S1.A5	iCH; WLJ.7; (Glass, 1997, p. 91)	Primary: system architect
Stage 2: Scope		
Tasks	**Focus group quote / academic reference**	**Actor responsible**
S2.A1	---	Primary: Taskforce. Secondary: users of existing system; users of new system
S2.A1.1	---	
S2.A1.2	---	
S2.A1.3	iCI.17-18	
S2.A2	iCD.2; iCN.10	Primary: system architect in consultation with users.
S2.A3	iCJ.1; WLB; WLH.6-8; WLI.4-5; WLM.7-8	Primary: taskforce
S2.A3.1	iCJ.1; WLH.6-8	
S2.A3.2	---	
S2.A3.3	---	
S2.A3.4	---	
S2.A3.5	WLB; WLI.6-7	
S2.A3.6	iCJ.1; WLB; WLH.6-8; WLI.6-7	
S2.A4	iCI.5-8; iCK.9-10; iCL.2; iCP.3; WLD; WLH.1-5; WLH.6-8; WLH.15-19; WLH.25	Primary: Taskforce, system architect. Secondary: users
S2.A4.1	WLD	
S2.A4.2	iC.6; WLI.3	
S2.A4.3	WLI.1-3; WLI.4	
S2.A4.4	iCD.3; iCI.5-8; iCK.9-10; iCN.1; WLD; (Kasunic, 2004)	
S2.A5	iCJ.2; iCJ.11-14; iCK.13-14; iCN.10; iCO.1; WLD.5; WLH.24	Primary: Taskforce, system architect. Secondary: users
S2.A6	iCG; WLH.20-23	Primary: taskforce, system architect. Secondary: political authorities, policymakers
S2.A7	iCD; WLE; WLH.19	Primary: taskforce
S2.A7.1	iCD; (Hackitt, 2018)	
S2.A8	iCC; iCK.9-10; WLL	Primary: taskforce, system architect. Secondary: users
S2.A9	iCE; iCM; WLE	Primary: taskforce. Secondary: users, beneficiaries
S2.A9.1	iCE.1	
S2.A9.2	iCI.17-18	
S2.A9.3	---	
S2.A10	iCI; iC.1; iCK.5; WLC	Primary: taskforce
S2.A10.1	iCI; iC.1; iCK.5	
S2.A10.2	iCI; iC.1; iCK.5	
S2.A11	iCF; WLM.27; WLM.29; (Kasunic, 2004)	Primary: taskforce, system architect. Secondary: users
S2.A11.1	(Glass, 1997)	
S2.A11.2	iCC.2; iCC.3; WLD.6; (Kasunic, 2004)	
S2.A11.3	iCF; iCN.9; WLH.1-5; WLM.22	
S2.A11.4	iCN.9; WLH.1-5; WLM.22	
S2.A11.5	(Kasunic, 2004)	
S2.A12	WLC; WLH.1-8	Primary: taskforce
S2.A13	---	Primary: taskforce. Secondary: policymakers, political authorities
Stage 3: Develop		
Tasks	**Focus group quote / academic reference**	**Actor responsible**
S3.A1	WLH.9-14	Primary: system architect
S3.A1.1	iCI.5-8; WLH.9-14	
S3.A1.2	WLH.9-14	
S3.A2	---	Primary: system architect. Secondary: users

S3.A2.1	iCG; WLH.20-23	
S3.A2.2	iCI.9-10	
S3.A2.3	---	
S3.A2.4	iCI.9-10; iCN.2; iCP.1-2; WLH.14	
S3.A2.5	iCK.6; iCP.3; WLI.3	
S3.A3	Follow on action from S2.A11	Primary: taskforce. Secondary: users
S3.A3.1	Follow on action from S2.A12.3	
S3.A3.2	iCE.1; iCI.17-18	
S3.A4	iCJ.14	Primary: system architect
S3.A5	WLH.15-19	Primary: taskforce. Secondary: system architect, users
S3.A6	iCP.4; (Kasunic, 2004); Follow on action from A2.13	Primary: taskforce. Secondary: users, pilot delivery team, pilot participants
S3.A6.1	---	
S3.A6.2	iCI.5; (Kasunic, 2004)	
S3.A6.3	Glass (1997, p. 92)	
S3.A6.4	(Kasunic, 2004)	
S3.A6.5	---	
S3.A6.6	Glass (1997, p. 92); (Kasunic, 2004)	
S3.A6.7	(Kasunic, 2004)	
S3.A6.8	(Kasunic, 2004)	
S3.A6.9	iCJ.2; (Kasunic, 2004)	
S3.A6.10	(Kasunic, 2004)	
S3.A6.11	(Kasunic, 2004)	
S3.A6.12	iCI.4; (Glass, 1997, p. 91); Wyler (2021)	
S3.A6.13	iCI.4	
S3.A6.14	(Glass, 1997, p. 91)	
S3.A6.15	(Glass, 1997, p. 92)	
S3.A6.16	(Glass, 1997, pp. 92–3)	
S3.A6.17	iCI.5	
S3.A6.18	WLD.3	
S3.A7	iCJ.7-10; iCL.3-5; WLH.23	Primary: system architect
S3.A7.1	iC.2; WLM.1	
S3.A7.2	WLA; WLJ.2	
S3.A7.3	iCK.6; WLI.3	
S3.A7.4	WLI.8; WLM.18	
S3.A7.5	WLH.13	
S3.A7.6	WLM.12	
S3.A7.7	WLH.1-8; WLJ.6; WLM.31	
S3.A7.8	WLH.15; WLJ.5	
S3.A8	WLH.1-8	Primary: taskforce
S3.A8.1	iCB.1; iCK.7; iCK.8; iCK.9; WLH	
S3.A9	iCP.3; WLD.1; WLH.25; WLJ.4	Primary: taskforce
S3.A10	WLH.26-27	Primary: taskforce
S3.A11	iCD; WLE; WLH.19	Primary: taskforce
S3.A12	iCJ.2; iCJ.11-14; iCO.1; WLD.5; WLH.26; WLI.9-10	Primary: taskforce. Secondary: educational institutions, service providers, industry associations
S3.A12.1	iCJ.2; iCJ.11-14	
S3.A13	iCJ.2; iCJ.11-14; iCO.1; WLD.5; ; WLH.26; WLI.9-10	Primary: educational institutions, service providers, industry associations
Stage 4: Pilot		
Tasks	**Focus group quote / academic reference**	**Actor responsible**
S4.A1	Follow on action from S3.A6.17-8	Primary: taskforce. Secondary: service providers, system architect, technology providers
S4.A2	Follow on action from S3.A6	Primary: taskforce. Secondary: pilot delivery team
S4.A2.1	Follow on action from S3.A6.15	
S4.A2.2	Follow on action from S3.A6.12	
S4.A2.3	---	
S4.A3	Follow on action from S3.A3	Primary: taskforce
S4.A3.1	WLA.2; WLE	
S4.A3.2	---	
S4.A3.3	---	
S4.A3.4	WLJ.7	
S4.A4	iCL.1	Primary: taskforce. Secondary: pilot delivery team
S4.A4.1	---	
S4.A4.2	WLK	
S4.A4.3	---	
S4.A4.4	WLJ.4	
S4.A5	Follow on action from S3.A2.3	Primary: taskforce. Secondary: users, pilot delivery team
S4.A6	---	Primary: taskforce, system architect

S4.A7	iCP.12; (Kasunic, 2004)	Primary: taskforce
Stage 5: Refine		
Tasks	**Focus group quote / academic reference**	**Actor responsible**
S5.A1	Follow on action from S4.A6	Primary: system architect
S5.A2	Follow on action from S4.A6	Primary: taskforce, system architect
S5.A3	WLH.26; WLI.9-10; WLM.26	Primary: educational institutions, service providers, industry associations
S5.A4	WLH.15-19; WLH.18	Primary: taskforce
S5.A4.1	---	
S5:A5	iCI.3	Primary: taskforce
Stage 6: Adopt		
Tasks	**Focus group quote / academic reference**	**Actor responsible**
S6.A1	---	Primary: taskforce
S6.A1.1	---	
S6.A2	WLH.1-8; WLJ.6	Primary: taskforce
S6.A3	WLI.9-10; WLM.26	Primary: educational institutions, service providers, industry associations
S6.A4	---	Primary: taskforce

Appendix J: Questions asked to participants of the roadmap validation survey

1. How easy do you think the ***macro roadmap*** is to understand?
    - Very easy
    - Somewhat easy
    - Somewhat difficult
    - Very Difficult
2. How representative do you think the ***macro roadmap*** is in meeting the needs of the sector to achieve digitalisation through DLT and SC integration?
    - Very representative
    - Somewhat representative
    - Marginally representative
    - Not at all representative
3. How useful is the ***macro roadmap*** in fulfilling its intended purpose – to support the sector in reaching a state of readiness to adopt DLT/SC applications?
    - Very useful
    - Somewhat useful
    - Marginally useful
    - Not at all useful
4. What do you think would make the ***macro roadmap*** more effective?
    (Open question for optional comments.)
5. How easy do you think the ***meso roadmap*** is to understand?
    - Very easy
    - Somewhat easy
    - Somewhat difficult
    - Very Difficult
6. How representative do you think the ***meso roadmap*** is in meeting the needs of the sector through implementing DLT and SC applications in construction?
    - Very representative
    - Somewhat representative
    - Marginally representative
    - Not at all representative
7. How useful is the ***meso roadmap*** in fulfilling its intended purpose – to support development and implementation of DLT and SC applications in construction?
    - Very useful
    - Somewhat useful
    - Marginally useful
    - Not at all useful
8. What do you think would make the ***meso roadmap*** more effective?
    (Open question for optional comments.)

Appendix K: Validation comments on the roadmaps

Comments on the Macro Roadmap

Note: comments are copied verbatim from the survey, hence, typos and grammatical errors remain.

	Macro roadmap - comment from open question	How the feedback was addressed
1.	Assigned dates and owners/responsibilities. There are a lot of parallel tasks with long durations. The detailed breakdowns are useful but haven't seen them all overlaid. You could perhaps indicate/heat map where the largest effort is for each of the "A" tasks. However, appreciate it is high level and at the beginning of the journey, so the information may come at a later date.	To be considered for future development of the roadmap.
2.	It should be extended to show differences of adopting blockchain for different purposes in construction	This included in Action 1 – SoR.T8.
3.	I think the links between regulation, standard legal contracts and the underlying DLT implementation(s) are important. As the overall solutions in this space will not be successful unless these are all aligned. Having a layered approach, like in other aspects of software solutions is a worthwhile approach, so there is a separation key concepts and their dependencies, especially as the landscape evolves and different DLT solutions will come along, and others will likely fall out of favour. For example, having standards-based contracts expressed in formats like legals schema/Accord Project allows separation between the contract definition and implementation on a number of different DLT solutions	Standardisation of smart legal contracts has been captured in the revised version of the roadmap in the *DLT/SC Infrastructure* action. The inclusion of the task considering DLT/SC technologies in SoR also address this to an extent.
4.	A diagram that shows relationships with other digital technologies and vectors o change in the industry.	Excluded for being out of scope. It will be considered in future work.
5.	Easier to understand for non-tech ppl; consider imminent and future developments.	More detail has been added to each task to make it clearer for all audiences.
6.	Identify specific use cases in order of benefit	This has been captured in the *DLT/SC Taskforce* action.
7.	The macro roadmap is clear and extensive however maybe it could be more focused on the targeted sector	The terminology has been made to be more construction-specific.
8.	appreciate it is a macro roadmap, but more understanding of what flows on from what would be good.	Arrows showing the relationships between tasks and actions have been included.
9.	it is quite difficult to comment on just the 8 action headlines - I would need to look at and understand more of the detail within each action and what is achieved over the course of the 24 months - e.g., what are the outputs and deliverables within each action? Does sector engagement include dissemination of the results of R&D and pilots? Does benefits management include identification and assessment of potential market size and opportunities that would help commercial organisations justify the investment required to develop/implement/adopt DLT/SC applications? what happens beyond 24+ months? presumably the Taskforce will not be required after a certain point, and the initial infrastructure requirements will be in place - it may be useful to indicate when some actions would be completed	Additional tasks or amendment of existing tasks have been included to cover these comments. The end point of the taskforce is too early to state at this point in time this comment has been addressed in text.
10.	I think associated "worked" examples (where possible) would help bring understanding to the target audience within the different sections.	This will be included in future work.
11.	I believe that scoping and sector-wide engagement would be linked more closely, with R&D following that to demonstrate capabilities and benefits of this technology, followed by infrastructure development based upon what is discovered during R&D	While the actions are not intended to be in priority order, there are links between them and therefore the order of the actions had been changed to reflect this comment. {scope, engagement, R&D, infrastructure} Links between tasks from different actions have also been included.
12.	There are current initiatives that are creating momentum and shift change within the sector such as the IPA's transforming infrastructure roadmap alongside digital transformation changes in government/organisations i.e., National Highways Digital Roads. I believe by incorporating these developments in terms of government/industry focus alongside staggering the A3-A8 tasks would make the roadmap more clear and show that not each element has the same timescale or prioritisation.	Timescales have been revised based on this and other comments and description of the timescales across and within actions given in the body of the thesis.

	Macro roadmap - comment from open question	How the feedback was addressed
13.	I understand the A3-A8 elements as parallel actions/tasks. I believe A7 and A8 should inform / be the drivers for A3-A6 and therefore should be the first elements	The order has been changed to reflect this and other comments as best as possible though the comments are conflicting with regards order.
14.	There's quite a lot of information on the roadmap to get a good understanding of it in one short video. What I was trying to figure out was what tasks were involved with each activity, whether or not there was enough time to complete these and if the tasks could provide the required outputs for the activities. Maybe having some core outputs listed under each activity might help provide a bit more clarity about the proposed outcomes.	This level of detail will be included in further work.
15.	More written and transparent information about each item	More detailed information for each task and clearer links have been included.
16.	The inclusion of educational materials catering to different roles and responsibilities across sectors.	Updated to reflect this.
17.	The macro roadmap proposed sounds complete and sound! It might gain in more clarity if relationships/dependencies between Actions, Aubactions, and Tasks would have been defined. That would help identifying (later...) what input and output are expected for each task and what would be the critical path for the whole planning.	Identify the inputs and outputs for each task, critical path for the entire plan will be considered in the next iteration of the roadmap.
18.	Because there are only really two start phases - a different format might be more useful	The two starting actions are required to drive the remainder of the roadmap, the actions of which can run in parallel. The level of resources will depend on which actions and tasks are prioritised by the taskforce, staggering may be the option.
19.	The timeline seems too simplistic considering the activities and actors involved. It's comprehensive enough looking at the overall scope considered.	Timeline will be revised once a taskforce is in place based on resources and each action is likely to be broken down into small tasks and subtasks. It is designed to be a relatively short timeframe to push the sector to work quickly rather than stick to the pace they are current used to.
20.	The list of actions is helpful, but the timeframe is suggesting an accuracy that I doubt can be really known. I would prefer a relative timeframe, e.g., how long something is expected to take relative to the others. Also I wonder if some actions are more important than others? Do they really all need to happen in parallel? If A3-A8 is in parallel, what does the numbering mean? Why is A3 before A4? Overall, the timeframe and numbering is a bit unclear to me. I agree with the list of actions though.	The numbering does not represent priority of actions within the roadmap. It is intended for coding and identification of tasks. The A# has been removed and replaced with an acronym to represent the action.
21.	More precise actions for more precise actors. Not clear how will actually undertake the actions set out so far. It says "the sector should do this" as if the sector is a precise individual or organisation. Government? Professional bodies?	Actors assigned to tasks have been made more specific with regards who will undertake each task.
22.	The roadmap appears to give the impression we are at 'ground zero'. 24 months, although a typically reasonable timeframe, is long way into the future from the perspective of people/companies who have already innovated and commercialised DLT and/or Smart contracts in the construction industry. Because DLT and SC innovation is so 'Fast and Furious' regulation and governance will always have a hard time keeping up. We have current examples in the US regulatory battles with FinTech DLT/SC innovations. Maybe the there is an opportunity for a more Organic, Haphazard Road map which puts Funding and R&D at the Forefront... and allows true innovation to unveil a more 'Agile' approach?	The roadmap is designed to work alongside organisations/start-ups developing and advancing the technology. Many of these tasks and actions will be too slow for some developments but it is expected that the taskforce will keep abreast of advancements and account for them as the roadmap is delivered. The roadmap is a live artefact that should be reviewed and revised periodically to reflect activity within the sector.
23.	It should be relevant to have a vision clustering the Actors responsible for the task/action, e.g., the taskforce seems over-scheduled. That vision that integrated everything seems to indicate a waterfall methodology (based on the directions of the narrows). When I see the actions detailed, it appears to be a more interactive flow.	The roadmap has been updated to include more detailed interactions between the tasks within actions and across actions. The arrows from the figure giving a birds eye view of the roadmap have been removed.
24.	I think that in the initial stages it may be useful to compare blockchain technology with other technologies currently in use or under development in the construction sector to understand the added value offered by the adoption of blockchain in the sector.	Added a new task to Scope of Requirements (SoR).
25.	I think its difficult to create a step-by-step roadmap for DLT at this point because the technology is very new; however, its an excellent backdrop for things to consider when transitioning from theory to testing. Also, it provides a useful foundation for newcomers in the space.	---

	Macro roadmap - comment from open question	How the feedback was addressed
26.	Overall, I think this is a very good framework that identifies key themes and actions, and would be a good basis for developing a programme of work in this area. Identifying specific organisations to lead on individual themes and areas of work would be useful.	---
27.	The scoping needs to be longer and broken down into 2 sections. One section identifying all the existing problems with current contracting methods, and then the second to scope how a DLT/SC version of that should be redesigned to actually solve those problems (as opposed to just digitising existing contract forms which contain too much ambiguity to be truly digitised therefore setting the process up to fail)	Restructured Scope of Requirements and added new tasks to reflect this comment.
28.	The map doesn't tell me what the "new state" we are trying to get to is and why we want to do this.	This has been added to SoR.T6.

Comments on the Meso Roadmap

Note: comments are copied verbatim from the survey, hence, typos and grammatical errors remain.

	Meso roadmap - comment from open question	How the feedback was addressed
1.	Need more substance for each item, but appreciate that will come over time. Logically, it makes sense to me. Perhaps in the first part you could assess the value proposition as well as the gaps (not just plugging holes in a broken system, but redefining how we work...). For this you will need to consider current and future technologies coming into construction - 5G technology, green financing, off-site construction (DfMA, MiC, etc,). You will also need to consider developments and approaches in different regions and the application/changes needed for different parts of the world.	Included value proposition in stage 1. The remainder of the comment is addressed in text.
2.	I think that It considers the blockchain as a process rather than a technology. Therefore, the meso roadmap should be specified according to the use case.	The meso roadmap is intended to be applied to different use cases and therefore does not specify a specific use. Thus, the roadmap is adaptable to any use case/application.
3.	a small detail but if the readability of this could be improved	Readability has been improved where possible.
4.	I am not certain the meso-roadmap should rely on government intervention for adoption- have you bought of alternatives in adoption, i.e or example bottom up from the industry?	The meso roadmap is not intended to include government intervention but the macro roadmap includes learning from specific applications. This has been made clearer in the meso roadmap where references to government are made.
5.	May be complex for many ppl in industry to understand utilise. Also how it relates to usual split/stages of works	It is not designed to follow the asset lifecycle and so does not map to the stages of work. However, specific applications that do require such mapping can adapt the roadmap to their needs.
6.	As the macro, also the meso roadmap is complete and extensive but maybe it needs to focus on the sector, in this version it is not specific. Maybe there is a micro-scale where the methodology could fit the specific requirements	A micro-scale roadmap is planned for further work. The roadmap is designed to be applicable to construction but also adaptable to other sectors.
7.	I think it looks great!	---
8.	greater clarity over the use of the terms "develop", "pilot" and "proof of concept". I think many would see proof of concept as an initial, experimental implementation - typically TRL 3. A pilot, would be to validate the (further developed) technology in an industrial setting (TRL 5/6). A fully developed system would be TRL 8. The meso roadmap suggests the new system is developed in S3 and then has a mix of PoC and pilot in S4 and then refinement based on these S1 refers to "the new application" - does this mean that a number of these roadmaps would be in development concurrently for a range of applications? if so, should there be some cross-application communication or sharing of components, or is that all dealt with in the macro roadmap?	All valid points and address in the body of the text.
9.	there are a lot of tasks included in each step (gate)...this makes the roadmap a bit difficult to comprehend e.g., step 3 - adapt/create new processes is by itself a huge undertaking, and then on top of that you have governance etc...this is all true, but very general...for the sector with so many different stakeholders it might be different points of view, business/governance models necessary	This roadmap is designed to guide development and not act as a methodology to follow. Therefore, different tasks will require further planning for each application to be applicable to them and indeed not all tasks will be applicable for each application. This has been discussed in the body of the text.
10.	I prefer this roadmap structure, it comes across as a roadmap for a	---

Meso roadmap - comment from open question		How the feedback was addressed
	disruptive "startup" venture. The route to the pilot "proof of concept" is direct. This will initiate change rather than seek permission for change which is the right road to take.	
11.	This appears a more suitable staging of key events than the macro roadmap. There should be emphasis on the need for an agile approach with iterative refinement within stages S3-S4	Iterative refinement has been included in stages 3 to 5.
12.	It seems a well defined roadmap	---
13.	I do think there is a lot going on within this roadmap and perhaps stepping back towards answering the 'why' and then creating the foundation for change through DLT/SC incorporation would be a better approach?	The detail of this roadmap is acknowledged and it could act as a deterrent to its use. However, it is intended to provide support to development and implementation of new applications and therefore the level of detail can be tailored to support those using it.
14.	Easy to understand. Clear line between stages and the introduction of gates means there are objectives to be met before moving on the next state	---
15.	Again - i'd need a bit more time to understand the roadmap in detail before cofidently answering the previous questions but at a quick glance the roadmap appears to present the detail required for teh roadmap activities and deliverables. This was easier to follow than the macro roadmap due to the detail provided.	---
16.	Allow linkages and back-analysis between tasks	This has been included with integration for S3 and S4 and discussion in the text through an agile approach.
17.	Try to adapt the linear roadmap into a cyclical one. This will allow multiple improvement iteration rather than assuming that a singler refinement step is enough.	This has been done following a more agile approach.
18.	It would be better/more effective if the meso roadmap process could be less sequential and allows integrating some loops/iterative processes so we can keep updating previous Actions/outcomes while implementing the roadmap. As you should be aware of, sequential application development methods have been proven to be less effective when it comes to complex and big R&D projects where user needs are not well/clearly defined. Other methods such as Agile, design thinking, etc. seem to be more suitable and allow both flexibility and iterative & effective development.	This has been done following a more agile approach.
19.	Seems reasonably practicable. The use of gateways is useful. An exit strategy in case of demonstrated lack of value or engagement from the industry users could be useful. Is the benefit-cost ratio considered at some stage? - maybe I missed it, not sure.	A cost-benefit analysis task has been included in Stage 2.
20.	Overall quite clear. I would prefer colouring of the steps according to the socio-economic framework (red, blue, grey, purple). I would find this more useful rather than short/medium/long term.	This is acknowledged and will be considered in further work. The challenge is that many tasks encompass several of the socio-technical dimensions, which, at this stage will be difficult to demonstrate.
21.	Making it more bespoke to DLT and SC. In it's current form, it is quite bespoke. It could equally apply to adopting AR/VR or AI in our industry.	It is designed such that it can be applicable to other technologies so as not to reinvent the wheel each time a new technology becomes available.
22.	The format of the meso roadmap is recognisable by Construction industry stakeholders and appears to be a bridge between the different 'construction' and 'digital' worlds. There is a third 'world' which is the underlying purpose for attempting to join 'Construction' and 'digital' - That is Business/commercial world. Which leads me to ask - Who is the road map for? It is a Business Incubator/accelerator process roadmap...? is it for Gov't/insptutions seeking to Innovate within their existing business models..? How is the process funded? Would it need an incentive of Stakeholders and finance 'in place' to attract engagement from innovative businesses or investors? As a DLT/SC innovative business in the Construction sector, I will be pleased to engage further - Good work.	These comments are address in text.
23.	Concerning the meso Roadmap, it seems that (based on the "links" representation) that only "Process" and "Policy" are driving the tasks, e.g.,, there is no "Technology" deliverable (backend, middleware, frontend specifications...).	These are included in stages 2 and 3 but the roadmap acknowledges that a great deal of the work involved in adopting a new technology is not just about the technology, rather the socio part of a socio-technical approach. However, the technology elements have been reinforced in the roadmap.
24.	Due to the formality of the roadmap, I can see it being useful for	The roadmap can be used as a "tool" for SMEs to

Meso roadmap - comment from open question		How the feedback was addressed
	industry-wide and governmental adoption, however, from the perspective of SMEs, they might find it too administratively intensive/scary. What if an SME just wants to run a very small-scale POC just to see how blockchain works? - how can we make it easier to provide them these free tools without enforcing a prescriptive process.	consider the different aspects that might be relevant to them - almost like a checklist. The tasks are not sequential through the coding to identify tasks suggest as such. A small scale SME looking to develop a POC would not be interested in this roadmap as its focus is on development of an application to reach the point of mainstream adoption.
25.	Nothing in particular comes to mind - I think this is one of the more thorough roadmapping exercises I've seen.	---
26.	Perhaps the slides are not as clear as a wider map would be. It was not always easy to visualise how each meso element connected to a macro element.	It was not easy to visualise the two together and how they integrate for the purposes of the survey. This has been addressed in the thesis and is now more clear.
27.	The plan is very high level and I don't get insight into exactly how these actions will be achieved?	They are guidelines to support the development of applications rather than to be a prescriptive methodology for individuals or organisations to follow. How the tasks are achieved and which ones are prioritised will be up to the application developers to decide.
28.	Need more substance for each item, but appreciate that will come over time. Logically, it makes sense to me. Perhaps in the first part you could assess the value proposition as well as the gaps (not just plugging holes in a broken system, but redefining how we work...). For this you will need to consider current and future technologies coming into construction - 5G technology, green financing, off-site construction (DfMA, MiC, etc,). You will also need to consider developments and approaches in different regions and the application/changes needed for different parts of the world.	Included value proposition in stage 1. The remainder of the comment is addressed in text.

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