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Developing a Framework for Prefabrication Supply Chain Integration in New Zealand using Blockchain Technology

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Abstract

Prefabrication or off-site fabrication in New Zealand is snowballing in terms of its contribution to the delivery of construction projects. The increasing demand for new houses and the lack of affordable accommodations in New Zealand evolved the need for innovative and effective project delivery systems instead of conventional types. The prefabrication sub-sector is considered leverage for eliminating the shortcomings of traditional construction systems. However, this sub-sector of the construction industry struggles with challenges such as low coordination and integration across its supply chain partners. These challenges are attributed to the inefficient foundation of communication and information flow.

This research addresses the problem of the relatively weak integration within New Zealand's prefabrication construction supply chain. The particular focus of the study is on information integration. The central point is that an effective and efficient exchange of information among supply chain stakeholders is imperative for enhancing supply chain integration in New Zealand's highly fragmented construction industry. Therefore, this study concludes that providing an effective information-integration-based platform for stakeholders involved in prefabrication projects will deliver integration improvement in the whole supply chain system.

Blockchain technology, as a secure information integration instrument, capably improves the integration of information flow within the prefabrication sub-sector. Blockchain, a decentralised, safe, and unalterable information storage, offers numerous benefits to investors, clients, end-users, and other organisations or individuals. This technology, via its inherent features such as decentralisation, consensus mechanism, and immutability, supports organisations engaged in the supply chain with more transparent and trustful interactions and information flow.

By adopting qualitative and quantitative data collection methods, this research provides insight into the applicability of blockchain technology within prefabrication construction supply chains. Minimum input requirements for blockchain according to types and patterns of information will be identified and categorised, and an applicable framework for using this new information integration technology will be proposed. Some key findings of this study are the identification and classification of (1) key stakeholders and recent project phases within the prefabrication supply chain, (2) flow of information across the stakeholders in different project phases, (3) important information attributes, (4) communication channels among stakeholders, and (4) impact of blockchain technology on facilitating information integration in the prefabrication construction industry of New Zealand.

This research utilised pilot interviews, a questionnaire survey, a focus group study, and a validation survey to verify the objectives of the research and validate the proposed blockchain-based framework. The findings of this research could also be relevant to other industries facing similar challenges that rely heavily on information inputs. By identifying the importance of efficient information integration and the attributes crucial for successful project outcomes, stakeholders can prioritise investments in technologies like blockchain to streamline communication and data sharing across the supply chain.

The identification of conventional communication modes like email, meetings, and internet-based applications in the prefabrication supply chain suggests a reliance on traditional methods for information exchange. However, the research underscores the importance of transparency, traceability, and reliability in communication, especially in the context of advanced information technology adoption. This implies a need for stakeholders to develop tailored communication strategies that leverage both conventional methods and emerging technologies to ensure effective collaboration throughout project phases.

Finally, the development of a practical document management framework utilising blockchain technology presents opportunities for innovation and collaboration within the prefabrication industry. By demonstrating the applicability of blockchain in addressing document management challenges and validating the framework through expert feedback, the research paves the way for industry practitioners to adopt similar approaches in their projects. This suggests a broader trend towards embracing digital solutions and collaborative platforms to enhance information exchange, transparency, and project efficiency in the prefabrication sector.

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List of publications

Journal articles – (published)

1) Bakhtiarizadeh, E., Shahzad, WM., Poshdar, M., Khalfan, M., & Rotimi, JOB. (2021). Blockchain and information integration: Applications in New Zealand's prefabrication supply chain. *Buildings MDPI, 11*(12), 608.
2) Bakhtiarizadeh, E., Shahzad, WM., Poshdar, M., & Rotimi, JOB. (2022). Blockchain technology applicability in New Zealand's prefabricated construction industry. *Engineering Management in Production and Services, 14*(1), 103-112.

Conference papers – (published)

3) Bakhtiarizadeh, E., Shahzad, W., & Rotimi, JOB. (2019). A process map for supply chain relationships in prefabricated construction. In *Proceedings of the 43rd Australasian Universities Building Education Association (AUBEA)* Conference, Australia, 112 – 123.
4) Bakhtiarizadeh, E., Shahzad, W., & Rotimi, J. (2020). Applying secure information-based mechanism for prefabrication supply chain integration: A review. In *Proceedings of the 5th New Zealand Built Environment Research Symposium (NZBERS),* Auckland, New Zealand, 71-78.
5) Bakhtiarizadeh, E., Shahzad, W., Poshdar, M., & Rotimi, JOB. (2021). Applicability of Blockchain technology in New Zealand's prefabricated construction industry: A potential solution. In *Proceedings of the 11th International Conference on Engineering, Project, and Production Management (EPPM),* Poland, 9.

Glossary

AUBEA	Australasian Universities Building Education Association
BRANZ	Building Research Association New Zealand
CCC	Construction Compliance Certificates
CO	Change Order
COVID-19	Corona Virus Disease of 2019
CR	Change Request
CRM	Customer Relationship Management
CSC	Construction Supply Chain
CSCM	Construction Supply Chain Management
DCN	Design Change Notification
EDA	Exploratory Data Analysis
EDI	Electronic Data Interchange
EPA	Engineering Plan Approval
EPPM	Engineering, Project, and Production Management
ERP	Enterprise Resource Planning
GDP	Gross Domestic Product
GIS	Geographic Information Systems
GPS	Global Positioning Systems
IFC	Issued for Construction
IPFS	Interplanetary File System
IT	Information Technology
KM	Knowledge Management

MBIE	Ministry of Business, Innovation and Employment
MDPI	Multidisciplinary Digital Publishing Institute
MUHEC	Human Ethics Committee of Massey University
NZBERS	New Zealand Built Environment Research Symposium
OSC	Off-site Supply Chain
OSCM	Off-site Supply Chain Management
PDF	Portable Document Format
RFI	Request for Information
RFID	Radio Frequency Identification
RIBA	The Royal Institute of British Architects
SCI	Supply Chain Integration
SCM	Supply Chain Management
SHA	Secure Hash Algorithm
UK	United Kingdom
USA	United States of America

Chapter 1: Introduction

1.1 Overview

Prefabricated construction in New Zealand requires particular attention to the factors inhibiting its efficiency and effectiveness, and the lack of supply chain integration is a significant issue limiting the performance of this sector (Shahzad, 2016; Nesarnobari, Shahzad, Jelodar, & Sutrisna, 2024). Collaborative relationships leading to positive prospects of future cooperation among supply chain partners are pivotal points that drive the integration of the supply chain within prefabrication construction. The study is topical and will look at information technology tools as a facilitator of a collaborative environment.

Blockchain technology, a new information technology mechanism, is revolutionary as it enables integration practices from which the prefabrication sub-sector will benefit immensely (Li, Greenwood, & Kassem, 2018). Blockchain, being an advanced transaction-based platform, offers a distributed and secure database which allows organisations to integrate their projects' information and knowledge to deliver better transparency to clients or end-users (Wang, Wu, Wang, & Shou, 2017). Also, this technology induces a more trustworthy and visible collaborative environment using accountable and traceable information-sharing platforms for organisational interactions (Li, Greenwood, & Kassem, 2018).

In New Zealand, there is a vital need to adopt innovation instead of traditional construction since the country is confronting a significant shortage of housing (Gordon & Curtis, 2018). For the next decade, Auckland alone requires approximately ten thousand new houses per year (Commerce Commission New Zealand, 2023), increasing the potential adoption of offsite construction rather than traditional construction (where construction sites accommodate site offices, machines, hangers, and material storage).

Moreover, there is a considerable number of low-quality and leaky buildings in New Zealand, for which innovative actions are required to prevent the rise of this crisis (BRANZ, 2022). Finally, supplying affordable housing is critically low in New Zealand due to its geographical isolation and the high cost of materials and human resources. This also strengthens the need for innovative construction practices (Shahzad, 2016).

Offsite construction is more feasible for isolated sites with low access (PrefabNZ, 2015). However, it resonates with a more complex supply chain since it involves different sites and more stakeholders (Darlow, Rotimi, & Shahzad, 2022). Maintaining efficient communication and information exchange throughout the process of completing a prefabricated project would substantially reduce this complexity (Koolwijk, Van Oel, Wamelink, & Vrijhoef, 2018). This study provides a framework for a more effective and efficient supply chain integration using blockchain and investigates how this technology impacts information integration.

1.2 Background

This section provides an overview of existing literature. The section is structured into three major parts: supply chain management and factors contributing to its integration, prefabrication in New Zealand's construction industry, and blockchain technology.

1.2.1 Construction supply chain management

1.2.1.1 Definition of supply chain management

Supply chain management (SCM) techniques are applied to different industry sectors, e.g., food production, pharmaceutical trades, and construction. SCM is originally a concept that flourished within the manufacturing industry (Vrijhoef & Koskela, 2000), and it plays a crucial role in structuring the supply networks of organisations and increasing their performance

(Behera, Mohanty, & Prakash, 2015). Various researchers have defined SCM in multiple ways according to their background and the industry they have investigated. These definitions are shown in Table 1-1 below.

Table 1-1: Supply chain management as defined by various authors.

Definition of Supply Chain Management (SCM)	Authors
SCM is a network of organisations, through the connection of upstream and downstream, involved in various activities and processes that produce value (services and products) for the final customer	(Christopher, 1994)
SCM is the management of the network of businesses and relationships across the supply network	(Lambert & Cooper, 2000)
SCM is "the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, to improve the long-term performance of the individual companies and the supply chain as a whole."	(Mentzer et al., 2001, p. 18)
SCM is "the integration of key business processes from initial raw material extraction to the final or end customer, including all intermediate processing, transportation, and storage activities and final sale to the end-product customer."	(Wisner, Tan, & Leong, 2014, p. 24)
SCM is "The task of integrating organisational units along a supply chain and coordinating material, information and financial flows to fulfil customer demands to improve the competitiveness of a supply chain as a whole."	(Stadtler & Kilger, 2002, p. 5)

According to these definitions, it is realisable that the concept of SCM includes an efficient flow of materials to the end-user and information to the supplier, employing integration, coordination, and cooperation among its members. Still, the definition is continuously being revised by different authors in different industries and use cases (Enz & Lambert, 2023). Nevertheless, the underlying premise of supply chain management can be

founded on systems thinking, which magnifies the importance of considering all single parties involved in delivering a product (or service) as significant collaborators to a more substantial system.

SCM inherently lacks significant stakeholder collaboration and coordination (Stadtler & Kilger, 2002). Within an organisation, inefficient integration of all supply networks barricades the sufficient flow of orders and products between suppliers and customers (Koolwijk et al., 2018). Also, old-fashioned production methods are now being replaced by innovations and advanced technologies, which requires the manager's flexibility to resist the reluctance to adopt new technologies (Chowdhury, Rodriguez-Espindola, Dey, & Budhwar, 2023). Low transparency, traceability, and lack of trust are other issues leading to inefficiency in SCM (Koolwijk et al., 2018; Jayashri, Rampur, Gangodkar, Abira, Balarengadurai, & Kumar, 2023). For a SCM to succeed, a change from individual functions to integrating key supply chain processes is required (Mantravad, & Srai, 2023).

1.2.1.2 Overview of construction supply chain management (CSCM)

Construction Supply Chain Management (CSCM) encompasses all the processes integral to project delivery, spanning from procuring necessary components to delivering the finalised project to the end user (Behera et al., 2015). One historic definition characterises it as the efficient management of the flow of information, materials, processes, and activities between upstream and downstream organisations to ensure the delivery of high-quality and reliable products to the end user (Akintoye et al., 2000). More recent studies define it as integrating critical business processes, covering all steps from processing to the final sale. (Chowdhury et al., 2023).

The construction sector's supply chain involves various participants, including the design team, suppliers, builders, sub-contractors, and distributors. The complexity of suppliers' networks in construction is contingent on project size; in large projects, the number of suppliers may exceed hundreds (Behera et al., 2015). Consequently, there is a critical imperative to enhance the adaptability of Supply Chain Management (SCM) techniques with the latest technologies to cope with this complexity effectively.

Managing supply chains of construction projects comprises the understanding of traceability of products, services, labour forces, activities, and knowledge/information that transform the raw materials into a finished product (Konukcu, 2011). A construction project encompasses different steps throughout its lifecycle, such as initialising and site set-up, designing, planning, procuring, manufacturing, construction, and demolition (Behera et al., 2015). Therefore, there is a dominant reliance on coordination, collaboration, and information integration in these cross-disciplinary processes in the construction supply chain. Koc & Gurgun (2000) also note that construction supply chain management, which has a temporary project-centric configuration and make-to-order attitude, needs information integration, collaboration, and long-term partnership to be productive.

However, CSCM is characterised by many issues and shortcomings, resulting in its poor performance and unproductivity. These issues are explained in Table 1-2. The flow of knowledge and information within the downstream and upstream supply chain is a critical issue in the construction supply chain. There is a substantial dependency on experience or information management for transparent long-term relationships and supply chain integration (Konukcu, 2011).

Additionally, in the construction supply chain, certain unique products are tailored specifically for individual projects. Consequently, employing repetitive supply chain techniques for one project may not be suitable for another, leading to instability, fragmentation, and knowledge loss (Konukcu, 2011). The prevailing culture in construction management poses a challenge to the integration of innovation, contributing to increased complexities and rendering the construction industry a hesitant adopter of supply chain information technologies (Shahzad, 2011; Sooriyamudalige, Domingo, Shahzad, & Childerhouse, 2020). Hence, there is a critical need to enhance information technology platforms within the industry to efficiently capture and preserve the knowledge and information embedded in supply chains.

Table 1-2: Impediments to an effective and efficient CSCM

Barriers as identified by different authors	(Behera, Mohanty, & Prakash, 2015)	(Akintoye, McIntosh, & Fitzgerald, 2000)	(Jaillon & Poon, 2010)	(Bidabadi et al., 2016)	(Blismas, Arif, & Wakefield, 2009)	(Harland et al., 2007)	(Dainty, Millett, & Briscoe, 2001)	(Shahzad, 2016)	(Čuš-Babič et al., 2014)	(Gibb, 1999)	(Rahimia et al, 2017)	(Prajogo & Olhager, 2012)	(Zhai, Reed, & Mills, 2013)
Temporary and negative project-based viewpoint	*			*						*			*
Reluctance to adopt innovations and information technology			*	*	*		*	*		*	*		*
Vague regulations and strategic legislation		*			*		*	*			*		*
Low transparency and traceability	*					*	*		*	*			
Decentralised or fragmented nature	*	*								*	*		
Low collaboration and partnership	*	*	*	*		*	*	*	*	*			*
Lack of trust	*				*	*		*	*			*	
Poor information sharing or knowledge integration	*					*	*	*				*	
Time and cost overruns				*			*						*

1.2.1.3 Supply chain integration in the construction industry

Supply Chain Integration (SCI) plays a pivotal role in supply chain management (Konukcu, 2011). The effective implementation of inter- and intra-organisational Supply Chain Management (SCM) necessitates integrating processes and flows (Enz & Lambert, 2023). In a broader sense, a supply chain comprises distinct organisations collaborating to deliver a product or service, aiming to enhance supply chain performance and integrity. Integration involves achieving stability and consistency in project delivery systems and fostering collaborative relationships with seamless flows (Mantravadi, & Srai, 2023).

The prevailing approach to supply chain integration emphasises viewing the supply chain as an integrated, value-generating flow, as opposed to a series of isolated activities (Behera et al., 2015). Extensive research has been conducted on the value of integration in the supply chain, indicating that integration across all tiers of the supply chain contributes to time and cost reduction, enhanced responsiveness to change, streamlined decision-making processes, and the cultivation of transparency and trust (Cheng et al., 2010).

An integrated supply chain is instrumental in overseeing the processes of construction projects, encompassing design, planning, construction, and maintenance. It fosters collaboration and trust among the delivery team, promoting a cohesive project team (Segerstedt & Anders, 2010; Khanuja & Jain, 2020). Awasthi & Grzybowska (2014) assert that integration establishes a cooperative work environment wherein all stakeholders mutually influence one another concerning their responsibilities, communication, and knowledge sharing.

Certain researchers have categorised Supply Chain Integration (SCI) practices distinctly. For example, Fabbe-Costes (2007) conducted an extensive literature review, proposing an inclusive classification framework wherein SCI is categorised into four elements: integration

of information, integration of activities, integration of technologies, and integration of actors. Khanuja & Jain (2020), in their critical examination of the relationship between integration and performance in the supply chain, conclude that while there is a direct relation between performance and SCI, achieving integration is more challenging in practice than in theory. This difficulty is often attributed to the reluctance of supply chain practitioners to adopt innovations (Chowdhury et al., 2023).

Also, Jayashri et al. (2023) contend that integration in construction supply systems has been fragmented and exhibits a gradual uptake of advanced technologies. Various barriers to integration originate from traditional project delivery networks, a deficit of trust and transparency, and the prevalence of short-term decentralised relationships (Enz & Lambert, 2023, Khanuja et al., 2020).

Successful Supply Chain Integration (SCI) hinges on vital elements such as information sharing and efficient communication among stakeholders throughout the supply chain, particularly involving all parties in the early stages of projects (Konukcu, 2011). For instance, the engagement of suppliers and contractors in the initial phases of the design process can enhance coordination and integration in terms of information exchange, potentially reducing the risk of reworks and changes (Love, Irani, & Edwards, 2004). However, due to the inherent nature of the construction industry, there is still room for improvement in the integration of flows, specific knowledge, and information within the supply chain (Bidabadi et al., 2016).

1.2.1.4 Trust and transparency

Trust is recognised as a complex issue influenced by various factors, and in the context of a construction project, it can significantly impact the project's outcomes in terms of time, cost, and quality (Akintoye et al., 2000). The degree of trust is shaped by individuals'

perspectives on shared objectives, with people establishing a baseline of trust and placing their confidence in others when collaborating towards common goals (Khalfan, McDermott, & Swan, 2007). Mistrust, especially in financial matters, has a substantial impact on projects (Konukcu, 2011), and it worsens when there is a lack of transparency in transactions between suppliers and customers (Zhao, Fan, & Yan, 2016).

Trust is an essential prerequisite for the success and efficiency of Supply Chain Management (SCM) (Samarasinghe, Tookey, & Rotimi, 2013). However, in the construction supply chain, the absence of genuine relationships and transparent communication hampers the effective and efficient delivery of projects (Konukcu, 2011). The costs and impacts of challenges could be mitigated, and trust and transparency among supply chain partners could significantly increase if a platform allowed all involved members to exchange information and knowledge promptly upon becoming aware of problems (Khalfan, McDermott, & Swan, 2007).

1.2.1.5 Collaboration and partnering

Effective collaboration and partnership among stakeholders stand out as significant contributors to an integrated supply chain. Collaboration refers to cooperative relationships among supply chain partners with the aim of achieving specific objectives, and it wields a substantial influence on project performance in terms of cost, time, and quality (Bidabadi et al., 2016). Long-term collaboration among supply chain organisations enhances innovation opportunities and improves client satisfaction (Koolwijk et al., 2018). In a collaborative Supply Chain Management (SCM) setting, all involved partners align with a common organisational value and business purpose (Deep, Gajendran, & Jefferies, 2021). The failure to foster collaboration would likely result in diminished trust among partners.

Collaboration or partnership is acknowledged as a crucial element for advancing supply chain integration. According to Mentzer et al. (2001), the definition of integration can be inferred from the coordination and collaboration within Supply Chain Management (SCM), resulting in improved management of flows (services, products, information, and finance) across suppliers and customers. Integrated Construction Supply Chain Management (CSCM) stems from effective synergy among construction actors. For example, a project team can collaboratively share information and knowledge about the project, enhancing communication with other actors to improve the performance and integration of their organisation.

Effective collaboration is believed to necessitate robust communication and a well-established information system among partner organisations (Deep et al., 2021). Additionally, it requires a positive embrace of technologies (Konukcu, 2011; Zhao et al., 2016). As Cheng et al. (2010) conclude, developing methodologies, tools, and technologies for integrating collaboration among supply chain partners is a fundamental requirement of a collaborative system. Casino, Dasaklis, and Patsakis (2019) also identify information technologies as an effective means of promoting collaboration among supply chain members. Hence, to enhance Supply Chain Integration (SCI) through partnership, adopting innovative platforms and new technologies for managing and sharing information is deemed beneficial (Jayashri et al., 2023).

1.2.1.6 Information exchange

Efficient coordination of flows throughout the supply chain can be achieved by adopting the latest information and communication technology advancements. Standard construction

projects typically face challenges and complexities such as widely dispersed or decentralised information, which can result in incorrect and defective product deliveries (Behera et al., 2015).

While recent advancements and the integration of information technologies in the construction industry have led to improvements in project quality and efficiency (Rahimian et al., 2017), certain shortcomings, such as insufficient information sharing, hinder its overall productivity (Rahimian et al., 2017; Vrijhoef et al., 2000). According to Cheng et al. (2010), the highly dynamic nature of construction supply chains and their susceptibility to structural changes often deter participants from collaborative efforts, hindering the establishment of trust and efficient information sharing.

The exchange of information within supply systems necessitates integration and management to create opportunities for substantial improvements in supply chain integration. Hatmoko and Scott (2010) describe Construction Supply Chain Management (CSCM) as a system in which suppliers, contractors, clients, and other parties collaborate to efficiently carry out construction projects using information. Information integration involves exchanging information among supply chain partners, aiming to achieve real-time transmission of information throughout the supply chain system (Prajogo & Olhager, 2012). The integration of information holds the promise of logistics integration, which pertains to specific logistics practices and operational activities coordinating the flow of materials from suppliers to customers (Stock et al., 2000). While many researchers emphasise the critical role of information integration in efficient supply chain management, the practical development of information exchange for this purpose remains somewhat lacking (Samarasinghe, Tooki, & Rotimi, 2013). This is attributed to stakeholders' reluctance to adopt innovations or digital technologies (Bidabadi et al., 2016).

Information sharing within the supply chain significantly enhances business collaboration and trust. According to Yu (2001), information sharing effectively manages and improves large supply chain systems. Although decentralisation is a characteristic of the supply chain, uncertainties arise when one party alters information within a supply chain, and other parties are unaware or receive the information late (Abeyratne & Monfared, 2016). This can lead to changes in the delivery time of products to the site and an increase in relative costs. Similarly, Čuš-Babič et al. (2014) demonstrate that information generated by multiple sources can result in disintegration, scepticism, and low communication efforts among parties.

A consistent flow of information and the secure storage of project information without the risk of alteration can contribute to improved integration and performance in supply chain systems. Adopting a secure platform for information exchange and establishing a secure repository for information can lead to enhanced decision-making, collaboration, and transparency (Casino et al., 2019). Furthermore, all stored data can be utilised as project knowledge for future endeavours upon project completion.

1.2.1.7 Sustainability

In the construction industry, sustainability poses a significant and challenging concern. Given the involvement of various participants in construction supply chains, the impacts of their deliveries on society and the environment must be considered. Each organisation participating in project or service delivery must adopt sustainable Construction Supply Chain Management (CSCM) practices. Project performance factors such as time, cost, and quality are now being extended to include additional measures related to social and environmental elements (Saberi et al., 2018). The challenges of the construction supply system involve reducing waste and energy consumption, decreasing carbon emissions, and utilising recyclable materials and products to mitigate adverse environmental and social consequences (Konukcu,

2011). Adetunji, Price, and Fleming (2008) define sustainable supply chain management as identifying ecological and social issues, assessing their risks and impacts, and implementing mitigation measures.

The effective implementation of sustainable Supply Chain Management (SCM) continues to be a subject of current controversies. While many of these concerns can be addressed intra-organisationally, even more significant benefits can be derived if collaborative relationships emerge within and between organisations involving all individuals in the supply chain (Adetunji, Price, & Fleming, 2008). Bidabadi et al. (2016) elaborate that many sustainability issues stem from a lack of transparency and trust, hindering long-term collaboration and integration of supply chain stakeholders to build a green environment.

In the construction industry, where a vast array of products is utilised to complete a project, the provenance of raw materials becomes a crucial consideration. The quality of services and materials evokes the necessity for an effective and traceable supply chain information system, allowing transparent tracking of information related to the origin of goods (Saberi et al., 2018).

Many of the issues mentioned above, stemming from a lack of trust and a collaborative environment among construction actors, are rooted in inadequate infrastructure for effective information integration. Sustainability issues are no exception. Generally, construction supply chains face significant challenges in enhancing their projects' cost, time, and quality without sufficient focus on their deliveries' social and environmental impacts. By considering the element of cost in a broader sense, including the social and environmental costs of projects, organisations can obtain a more accurate assessment of their projects and an overall view of construction processes. Advanced technologies and information systems are helpful for

measuring these elements, especially when there is a need to capture cost-related information for evaluating organisational performance in relation to sustainability considerations. Additionally, the adoption of innovations such as prefabrication technology in the context of the construction supply chain has shown a positive influence on reducing sustainability problems (Shahzad, 2016). However, maintaining effective information integration within the prefabrication subsector requires more extensive investigation.

1.2.2 Overview of prefabrication construction

The primary focus of this study is to establish an information integration platform in the prefabrication supply chain. Initially, an overview of prefabrication is presented. Subsequently, the significant issues impeding the effective prefabrication supply chain are investigated, and finally, a proposal for an effective information integration technology is put forward.

1.2.2.1 Prefabrication or Off-site Construction

Various synonyms are used for prefabrication technology, including offsite manufacturing, offsite fabrication, pre-assembly, offsite construction, and prefabrication. All of these terms denote the process of constructing a component, a portion, or an entire structure of a larger project at a location separate from the final installation site (Shahzad, 2016). PrefabNZ (2013) asserts that offsite manufacturing or prefabrication is an innovative approach in the built environment, involving the manufacturing and assembly of a building or its essential components before being erected and installed at the final location. The key distinction between conventional construction and prefabrication systems lies in the fact that, in prefabrication, components are produced offsite rather than onsite. Prefabrication is considered an innovative technology in the construction industry, focusing on minimising onsite construction activities by transferring a significant portion of the processes to a controlled factory environment offsite

(Shahzad, 2016). Similarly, Burgess et al. (2013) characterise prefabrication as the systems and structures that enable the construction of a complete or partial building away from the final location.

Shahzad (2016) examines the benefits and impacts of prefabrication in the New Zealand construction industry, suggesting that this innovation can potentially alleviate productivity challenges (such as time, cost, quality, and safety issues) associated with conventional construction methods. Shahzad, Rajakannu, and Kordestani Ghalenoei (2022) similarly argue that prefabrication is environmentally friendly, reduces waste and carbon footprint, is more sustainable, and enhances safety compared to conventional construction methods.

However, the construction industry, particularly offsite manufacturing, lags in supply chain practices and efficiency (Segerstedt & Anders, 2010; Bankvall et al., 2010; Shahzad, 2016). Complexities in prefabrication supply chains are higher compared to traditional methods due to dispersed working sites, necessitating better collaboration and more transparent communication (Mostafa, Chileshe, & Zuo, 2014). Additionally, managing the flows of information and materials and responding quickly to any changes in customers' demands or design requires dynamic concurrent-management strategies and flexibility among supply chain partners to ensure the effective integration of the prefabrication supply chain (Gibb & Isack, 2003; Mostafa et al., 2014).

1.2.2.2 Types of prefabrication

Before delving into the investigation of the current state of prefabrication in New Zealand and the obstacles to its adoption, this section provides an overview of the types of prefabrication construction. According to PrefabNZ (2018), offsite fabrication is classified into three categories: volumetric, non-volumetric, and modular fabrication. He elaborates that:

- Examples of non-volumetric systems would be parts of a structure, frame, cladding, partitions, parts of pipework and so forth.
- Models for volumetric fabrication would be toilets or washrooms, lifts, plant rooms, and any facilities units.
- Modular building includes groups that form a whole or part of a structure, such as stand-alone units, medium-rise offices, and housing accommodations.

Shahzad and Mbachu (2012) expanded the classification to five categories, including:

- Component-based prefabrication: units and components such as precast beams and columns.
- Panelised prefabrication, such as precast floor or wall panels.
- Modular prefabrication: such as pods or modules.
- Hybrid prefabrication: a combination of panelised and modular prefabrication.
- Complete building prefabrication.

It can be deduced that prefabrication can be broadly categorised into two main types: fully fabricated and partially fabricated Fully fabricated buildings involve the offsite prefabrication of an entire structure, while partially fabricated buildings refer to the partial completion of a structure in a remote location.

1.2.2.3 Prefabrication in New Zealand

Prefabrication has been an innovative element of the New Zealand construction industry since colonisation in the early 18th century (PrefabNZ, 2013). Despite the industry's resilience in adopting innovative construction methods, the current utilisation of prefabrication in New Zealand remains relatively low (Shahzad, 2016; Darlow et al., 2022). Prefabrication offers

several functional benefits, including reduced onsite work and waste production, recycling and reuse opportunities, improved health and safety, better quality control, and customised design options (Kaufmann & Remick, 2009; PrefabNZ, 2015). However, the design and construction industry in New Zealand has been somewhat constrained by a tendency to adhere to traditional production techniques (PrefabNZ, 2018).

A study by Burgess et al. (2013) published by the Building Research Association New Zealand (BRANZ) revealed that the construction, maintenance, and demolition of building projects in New Zealand are responsible for the following:

- 40 per cent of the use of raw materials in New Zealand
- 40 per cent of the energy consumption
- 40 per cent of waste production, and
- 35 per cent of CO2 emissions

This implies that to enhance efficiency and address the mentioned issues in New Zealand's construction industry, adopting prefabricated construction should be accelerated since prefabrication targets waste and carbon emission reduction (PrefabNZ, 2018). The uptake of prefabrication in New Zealand relies on a clear understanding of prefabrication and a collaborative approach across the supply chain involving customers, builders, manufacturers, and designers (PrefabNZ, 2013). Facilitating the uptake involves a collaborative approach to disseminating technical knowledge and information, leading to a more efficient prefabrication design and construction industry (PrefabNZ, 2018). Additionally, Bell (2009) explains that close relationships among stakeholders in the New Zealand construction industry would address the interconnected nature of perceptions and challenges affecting market demand and hindering

the expansion of prefabrication. A more detailed overview of impediments to the uptake of prefabrication, as identified by various researchers, is provided in the following subsection.

1.2.2.4 Impediments to the uptake of prefabrication

Despite the numerous benefits of prefabrication for the construction industry, the adoption of this innovation is considered low. Darlow et al. (2022) articulate the prominent impacts of prefabricated housing in New Zealand and highlight the construction industry's criticism for poor productivity, insufficient adoption of innovation, and inconsistent quality. Bell (2009) attributes the limited improvement of prefabrication to performance-based issues in the construction industry. Several barriers inhibit the widespread adoption of prefabrication, and as depicted by Shahzad (2016), the most significant ones include:

- Reluctance to adopt innovation or information technology.
- Transportation restrictions.
- Low collaboration and trust.
- Poor information integration.

PrefabNZ (2018) specifies four critical problems impeding the uptake of prefabrication in New Zealand and offers:

- Widening perceptions through information to dispel misconceptions.
- Connecting and communicating effectively with clients to broaden the market size.
- Assisting and streamlining the use of innovation in the market.
- Disseminating technical and experiential knowledge for escalating awareness.

However, it is subsequently suggested in the report that the inertia of New Zealand's construction industry to adopt innovative approaches and envision long-term collaborative

relationships is the predominant issue that needs to be addressed. Zhai et al (2017) also examine the prefabrication industry in China and conclude that a lack of trust among different actors is resulting in impaired supply chain management.

Moreover, Blismas et al. (2005) and Navaratnam et al (2022) enumerate constraints to the uptake of prefabrication in Australia:

- Site constraints: such as limited site space, limited skilled labour onsite, and restriction to movement of prefabricated units onsite.
- Process constraints: such as the inability to freeze the design stage, low capacity of vendors, short project timeline, and transportation limitations.
- Procurement constraints: such as the obligation to interact only with a limited number of suppliers, low expertise in prefabrication inspections, and lack of enough suppliers.

By comparing various opinions about the impediments to the uptake of prefabricated construction, it can be inferred that the issues hindering the uptake of prefabrication are mainly rooted in the reluctance to adopt innovative construction approaches, low level of effective information integration, and inefficient information integration, leading to many other drawbacks, such as a poor collaborative and trustworthy supply chain environment.

In summary, prefabrication is still regarded as an innovative and promising way of alleviating traditional building constraints. The barriers to its uptake are the focal attention of researchers and industry practitioners. Many of the impediments mentioned above can be mitigated by incorporating information-based advanced technologies, such as blockchain technology.

1.2.3 Distributed ledger technology (Blockchain)

Distributed Ledger Technology (DLT), commonly known as "Blockchain," is a consensus-based ledger that facilitates secure and tamper-proof transactions among users (Penzes, 2018). The first blockchain was invented in 2008 by Satoshi Nakamoto for cryptocurrency transactions, specifically Bitcoin. It operates as a network where various nodes conduct transactions publicly or privately without the need for a central financial institution (Nakamoto, 2008). This technology establishes a peer-to-peer network where digital signatures accompany transactions to prevent double-spending in the absence of a trusted third party. The network timestamps all transactions chronologically using hashes in an ongoing block, creating an immutable record that requires consensus for any alteration (proof-of-work) (Penzes, 2018). Hashed blocks involve transforming blocks into alphanumeric strings through an algorithm (Lemieux, 2016). Digital signatures, a form of cryptography, use one public key and one private key to verify the authenticity of electronic documents or messages (Lemieux, 2016).

Blockchain closely resembles a cloud database on the internet, with the key distinction being its distributed nature. Unlike a centralised database with a single source for information and multiple accesses, blockchain is decentralised and exists in multiple locations. Various scattered sources can be updated simultaneously within the blockchain (Penzes, 2018). When new information or a transaction is poised to be added to the chain, the peer-to-peer consensus mechanism comes into play to validate the information without needing an intermediary (Lu & Xu, 2017).

Blockchain operates in either public or private networks. In a public network, access to the ledger information is open to everyone, while in private networks, individuals must be granted access (Li, Greenwood, & Kassem, 2018). In both systems, transactions are

cryptographically secured and require unanimous verification before being added to the chain of blocks (Nakamoto, 2008). This feature ensures the creation of tamper-proof and immutable blocks of records. When a transaction occurs between two nodes, the sender digitally signs the transaction (using their private key and the public key of the next owner) and encrypts it with a hash value of the previous transaction before adding it to the chain. The recipient can access the transaction information using their private key, ensuring it remains unchanged throughout the transfer. Simultaneously, the transaction is broadcasted to the network for approval by all nodes before being added to the chain.

A simplified explanation of the transaction process with blockchain, as outlined by Penzes (2018), is as follows:

1. **Initiation**: The transaction begins between two parties, creating unique data.
2. **Propagation**: The transaction data is shared with the network of nodes.
3. **Verification**: Other users validate the transaction to confirm the legitimacy of the sender and receiver and ensure the transaction has not been duplicated.
4. **Consensus**: Upon user agreement, the validation process is completed.
5. **Hashing**: The information is hashed and transferred to a block.
6. **Blockchain Addition**: The block is added to the chain of blocks.
7. **Record**: The digital data is permanently recorded with an unalterable history.

1.2.3.1 Application of blockchain in construction supply chain

The construction industry is widely recognised as one of the most fragmented sectors (Love, Irani, & Edwards, 2004). Managing an extensive supply chain, overseeing project progress, and monitoring time and cost demand significant efforts. Furthermore, construction projects contend with numerous issues, including faults, mistakes, incidents, delays, and

reworks. The sector grapples with a persistent lack of accountability coupled with low-profit margins; organisations must strategise ways to minimise blame and condemnations stemming from failures (Penzes, 2018).

Recently, web-based supply chain management systems have gained widespread adoption globally, facilitating the integration of supply chain networks (Ngai, Cheng, & Ho, 2004). Information technology (IT) systems for SCM, including Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), and Electronic Data Interchange (EDI), are gradually being supplanted by cloud-based technologies like the Internet of Things (IoT), drones, GPS receivers, and RFID (Xing, Qian, & Zaman, 2016). These advancements enable swift and efficient real-time information exchange among supply chain partners. Additionally, these technologies reduce harmful human interventions within information databases (Ngai et al., 2004).

The integration of information technologies into the supply chain has yielded several advantages. Firstly, it has reduced product development time by facilitating communication among the production team. Secondly, it has led to a reduction in the cost and prices of products. Lastly, it has contributed to improved product quality, aligning with customers' expectations (Chou, Tan, Yen, 2004). However, despite the potential value that cloud-based technologies bring to SCM, there are associated challenges with using technologies in the construction industry. Finch (2004) highlights information and data security as a significant concern, given the high risk of manipulation or alterations by hackers. These SCM systems provide access to the information repository for all supply chain members, both inter- and intra-organisationally. This poses a risk in the construction supply chain, as project-related information is vulnerable to inadvertent or intentional changes by any user (Penzes, 2018; Tse et al., 2017). Such

alterations can negatively impact an organisation's market competitiveness and erode trust among partners.

In contrast to conventional delivery systems and web or cloud-based databases, blockchain technology provides a suitable solution for addressing security concerns. Operating on a proof-of-work mechanism, blockchain requires consensus-based agreement among users for any changes to the contents stored in its blocks. This feature can be instrumental in preventing malicious attacks on organisational information databases. Moreover, in the construction industry, where disputes over payments are prevalent (Sutrisna & Goulding, 2019), blockchain can serve as a reliable and trustworthy contract administrator. It offers a secure and error-free process for executing payments and managing contracts (Li et al., 2018). These unique capabilities set blockchain apart and make it an effective tool for enhancing security and reliability in information management, attributes not readily found in traditional delivery systems or web and cloud-based databases.

The advent of blockchain introduced a groundbreaking innovation known as smart contracts — a digital contract designed to execute its terms and conditions automatically when fulfilled (Li et al., 2018). In the construction industry, the issue of missed and late payments is a significant challenge, leading to business failures, disputes, and strained collaborations (Li et al., 2019). Smart contracts offer a solution by preventing disruptions in the relationships between partners within the construction sector due to financial issues. Integrating smart contracts with blockchain technology enables the automatic execution of contract terms, with commitments embedded in a permanent and unalterable platform (Abeyratne & Monfared, 2016). This automation enhances the potential for establishing a trustworthy environment within construction supply chains, where disputes and human errors often impede long-term transparency and trust among partners, hindering supply chain integration (Saberi et al., 2018).

Various authors have acknowledged several potential benefits of blockchain. According to Lu and Xu (2017), the data and information within a supply system that are recorded in the blockchain contribute to a collaborative, transparent, traceable, and intermediary-free system. Penzes (2018) contends that blockchain in supply chain management ensures that all information and documentation are accessible to all parties but resistant to falsification. Additionally, Zhao et al. (2016) suggest that the immutability of details in the chained blocks of documents results in a reliable and secure transaction. This trust mechanism established by blockchain allows supply chain partners to share information or assets without any concerns about fraud.

Furthermore, with the increasing emphasis on sustainability and the origin of materials used in construction projects, one of the most prominent features of blockchain in Construction Supply Chain Management (CSCM) proves valuable. As highlighted by Li et al. (2018), when all information is gathered in blocks, it streamlines traceability, enabling clients or end-users to trace all production processes back to the origin of products. Consequently, consolidating project information and incorporating it into the blockchain would significantly improve logistics efficiency, information flow, transparency, and trust (Zhao et al., 2016). Through the adoption of blockchain as a secure platform for conducting transactions and sharing information, stakeholders can address issues of material counterfeiting, and customers can have confidence in the quality of materials (Lu & Xu, 2017).

Table 1-3 below is the comparison between blockchain technology and other databases in terms of their influences on the aforementioned supply chain issues:

Table 1-3: Comparison table for blockchain and other networks (Deduced from sources: (Chowdhury, Colman, Kabir, Han, & Sarda, 2018; Hackius & Petersen, 2017))

Attributes	Blockchain technology	Web-based databases	Traditional supply chain techniques
Data/information security	High	Low	Medium
Information sharing transparency	High	Medium	low
Process automation	High	High	Medium
Administrations costs	Medium	Low	High
Decentralisation of access	Decentralised	Semi-decentralised	Centralised
History of records	Clear	Vague	Vague
Intermediary dependency	Low	High	High
Regulatory framework compliance	Low	Low	High
Traceability of products' path	High	Low	Low
Seamless collaboration	High	Medium	Low
Cost of inventory management	Low	Medium	High
paperwork	Low	Low	High
Waste production	Low	Low	High
Energy consumption	High	Medium	Low

1.2.3.2 Application of blockchain in other industries

The application of blockchain technology has been explored across various sectors, including the pharmaceutical and healthcare products industry, education, security, food, and agricultural trades. Pan et al. (2019) delved into the potential use of blockchain in carbon trading, highlighting its capability to record information flow, facilitate decentralised transactions between demanders and suppliers, and contribute to improving global greenhouse gas reduction through an enhanced carbon trading market. As Mannaro, Pinna, and Marchesi

(2017) examined in the energy trading market, blockchain can be collaboratively employed to facilitate energy exchange between producers and customers without needing third-party intervention. For example, a household could sell excess electricity from solar panels directly to a neighbour.

In the food industry, where the safety of foods and their ingredients is a significant concern, blockchain can bring about substantial positive impacts. Tse et al. (2017) investigated the advantages of blockchain in the Chinese food industry. They observed that this technology significantly improves the security of health-related information in the food supply chain by establishing a permanent and tamper-proof record of information. Additionally, Hackius and Petersen (2017) discovered that blockchain in the food supply chain provides customers with a reliable source of origin, enabling them to trace the information of their products.

Moreover, blockchain in the healthcare industry can play a crucial role, impacting various areas such as healthcare product records, online patient registration, medical data and information sharing, and the identification of counterfeit drugs (Casino, Dasaklis, & Patsakis, 2019; Yue, Wang, Jin, Li, & Jiang, 2016; Zhao et al., 2016). Given the value of healthcare information, a secure and stable platform is essential for storing or sharing it, free from volatility or susceptibility to change. Blockchain offers a dependable system, allowing patients to control their medical data personally instead of being scattered across diverse medical systems (Yue et al., 2016). Additionally, in pharmaceutical product logistics, blockchain provides assurance of product quality, enabling supply chain managers to streamline the procurement process for healthcare products.

Blockchain can also find applications in recording and managing educational data within educational systems. According to Devine (2015), teachers can utilise blockchain to store their

students' learning achievements and share information with their guardians. Additionally, this technology can be employed in scholarly publications to improve manuscript submission and verification processes (Casino et al., 2018).

1.2.3.3 Blockchain in New Zealand's prefabrication supply chain (research gap)

The prefabrication subsector of New Zealand's construction industry, in certain instances, presents greater complexity compared to traditional construction methods (Jaillon & Poon, 2010). In the prefabrication supply chain, the distribution of information may be more intricate because multiple actors are involved in a given project. The classification of suppliers into "direct" and "indirect" categories poses a substantial challenge for construction stakeholders to efficiently exchange necessary information or documents, such as drawings, calculations, schedules, and production details, with increased speed and accuracy (Burgess et al., 2013; Shojaei, 2019). Additionally, obtaining regulatory approvals or consent procedures in prefabrication is complicated due to the diverse nature of worksites and time-consuming inspection processes (Shahzad, 2016). This complexity can result in extended project completion time. Moreover, within this industry, quality-related challenges such as defects and reworks often stem from ineffective traceability, coordination, and collaboration among prefabrication supply chain partners (Bell, 2009; Shojaei, 2019). These issues can negatively impact the integration and development of efficiency within this subsector. Trust is also a significant concern hindering the adoption of prefabrication in New Zealand (Shahzad, 2016). Many conflicts and trust issues arise from insufficient information sharing and a lack of transparency in collaboration (Handfield & Bechtel, 2002). In the context of prefabrication, trust refers to the reliance and confidence that stakeholders place in technological tools, systems, and processes. It involves believing that technologies will deliver the expected

outcomes without significant disruptions, error, or failure (Cai, Jun, & Yang, 2010). The absence of trust in prefabrication projects hampers future collaborations, adversely affects stakeholder relationships, and diminishes managers' willingness to embrace innovative practices (Shahzad & Mbachu, 2012).

Despite being a relatively new concept, New Zealand industries, with the right policies and approaches, have the potential to derive social, economic, and environmental benefits from the advanced phenomenon of blockchain. Despite its geographical isolation, New Zealand demonstrates adaptability in adopting innovations for business development and is performing well in the global market (Burgess et al., 2013). Blockchain technology holds significant potential to impact the growth of domestic businesses, especially in the prefabrication construction industry, where the practical deployment of this technology is not yet widespread.

However, the theoretical framework supporting the application of blockchain technology has not been extensively tested in either the construction industry or its prefabrication subsector. The clients' demand for tracing the origin of products used in construction projects and the prefabrication supply chain partners' need for seamless integration within their supply systems highlight the necessity of this research. In this study, blockchain technology is employed as an information-sharing facilitator to enhance the efficiency and effectiveness of supply chain integration within the prefabrication subsector of New Zealand's construction industry. The central hypothesis of this study is that adopting blockchain technology as a mechanism for improving information integration leads to increased effectiveness and efficiency in prefabrication supply chain integration.

1.3 Conceptual framework of the study

In this section, a conceptual model is presented based on the findings of the literature review (Figure 1-1). The factors contributing to an integrated supply chain were explored and discussed in the literature review. Challenges hindering the development of an effective and efficient prefabrication supply chain were identified, with information exchange among stakeholders recognised as a barrier to achieving effective supply chain integration. The conclusion drawn was that the absence of innovations or information technology hampers the collaborative environment in the supply chain and has a detrimental impact on the evolution of trust. An advanced information integration technology, namely blockchain, was identified as a facilitator of information integration and collaboration.

Efficient information sharing plays a crucial role in directly enhancing the material flow, fostering trust and collaboration among partners, reducing costs, integrating the supply chain, and positively impacting customer satisfaction (Cai, Jun, & Yang, 2010; Gibb & Isack, 2003; Prajogo & Olhager, 2012; Sahin & Robinson, 2002). Consequently, the conceptual framework developed in this study outlines the main factors influencing obstacles to prefabrication supply chain integration and highlights the potential impacts of utilising blockchain technology in this domain.

Establishing an effective information exchange system among prefabrication supply chain stakeholders, coupled with retaining all project information in a secure and tamper-proof database, is evidently poised to enhance interactions, security, transparency, and trust (Naz et al., 2019; Čuš-Babič, Rebolj, Nekrep-Perc, & Podbreznik, 2014). This, in turn, contributes to a more effective and efficient supply chain integration. Moreover, preserving information from completed projects serves as a repository of project knowledge, offering a trustworthy source of documents for future projects (Konukcu, 2011).

Blockchain technology offers a secure and tamper-proof database for information exchange among organisations in the supply chain (Penzes, 2018). This mechanism essentially functions as a decentralised ledger, granting users the right to amend existing contents only with the permission and agreement of other users (Kuzlu et al., 2019). This capability stands in contrast to typical web-based ledgers, where anyone with permission can alter the contents stored in the database (Naz et al., 2019). Consequently, this technology has the potential to mitigate issues stemming from a lack of information integration. However, it's important to note that the effectiveness of this technology relies on the assumption that the input information to the blocks is genuinely correct and credible (Lemieux, 2016).

The conceptual framework highlighting the important facets described above is shown in Figure 1-1 below:

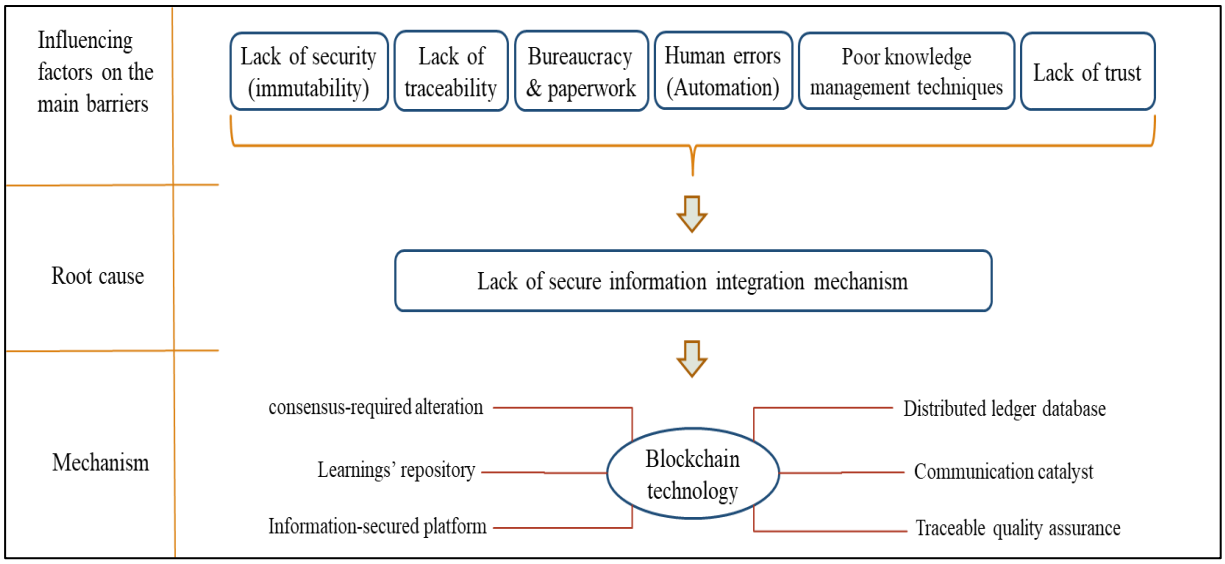

Figure 1-1: Conceptual model for blockchain-based information integration in prefabrication supply chain

1.4 Summary of the literature

Construction stands as one of the largest industries globally. In New Zealand, it constituted a 3.8% contribution to the Gross Domestic Product (GDP) in the third quarter of

2023 (StatsNZ, 2023). Despite its significant economic role, the industry suffers from several inherent challenges: low productivity, low material quality, and a lack of collaboration and information sharing among stakeholders (Li et al., 2019). While traditional construction faces these challenges, prefabrication emerges as a valuable innovation, offering solutions by minimising defects, reducing time and costs, and enhancing overall performance.

Supply chain management (SCM) techniques are increasingly applied across various industries. Despite several studies on SCM in the construction industry, there is a notable scarcity of research specifically focused on prefabricated construction. This gap in research requires extra attention given the efficiency and effectiveness of current prefabrication supply chain systems. Key factors contributing to effective supply chain management in this context include collaboration between project partners, the unrestricted flow of information, and the establishment of trust among stakeholders (Bidabadi et al., 2016).

The primary goal of this study is to employ blockchain technology as an information integration mechanism to enhance security, trust, collaborative relationships, traceability, and transparency within the context of New Zealand's prefabrication supply chain. The aim is to achieve a more effective and efficient supply chain integration, making this the research's focal area and targeted objective.

1.5 Research aim and objectives

This study aims to develop a framework for ensuring the integration of the prefabrication supply chain using blockchain technology. To achieve this goal, the following objectives are pursued:

1. To identify the prefabrication project phases and stakeholders involved in New Zealand's prefabrication supply chain.
2. To determine the engagement of each stakeholder and explore their interconnectivity in New Zealand's prefabrication supply chain.
3. To identify, assess, and categorise the types and modes of interactions among stakeholders involved in the prefabrication supply chain in New Zealand.
4. To ascertain the applicability of blockchain technology in New Zealand's prefabrication supply chain from the identified interactions.
5. To develop a framework for enhancing supply chain integration in New Zealand's prefabrication subsector using blockchain technology.

1.6 Research questions

The research addresses the questions below:

- **Question 1:** Who are the main stakeholders involved in New Zealand's prefabrication construction supply chain?
- **Question 2:** How can the interactions among supply chain stakeholders in New Zealand's prefabrication construction industry be enhanced?
- **Question 3:** What are the types and modes of information required to facilitate the integration in the prefabrication supply chain?
- **Question 4:** How could the application of blockchain technology enhance the integration of the prefabrication supply chain?
- **Question 5:** What framework can be developed using blockchain technology to enhance the prefabrication supply chain?

1.7 Significance of the study

Prefabrication technology is recognised as an innovative alternative to traditional construction methods. This innovation holds the potential to enhance the quality of houses, reduce overall project costs and timelines, minimise waste production and energy consumption, and increase productivity within the construction industry (Shahzad, 2016). However, the low efficiency of current supply chain practices poses a barrier to the widespread adoption of this innovation, demanding extra attention. Blockchain, hailed as the latest innovation in cryptographic relationships, is anticipated to offer substantial benefits to the prefabrication sub-sector (Penzes, 2018). Presently, there is limited understanding of the actual performance of blockchain in the prefabrication supply chain. This research aims to serve as a valuable resource for future research endeavours, proposing a more effective supply chain integration through innovative blockchain technology. Additionally, this study is both people and process-focused, aiming to introduce an emerging but innovative model that enhances dynamic interactions among prefabrication supply chain stakeholders in New Zealand.

1.8 Contribution to knowledge

Despite abundant research on supply chain management (SCM) in the construction industry, there is limited research focusing on the prefabrication supply chain. This gap in research is particularly crucial when addressing the significant obstacles inhibiting the efficiency and effectiveness of prefabrication supply chain systems. Therefore, the current study aims to provide insights into supply chain integration in prefabrication.

The application of blockchain technology has begun to be explored globally, and it presents a modern practice from which the prefabrication industry can benefit. Prefabrication projects involve complex supply chains with multiple stakeholders (Shahzad, 2016).

Blockchain can be used to track the flow of materials and payments, reducing delays and disputes. This research explores how blockchain can be integrated into supply chain management systems to optimise logistics and reduce inefficiencies and information disintegration.

Also, construction projects involve sensitive data such as architectural plans, financial transactions, and legal agreements (Shojaei, 2019). Blockchain's cryptographic features can enhance data security by providing a tamper-resistant and immutable record of transactions (Naz et al., 2019). This research contributes to the focus on developing secure blockchain solutions tailored to the unique needs of the prefabrication industry.

Moreover, the construction industry is subject to various regulations and standards governing safety, environmental sustainability, and building codes (Rahimian et al., 2017). Blockchain technology can help ensure regulatory compliance by providing a transparent and auditable record of activities throughout the project lifecycle. This research can help industry practitioners and researchers assess the regulatory implications of blockchain adoption in construction and identify best practices for compliance.

Utilising blockchain to enhance information integration and stakeholders' interactions across the prefabrication supply chain holds potential value for industry practitioners and researchers. Currently, there is scant knowledge about the challenges in the prefabrication supply chain in New Zealand. This study seeks to address this knowledge gap and aims to provide a valuable foundation for future research, which can contribute positively to a resilient supply chain in the prefabrication industry.

The knowledge gap identification process is shown in Figure 1-2 below:

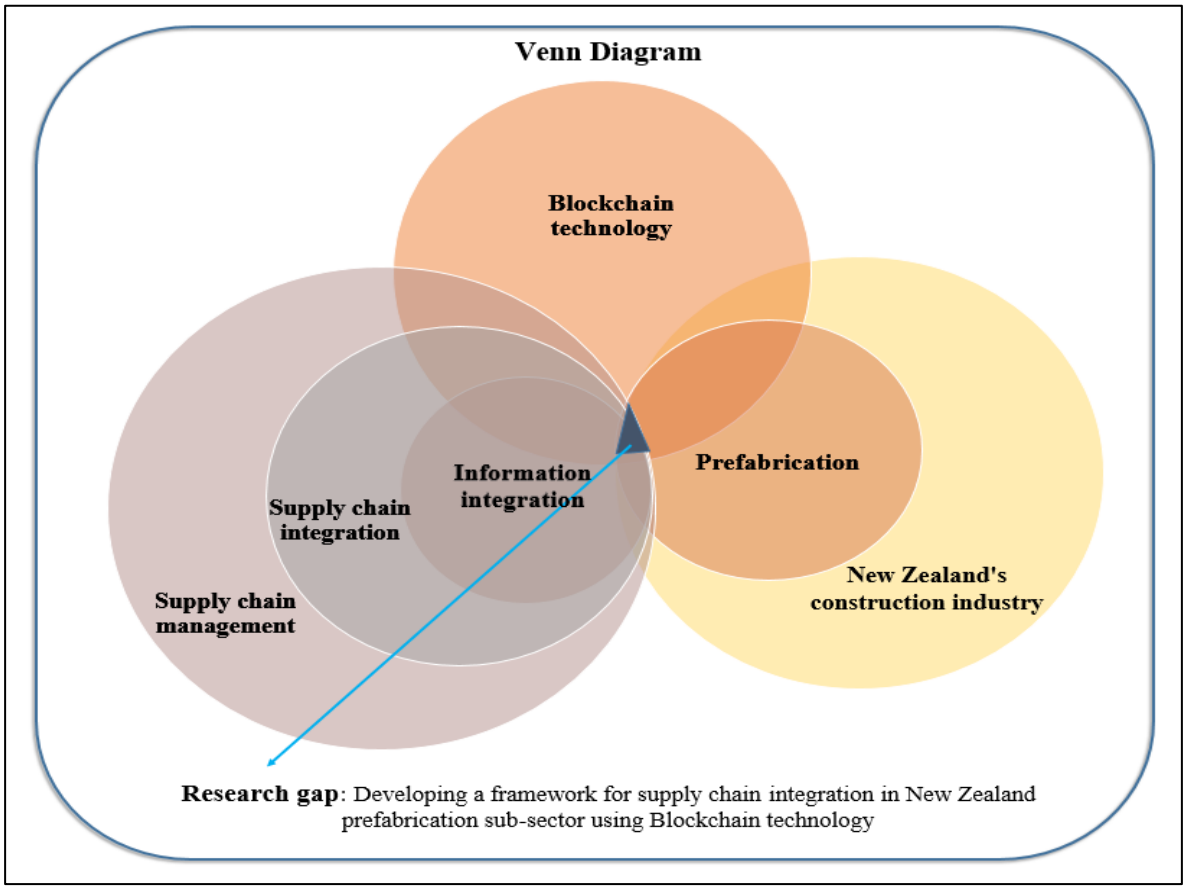

Figure 1-2: Venn diagram for research focus

1.9 Research methodology

1.9.1 Overview

This section of the research outlines the process of selecting a methodology for conducting the study. The chosen research philosophy is explained, and a comparison is made with other philosophical alternatives and perspectives. There has been a longstanding debate among scholars regarding research methodologies and philosophies, resulting in two opposing viewpoints: Unificationism and Pluralism. Unificationists argue for using a single specific research philosophy, methodology, or paradigm, while pluralists believe that embracing the diversity of the field is beneficial in making research a genuine scientific discipline (Saunders,

2011). In this research, a pluralistic approach will be adopted to compare multiple philosophical perspectives, and ultimately, one particular approach will be chosen, outlined, and justified.

This study involves a comprehensive process that includes an in-depth review of relevant literature, data collection, analysis, and framework development. To achieve the research objectives, a thorough literature review is conducted, supplemented by questionnaire surveys and interviews with experts in the construction industry. By combining qualitative and quantitative research approaches, a mixed-method approach is adopted to collect and analyse the data. The analysis of the gathered data will guide the development of a practical framework aimed at promoting prefabrication supply chain integration.

1.9.2 Research method

Research is a structured approach to exploring new facts and expanding knowledge (Walliman, 2017). The nature of research is influenced by various factors, including location, financial considerations, data collection techniques, analysis methods, and the availability of literature and resources (Fellows & Liu, 2015). Due to these factors, research can be both indefinite and limited. Therefore, it is essential to systematically plan a comprehensive investigation into different research methods to streamline the study process and mitigate associated complications.

In each research stage, whether consciously or not, the author inevitably makes several assumptions and forms ideas based on their perspective and knowledge (Walliman, 2017). These assumptions may pertain to human cognitive understanding (epistemology), the nature of realities and facts encountered during the research (ontology), and the degree to which the author's values influence the research process (axiology) (Saunders, 2011). These assumptions systematically develop and shape the overarching philosophy of the author (Saunders, 2011).

A well-developed philosophy ensures a coherent strategy, methodology, data collection, and reliable analysis in the research process (Fellows & Liu, 2015).

1.9.2.1 Ontological perspective

Ontology is considered the set of assumptions and beliefs concerning the existence and nature of reality (Bell, Bryman, & Harley, 2018). These ontological assumptions play a crucial role in shaping the authors' perspectives on research and influence the trajectory of the study. Ontology involves the examination of research objects, such as individuals' lives and organisational artefacts (Walliman, 2017). In essence, it consists of the study of what exists and the nature of that existence within the context of the research.

In other words, the author's ontology determines how they perceive the world and what they choose to investigate (Fellows & Liu, 2015). Philosophical positions in ontology can be broadly categorised into "objectivism" and "subjectivism" perspectives. Advocates of objectivism assert that the existence of social phenomena and their implications is independent of social actors and lies beyond our influence. On the other hand, supporters of subjectivism believe that social realities are continually constructed by social actors (Grix, 2002).

According to Saunders (2011), ontological objectivists adopt a perspective aligned with realism, positing that social entities are akin to physical objects in the world, and their existence is independent of our perceptions. In contrast, subjectivists incorporate humanities and art into their assumptions, contending that social phenomena are constructed through the influence of human beings on each other. In its most extreme form, ontological subjectivism aligns with nominalism, suggesting that the structure of social realities is created by us and there is no reality in the social world that cannot be attributed to people's experiences and perceptions. In a less extreme form, subjectivists embrace constructivism, implying that reality and social

phenomena are partially shaped by the interaction of social actors and their interpretation of the world (Saunders, 2011).

1.9.2.2 Epistemological perspective

Epistemology is a philosophical branch that deals with the theory of knowledge, specifically focusing on the methods, validation, and ways of obtaining knowledge about social reality (Grix, 2002). According to Bell et al. (2018), epistemology involves assumptions about knowledge and addresses the question of what should be considered acceptable and legitimate knowledge. In simpler terms, epistemology is associated with determining 'what' and 'how' we can know about acceptable knowledge regarding social reality.

Epistemology is divided into two main branches: "empiricism," which is concerned with knowledge gained through sensory experience, and "rationalism," which involves knowledge acquired through solid logic and reasoning (Walliman, 2017). Other terminologies are also used to describe the classifications of epistemological positions. Bell et al. (2018) elaborates on two opposing perspectives within epistemology: "positivism" and "interpretivism."

Epistemological positivists argue that all knowledge about social reality should be derived from natural sciences through measurable and observable facts. They adopt a numerical and evidential viewpoint, asserting that only observable and measurable phenomena are credible and authentic (Saunders, 2011). In contrast, epistemological interpretivists advocate for recognising the distinction between objects of natural sciences and human beings. They assert that a social scientist is required to perceive and interpret the abstract meanings of social actions (Bell et al., 2018). In terms of epistemological positions, objectivists align with positivism, while subjectivists align with interpretivism.

1.9.3 Establishment of a philosophy for the study

Establishing an appropriate ontological and epistemological philosophy for research is crucial in guiding the selection of a suitable method. This study investigates stakeholders' relationships and information flows in the prefabrication supply chain and proposes an advanced information integration tool to enhance integration. Given that the study involves interviews and gathers opinions from industry practitioners, a positivist philosophy alone may not be sufficient. While construction experts' shared values and beliefs will be used to understand shortcomings in the effective prefabrication supply chain, the constantly changing nature of human interactions significantly impacts information integration. This aspect leads the research to lean towards adopting a constructivist perspective.

For this study, the reality is seen as being constructed through organisational culture, and therefore, the research philosophy is built upon social interactions. It is adaptable to changes in human behaviour and will evolve with any shifts in the organisational landscape.

Furthermore, this study aims to identify a mechanism for enhancing information integration in the prefabrication supply chain and delves into how this improvement can be achieved and what tools are required for this purpose. Additionally, the study investigates the relationships and flow of information among stakeholders in the prefabrication supply chain and recognises barriers to improvement. Given the importance of industry experts' opinions in data collection, this study appears to be inductive and more aligned with an interpretivist’s perspective. Through gaining an understanding of the interviewees' perspectives, this study seeks to acquire knowledge about the reality of enhancing prefabrication supply chain integration.

However, the process of analysing the data related to the relationships and information exchange among prefabrication stakeholders involves quantified measures, which steers the study towards a deductive approach and positivist perspectives. Additionally, considering the nature of blockchain technology, which is designed to provide a secure platform for information, this can be seen as a regulation associated with the technology. Hence, this fact supports adopting an objectivism philosophy for this research.

In this context, the philosophy of pragmatism seems more feasible for this study. Pragmatism seeks to reconcile subjectivism and objectivism by considering concepts, hypotheses, ideas, and findings in terms of their pragmatic consequences in a particular context (Saunders, 2011). Pragmatism offers a more flexible approach, focusing on research outcomes and connecting theories and practices. A pragmatic researcher has greater freedom in adopting multiple methods and techniques.

When the primary determinant of a research strategy is the questions and problems that the researcher aims to address, pragmatism becomes the most viable choice (Saunders, 2011). Therefore, this research adopts a pragmatism philosophy because it effectively connects theory to practice. This flexible philosophy not only moderates positivist and interpretivist viewpoints but also allows the researcher to adopt multiple research methods, including qualitative and quantitative approaches (Fellows & Liu, 2015).

1.9.4 Research approach

Adopting blockchain technology, being an emerging technology, is relatively new to the perspective of industry practitioners. Given the limited studies on the impacts of this technology on supply chain integration, its practical implementation has not been thoroughly explored. This research encompasses qualitative measures such as trust, collaboration, and information within

its context, which cannot be easily quantified. Research methods are typically classified as qualitative, quantitative, or mixed methods based on data collection techniques and analysis procedures (Walliman, 2017). In this research, the qualitative approach appears to be more suitable for capturing the nuanced aspects of trust, collaboration, and information in the context of adopting blockchain technology in the supply chain.

1.9.4.1 Exploratory/Qualitative method

The qualitative method is often called an inductive approach to conducting research and is closely associated with the interpretivist philosophy (Saunders, 2011). Qualitative research employs a naturalistic approach to understanding phenomena in context-specific settings (Golafshani, 2003). This method involves collecting data from various sources to understand individual participants, including their opinions, perspectives, and attitudes (Nassaji, 2015). According to Creswell and Creswell (2017), qualitative methods focus on studying the context or setting of participants and rely on interviews or observational data where personal values can be brought into the study. Qualitative research enhances the description and explanation of real-world phenomena (Bradley, Curry, & Devers, 2007) and extracts findings from real-world settings (Patton, 2015).

Qualitative researchers exhibit greater flexibility and responsiveness to changes that may arise during their study, allowing them to investigate different cases and describe complex phenomena thoroughly. However, it is essential to note that qualitative data may have lower credibility than quantitative data, and the data collection and analysis process in qualitative research is often time-consuming. Additionally, the findings and results of a qualitative study can be influenced by the personal beliefs and biases of the researcher (Johnson & Onwuegbuzie, 2004). While qualitative research provides rich insights and a deeper understanding of the

subject matter, researchers must be mindful of potential limitations and biases in their interpretations.

1.9.4.2 Descriptive/Quantitative method

The quantitative method is often referred to as a deductive approach to conducting research and is closely associated with positivism philosophy (Saunders, 2011). Quantitative data deals with numbers and statistics used to record information about society and sciences, such as density, temperature, pressure, population, and cost indices (Walliman, 2017). Quantitative methods enable measuring relationships between numerical variables and facilitate statistical analysis (Saunders, 2011). According to Golafshani (2003), quantitative methods offer more reliability when dealing with measurable facts. Experimental studies and questionnaire surveys fall within the realm of this method.

While data collection and analysis using the quantitative method are relatively fast, replicable, and precise, the researcher may miss other phenomena occurring along the research path (Johnson & Onwuegbuzie, 2004). Additionally, the knowledge produced by a quantitative researcher may be too general and abstract, limiting the practical application of the gained knowledge to specific contexts, situations, and individuals (Johnson & Onwuegbuzie, 2004).

1.9.4.3 Mixed method

Mixed-method research involves the combination of both qualitative and quantitative methods, as the name implies. It is employed when both qualitative and quantitative data collection and analysis are deemed necessary (Bell et al., 2018). This research method has become increasingly popular in social science research (Bell et al., 2018). The mixed-method approach aims to satisfy the requirements of both interpretivists and positivists, resulting in more valid research findings (Golafshani, 2003). By balancing the weaknesses and strengths of

quantitative and qualitative methods, mixed methods address the shortcomings inherent in each individual approach (Fellows & Liu, 2015).

The mixed-method approach provides more substantial evidence for results and conclusions through the corroboration and convergence of findings (Johnson & Onwuegbuzie, 2004). Researchers using this method can employ words, narratives, and pictures to add meaning to numerical data and vice versa. However, the process of combining methods can be challenging for a researcher, especially when multiple approaches need to be implemented concurrently (Johnson & Onwuegbuzie, 2004). Additionally, this approach can be more time-consuming and expensive compared to using a single method (Creswell & Creswell, 2017).

1.9.4.4 Research method selected for the study

Given the scope of quantitative, qualitative, and mixed research methods and adopting a pragmatism philosophical perspective, this research opts for a mixed-method approach. Investigating the current implementation of blockchain technology within prefabrication supply chains, exploring how information is exchanged among stakeholders, and mapping their interrelationships necessitate a qualitative approach to data collection. Simultaneously, a quantitative method is employed to determine and categorise the engagement of each stakeholder involved in the prefabrication supply chain in each phase of prefabricated construction.

1.9.5 Research process

1.9.5.1 Data collection

The sequence of this research is indicated in Figure 1-3. The study involves an in-depth literature review, data collection and analysis, research findings, and validation. These steps are mapped to the corresponding objectives and are presented in three stages. As outlined, this

research employs mixed methods for data collection and analysis. The first stage of data collection involves conducting an in-depth literature review. This section serves to identify the current innovations in the prefabrication supply chain and the application of blockchain technology in this sector.

Following the literature review, the second data collection stage involves semi-structured interviews and questionnaire surveys. Semi-structured interviews are employed to gather opinions from prefabrication experts, identifying stakeholders in the prefabrication supply chain and exploring their interactions. Questionnaire surveys are used to reinforce and identify the involvement of each stakeholder in different project phases within the context of New Zealand and collect data on categorising and comparing stakeholders' interaction types against blockchain requirements. This process establishes a map of prefabrication supply chain stakeholders' interrelationships based on information exchange among them. Subsequently, a blockchain framework is developed to target the improvement of supply chain integration in prefabrication construction. The developed framework is validated through focused group interviews.

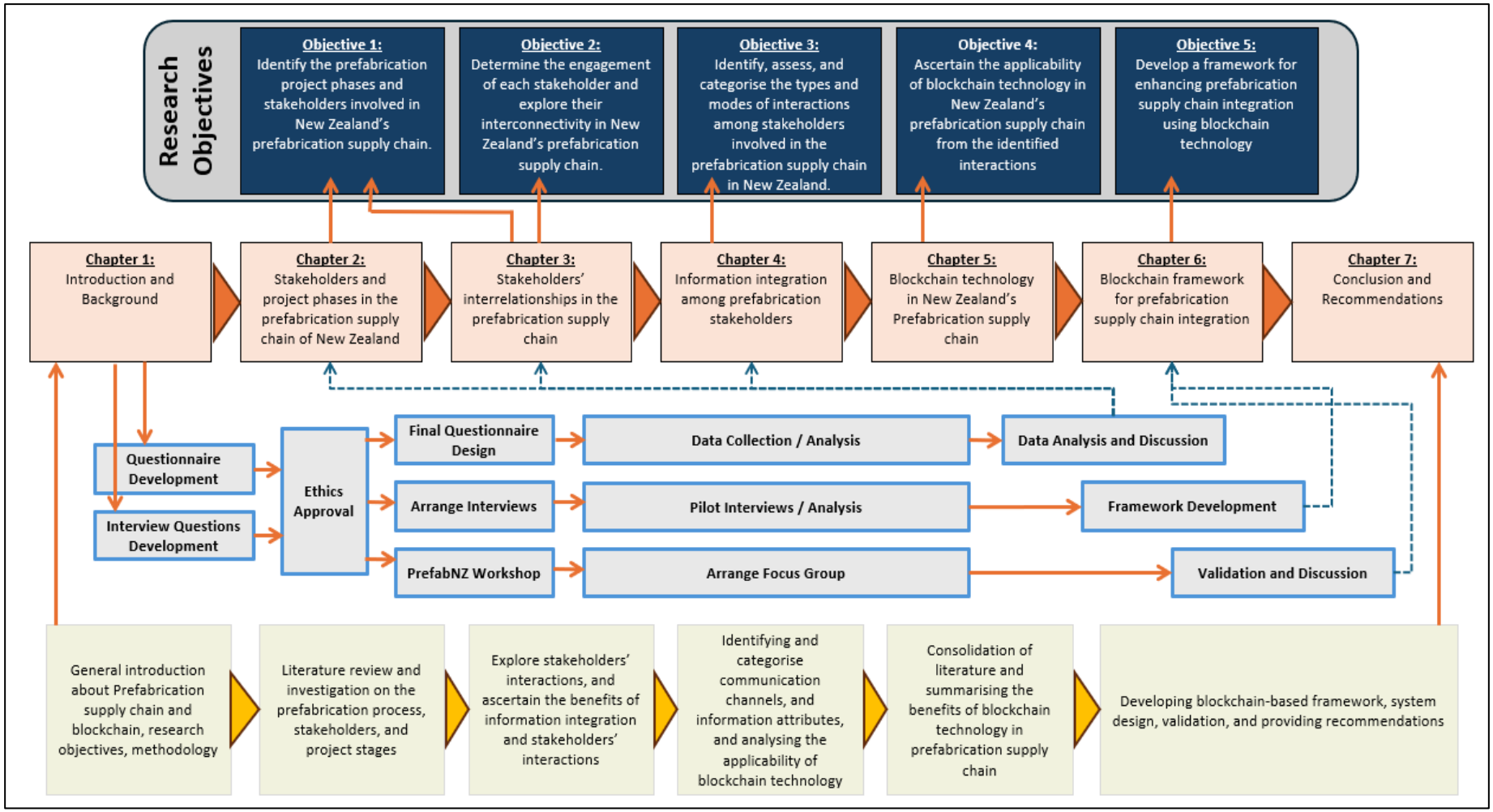

Figure 1-3 Research design for this study

1.9.5.1.1 Stage 1 – In-depth literature review

The literature review is crucial in conducting research, enabling the author to identify valid knowledge gaps (Fellows & Liu, 2015). It not only solidifies the theoretical foundation of the research but also guides the researcher in problem identification. This study's in-depth literature review is undertaken based on previous studies in the form of journal articles, books, and reports. This review aims to establish and synthesise the relationships among three variables: blockchain, supply chain integration, and prefabrication construction. This step aids the author in understanding the current state of blockchain technology, barriers to adopting innovative technology, and challenges in the uptake of the prefabrication supply chain within New Zealand's construction industry. Additionally, this step helps identify associated stakeholders involved in prefabrication supply chains and gain an understanding of the interactions, including information, documents, knowledge, and data exchange among them.

1.9.5.1.2 Stage 2 - Semi-structured interviews and questionnaire survey

Interviews are considered a qualitative data collection technique that provides the author with the viewpoints and behaviours of people (Saunders, 2011). Semi-structured interviews are used in this research. In this method of data collection, questions are partially structured, allowing the interviewer and interviewee more flexibility than a structured interview (Fellows & Liu, 2015).

This research uses semi-structured pilot interviews to establish the connection between blockchain technology and prefabrication supply chain practices. Additionally, stakeholders' interactions are scrutinised and mapped using the data gathered from these interviews. The interview participation invite was extended to 12 professionals with expertise in prefabricated

construction, of whom six expressed interest. Each of these experts boasted over a decade of experience within New Zealand's construction sector.

Furthermore, a questionnaire survey is used to collect data from prefabrication practitioners and academic experts. A questionnaire survey is a quantitative means of collecting data for research (Bell et al., 2018). In this research, the questionnaire survey is utilised to determine and pinpoint the involvement of each stakeholder identified in each stage of prefabrication construction projects. Completing this step is essential, as it involves understanding the information-based interactions among identified stakeholders in each phase of prefabrication construction. The survey was distributed to OffsiteNZ, an organisation comprising approximately 350 members from the design and construction sectors.

1.9.5.1.3 Stage 3 – Focused group interview

In this stage, the information and data collected from literature, interviews, and questionnaire surveys are synthesised. A framework for improving prefabrication supply chain integration using blockchain technology is proposed and validated through focused group interviews and a validation survey (Appendix 4). This type of interview allows participants to engage in an interactive discussion (Saunders, 2011). Additionally, focused group interviews can provide reliable data within a short period (Fellows & Liu, 2015). This stage accomplishes the fifth objective of the research.

1.9.5.2 Sampling method

When it is unfeasible to collect data from the entire population, the necessity of sampling arises. Budget and time are important factors that need to be considered when selecting sampling as an alternative to a census. Surveys use sampling techniques to collect data from a small-scale population to understand the larger population to a particular level of confidence

(Fellows & Liu, 2015). In this research, a combination of purposive and snowball sampling is adopted for data collection. This convenience sampling approach is employed by initially focusing on reaching out to several familiar OffsiteNZ members and then employing a snowball technique to recruit additional respondents through their networks. This method was chosen due to the difficulties in accessing all members of OffsiteNZ.

Purposive sampling ensures respondents have adequate experience in the prefabrication construction industry to participate in the survey. The snowball approach helps obtain responses from other professionals who meet the criteria of minimum working experience. Given the developing nature of prefabrication in New Zealand and the novelty of blockchain technology, finding a sufficient sample size of respondents could be challenging. Thus, the combined sampling approach can help overcome this challenge.

1.9.5.3 Data analysis

Once the data is collected, the next step is analysing the gathered data. Various techniques are available for analysing data, and choosing an appropriate technique is subject to the research questions (Bell et al., 2018). This study aims to develop a framework for ensuring prefabrication supply chain integration, so the selected techniques should align with this objective.

For analysing collected data from the questionnaire survey, Exploratory Data Analysis (EDA) is used. This statistical technique has widely been employed by many researchers in the field of supply chain management and firms' performance since it is useful for measuring and summarising data among variables in a rational way (Saunders, 2011). The results from this type of analysis assist in recognising the contribution of stakeholders in different stages of prefabrication projects, identifying the key elements of communication channels and information exchange, and exploring the applicability of blockchain technology in this sector.

Content analysis and quantitative descriptive analysis are used to analyse data collected qualitatively from interviews. Content analysis is a flexible and systematic approach to analysing qualitative data, suitable for realising themes or patterns within a qualitative dataset (Saunders, 2011). In this study, qualitative data collected from interviews is analysed to organise and categorise the interview data, allowing the extraction of relevant information patterns.

1.9.6 Validity and reliability of the study

Validity and reliability are crucial elements in any research as they guarantee the quality of research findings (Saunders, 2011). The subsequent sections elucidate the course of reliability and validity in this study.

1.9.6.1 Reliability

Reliability, as elucidated by Golafshani (2003), pertains to consistency in research outcomes. It can also be defined as the degree to which measures are free from error and, therefore, yield consistent results, i.e., the consistency of a measurement procedure (Thanasegaran, 2009). The results are considered more reliable if consistent and replicable findings are achieved in research. Unreliable research is considered invalid, as errors and biases can impact the outcomes and interpretations (Saunders, 2011).

Saunders (2011) argues that threats to reliability stem from errors and biases of both researchers and participants. Therefore, to enhance the reliability of the research, efforts should be made to mitigate errors and biases. This study takes steps to minimise interviewees' errors and biases by arranging interviews in an enclosed and comfortable setting and selecting a convenient and prearranged timeframe. Additionally, questions in the questionnaire are organised systematically and formulated concisely to facilitate participants' thorough

understanding. The author's interpretations of interviews are minimised by having interviewees review and verify the transcripts after each interview.

1.9.6.2 Validity

The quality of research is contingent not only on reliability but also on validity (Saunders, 2011). For research to be valid, it must be consistent with the intended outcome and exhibit consistency (Golafshani, 2003). Essentially, validity refers to the accuracy of the measures used, the analysis precision, and the result's generalisability (Saunders, 2011). Achieving effective research validity involves considering multiple sources and ensuring that it occurs consistently over time (Thanasegaran, 2009).

According to Saunders (2011), there are two primary criteria for validity: internal and external. External validity in research refers to the extent to which the findings can be generalised to dissimilar contexts and settings (Fellows & Liu, 2015). On the other hand, internal validity is associated with the ability of a measuring scale (e.g., a questionnaire) to measure what the author expects it to measure (Saunders, 2011).

Internal validity is divided into three forms: content validity, criterion-related validity, and construct validity (Saunders, 2011). Content validity refers to the degree to which the measuring tools provide satisfactory coverage of research questions (Fellows & Liu, 2015). Criterion-related validity is considered the ability of research questions (measures) to draw accurate and precise inferences or predictions (Thanasegaran, 2009). Construct validity refers to the degree to which the research questions actually measure what they intend to measure (Saunders, 2011).

The research focus in this study was established based on an in-depth literature review and initial interviews. Research questions were determined accordingly to address the research

focus through semi-structured interviews, questionnaire surveys, and focused group interviews. For content validity, these measuring aids cover all aspects of the research and provide satisfactory answers to the research questions. These questions are verified by academic supervisors, peers, and experts to ensure the feasibility of questions and their predicted answers and, therefore, to meet the criterion-related validity. In the end, construct validity is achieved by using analysing software and tools to test whether the results are genuinely in line with the actual questions identified for the research.

1.10 Ethical considerations

Ethical considerations are essential elements for an author when conducting research. Ethics in research, as defined by Saunders (2011), refers to the behaviour and moral standards that researchers maintain when driving their research in accordance with the rights of participants or the people who are the subject of the study. Ethics in research help prevent disruptions to social values during the research process.

In this research, all ethical principles are considered and maintained from the outset to the finishing point. Ethical approval for this research has been granted by the Human Ethics Committee of Massey University (MUHEC), declaring that the study falls within the low-risk category. The Ethics Notification Number is 4000021397. Codes of ethical conduct at Massey University ensure respect for the confidentiality and privacy of participants. An invitation to participate is used before collecting data. Participants were fully informed about the purpose, procedures, risks, and benefits of the research before agreeing to participate. They had the freedom to consent or decline participation without coercion. Participants' personal information and the entity’s names and sources were disclosed or kept confidential in any report or article. Safety principles throughout all stages of data collection were adhered to.

Table 1-4: Research outline

Ch#	Chapter Title	Related Paper Title	Research Objective	Methodology	Analysis
1	Introduction		To establish the scope, context, and significance of the research		
2	Stakeholders and project phases in the prefabrication supply chain of New Zealand	A process map for supply chain relationships in prefabricated construction	To identify the prefabrication project phases and stakeholders involved in New Zealand's prefabrication supply chain.	Literature review	Descriptive analysis
3	Stakeholders' interrelationships in the prefabrication supply chain	• Blockchain technology applicability in New Zealand's prefabricated construction industry • Applicability of Blockchain technology in New Zealand's prefabricated construction industry: A potential solution	To determine the engagement of each stakeholder and explore their interconnectivity in New Zealand's prefabrication supply chain.	Literature review Semi-structure interview Questionnaire survey	Thematic analysis / Descriptive analysis
4	Information integration among prefabrication stakeholders	Blockchain and information integration: Applications in New Zealand's prefabrication supply chain.	To identify, assess, and categorise the types and modes of interactions among stakeholders involved in the prefabrication supply chain in New Zealand.	Literature review Questionnaire survey	Descriptive analysis
5	Blockchain technology in New Zealand's Prefabrication supply chain	Applying secure information-based mechanism for prefabrication supply chain integration: A review	To ascertain the applicability of blockchain technology in New Zealand's prefabrication supply chain from the identified interactions	Literature review Questionnaire survey	Descriptive analysis
6	Blockchain framework for prefabrication supply chain integration		To develop a framework for enhancing prefabrication supply chain integration using blockchain technology	Literature review Focus group interview Validation survey	Descriptive analysis
7	Conclusion		To provide concluding remarks, recommendations for future research, and limitations of the study		

1.11 Thesis Structure

In adherence to Massey University guidelines and following the thesis with publication format, this PhD dissertation is structured to include five publications. The comprehensive framework comprises an introductory chapter, five core chapters, and a concluding chapter. Each of these components has been meticulously crafted to align with and accomplish the defined objectives of the thesis.

Chapter 1: Introduction

This section outlines the literature existing in supply chain management. The influential factors of supply chain enhancement are discussed in various subheadings. The literature review proceeds with a focus on investigating the current relationships of prefabrication supply chain partners in terms of information flow. Consequently, the opportunities and barriers to an effective and efficient prefabrication supply chain are investigated. The findings from the literature reveal that there is a lack of a secure information integration platform within the supply chain. Also, it is inferred that to obtain a better supply chain integration, there is a crucial need to adopt advanced information integration technologies. Then, a conceptual model is indicated that highlights the impact of blockchain technology as an information integration mechanism on supply chain integration. Finally, the research philosophy and methodology are appraised thoroughly, and a particular method is selected for the research.

Chapter 2: Stakeholders and project phases in the prefabrication supply chain of New Zealand

This chapter is dedicated to understanding the impediments hindering the uptake of prefabrication construction, exploring prefabrication project stages, and identifying the stakeholders involved in the prefabrication supply chain in New Zealand, using extensive

literature review and analysis. The chapter's findings contribute to developing a process map illustrating the interconnectivity of the stakeholders within a typical prefabrication project in New Zealand, thus addressing the first objective and partially fulfilling the second objective of this thesis.

***Manuscript*:** Bakhtiarizadeh, E., Shahzad, W., & Rotimi, JOB. (2019). A process map for supply chain relationships in prefabricated construction. In *Proceedings of the 43rd Australasian Universities Building Education Association (AUBEA)* Conference, 112 – 123.

Chapter 3: Stakeholders' interrelationships in the prefabrication supply chain

To understand stakeholders' interconnectivity across various stages of prefabrication projects, a comprehensive literature review was undertaken to identify and categorise these interconnections. Subsequently, a pilot study was completed to validate the identified stakeholders and assess the intricacies of their relationships during specific project phases in New Zealand. Consequently, a questionnaire survey was developed to quantify the significance of information integration among diverse organisations, identify the attributes of information deemed essential for the success of the prefabrication supply chain, and ascertain the perceived advantages of employing blockchain technology in the prefabrication industry. The development of this chapter was aligned with accomplishing the second objective of this study and, in part, seeking answers to the fourth objective.

***Manuscript*:** Bakhtiarizadeh, E., Shahzad, WM., Poshdar, M., & Rotimi, JOB. (2022). Blockchain technology applicability in New Zealand's prefabricated construction industry. *Engineering Management in Production and Services, 14*(1), 103-112.

Manuscript: Bakhtiarizadeh, E., Shahzad, W., Poshdar, M., & Rotimi, JOB. (2021). Applicability of Blockchain technology in New Zealand's prefabricated construction industry:

A potential solution. *In Proceedings of the 11th International Conference on Engineering, Project, and Production Management (EPPM), Poland,* 9.

Chapter 4: Information integration among prefabrication stakeholders

To achieve the third objective and ascertain the fourth objective, this chapter employs an exploratory approach and focuses on identifying communication channels within the prefabricated construction supply chain in New Zealand. From the identified stakeholders and prefabrication project phases, the relationships between clients and subcontractors within the technical design, construction, and handover phases of a typical prefabrication project are explored. The methodology involves using a questionnaire survey to identify the modes of information exchange between clients and contractors and explore the qualities of information deemed critical for enhancing the prefabrication supply chain.

Manuscript: Bakhtiarizadeh, E., Shahzad, WM., Poshdar, M., Khalfan, M., & Rotimi, JOB. (2021). Blockchain and information integration: Applications in New Zealand's prefabrication supply chain. *Buildings MDPI, 11*(12), 608.

Chapter 5: Blockchain technology in New Zealand's Prefabrication supply chain

The primary aim of this chapter is to reinforce the findings presented in Chapters 3 and 4 of the thesis, aligning with the overarching goal of achieving the fourth objective outlined in the research. A literature-based study was conducted to ascertain the applicability of blockchain technology in the prefabrication supply chain in New Zealand, supplementing the first three objectives of the research.

Manuscript: Bakhtiarizadeh, E., Shahzad, W., & Rotimi, J. (2020). Applying secure information-based mechanism for prefabrication supply chain integration: A review. In

Proceedings of the 5th New Zealand Built Environment Research Symposium (NZBERS), Auckland, New Zealand, 71-78.

Chapter 6: Blockchain framework for prefabrication supply chain integration

This chapter accomplishes the fifth objective by developing a framework for the practical adoption of blockchain technology in the prefabrication supply chain in New Zealand. This chapter employs a qualitative approach to design an information integration framework for enhancing the information exchange among the prefabrication stakeholders. The framework was presented to the prefabrication and blockchain experts in a focus group session, and then the framework's validity was quantitatively analysed through a validation survey.

Chapter 7: Conclusion

This chapter concludes with remarks and provides recommendations, theoretical and practical framework implementation, and research limitations.

Chapter 2: Stakeholders and project phases in the prefabrication supply chain of New Zealand

2.1 Prologue

This chapter combines a literature review with empirical observations to examine the current state of integration within New Zealand's prefabrication supply chain and to pinpoint obstacles hindering its productivity. Using a comprehensive review of the literature and the Royal Institute of British Architects (RIBA) plan of work 2013, this chapter develops a process map outlining the flow of information within New Zealand's prefabrication supply chain. Consequently, the implementation of blockchain technology as a potential solution to address the obstacles in the prefabrication supply chain is investigated.

A review of relevant literature on the prefabrication supply chain facilitates the identification of stakeholders engaged in prefabrication projects. Also, RIBA plan of work alongside the literature review assist in identifying the different phases of prefabrication projects and the flow of information among the stakeholders within each phase. A comparison review of the newer RIBA plan of work version 2020 has also been conducted in the background to ensure the currency of the identified project phases and the result is basically the same. Finally, this chapter concludes that integrating the identified flow of information among the stakeholders in each phase could help improve the integration of the overall prefabrication supply chain using advanced technologies such as blockchain.

The current chapter is based on the following article:

Bakhtiarizadeh, E., Shahzad, W., & Rotimi, JOB. (2019). A process map for supply chain relationships in prefabricated construction. In *Proceedings of the 43rd Australasian Universities Building Education Association (AUBEA)* Conference, Austraila,112 – 123.

2.2 Abstract

Supply chain management (SCM) techniques are applied to different industry sectors, e.g., food production, pharmaceutical trades, and construction. Despite a handful of research conducted on SCM in the construction industry, research focusing on the prefabrication supply chain is limited, particularly where the major obstacles inhibiting the efficiency and effectiveness of prefabrication supply chain systems demand attention. Therefore, the current study provides insight into supply chain integration in prefabrication. A review of relevant literature coupled with experiential learning is employed to map supply chain relationships and information flow in the prefabrication subsector of the construction industry in New Zealand. The objective is to establish inter-relationships of prefabrication supply chain partners and investigate the impediments to achieving optimum benefits in SCM and any innovation opportunities. This study shows that any mechanisms eliminating intermediaries and distributing supply chain information more effectively deserve attention. An unalterable information database in the supply chain could vividly accelerate business interactions and produce more transparent collaborations and trust among prefabrication project partners.

2.3 Introduction

Construction is one of the biggest industries in the world. In New Zealand, it made a contribution of 3.7% to the Gross Domestic Product (GDP) in the first quarter of 2019 (StatsNZ, 2019). However, the industry is still suffering from many inherent issues, including low productivity, poor quality of materials, lack of trust, and lack of collaboration and information

sharing among all the stakeholders (Li, Greenwood, & Kassem, 2019). Whilst the conventional type of construction is suffering from such issues, offsite manufacturing or prefabrication has been recognised as an effective solution to target these problems by reducing defects, lowering lifecycle time and costs, improving the quality of final deliverables, and growing sustainability (Shahzad, 2011). In New Zealand, the uptake of prefabrication is higher than in other countries, with an estimated 32% uptake in 2015 compared to Australia at 3%, the UK at 4%, Spain and France at 5% (PrefabNZ, 2015).

Business interactions are being accounted as a vital turning point for acquiring high benefits in supply systems (Nicholas & Edwards, 2003). Effective flow of information and collaboration between project partners contribute to effective supply chain integration and trust (Bidabadi et al., 2016). To meet these requirements, a clear map of interrelationships with respect to the flow of information must be established to provide all the construction stakeholders with an insight into prefabrication supply chain integration.

A study by Black, Akintoye, and Fitzgerald (2000) indicates that integration of relationships, which is an effect of information integration, can bring improved performance and reduce conflicts in the construction supply chain. Hence, when information sharing is built explicitly among all involved parties, significant benefits, including cost benefits, transparency, stakeholder satisfaction, trustworthy collaboration, and better-quality products, are obtained. Also, Cai, Jun, and Yang (2010) advise that effective information sharing contributes to transparent relationships and improves trust and coordination.

However, there are a few barriers deterring efficient supply chain management. Reluctance to adopt new technologies, low transparency and traceability, and lack of appropriate information technology are considered some hurdles (Akintoye et al., 2000;

Harland et al., 2007). In addition, a shortage of secure and tamper-proof blocks of information and knowledge precedents within the supply chain is considered another hindrance (Penzes, 2018). Therefore, the current paper provides a baseline for the prefabrication supply chain efficiency by establishing an information-based relationships map of prefabrication supply chain partners in New Zealand.

This study utilises a literature review and empirical observations to investigate the existing status of prefabrication supply chain integration in New Zealand and to identify limitations to gaining a productive supply chain. Showing the arrows of relationships and information directions among supply chain stakeholders, findings reveal a deficiency in having an appropriate platform for information storage when it comes to integration and collaboration within the supply chain.

2.4 Literature review

Different synonyms that are interchangeably used, such as offsite manufacturing, offsite fabrication, pre-assembly, offsite construction, and prefabrication, all signify the process of building a component, a portion, or a complete structure of a bigger project remotely. Offsite fabrication is classified into five types, including component-based (units and components such as precast beams and columns), panelised (such as precast floor or wall panels), modular (such as pods or modules), hybrid (combination of panelised and modular prefabrication) and complete building prefabrication (Shahzad, 2016). Prefabrication is a potential remedy for traditional construction drawbacks and is perceived to be sociologically, economically, and environmentally advantageous regarding the reduction of waste and defects and promoting sustainability (Al-Ma’aitah, 2018; Kaufmann & Remick, 2009).

A study report published by BRANZ characterises prefabrication as the system and structure that facilitates the construction of a complete or a part of a building away from the final location (Burgess et al., 2013). Prefabrication is envisaged as an innovative form of construction. Shahzad (2016) scrutinises the major benefits and impacts of prefabrication in the New Zealand construction industry and states that this innovation has the potential to shorten the productivity problems arising during the use of conventional construction methods.

From an environmental standpoint, prefabrication in construction supply chain management (CSCM) reduces sustainability issues by minimising carbon footprint and waste (Wong, Kanellopoulos, & Edmonson, 2018; Kaufmann & Remick, 2009). However, the construction industry, particularly the offsite fabrication is lagging in terms of supply chain practices and efficiency (Segerstedt & Anders, 2010; Shahzad, 2016), and some factors that inhibit the uptake of offsite construction supply chain are identified as lack of trust, collaboration, and information integration among the partners in the supply chain (PrefabNZ, 2015; Shahzad, 2011; Zhai, Reed, & Mills, 2013).

2.4.1 Impediments to an efficient offsite construction

Prefabrication is an innovative technology, and supply chain management techniques for this innovation are tailored according to the project circumstances. The concept of a prefabrication supply chain principally conforms to fundamental CSCM implications, and therefore, the barriers to efficient and effective prefabricated project supply chains are mostly identified as analogous to conventional or onsite projects. Some impediments to the effective supply chain in this sector have been diagnosed by various authors and are indicated in Table 2-1.

Among the factors shown in Table 2-1, key constraints that inhibit the improvement of this innovative technology are:

- Reluctance to adopting innovation or information technology.
- Transportation restrictions.
- Low collaboration and trust.
- Poor information integration.

Information sharing and integration of systems require trust and coordination (Cheng et al., 2010). Poor information sharing results in a lack of trust, and a low level of trust among stakeholders leads to low collaboration and reluctance to adopt innovation or technologies (Shahzad, 2016). Having a safe and secure repository for retaining knowledge and information about supply chain exercises leads to better supply chain integration and helps to maintain this information for future projects (Penzes, 2018).

2.4.2 Information integration

Typical construction projects consist of 5 phases where problems and complexities may arise, such as widely dispersed or decentralised information (that leads to wrong and defective product delivery) (Behera, Mohanty, & Prakash, 2015). Although the transformation of traditional or onsite construction to offsite construction improves the quality, customer satisfaction, efficiency, predictability, and sustainability of projects (Rahimian et al., 2017), some deficiencies, such as lack of effective information sharing, barricade the productivity of it (Rahimian et al. 2017; Vrijhoef & Koskela, 2000). Cheng et al. (2010) assert that since construction supply chains are highly dynamic and the structures are always susceptible to change, participants hesitate to work collaboratively to build enough trust and to share information efficiently.

Information exchanged within supply systems needs integration and management to provide the opportunity for fundamental improvement in clients' and suppliers' preferences and supply chain integration. Hatmoko and Scott (2010) note that CSCM is a system where suppliers, contractors, clients, and all other parties work collaboratively to use information in order to carry out construction projects effectively and efficiently. Therefore, by devising a way to develop information integration, lots of bespoke issues pertinent to inefficiency in this industry would be minimised.

Information integration refers to the sharing of information among the supply chain partners, and its main purpose is to achieve real-time transmission of information throughout the supply chain system (Prajogo & Olhager, 2012). Integration of information promises logistics integration, which refers to particular logistics practices and operational activities that coordinate the flow of materials from suppliers to customers (Stock et al., 2000). Even though many researchers believe that information integration is necessary for efficient supply chain management (Frohlich & Westbrook, 2001; Patterson et al., 2003; Sahin & Robinson, 2002; Samarasinghe et al., 2013), information exchange is not quite practically developed in CSCM due to the reluctance of stakeholders to using innovations and digital technologies (Cox & Ireland, 2002; Fawcett & Magnan, 2002).

Information sharing in the supply chain greatly enhances business collaboration and trust. As Yu (2001) explains, information sharing is an effective way of managing large supply chain systems. He elaborates that although decentralisation is an attribute of the supply chain, uncertainties arise when information within the supply chain is changed by one party and other parties remain unaware or get informed late (Yu, 2001). This could generate a change in the delivery time of products to the site and an increase in the relative costs. Likewise, Čuš-Babič

et al. (2014) demonstrate that data or information generated by multiple sources results in disintegration, scepticism, and low level of communication efforts among parties.

With an effective flow of information and maintaining information in a safe platform without the concern of alteration, supply chain systems can achieve better integrity and performance. Adopting a safe and secure platform for trading information and creating a safe home for information to be deposited could effectively result in better decision-making, collaboration, transparency, and trust (O'Brien & Marakas, 2005).

Table 2-1: Impediments to an efficient and effective prefabrication supply chain management

Barriers as defined by different authors	(Behera et al., 2015)	(Blismas et al., 2005)	(Akintoye et al., 2000)	(Jaillon & Poon, 2010)	(Bidabadi et al., 2016)	(Blismas et al., 2009)	(Harland et al., 2007)	(Shahzad & Mbachu, 2013)	(Shahzad, 2016)	(Čuš-Babič et al., 2014)	(Gibb, 1999)	(Rahimian et al., 2017)	(Gibb & Isack, 2003)	(Prajogo & Olhager, 2012)	(Zhai et al., 2013)	(Sutrisna & Goulding, 2019)
Temporary and negative project-based viewpoint	*	*			*						*		*		*	
Lack of commitment of managers and experts		*	*		*			*	*						*	
Reluctance to adopt innovations and information technology		*		*	*	*		*	*		*	*			*	*
Vague regulations and strategic legislation			*			*		*	*			*			*	
Low transparency and traceability	*						*	*		*	*					
Decentralised or fragmented nature	*		*								*	*	*			
Low understanding of concepts			*					*	*			*			*	*
Low collaboration and partnership	*		*	*	*		*	*	*	*	*				*	
Lack of trust	*	*				*	*		*	*				*		
Poor information sharing or knowledge integration	*	*					*	*	*				*	*		*
Low data and information accuracy	*													*		*
Lack of sufficient suppliers		*						*	*		*		*		*	
Limited site storage		*				*		*	*						*	
Longer lead time and lengthy design process		*		*					*		*	*			*	
Transportation constraints		*		*		*		*	*		*	*			*	
Inadequate risk management techniques																*

2.5 Research method

This study investigates the supply chain integration issues in the prefabrication sector, understands the status quo of relationships and information directions, and finds the corresponding solution for improving innovation opportunities and enhancing supply chain integration in New Zealand. The paper adopts a qualitative research approach, which can improve the description and explanation of real-world phenomena (Bradley, Curry, & Devers, 2007) and is the sort of research that extracts findings from practical settings (Patton, 2015). This research method often involves collecting data from different sources (Nassaji, 2015) and relies on observation to examine the situation and investigate the norm (Walliman, 2017). Also, Creswell and Creswell (2017) describe that qualitative methods are the study of context and are based on observations where personal values can be brought into the study. As such, for this study:

- First, a review of relevant literature is used to grasp a basic understanding of prefabrication technology. This step helped identify the key stakeholders involved in the prefabrication supply chain and various stages of a project.
- Second, based on empirical learnings and the understanding developed from literature, stakeholders' inter-relationships within each stage with respect to the prevalent flow of information were identified.
- Finally, observation of information-sharing processes among prefabrication supply chain partners was employed to map the information-based inter-relationship.

A similar approach of research was used by Kalian, Watson, Agbasi, Anumba, and Gibb (2004) for process mapping the relationships associated with the flow of information within the

rain-screen cladding supply chain of the UK construction industry and by Gray and Al-Bizri (2007) for modelling the supply of detailed fabrication and production information.

2.6 Findings and discussion

Construction projects often require integration between various entities to achieve a certain goal (Behera et al., 2015). Supply chain practices cannot be enhanced without efficient integration and collaboration. Doran and Giannakis (2011) advise that to ensure that offsite practices can compete effectively with onsite practices and to overcome negative facets of the prefabrication supply chain, there is a need to increase supply chain integration and relationships.

To model interconnectivity, there is a need for exploration of information flow and sharing processes within the offsite supply chain. A literature review has been employed to identify the stakeholders and prefabrication project stages. Involved parties in an offsite construction supply chain are statutory bodies, clients or customers, consultants, builders or developers, subcontractors, manufacturers, direct and indirect suppliers, and transporters or distributors (Behera et al., 2015; Chinyio & Olomolaiye, 2009; Gibb, 1999; Shahzad, 2011; Smith, 2016; Smyth & Pryke 2008).

According to the Royal Institute of British Architects (RIBA) Plan of Work 2013, construction project phases comprise eight stages that form the building processes from the project's inception to handover and maintenance. Gibb (1999) clusters the construction of a two-storey office building (by modular construction approach) into 12 phases and compares that to its traditional approach. Using the RIBA plan of work as a default scheme and tailoring it for offsite construction, the proposed process map of this study entails 12 phases (Figure 2-1), and they are described as follows:

Strategic definition: A generic assessment of the project from a strategic standpoint, as well as defining and briefing the client's business and identifying core requirements of the project occur in this stage. Collaboration and information exchange between client and consultant take place at this stage.

Preparation & briefing: The purpose of this stage is to define project objectives and scope, appraise sustainability, assign project budget, undertake feasibility studies, review and exchange project information, and carry out risk assessment. Project briefing with regard to opportunities and constraints is initialised. Generic discussion regarding the suitability and feasibility study occurs, and information flows between client and consultant.

Concept design: Concept design includes proposals for structural design and specifications, primary cost information, strategic information with respect to the design programme, and finalisation of the project brief. Engineers and architects usually collaborate on the design phase (Behera et al., 2015). The flow of information in this stage is among statutory bodies, clients, and consultants.

Developed design: Developed design consists of updated and coordinated structural design, cost information, and project strategies. A number of design revisions or iterations might happen in this stage. Builders and subcontractors are informed of the holistic plans and design process in this stage, and they are engaged from this stage to the post-project review phase (Vilasini, Neitzert, Rotimi, & Windapo, 2012). The flow of information is among statutory bodies, clients, consultants, builders, subcontractors, and direct suppliers.

Production planning: According to Behera et al. (2015), this stage entails identifying required raw materials for manufacturing, determining the quantity of materials, price queries

and quotations from suppliers. Information streams among consultants, builders, manufacturers, and direct and indirect suppliers at this stage.

***Technical design*:** Technical design contains all architectural, structural, electrical and mechanical plans, drawings, proposals, and strategies. Indirect suppliers will be aware of the designated parts that need to be completed offsite. The information is exchanged here among statutory bodies, clients, consultants, builders, subcontractors, manufacturers, and direct and indirect suppliers.

Construction (site set-up and initialisation): Initialisation comprises the development of the construction programme, preparation of the site, commencing the construction of the foundation, and execution of pre-requirements before all prefabricated components or panels must be shipped to the site. A flawless collaboration is necessary among the involved parties at this stage to prevent delays and reworks. The information flow is considered among statutory bodies, clients, consultants, builders, subcontractors, and direct suppliers.

Construction (offsite): In this segment, according to Behera et al. (2015), materials that are off-the-shelf and that need to be prefabricated are classified. Offsite manufacturing in accordance with the construction programme and detailed design is developed, and transportation planning is initialised (Kaufmann & Remick, 2009). Information and data exchange in this section happens among statutory bodies, clients, consultants, builders, subcontractors, manufacturers, indirect suppliers, and distributors.

Construction (transportation and assembly on site): Materials and components fabricated offsite are transported to the site for being erected. Efficient information sharing is essential for managing the interval between the current shipment being erected and the next shipment to have a smooth transportation flow and avoid warehouse surges. Information in this

phase is shared among statutory bodies, clients, consultants, builders, subcontractors, manufacturers, and distributors.

Handover and Closeout (pre-commissioning and commissioning): The project is completed and can be handed over to the end-user or client. The contract's terms and conditions have been met, and the surplus materials are stored for future projects (Gibb, 1999). Also, this step involves collaboration and information sharing among statutory bodies, clients, consultants, builders, and subcontractors.

In-use and maintenance (guarantee period): This phase encompasses post-occupancy and commissioning evaluation, performance monitoring, development planning, and as-built information updates. Interaction and information are updated among statutory bodies, clients, consultants, and builders.

Demolition: Project strategies defined at the beginning of the project should be in accordance with sustainability codes and standards and must be implemented with respect to long-term impacts on the environment. Waste reduction is achieved with effective sustainability consideration in the context of projects, and the ability to dismantle the components for future use rises. The client or end-user needs to inform statutory bodies in this case.

The customer–supplier relationship links the parties involved in a construction supply chain and enhances the overall integrity (Love et al., 2004). Lack of communication and effective information integration leads to poor supply chain performance (Humphreys, Matthews, & Kumaraswamy, 2003). In case supply chain integration deteriorates, project time encounters delays, costs will overrun, and quality will be exacerbated (Meng, 2012). As depicted in Figure 2-1, the flow of information and interaction among different parties is complex, which may pose challenges to achieving effective collaboration and integration. The

problem of inefficient offsite construction supply chains can be addressed by developing information integration and adopting advanced technologies as a solution.

2.7 Blockchain as a potential solution

Construction projects often require integration between various entities to achieve a certain goal (Behera et al., 2015). Supply chain practices cannot be enhanced without efficient integration and collaboration. Doran and Giannakis (2011) advise that to ensure that offsite practices can compete effectively with onsite practices and to overcome negative facets of the prefabrication supply chain, there is a need to increment supply chain integration and relationships. Thus, developing a framework for applying advanced technologies, e.g., Distributed Ledger Technology (DLT), to control the information flow among entities provides all construction practitioners with a better opportunity to increase the effectiveness and efficiency of the supply chain.

Today, as organisations are moving toward e-commerce, where all the transactions are accomplished online, adopting technology can substantially reduce bureaucracy and paperwork, improve communication and information sharing, enhance collaboration and trust among stakeholders, and reduce supply chain cycle time (Handfield & Bechtel, 2002).

Blockchain is a consensus-based ledger which facilitates transactions among its users by providing them with a secure and tamper-proof database. Blockchain was originally invented for crypto-currency transactions (e.g., Bitcoin), and it represents a network where various nodes perform transactions publicly or privately. In a public network, everyone is able to access the information of the ledger, and in a private network, people need to be granted access to engage (Li, Greenwood, & Kassem, 2018).

Blockchain technology operates through a decentralised peer-to-peer (P2P) network, and it is immutable or unalterable; it decreases dependency on intermediaries such as banks or insurance companies, and it contains an algorithm and proof-of-work mechanism to validate transactions among all nodes (Zhao et al., 2016). Information sharing with others is a main concern for most companies that provide intermediary services in industries (Lu & Xu, 2017). As Penzes (2018) explains, Blockchain used in supply chain management provides all information and documentation accessible to all parties but impossible to falsify. Also, Zhao et al. (2016) advise that the immutability of information in a chained block leads to trust and secure transactions. With this trust mechanism arising from blockchain, supply chain partners are able to share their information or assets without the concern of fraud.

One of the most dominant importance of blockchain in CSCM is that when all information and data are accumulated in blocks, it simplifies the traceability and helps clients or end-users to track back all processes to the provenance of products (Li et al., 2018).

Therefore, by consolidating project information and integrating it into the blockchain, logistics efficiency, information flow, transparency, and trust would be highly improved, and the dependency on intermediaries would become less (Zhao et al., 2016). By adopting blockchain as a safe platform for transferring transactions and exchanging information, customers can also be assured of the quality of the materials (Lu & Xu, 2017).

Key players / stages	statutory bodies (HSE, BCA, QA, Fire & rescue)	Client (building owner)	Consultant (Design team)	Builder (Developer)	Subcontractor	Manufacturer	Indirect supplier	Direct Supplier	Distributor
Strategic Definition (Inception, Briefing, Business case,...)		C	©						
Preparation & Brief (Develop project objectives, Budget, Limitations, Feasibilty study, sustainability plans,....)		C	©						
Concept Design (outline proposals and plans, cost and budget information, project strategies, site info,...)	O	C	©						
Developed Design (coordinated and updated design and proposals, strategies and....)	O	C	©	B	SC			DS	
Production Planning (coordinated and updated design and proposals, strategies and....)			©	B		M	IS	DS	
Technical Design (All plans and drawings, proposals and strategies according to the Design Responsibilities Matrix)	O	C	©	B	SC	M	IS	DS	
Construction (onsite preparation and initialising)	O	C	©	B	SC			DS	
Construction (Offsite)	O	C	©	B	SC	M	IS		D
Construction (transportation and assembly onsite)	O	C	©	B	SC	M			D
Handover and Close out (Pre-com and commissioning)	O	C	©	B	SC				
In use & Maintenance (post-occupancy and guarantee period)	O	C	©	B					
Demolition	O	C							

Figure 2-1: Relationship and information flow among prefabrication supply chain partners

2.8 Conclusion

Supply chain management in the construction industry is considered to be the network of activities that provide customers with economic value to the function of contract management, service and material procurement, delivery, and facilities management (Love et al., 2004). The construction industry is very complex since many subcontractors and vendors are involved. Most of the problems associated with conventional construction (socially, economically and environmentally) have been mitigated using innovations such as prefabrication. Yet within this subsector, lack of information sharing, which stems from unsecured information integration, results in low trust and transparency among entities. Also, Gordon and Curtis (2018) explain that New Zealand is experiencing low productivity, unsustainable materials, leaky buildings, and low-quality components and products used in construction. This issue can be attributed to the lack of efficient supply chain integration in terms of ineffective information integration and low traceability function. Many parties engaged in supply systems normally work individually with low levels of shared information, inhibiting the supply chain integration and traceability of prefabricated products in New Zealand. In an integrated supply chain, information is shared securely and becomes available among the members without any change. This enhances supply chain visibility and avoids information delays and distortions (Cheng et al., 2010).

Blockchain technology (or distributed ledger technology) that ensures traceability, transparency, and security demonstrates the potential for mitigating supply chain management problems. With blockchain, information recorded in a shared ledger provides stakeholders with an auditable and secure platform that allows them to track back the processes of supplying a

product to the origin of materials. In addition, it streamlines transactions among users (peer-to-peer) by reducing the reliance on intermediaries in the network.

This paper represented an information-based relationships process map of New Zealand's prefabrication supply chain. Findings show that using blockchain technology contributes to eliminating intermediaries and helps the effective diffusion of supply chain information. This technology also accelerates business interactions and produces more transparent collaborations among prefabrication project partners. A review of relevant literature along with empirical observations was adopted in this study to identify the existing information integration of the prefabrication supply chain in New Zealand. Also, limitations to gaining a productive supply chain were indicated. The paper concluded that there is a lack of trustworthy platforms for information storage when it comes to having integrity within the supply chain, and this issue can be addressed by adopting a digital shared ledger.

2.9 Epilogue

This chapter outlines the key challenges in the uptake of prefabrication supply chain in New Zealand, drawing from the key concepts of previous studies. It also identifies 9 stakeholders and 12 project phases in New Zealand's prefabrication supply chain and provides a process map depicting the complexity of those challenges along with a potential platform to tackle them. The key outcome of this chapter underscores a knowledge gap concerning the prefabrication supply chain and it is then inferred that information integration plays a crucial role in the integration of supply chain. Therefore, the need for further investigation into the drivers of information integration within the prefabrication supply chain is highlighted. As such, the next chapter delves deeper into examining information integration among the

identified stakeholders through pilot interviews. Additionally, it explores the utilisation of technological tools and their advantages in the prefabrication industry, followed by an investigation into the benefits of engaging blockchain technology.

Chapter 3: Stakeholders' interrelationships in the prefabrication supply chain

3.1 Prologue

This chapter takes a deep dive into ascertaining the information integration and interaction of the stakeholders in different phases of prefabrication projects as identified in the previous chapter. The diagram depicted in the previous chapter (Figure 2-1) was put forward for validation through pilot interviews with industry experts. This is the first step taken towards identifying the stakeholders' interrelationships and incorporating the understanding of information integration in the context of the prefabrication supply chain in New Zealand. Subsequently, a questionnaire survey was used to assess the significance of integrating information across various prefabrication organisations and identifying the crucial information attributes necessary for the success of prefabrication projects. Finally, the advantages of adopting technological advancements in comparison to blockchain technology are examined, with the latter recommended as a viable solution for tackling challenges in information integration practices among prefabrication organisations. This chapter then concludes the necessity of further investigations on the potential of blockchain technology for information integration in the prefabrication supply chain.

The current chapter is based on the following two articles:

First, a paper was submitted and presented at the Engineering, Production and Project Management (EPPM) conference 2021. Among many other articles, this paper was selected by

the conference scientific committee and published in the special issue of the Engineering Management in Production and Services (EMPAS) journal.

1. Bakhtiarizadeh, E., Shahzad, W., Poshdar, M., & Rotimi, JOB. (2021). Applicability of Blockchain technology in New Zealand's prefabricated construction industry: A potential solution. In *Proceedings of the 11th International Conference on Engineering, Project, and Production Management (EPPM), Poland,* 9.
2. Bakhtiarizadeh, E., Shahzad, W., Poshdar, M., & Rotimi, JOB. (2022). Blockchain technology applicability in New Zealand's prefabricated construction industry. *Engineering Management in Production and Services*, *14*(1), 103-112.

3.2 Abstract

Different industries are modernising their systems and introducing innovations to their management practices. However, the construction industry is recognised for its lack of technological systems on which the success of this sector is deemed to be heavily dependent. Previous studies have focused on enhancing the off-site construction supply chain. However, studies on the importance and utilisation of technology in this sub-sector are scarce, predominantly where the efficiency of off-site supply chain management is stalled as a consequence of the slow implementation of technology. Thus, this article employs an exploratory approach by providing insight into the applicability of blockchain technology in New Zealand's off-site construction and demonstrates the benefits associated with adopting this technology. A literature review was used to identify stakeholders' interrelationships in different stages of prefabrication projects. Then, a pilot interview with industry experts followed by a questionnaire survey was used to determine the involvement of stakeholders in

different phases and the benefits that blockchain technology can bring to this industry. The results indicate that using blockchain as a secure information management system could improve the integration of prefabrication supply systems by producing a collaborative atmosphere among the organisations involved.

3.3 Introduction

The construction industry in New Zealand is overtaking other industries and has become one of the major contributors to the national GDP (Huang & Wilson, 2020). Supply chain management in this industry is considered a significant pivotal point of success for organisations performing roles in the highly competitive construction market (Samarasinghe, Tookey, & Rotimi, 2013). However, fragmentation is an inherent attribute adhered to the construction sector, and it can deteriorate in off-site (prefabrication) construction where the concentration of work is scattered across “off” and “on” construction sites (Zhai, Zhong, Li, & Huang, 2016). In New Zealand, prefabrication demands specific consideration around the barriers to its efficiency; supply chain integration is perceived as one of the main core subjects requiring enhancement (Darlow et al., 2022). Studies have shown that information exchanged across the entire supply system in a prefabricated project can substantially impact the outcome of the supply chain (Briscoe, Dainty, & Millett, 2001). Numerous documents: design/construction drawings, RFIs, quality assurance documents, and statutory approvals are regarded as the types of information being exchanged daily within the supply system of prefabrication projects and managing the integration of this information results in a positive future collaboration among the supply chain partners (Bakhtiarizadeh, Shahzad, & Rotimi, 2019).

Prefabrication is acknowledged as a solution to deficiencies in traditional construction methods. Reduced time and costs, enhanced quality of finished products, and increased sustainability are some benefits associated with prefabrication (Shahzad, Mbachu, & Domingo, 2015). However, several impediments to the uptake of prefabrication disturb efficiency in its supply chain systems. Little transparency around the distribution of works at different sites, lack of the adoption of new advanced technologies, and ineffective information-sharing systems are considered some of them (Jaillon & Poon, 2010). The root cause of the mentioned issues can be linked to inappropriate information integration techniques.

Integrated information ensures an integrated supply chain, and an integrated supply chain ensures the swift processes of preparation, design, manufacture, construction, and assembly (Čuš-Babič et al., 2014). It also provides trust among various stakeholders involved in a prefabricated construction project (Bankvall et al., 2010). Hence, using an effective information integration platform, such as blockchain, leads to improved trust and integration among participants involved in the supply chain of prefabrication projects (Casino, Dasaklis, & Patsakis, 2018). The predominant benefit of blockchain technology compared to other technologies is the decentralisation and anonymity of the data stored in it (Li, Greenwood, & Kassem, 2019). Contrary to recent technologies, blockchain helps process and save information on multiple remote computers, allowing organisations to store their information systematically in different locations (Li et al., 2018).

This technology offers integration in the prefabrication and provides a secure decentralised database, helping prefabrication supply chain organisations to exchange and store their information effectively (Wang, Wu, Wang & Shou, 2017). Therefore, blockchain

provides a transparent and secure information-sharing platform for the prefabrication supply chain (PrefabNZ, 2018).

Different studies have shown various process maps of the prefabrication supply chain. For instance, a study by Bakhtiarizadeh, Shahzad, and Rotimi (2019) explored prefabrication project phases and stakeholders involved in the supply chain. Also, other studies have demonstrated the value of information sharing across supply chain allies in the construction and design of projects (Samarasinghe et al., 2013; Čuš-Babič et al., 2014). However, little research has been conducted on New Zealand's prefabricated construction, and there is inadequate knowledge of the advantages of blockchain technology in this industry.

This study undertook a pilot interview with six prefabricated construction professionals to ascertain the interaction of stakeholders in different phases of prefabrication projects. Also, a questionnaire survey was used to identify the core impediment to the integration of prefabrication and to ascertain the applicability of blockchain technology with its related potential advantages. The following section of this article presents a review of previous studies. The second section discusses the research methodology, data collection, and analysis tools. The third part describes the analysis and discussion of the results. The article concludes with remarks.

3.4 Literature review

Prefabrication is considered an innovative method of construction that facilitates the construction of a portion of a building remotely or far from the final location (Shahzad, 2016). The major benefit of prefabrication over traditional construction methods is the low level of inefficiencies in productivity measures like time, cost, and quality (Darlow et al., 2022). In

New Zealand, prefabrication is increasingly contributing to the delivery of construction projects (Darlow et al., 2022; PrefabNZ, 2018). The rising demand for newly built houses and the shortage of affordable dwellings are increasing the need for a more effective and innovative project delivery system (Shahzad & Mbachu, 2013).

Despite the benefits of prefabrication, the industry struggles with several issues, such as low integration and coordination among its supply chain organisations (PrefabNZ, 2015). Integration in supply systems refers to the consistency of delivery systems and uniformity of information sharing among stakeholders (Dainty, Millett, & Briscoe, 2001). The complexity of integration in supply chains depends on the project size. Typically, the number of actors exchanging information in large projects can exceed hundreds, giving rise to the need to adopt innovative technologies in the supply chain integration techniques (Briscoe, Dainty, & Millett, 2001).

Adopting technology in the construction supply chain has become critical for enhancing supply chain integration (Wang, Wang, Hao, Jie, Xu, & Qiying, 2020). Some examples of technological systems being used in supply chains are Enterprise Resource Planning (ERP), Electronic Data Interchange (EDI), Customer Relationship Management (CRM), Drones, Internet of Things (IoT), RFID, and GPS receivers (Wang et al., 2017). These systems have helped the uniformity and integration of information and, consequently, the integration of supply chains. Using these technologies, supply chain partners can exchange real-time information efficiently and effectively. Also, with the help of these technologies, unsafe human interference in information repositories can be minimised (Ngai, Cheng, & Ho, 2004).

Information integration is considered collaborative, uniform, and controlled information sharing, and a lack of information sharing results in decreased traceability, transparency, and trust (Prajogo & Olhager, 2012; Mentzer et al., 2001). Integration and efficient exchange of information in supply systems require coordination and trust (Cai, Jun, & Yang, 2010). The low level of trust results in low collaboration and reluctance to adopt technologies (Shahzad, 2016). Therefore, providing a secure technological source/storage for storing organisational information can lead to a more collaborative and efficient supply system with a higher level of trust (Korpela, Hallikas, & Dahlberg, 2017).

One advanced technological system recently introduced globally is Distributed Ledger Technology (DLT) or blockchain technology. Blockchain is a secure consensus-based ledger that simplifies connections among its operators (Penzes, 2018). Blockchain was originally developed for crypto-currency transactions and designed based on a network of public and private decentralised nodes (Saberi, Kouhizadeh, Sarkis, & Shen, 2018). This technology enables immutable peer-to-peer (P2P) communication through a secure transaction database (Turk & Klinc, 2017).

New Zealand is resilient in adopting innovations and technologies (PrefabNZ, 2013), and blockchain can positively impact the enhancement of supply chains, especially in the prefabrication industry. Blockchain's traceability function is important for supply chain partners since prefabricated construction struggles with multiple stakeholders and suppliers from local or international companies (Bell, 2009). This function also helps clients/customers track the provenance of the materials used in their final products, improving their trust and perspective on the genuineness of resources (Casino et al., 2018).

Similarly, blockchain technology helps facilitate interactions and information exchange among supply chain organisations in an organised manner (Prajogo & Olhager, 2012). This, in turn, results in the transparency of information and improved accountability of each partner regarding their contribution to the project delivery in New Zealand (Chowdhury, Colman, Kabir, Han, & Sarda, 2018). Providing transparency in the stakeholders' interactions can reduce quality problems and improve organisational trust and confidence (Yang et al., 2020).

Moreover, as opposed to other pre-mentioned technological systems, blockchain provides more data/information security to its users, helping supply chain organisations benefit from a safe information repository in which its stored information can be withdrawn and used for future projects (Li et al., 2019). Security in the information exchange is understood as legitimate or trusted information transmission across the communicators and safekeeping of the data-generating processes (Tse et al., 2017). Security and trust are interlinked in the prefabrication supply chain. As prefabrication processes encompass a variety of information and sources, information security guarantees trustworthy digital communication and the reliability of shared information (Lemieux, 2016).

In summary, blockchain can be the potential remedy for the shortcomings in the prefabrication supply chain integration in New Zealand. This technology can be used for information integration and, consequently, supply chain integration (Wang et al., 2020). Blockchain has the potential to resolve the problems stemming from the traceability of the origin of the products, transparency of exchanged information and security of systems used for prefabrication stakeholders' information sharing.

Previous studies have investigated the integration of prefabrication supply chain stakeholders and the potential benefits of using information technology. However, few studies have been conducted in New Zealand, and there is little knowledge about the applicability and benefits of using blockchain technology in the prefabrication supply chain. This study addresses the investigation gap in this area and provides insights into utilising blockchain technology in New Zealand's prefabrication industry.

3.5 Research methodology

This study adopts mixed research to data collection and analysis as a complementary approach (Johnson, Onwuegbuzie, & Turner, 2007). A literature review was carried out to identify and categorise stakeholders' interconnectivity in different stages of prefabrication projects. Then, a pilot study was conducted to ascertain the validity of identified stakeholders and the complexity of their relationships in certain project phases in New Zealand. Then, a questionnaire survey was developed. Firstly, it aimed to measure the significance of information integration among different organisations. Secondly, it sought to find the attributes of information essential for the success of the prefabrication supply chain and, finally, to ascertain the advantages of using blockchain technology in this industry.

3.5.1 Identification of stakeholders and phases of prefabrication

In order to identify the project development phases and stakeholders involved in prefabrication projects in New Zealand, two methods were used: literature review and interview. A total of 12 different phases of projects and a list of nine groups of stakeholders were primarily identified through a literature review. A pilot study was undertaken to ascertain the reliability and validity of the identified phases and stakeholders. A participation invite was

sent to 12 prefabrication construction experts, and six of them showed their inclination to participate. All experts had more than ten years of experience in New Zealand's construction industry. A process map of the 12 project phases and nine stakeholders was shown to them in separate interviews, and they were asked to check the correctness of the identified phases and stakeholders concerning their interrelationships in New Zealand.

3.5.2 Data collection

A questionnaire survey was developed to explore the significance of information integration and the attributes of information contributing to the growth and success of the prefabrication construction supply chain (CSC) in New Zealand. Numerous current studies have employed the questionnaire survey as an efficient tool for collecting stakeholders' viewpoints and opinions pertinent to the CSC (Black, Akintoye, & Fitzgerald, 2000). In this study, the questionnaire contained three relatively similar sections. A short overview of definitions was provided at the opening of the questionnaire, followed by a segment for collecting the basic information of participants. The respondents were from a broad spectrum of organisations, including, but not limited to, clients, contractors, designers, consultants, and suppliers. They were asked to answer the questions from clients' or contractors' perspectives. In the final section, respondents were required to answer multiple questions about utilising technology in their organisations, the disadvantages of non-integrated information exchange, the necessary quality of information for the success of prefabrication, and the advantages linked to using blockchain technology.

The questionnaire survey was sent to the PrefabNZ, an umbrella organisation for prefabrication in New Zealand, with around 350 members (including individuals and

prefabrication firms). The minimum sample size calculated was 132 (at 95 % confidence interval; $p<0.05$). The study participants were initially randomly sampled from PrefabNZ members. After that, a snowball technique was used so the study could develop an in-depth exploration of the applicability of blockchain in prefabrication (Creswell, 2005) and increase the diversity of the sample through a range of viewpoints (Kirchherr & Charles, 2018). To meet the snowball sampling technique requirements, the participants were encouraged to share the online questionnaire with their co-workers and others they perceived as qualified in New Zealand's prefabrication industry. At the end of the data collection, 27 valid responses were collated, forming the basis for the data analysis. This represents a response rate of 20.4 %. Normally, studies related to construction have a rate of 20 to 30 % (Hwang, Shan, & Looi, 2018). With direct reference to the questionnaire survey, nine respondents had over 15 years of related experience, seven between 10 and 15 years, eight between 5 and 10 years, and three less than five years. Also, 12 participants answered from clients' and 15 from contractors' standpoint.

3.6 Results and discussion

Prefabricated construction is better for geographically dispersed construction sites (PrefabNZ, 2018). However, this approach involves a more complex supply chain than traditional construction methods (Shahzad et al., 2013). Keeping an effective way of information exchange throughout prefabricated projects can considerably decrease this complexity (Wang et al., 2020). Integration of information among stakeholders in the prefabrication supply chain is complex, giving rise to myriad challenges in obtaining effective supply chain integration (Jaillon & Poon, 2010). Adopting information technology is necessary to streamline the complex information exchange processes and facilitate the prefabricated

construction supply chain. In this study, the analysis of the questionnaire survey has been carried out in three steps: 1) utilisation of technology, 2) drawbacks associated with lack of information integration, and 3) advantages of blockchain technology in the prefabrication supply chain.

3.6.1 Prefabrication phases and stakeholders

A literature review and pilot interviews were used to identify the connection of prefabrication stakeholders with the phases of prefabrication projects in New Zealand. The nine groups of stakeholders comprise statutory bodies, clients, consultants or designers, developers, subcontractors, manufacturers, indirect and direct suppliers, and distributors or logistics enterprises with reference to (Gan, Chang & Wen, 2018) and (Bakhtiarizadeh et al., 2019). This study did not examine other stakeholders previously identified by other researchers. For example, Zhai, Reed, and Mills (2013) categorised the stakeholders into six groups, excluding the Chinese government. However, in New Zealand, the role of government or statutory bodies is also relevant to the prefabrication projects.

Moreover, according to the Royal Institute of British Architects (RIBA) Plan of Work 2013, a construction project's lifecycle undergoes eight phases from initiation to delivery. Also, Gibb (1999) classifies a modular construction project into 12 phases and compares them to the traditional construction approach. Using the mentioned research and with reference to the previous study by Bakhtiarizadeh et al. (2019), twelve prefabrication phases were tailored and tested for this study. The phases are Strategic Definition or Initialisation, Preparation and Briefing, Concept Design, Developed Design, Production Planning, Technical or Detailed Design, Construction (on-site preparation, off-site manufacturing, and transportation for

assembly), Handover, Maintenance, Demolition (according to the sustainability criteria for future project use).

Interviewees also acknowledged that the three phases, Detailed Design, Construction, and Handover, are the main phases intricately engaging most of the stakeholders. Also, they highlighted the essential roles of clients and contractors who are consistently involved from the inception until the end of projects and whose responsibilities are not limited to certain project phases.

3.6.2 Utilisation of technology

Adopting information technology in the supply chain has brought many benefits to different industries. Firstly, it has helped reduce product development timeframes by enabling easier collaboration among the production crew. Secondly, it has reduced production costs. And lastly, it has enhanced the quality of products to match customers' requirements (Chou, 2004). Advanced systems, e.g. Electronic Data Interchange (EDI), Customer Relationship Management (CRM), and Enterprise Resource Planning (ERP) are some examples of information technology systems being used for Supply Chain Management (SCM). However, these are being superseded by web-/cloud-based technologies such as the Internet of Things (IoT) and drones, enabling the swift and effective flow of real-time information across supply chain stakeholders (Ngai et al., 2004; Xing, Qian, & Zaman, 2016).

Despite the added value of cloud-based technologies to SCM, there are still a few problems related to them. For instance, information security can be deemed an issue since there is always a risk of malicious attacks by hackers (Finch, 2004). Also, accessibility to information repositories for every supply chain member can be considered another issue (Chou, 2004). In

the construction industry, the abovementioned issues can jeopardise organisations' critical information and trust among supply chain partners since all information is prone to change by any user, either randomly or deliberately (Tse et al., 2017). With reference to the questionnaire in this study, 19 (out of 27) respondents demonstrated that information technology (in general) is used in their organisations, and 17 of them agreed that technology would be useful as a facilitator for information integration.

3.6.3 Significance of information integration

Information integration in the supply chain contributes to collaboration, trust and logistics integration (Gielingh & Tolman, 1991). However, uncertainties in supply chains appear when information exchange is not quite streamlined. Literature has proved numerous drawbacks associated with lack of information integration, e.g. scepticism, distrust, and fragmentation among the partner organisations. In this study, an excerpt of previously studied drawbacks associated with lack of information integration was collected and incorporated into the survey. The respondents were asked to use a 5-point Likert scale and confirm the effect of those drawbacks on the outcome of their projects (Figure 3-1). Consequently, they also provided the attributes of information critical for the success of their supply chain (Figure 3-2).

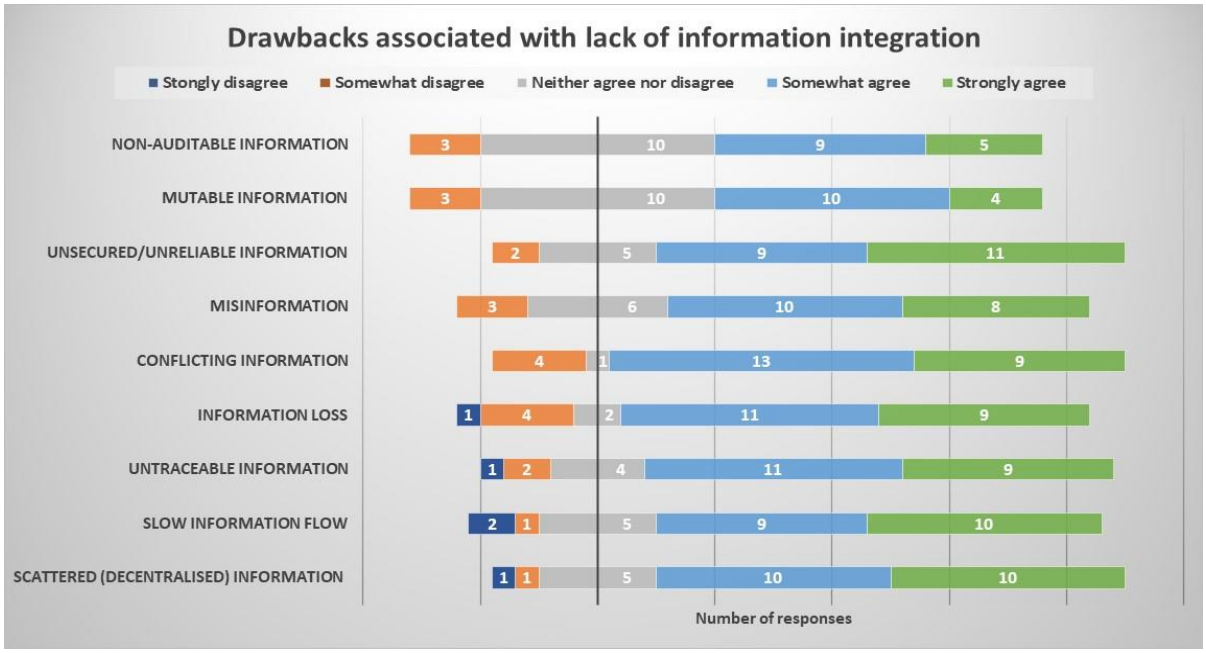

Figure 3-1. Importance of information integration

The identified drawbacks associated with a lack of information integration revolve around three main categories: transparency, traceability, and security. Information transparency is regarded as a decline in the uncertainty among information exchangers (Angeletos & Pavan, 2004). Transparent information in the prefabrication supply chain improves trust and collaboration among stakeholders (Wang et al., 2020). Traceability is the second critical attribute of information that helps the development of an efficient prefabrication supply chain. In the prefabricated supply chain, various types of materials are used, and the ability to trace the origin of these materials is highly crucial for prefabrication supply chain organisations and end-users (Saberi et al., 2018).

Information security is interpreted as the integrity of records and legitimacy of data (Lemieux, 2016). Information exchanged within an organisation varies from drawings and reports to legal documents (Sahin & Robinson, 2002). These types of information require an information exchange platform capable of storing the information securely for future use.

Therefore, a suitable information security engine is needed to warrant the secure knowledge and learning transition from one project to the next. This attribute is critical for the integration of prefabrication supply chains.

3.6.4 Benefit of using blockchain technology in the prefabrication Construction supply chain

There is a close-knit relationship between information integration and blockchain technology as an enabler of a secure information-sharing database. To diminish the disruptions to the prefabrication supply chain, information integration should be maintained and controlled constantly (Doran & Giannakis, 2011). Thus, blockchain technology would be a solution for creating integration in the prefabrication supply chain.

In New Zealand, the construction industry has long been intertwined with traditional construction approaches. However, with the rise of newer methods (e.g., prefabrication), industry experts are discovering the benefits of using technologies better. For this study, participants were asked to indicate their level of agreement with the benefits of information integration and blockchain technology. As indicated in Figure 3-3, the results show that the breakeven point of the benefits of information integration commensurate with the benefits associated with blockchain technology meets at 31 %.

Many studies have shown the ability of blockchain technology to store a range of information in different formats, such as models, sketches, images, drawings and recordings (Devine, 2015; Chen, Wang, & Zhang, 2018). Once these types of information are recorded on the blockchain, information integration is formed, and the prefabrication sector will benefit by

reducing fragmentation and improving transparency, traceability and information security.

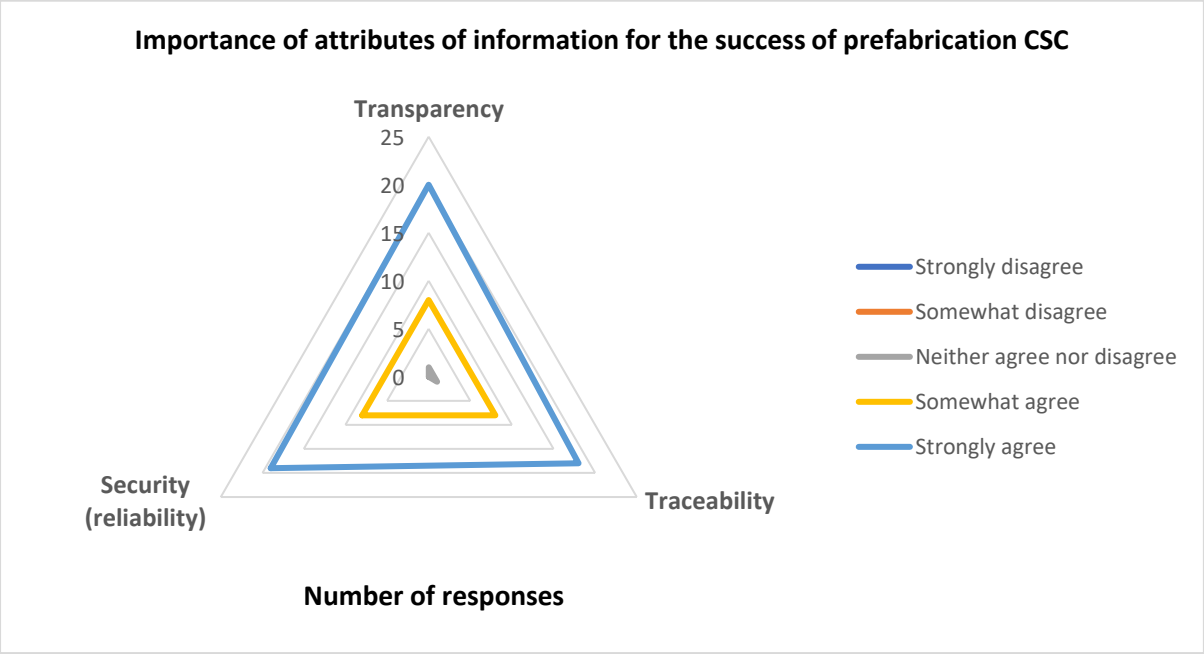

Figure 3-2. Important attributes of information

3.7 Conclusion

Construction Supply Chain Management is regarded as a network of tasks providing services and values to clients (Mentzer et al., 2001). Most of the social, environmental, and economic shortcomings of traditional construction appear to have been resolved using newer practices, such as prefabrication. However, in this subsector of the construction industry, information integration, which is a major driver of supply chain integration, has not been paid attention to, resulting in a low level of trust among stakeholders (Shahzad et al., 2015). Information is transmitted securely among the stakeholders within an integrated supply system without any unwanted alterations. Also, it helps the prefabrication supply chain benefit from the visibility and transparency attached to information integration platforms.

Blockchain technology, being an advanced information integration tool, represents a potential solution for dispelling inherent issues of supply chain systems by ensuring security, transparency, and traceability. Adopting this technology in New Zealand's prefabrication industry can help obtain a more streamlined and efficient supply chain integration.

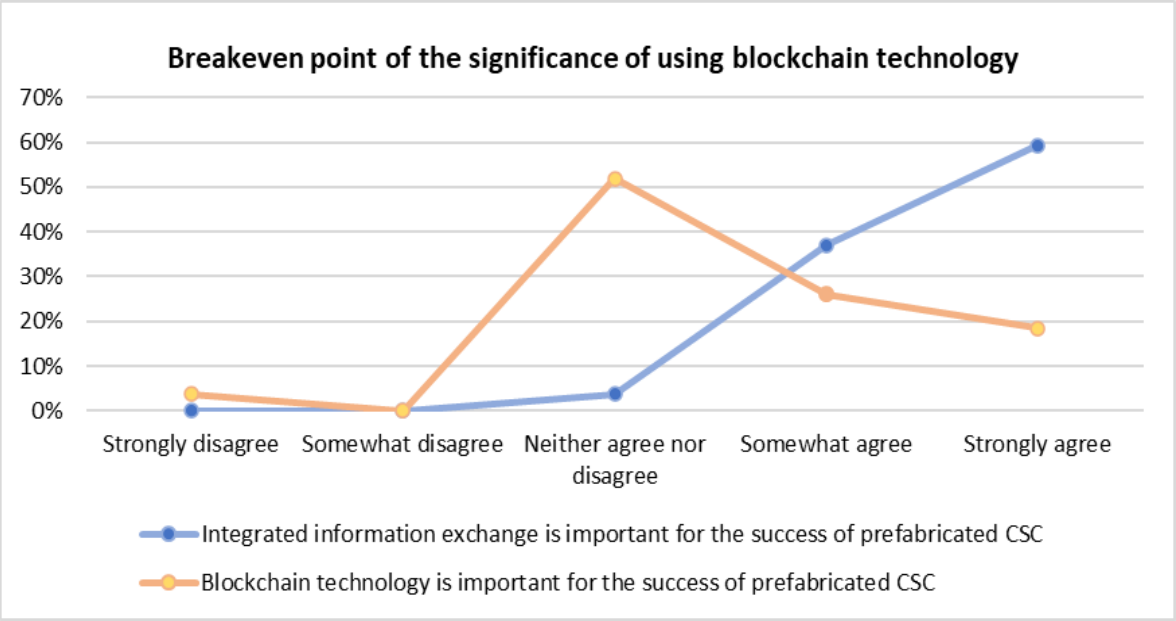

Figure 3-3. Significance of using blockchain technology

This study explores the stakeholders' engagement in different stages of prefabrication projects and ascertains the benefits of using blockchain technology in New Zealand's prefabrication supply chain. Firstly, 12 construction phases and nine groups of stakeholders were identified through a pilot interview with industry professionals. Then, the disadvantages associated with the lack of information integration and the importance of using blockchain technology as an information integration mechanism were explored by adopting a questionnaire survey to collect wider industry experts' opinions. Among the total of stakeholders and 12 project phases, two stakeholders and three phases were recognised as focal points in the supply chain network. The results show that using blockchain technology can enhance the integration of prefabrication projects by creating trust among organisations

working directly or indirectly in their supply systems. This technology also helps stakeholders with their business interactions and generates a transparent collaboration among prefabrication project partners.

One limitation of this study is that the data was collected from the experts within a certain period. Also, none of the participants had practically utilised blockchain technology as a tool in their professional experiences. In all cases, the technical definitions used in this study should have been explained to them clearly and upfront. The results of this study could be discussed by other studies which have provided frameworks for the uptake of the prefabrication supply chain. Blockchain technology will gradually become more accepted and mature, enhancing stakeholders' viewpoints on blockchain and other advanced IT systems.

3.8 Epilogue

This chapter validated the information integration links among prefabrication stakeholders using the results of the previous chapter and pilot interviews. The stakeholders' interactions were reviewed in each phase and, subsequently, out of 9 stakeholders and 12 project phases, two stakeholders and three phases were identified as the main focus area within the prefabrication supply chain in New Zealand. Through the course of interviews and questionnaire survey analysis it became clear that clients and subcontractors as the key stakeholders and three prefabrication phases of (i) detailed design, (ii) construction, and (iii) handover as the main project phases go through most of the complexity of information exchange and integration. Accordingly, the cruciality of further examinations around the two stakeholders and three phases gets exposed and becomes the focal point of the research. As such, a deeper investigation into how the information exchange among stakeholders is carried

out and which existing information integration platform is frequently used in the prefabrication supply chain is required to identify the important information attributes on which the success of prefabrication supply chain integration hinges. The following chapter targets the identification of the information exchange channels and information attributes correspondingly.

Chapter 4: Information integration among prefabrication stakeholders

4.1 Prologue

This chapter reports how blockchain technology, when used as a tool for integrating information, affects the integration of New Zealand's prefabrication supply chain. By identifying channels for exchanging information, this chapter evaluates the advantages of employing this technology to enhance the integration of the prefabrication supply chain. An exploratory approach is used to uncover the modes of information exchange between clients and contractors involved in prefabrication projects and delve into the characteristics of information deemed crucial for improving the prefabrication supply chain integration. The results indicate that transparency, traceability, and security of information constitute the most important attributes of information for which advanced technological platforms must be developed.

The current chapter is based on the following article:

Bakhtiarizadeh, E., Shahzad, WM., Poshdar, M., Khalfan, M., & Rotimi, JOB. (2021). Blockchain and information integration: Applications in New Zealand's prefabrication supply chain. *Buildings MDPI, 11*(12), 608.

4.2 Abstract

New Zealand's rising demand for new and affordable homes is driving innovative and effective methods for project delivery. Prefabrication or off-site construction is considered an innovative approach to project delivery that eliminates the limitations of traditional

construction methods. However, the prefabrication industry struggles with several challenges, including poor coordination and low supply chain integration among its partner organisations. There has been previous literature on improving the prefabrication supply chain integration, but few studies about the role of technology in this sector. Therefore, this article provides intuitions into the applicability and benefits of advanced technologies, namely blockchain, for improving supply chain integration in the context of prefabrication in New Zealand. A questionnaire survey was used to identify the channels used for information exchange between clients and contractors. Moreover, the questionnaire ascertained the positive effects of blockchain on enhancing supply chain integration between the two partners. Blockchain has proven to be a secure information integration instrument that can improve the integration of the prefabrication supply chain by fostering collaboration between organisations.

4.3 Introduction

Supply chain management concepts are effectively used in various industries. However, in the prefabrication industry, these concepts are relatively new (Shahzad, 2016). The rising demand for affordable and newly built houses in New Zealand urges modern and efficient project delivery systems (PrefabNZ, 2015). Construction organisations that perform roles in the highly competitive market of New Zealand consider supply chain management a critical part of success for their overall performance (Samarasinghe et al., 2013).

Prefabrication is recognised as a means of improving conventional construction procedures (Shahzad, Mbachu, & Domingo, 2015). Some benefits of prefabrication technology include shortened lead time, reduced costs and enhanced quality and sustainability (Shahzad, 2016; Jaillon & Poon, 2010). However, prefabrication in New Zealand needs specific

consideration concerning the factors inhibiting its performance. Poor supply chain integration is perceived to be a substantial problem preventing the efficient performance of this sub-sector in the construction industry (Zhai, Reed, & Mills, 2013). Supply chain management entails two key flows: Information and material (Prajogo & Olhager, 2012). Integration of these flows among supply chain partners, commonly referred to as Supply Chain Integration (SCI), is considered a crucial contributor to the effective management of supply chains (Power, 2005). Within the prefabrication sub-sector, cooperative interaction among supply chain allies is a fundamental driver of supply chain integration (Gan, Chang, & Wen, 2018). However, inadequate information exchange systems, little adoption of advanced technologies and low transparency in the diffusion of work at isolated sites are viewed as obstacles to prefabrication supply chain integration (Shahzad, 2016; Wang et al., 2020; Li, Shen, Wu, & Yue, 2019). The origin of the explained impediments can be attributed to the low level of information integration among organisations (Prajogo & Olhager, 2012; Cai, Jun, & Yang, 2010).

A supply chain with integrated information ensures swift and efficient design, fabrication, construction and assembly processes (Cˇuš-Babic et al., 2014). Additionally, trust among different prefabrication stakeholders is improved (Bankvall et al., 2011). Therefore, using an information integration tool such as blockchain, the supply chain participants in prefabrication projects benefit from improved trust and integration (Casino et al., 2018). The main advantage of Blockchain technology over other advanced technologies is the anonymity and decentralisation of its stored data (Li, Greenwood, & Kassem, 2019). Unlike other technologies, information/data on the blockchain is processed and stored across different isolated computers, allowing organisations to have their information tidily stored in multiple locations (Li, Greenwood, & Kassem, 2018).

Blockchain, a new era in the field of information technology, is revolutionary. This technology enables integration in the prefabrication sub-sector and offers a distributed and secure database, helping supply chain partners to communicate their project information efficiently (Wang et al., 2017). As a secure communication platform, blockchain provides a reliable and transparent information-sharing setting for supply chain stakeholders (Li, Wang, Liu, Liu, He, & Huang, 2018).

In New Zealand, blockchain-based systems can positively influence business growth, especially in the prefabrication sub-sector of the construction industry. Such systems and technologies are being adopted as part of New Zealand's resilience towards business development (PrefabNZ, 2018). One of the most prominent benefits of blockchain in New Zealand's prefabrication supply chain is its ability to provide traceability for clients/customers wishing to trace the origins of their materials (Bakhtiarizadeh et al., 2019). Supply chain organisations demand this ability since prefabricated construction is complicated with various stakeholders and suppliers involved (Gan et al., 2018). Moreover, with the help of blockchain technology, supply chain organisations can exchange information in an organised manner, resulting in better transparency in information sharing and better distribution of accountability of each partner with regard to their contribution to project deliveries in New Zealand (Wang et al., 2020; Chowdhury et al., 2018).

Previous literature has explored the integration of prefabrication supply chains and the advantages of utilising information technology. For example, Bakhtiarizadeh, Shahzad, and Rotimi (2019) developed a process map showing different stakeholders' inter-relationships in 12 development phases of prefabricated projects. Other studies have focused on client-contractor relationships and their engagement in specific phases of construction projects

(Kadefors, 1999; Jagtap & Kamble, 2020). Moreover, a few studies have shown the importance of information exchange among supply chain partners in project design and construction phases (Samarasinghe et al., 2013; C˘uš-Babic, 2014). Nevertheless, little research has been conducted in New Zealand's prefabrication industry, and there is limited knowledge of the use and benefits of blockchain technology. In this study, blockchain technology is considered an information exchange mechanism for improving integration in the prefabrication supply chain of New Zealand's construction industry. The benefits of this technology are explored to address the lack of investigation in this area.

Exploring communication channels among partner organisations helps evaluate the impact of blockchain technology on the integration and performance of the prefabrication supply chain. As such, in this research, a questionnaire survey was used to identify (1) the channels used for information exchange between clients and contractors in three phases: detailed design, construction and handover, and (2) critical information attributes. The survey findings helped strengthen arguments around the potential benefits of blockchain in the prefabrication supply chain in New Zealand. In this current study, we contend that blockchain technology can be crucial in enhancing information integration among partner organisations.

4.4 Literature review

4.4.1 Overview of prefabrication supply chain

According to Čuš-Babič et al. 2014 and Luo et al. 2020, supply chain management plays a vital role in successfully delivering prefabrication projects. Different industries use different supply chain configurations to achieve their desired environmental, social and economic outcomes (Bankvall et al., 2011).

A supply chain is a network of organisations that produce value for the end consumer by linking the upstream and downstream flow of materials and information (Christopher, 1994; Rebs et al., 2019). The primary principles of supply chain management can be discovered in systems thinking, where it is crucial to consider every individual involved in the product/service delivery lifecycle to be an important contributor to a larger system (Moon & Kim, 2005). Supply chain management is observed to be highly dependent on innovation and information technology (Papadonikolaki, Vrijhoef, & Wamelink, 2016).

In prefabrication, supply chain management requires more consideration. While prefabrication helps to reduce construction duration by transferring on-site activities to an off-site plant (PrefabNZ, 2018), it lags in supply chain practices (Luo et al., 2020). Due to the broken working sites, complexities in prefabrication supply chains are higher than in traditional ones (Lu, Chen, Xue, & Pan, 2018), intensifying the necessity of effective integration and communication. In addition, managing information flow and acting promptly in response to any variation to the design or customers' requests needs dynamic integration strategies among the prefabrication supply chain partners (Gibb & Isack, 2003).

In the prefabrication supply chain, unique products are primarily designed and constructed for distinctive projects. Therefore, the recurring pattern of supply chain methods for one project may not fit another and can cause the loss of information, fragmentation and instability (Konukcu, 2011). The current principles of supply chain management preclude innovation adoption, causing a slow usage of supply chain information technology in the prefabrication industry (Shahzad, 2016; Zhai et al., 2016). Increasing the knowledge of prefabrication and its supply chain techniques through investigation and implementation of technological tools will help the industry expert to benefit from innovation and integration.

4.4.2 Prefabrication in New Zealand

Different synonyms are interchangeably used for defining prefabrication technology, such as off-site fabrication, off-site manufacturing, off-site construction, pre-assembly and prefabrication (Gibb, 1999). All these synonyms are attributed to the process of constructing a portion/component/structure of a larger structure or a building remotely (Kaufmann & Remick, 2009).

There is a critical necessity for employing innovation in place of traditional construction approaches in New Zealand since a significant housing shortage is observable in the country (Gordon & Curtis, 2018; Shahzad, Hassan, & Rotimi, 2021). Moreover, due to New Zealand's geographical isolation and high material/human resource costs, the supply of affordable homes is insufficient (Burgess et al., 2013). Despite the resilience of New Zealand's construction industry in adopting innovations, the present utilisation of prefabrication, which is considered an innovative approach to construction in New Zealand, is relatively low (Shahzad, Mbachu, & Domingo, 2015).

Prefabrication delivers several practical benefits, including improved recycling of wastes, decreased on-site efforts, improved quality control and enhanced health and safety measures (Gan et al., 2018; Blismas, Pendlebury, & Gibb, 2005). However, utilising prefabrication methods in New Zealand hinges on industry experts' perception of prefabrication and their collaboration techniques within the prefabrication supply chain (Samarasinghe et al., 2013). Close-knit stakeholders' relationships in New Zealand's construction industry address the interrelated nature of the perceptions/challenges that affect the market's demand and hinder the expansion of prefabrication (Burgess et al., 2013).

The prefabrication sub-sector of New Zealand's construction industry has more complexities in comparison with traditional construction (Jaillon & Poon, 2010). In the prefabrication supply chain, information integration can be more intricate since the number of stakeholders involved in prefabrication projects is higher. The multiplicity of stakeholders imposes a hefty challenge on the construction partners to share their knowledge or information faster and more accurately (Shojaei, 2019). Besides, obtaining statutory approvals (e.g., resource or engineering consents) is difficult in prefabrication projects owing to the multiplicity of workplaces and complicated inspection procedures (Shahzad, 2016). Additionally, quality-related matters such as reworks and defects in prefabrication projects typically stem from inefficient information sharing or collaboration among the supply chain allies (Bell, 2009). These complexities can adversely impact the development of supply chain integration within this sub-sector. Trust is another issue in prefabrication. Most contradictions and trust-related disputes arise from poor transparent information exchange (Handfield & Bechtel, 2002). The absence of trust in prefabrication hinders future interactions, negatively impacts stakeholders' relationships and weakens stakeholders' viewpoints on adopting innovations (Bakhtiarizadeh et al., 2019; Höök, 2006).

Most impediments to the uptake and effective use of prefabrication technology in New Zealand's construction industry can be addressed using advanced information-based technologies (Darlow et al., 2022). For instance, blockchain technology could be helpful for creating information integration and, therefore, supply chain integration within this sub-sector. Blockchain has the potential to directly address the issues related to transparency of information sharing, traceability of products' provenance and security of information-sharing platforms used for stakeholders' communications.

4.4.3 Blockchain technology in New Zealand's prefabrication

Web-based supply chain management systems have recently gained popularity worldwide in integrating supply chain networks (Saberi et al., 2018; Papetti, Marconi, Rossi, & Germani, 2019). Information technology systems such as Customer Relationship Management (CRM) or Enterprise Resource Planning (ERP) are being challenged by cloud/web-based technologies, e.g., drones, GPS, RFID and Internet of Things (IoT) (Xing, Qian, & Zaman, 2016). Using these technologies, information exchange between supply chain partners has been made faster and more efficient (Sundram, Bahrin, Abdul Munir, & Zolait, 2018).

Despite the additional value of cloud-based technologies, a few issues are still associated with them. Chou et al. (2004) describe that information/data security can be deemed a substantial issue associated with these technologies since hackers' risk of manipulating or altering the stored contents is high. Meanwhile, these supply chain management systems provide cross-organisational access to the information repository (Li, Greenwood, & Kassem, 2019). This accessibility can be hazardous in the construction supply chain since all project information would be prone to change by any user, randomly or deliberately (Tse et al., 2017). These issues, in turn, will harmfully disturb trust and market competitiveness among supply chain organisations.

On the contrary, Blockchain technology can perform prominently better regarding cyber security. Distributed Ledger Technology (DLT), commonly recognised as "Blockchain", is a secure and consensus-based transactional register that streamlines connections among its users (Zhao et al., 2016). This technology offers a peer-to-peer (P2P) network where a digital

signature is attached to all transactions to prevent altering the original transactions (Saberi et al., 2018).

Blockchain is analogous to a centralised cloud data centre. Yet, the main distinction is that blockchain is decentralised, meaning that there are multiple sources/databases of information simultaneously accessible by dissimilar users from dissimilar locations (Chowdhury et al., 2018). Moreover, blockchain works by proof-of-work, meaning that users need a consensus-based agreement to make any changes to the contents saved in the database (Casino et al., 2018). This can assist organisations in obstructing malicious attacks on their information repositories.

There are other benefits to using blockchain, as identified by different researchers. For example, supply chain information/data recorded in blockchain will yield long-term transparency and trust by conserving the knowledge gained in the project (Lu & Xu, 2017). In addition to this, the immutability of details saved in blockchain fosters a secure atmosphere within which supply chain organisations can distribute their assets or information without being concerned about scams (Zhao et al., 2016).

This study aims to ascertain the impact of blockchain technology as an information integration tool on New Zealand's prefabrication supply chain integration. Identifying information exchange channels will assist in assessing the benefits of using this technology for improving the integration of the prefabrication supply chain in New Zealand. Figure 4-1 portrays the process model of this study.

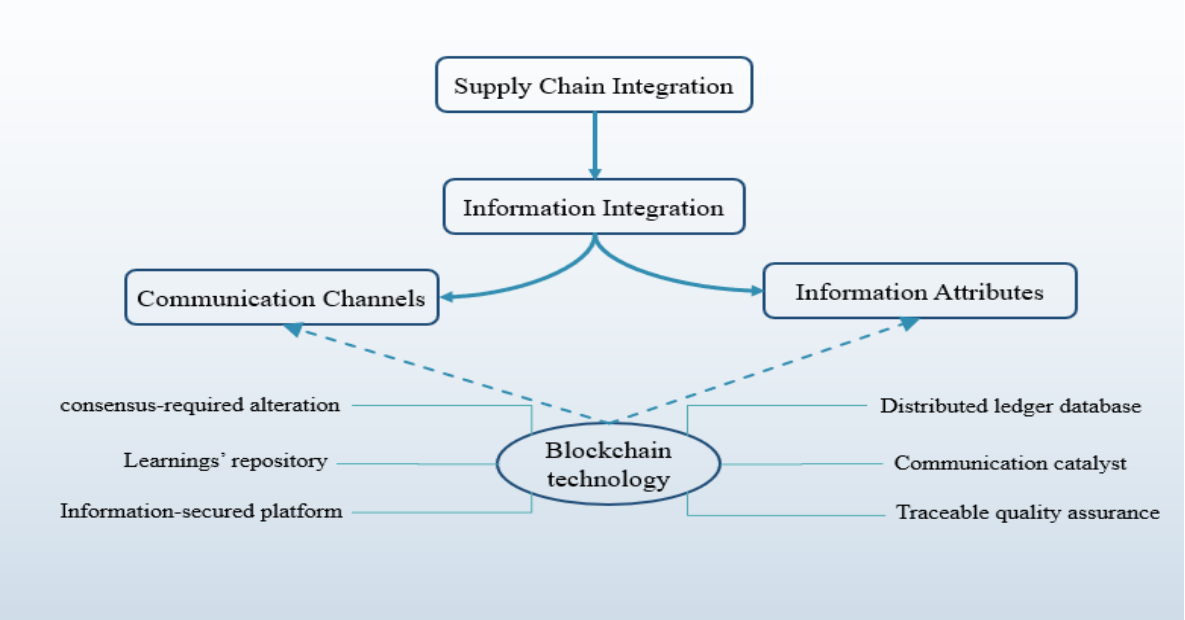

Figure 4-1: Knowledge gap design

4.5 Research design

This study uses an exploratory approach to identifying the communication channels in New Zealand's prefabricated construction supply chain. A questionnaire survey was utilised to (1) identify the modes of information exchange between prefabrication projects' clients and contractors and (2) explore the qualities of information critical for enhancing the prefabrication supply chain.

Many studies have utilised questionnaire surveys to collate experts' perspectives and ideas on the construction supply chain (Gan et al., 2018; Black et al., 2000). The questionnaire survey comprised three sections. A summary of the definitions was provided to the respondents in the opening statement. The next section obtained the preliminary demographic information of the participants. It is worth noting that respondents were requested to identify which major sector they belonged to, whether clients or contractors. Subsequently, participants were asked to respond to a number of questions associated with channels of information exchange and

attributes of information. Multiple-choice questions were incorporated into the questionnaire survey to gain respondents' answers regarding the types of information technology used for communication with other stakeholders. This was followed by five-point Likert scale questions to measure the participants' degree of agreement with the importance of information attributes to the success of New Zealand's prefabrication supply chain. Responses ranged on a scale of 1 (strongly disagree) to 5 (strongly agree). Respondents were also given an extra "Other" option with a textbox to provide their comments/other information.

After pre-testing the questionnaire survey, it was sent to PrefabNZ, which has about 350 members across the design and construction sector (https://www.prefabnz.com/Membership, Accessed on April 1, 2021). The study uses a convenience sampling strategy by first targeting a few familiar PrefabNZ members and using a snowball approach to recruit future respondents among their acquaintances. This snowball sampling method was utilised because of the challenges associated with accessing all PrefabNZ members. Snowball sampling is efficient and cost-effective (Naderifar, Goli, & Ghaljaie, 2017) and is mainly helpful for conducting surveys in which respondents are required to have relevant experience or knowledge on a particular subject (Walliman, 2017). Forty-one valid responses were obtained from experts who received the questionnaire. The demography of respondents can be viewed in Table 4-1.

Table 4-1: Participants' demographics.

Category	Sub-Category	% of Respondents
Stakeholders	Client	46%
	Contractor	54%
Prefabrication experience	0–4 years	59%
	4–8 years	20%
	8–12 years	17%
	Over 12 years	5%

In this study, a descriptive analysis technique was employed. Two steps were taken for the analysis: (1) Communication channels and (2) critical information attributes. First, the multiple-choice responses regarding the channels used for information exchange were split into three groups (detailed design, construction and handover), and the frequency of each response was counted and divided by the total number of responses in each phase. Then, the analysis for the second step was conducted based on the respondent's answers to the questions set out in the Likert scale. An average value greater than or equal to 2.6 for each question was deemed significant.

Errors and biases were lessened by sequencing and writing the questions precisely and succinctly without authors' interpretations, ensuring the reliability and validity of the findings. Moreover, as using subjective data in the questionnaire survey may increase the researcher's bias (Bell, Bryman, & Harley, 2019), we avoided that by promising confidentiality of data to the respondents, highlighting the importance of the subject and emphasising the significance of the accuracy of data that they provide. Moreover, as internal validity is commensurate with measuring what an author expects a measurement tool (e.g., questionnaire survey) to measure (Saunders, Lewis, & Thornhill, 2009), the questionnaire survey delivered satisfactory results of the questions, ensuring abated distortions in the data collected from the participants. The internal consistency between two groups of respondents, clients and contractors, was measured using Cronbach's Alpha test (Table 4-2). A score of 0.751 was returned as a result of this test, which is within acceptable ranges (Cronbach's Alpha > 0.70), thus a high internal consistency of the variables according to the participants' responses.

Table 4-2: Result of Cronbach's Alpha.

Construct	Variables	α
Information Exchange	Transparency Traceability Security (Reliability)	0.751

4.6 Results and discussion

In geographically dispersed construction sites, prefabricated construction is more suitable (PrefabNZ, 2018). However, the complexity of the supply chain in prefabrication is more than that in traditional construction (Shahzad & Mbachu, 2013). When information is exchanged effectively throughout prefabricated projects, this complexity can be decreased significantly (Wang et al., 2020). Information technology will streamline complex information exchange processes and facilitate the construction supply chain for prefabricated projects (Darlow et al., 2022).

4.6.1 Communication channels

Previous studies have shown that the types of information exchanged across the entire supply chain in a prefabricated project can substantially affect the project's outcome (Briscoe et al., 2001). A large number of documents, including design and construction drawings, quality assurance (QA) documents, requests for information (RFIs) and governmental permits/approvals are exchanged within the prefabrication supply chain on a daily basis (Bakhtiarizadeh et al., 2019; Achar et al., 2021). Effective integration of this abundance of information results in a positive future collaboration among supply chain partners (Darlow et al., 2022).

Various industries have benefited from the use of technologies in their supply chains. Information Technology (IT), firstly, has made collaboration within the production team easier, thereby decreasing the timeframes for the development of products (Gan et al., 2018). Additionally, it has resulted in lower production costs (Prajogo & Olhager, 2012). Finally, it has improved customer satisfaction by improving product quality (Saberi et al., 2018; Chou et al., 2004).

While collaboration has been streamlined through information technology, the best technological tool to be used has remained the major challenge for researchers and industry experts, triggering different approaches and technologies to be investigated thoroughly (Lee & Lim, 2001). Information integration is a prerequisite for effective collaboration (Costa & Tavares, 2012), and to integrate information, it is necessary to identify the communication channels among stakeholders (Costa & Tavares, 2012; Yang et al., 2020).

Communication channels in prefabrication supply chains have been studied in various ways. However, information technology has never been the focus of these studies. For instance, Evborokhai and Shittu 2020 studied different communication channels to improve communication management approaches and reduce disputes in the design phase of construction. Moreover, Achar et al. 2021 classified the channels of communication among different organisations in the construction industry and evaluated the role of these channels in the execution of housing construction projects. Traditional ways such as intranet/extranet-based emails, faxes and phone calls were studied by Wang et al. 2020, revealing the lack of automatic information-sharing systems and the importance of technological adoptions. Others identified different channels, such as video/audio conferences, face-to-face conversations, blogs, text messages and letters (Achar et al., 2021).

Communication channels in this study were clustered into 11 categories and incorporated in the questionnaire survey: Email, meeting, telephone, cloud database or applications, intranet or extranet, GIS systems, Building Information Modelling (BIM) software, video conference, verbal communication, workshops and social media. The questionnaire survey sought to determine the main channels (platforms) for exchanging information between clients and contractors in the prefabrication sector. The response to the questionnaire survey is presented as a clustered bar chart in Figure 4-2. According to the respondents, the traditional and most commonly used modes of communication in the prefabrication supply chain are email, meeting, telephone and internet-based applications (e.g., SharePoint) with an average of 90, 80, 50 and 50 per cent, respectively.

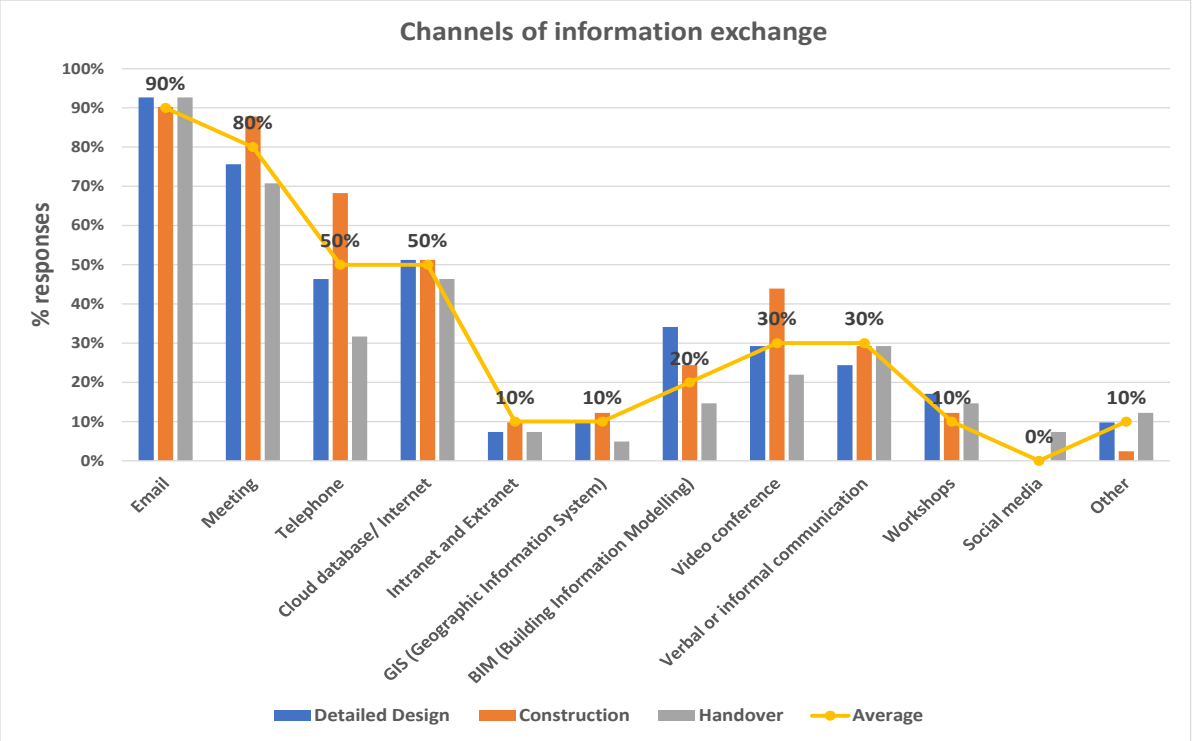

Figure 4-2: Channels of information exchange

These channels have been investigated in three phases: Detailed design, construction (off-site and on-site) and handover. The difference between the percentage of responses in these phases is commensurate with the concentration of actual construction works for a given prefabrication project. Depending on which phase the project is at, the communication channels switch their use case dominance. For instance, in the construction phase, face-to-face applications such as meetings, video conferences, or phone calls are dominant for quick actions to be taken on-site. Conversely, internet-based applications or formal communication channels such as emails are frequently used in the modelling or detailed design phase when acquiring statutory approvals and engineering consent occurs. The identified channels represent the views of contractors (54%) and clients (46%), showing relatively equal participation of both stakeholders. Moreover, 61% of participants indicated that IT (in general) is utilised in their organisations, and 83% suggested that technological tools could facilitate effective information integration.

4.6.2 Attributes of information

Logistics integration, trust and collaboration occur in the supply chain as a result of information integration (Jagtap & Kamble, 2020). However, when information exchange is not quite streamlined, supply chains experience uncertainty (Zhou & Benton, 2007). The absence of efficient information integration has been proven to cause several drawbacks in literature, including fragmentation, distrust and scepticism in supply chains (Awasthi & Grzybowska, 2014). Essential qualities of information affecting information integration are transparency, traceability and security (Wang et al., 2020; Cˇuš-Babic et al., 2014; Bakhtiarizadeh et al., 2019). Information transparency is interpreted as a decrease in the level of uncertainty or a reduction in the expectation of heterogeneousness among the participants in an uncertain

circumstance (Angeletos & Pavan, 2004). Transparency is acknowledged to be one of the most critical information attributes affecting supply chain success (Cˇuš-Babic, 2014). In the prefabrication supply chain, transparent information exchange enhances collaboration and trust among partner organisations (Wang et al., 2020). Traceability is another important quality of information contributing to enhancing supply chains. In prefabricated construction projects, where a vast number of materials are used to finalise a project, the characteristic of services and quality of materials give rise to the necessity of developing a traceable information integration system in which all the information regarding the origin of materials can transparently be traced (Saberi et al., 2018).

Moreover, prefabrication is a method of construction aiming to reduce waste materials, energy consumption and carbon emissions by using green products to ensure the preservation of social and environmental elements (Shahzad, 2016). These sustainability measures are acquired through mutual learning from in-development projects. A project's knowledge is primarily composed of the information collated and stored throughout the project, which is practically impossible to condense into words (Kazi, 2005). This kind of knowledge is mostly communicated through person-to-person interactions, with a high possibility of forgetting parts of it (Zhang et al., 2015). New IT systems can help capture the knowledge and convert it to easily stored data (Kazi, 2005). Konukcu 2011 states that some new IT systems are electronic bulletin boards, decision-making computer systems, web/online databases and knowledge gateways. These systems are substituted for decentralised systems where information security is assured (Li et al., 2018). The ability to trace the information flow for prefabricated materials used in construction projects ascertains the sustainability metrics and significantly improves

clients customers views on the genuineness of products, which helps supply chain partners build up better collaborative and trustworthy partnerships (Li, Greenwood, & Kassem, 2018).

The last information attribute investigated in this study is security. Information security refers to the long-term preservation of the authenticity of records and the integrity of the data (Lemieux, 2016). Information communicated in an organisation varies from reports or technical drawings to contracts and statutory documents (Sahin & Robinson, 2002). These forms of information need a protected information-sharing engine to enable the secure preservation of learning for future use. Thus, adequate information security systems are required to ensure the safe transition of one project's learnings to the next, assisting the integration of the construction supply chain.

In this study, the questionnaire survey determined to what extent transparency, traceability and security (system reliability) were, respectively, significant to the success of the respondents' organisations. These information qualities were tested using a five-point Likert scale to obtain experts' opinions on the importance and impact of each attribute on the success of the prefabrication supply chain in New Zealand. The result is presented in a clustered bar chart in Figure 4-3. A high percentage of respondents strongly confirmed that the identified attributes are crucial to the performance of the prefabrication supply chain. These three aspects can be connected to the strength of blockchain technology and the benefits it offers for integrating organisational information.

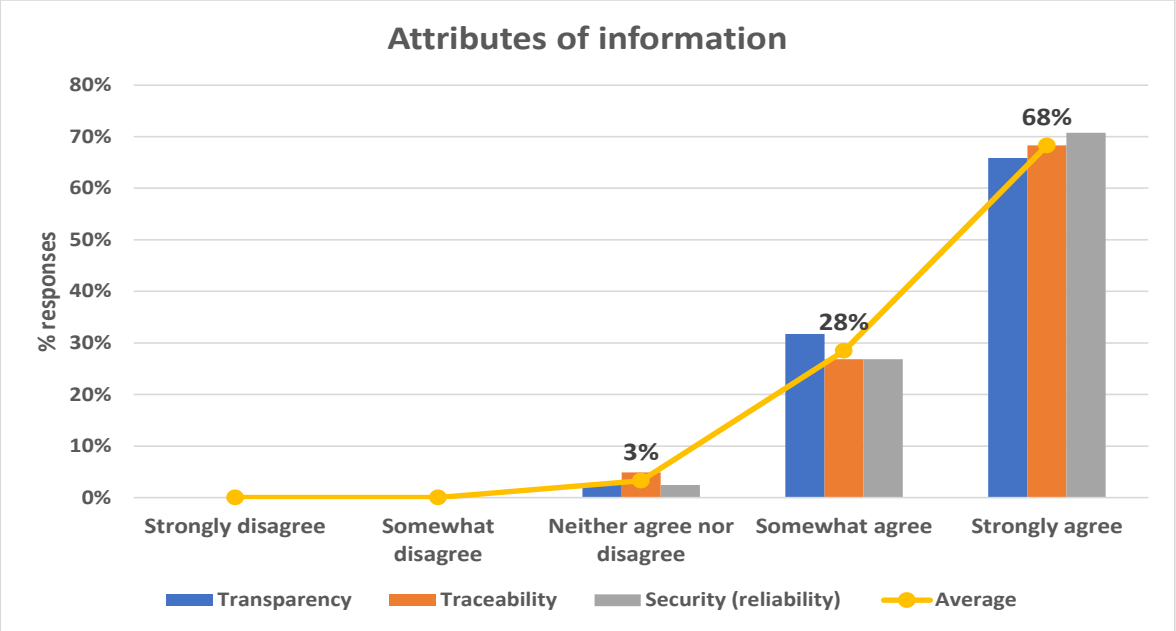

Figure 4-3: Important attributes of information.

4.6.3 Blockchain in the prefabrication supply chain

Historically, the construction industry in New Zealand has been primarily based on traditional construction methods (Shahzad, 2016). Prefabrication is a relatively newer approach that is becoming more popular, and industry experts are discovering its benefits. However, the adoption of IT systems is relatively low in the prefabrication sub-sector of New Zealand's construction industry (Shahzad & Mbachu, 2013). This is mainly due to the lack of awareness of prefabrication practitioners about the benefits of information technology (Burgess et al., 2013). Moreover, poor understanding of information integration strategies and lack of technical knowledge or expertise is predominant across supply chain parties (Harland et al., 2007), inhibiting the effective utilisation of technology and, conceivably, limiting the steps towards supply chain integration.

Information integration is closely related to blockchain technology as an enabling mechanism for providing a secure information-sharing database. Researchers have

demonstrated that blockchain technology is capable of storing a wide variety of data or information, such as sustainable building construction/design data, building performance information and equipment records (Yang et al., 2020). Similarly, they have confirmed that data/documents in various formats, e.g., images, models, drawings and videos, can be uploaded and saved on blockchain (Devine, 2015; Chen et al., 2018). Thus, the information on all transactions (such as manuals, handbooks, standards, specifications and regulatory compliance certificates) from different stakeholders in supply chains can be recorded and tracked on the blockchain (Wang et al., 2020; Yang et al., 2020). This information integration will bring many benefits to the construction sector, including reduced fragmentation of supply chain partners, enhanced scalability, reduced time/cost, high transparency, traceability and data security.

Blockchain's central novelty lies in its capacity to authorise, distribute and record transactions in unalterable registers. For blockchain to obtain ubiquitous popularity in prefabrication, it should address some of the fundamental challenges in this sub-sector, such as fragmentation, deficient quality products, security of information, bureaucracy, lack of trust leading to disputes and transparency (Li, Greenwood, & Kassem, 2018).

The fragmentation of prefabrication construction needs enhanced integration in the supply chain for effective performance (Jagtap & Kamble, 2020). From a wider perspective, the structure and governance of supply chains in the construction industry as well as trust, which is the underlying factor for fragmentation (Cheng et al., 2018), is highly affected by integration and innovation across supply chain actors (Wang et al., 2020). Blockchain's contributing characteristics, namely, transparency, traceability and security/immutability, have the innovative potential to introduce better integration and make a bridge between traditional and technological practices within the construction industry, allowing the industry to efficiently

promote trust and reduce resources and administration costs, durations and disputes. Moreover, from the governmental perspective, blockchain can provide the same services offered by statutory authorities and the corresponding private sectors in a decentralised and automated manner whilst preserving the same validity (Tezel, Febrero, Papadonikolaki, & Yitmen, 2021). Examples of such services in the construction industry are Engineering Plan Approvals (EPAs), resource consents and Construction Compliance Certificates (CCCs), all deemed bureaucratic and time-consuming in New Zealand.

Whilst New Zealand's government has strict border control measures and import/export regulations, the number of counterfeit products imported into New Zealand is of major concern. A Building Research Association New Zealand (BRANZ) study revealed that most construction products are often tested and certified overseas before being shipped to New Zealand. Problems with these products may take many years to emerge, and by the time the issues arise, the suppliers of products may no longer exist in the market (Allison & Warren, 2019). Therefore, prefabrication supply chain organisations rely on suppliers/manufacturers' product specifications to satisfy the Building Consent Authorities (BCAs) and their customers that the products used in their projects comply with regulatory requirements and are fit for the purpose.

Blockchain can play a significant role in transmitting quality assurance and certification information. The traceability function of blockchain can allow New Zealand's prefabrication supply chain organisations to conduct their product testing and shipment tracking in a real-time and consensus-based manner. This, in return, increases the visibility and control over the history of products from their origin to their final location. Moreover, instead of having the source of technical information generated by the supplier company and uploaded to their

company website for tracking, all partner organisations can simultaneously trace and verify the provenance of information flexibly. Enhanced visibility and control associated with this flexibility lead to better trust and transparency between organisations involved in the project.

Nevertheless, there are some challenges towards implementing blockchain technology in the prefabrication supply chain. Energy consumption is deemed one of the biggest concerns associated with blockchain's requirement of electricity usage for its computational process (Li, Greenwood, & Kassem, 2019). Legal matters such as ownership rights, standardisation, corruption and risk allocation are also other types of concerns attributed to blockchain where the intervention of centralised legal authorities is limited (Saberi et al., 2018). The readiness of industry experts, the lack of skilled blockchain professionals, the technological status quo of the construction industry and the cost of change are some other challenges towards the adoption of blockchain technology (Casino et al., 2018; Saberi et al., 2018; Yang et al., 2020). As blockchain grows and matures, different aspects of using this technology will be discovered, and its potential opportunities/risks can be practically examined.

4.7 Conclusion

The construction supply chain is viewed as a network/system of activities providing value and services to stakeholders (Mentzer et al., 2001). This value-generating network inherently confronts many challenges and complexities, reducing collaboration and growth opportunities (Bidabadi et al., 2016). Modern prefabrication practices appear to have resolved most concerns associated with traditional construction regarding economic, social and environmental limitations. However, little attention has been given to the integration of information, which is a significant driver of supply chain integration in this subset of the construction industry

(Shahzad, Mbachu, & Domingo, 2015). In an integrated supply chain, information is traded swiftly and securely among the stakeholders without alterations (Wang et al., 2020). The prefabrication supply chain can benefit from the transparency and visibility connected to information integration.

New Zealand is confronting a lack of affordable housing, high resource and material costs, defects and low-quality products and a lack of integration among the supply chain partners (PrefabNZ, 2018; Shahzad et al., 2021; Allison & Warren, 2019). Adopting information technology (in general) and information integration mechanisms (in particular) have been the primary focus of studies targeting the low integration and increase of efficiency and performance of supply chains (Bakhtiarizadeh et al., 2019; Darlow et al., 2022; Sundaram et al., 2018). However, blockchain technology has not yet been viewed as a feasible option.

As an innovative information integration instrument, blockchain technology has the potential to enhance supply chain structures by ensuring traceability, transparency and security (Li, Greenwood, & Kassem, 2018). New Zealand's prefabrication industry can benefit from adopting this technology to improve the transparency of information exchange, traceability of construction products' provenance, and protection of technical information while allowing visibility for partner organisations' analyses. Exploring communication channels between prefabrication organisations is a starting point for assessing the impact of blockchain technology on supply chain integration.

This study identifies information-sharing channels between clients and contractors and contends the strength of blockchain technology in New Zealand's prefabrication supply chain. By adopting a questionnaire survey as the data collection tool, several communication

platforms for transmitting information inter-organisationally between prefabrication clients and contractors in detailed design, construction and handover phases of projects were identified. Then, the importance of the critical information attributes needed for the success of the prefabrication supply chain was verified. Finally, the significance of adopting blockchain technology, an effective information integration tool, in place of traditional communication methods was explored.

The results demonstrated that traceability, transparency, and security of information exchange across organisations are of great importance and that blockchain technology has the potential to improve integration in prefabrication projects by fostering collaboration and trust among partner organisations. The findings provide an understanding of blockchain technology and prefabricated supply chain integration, which will assist stakeholders in enhancing their managerial decisions and supply chain strategies. Industry experts and managers could use this study's result to understand the essential attributes of information and current communication practices dominant in the prefabrication supply chains. Moreover, the impact of blockchain technology on the prefabrication supply chain in New Zealand, as described in this paper, can be understood. Future research will be conducted to provide a practical framework for employing blockchain technology as a means of information integration and, therefore, supply chain integration for New Zealand’s prefabrication industry.

Data was collected from the experts within a specified time frame, which limits the extensive findings of this study. The low response rate of the questionnaire survey is acknowledged, which is a result of the small-sized prefabrication sub-sector of New Zealand’s construction industry and the lack of industry professionals’ knowledge on the topic. The majority of the participants had limited knowledge of blockchain technology or had not

practically used it as an instrument in their professional practices. The findings of this research can feed into the prefabrication supply chain frameworks developed by other researchers. As blockchain technology evolves and becomes widely accepted, stakeholders' outlook on the blockchain or similar cutting-edge information technology systems can be improved.

4.8 Epilogue

In this chapter, information-sharing channels between clients and contractors were identified, and the value of blockchain technology in New Zealand's prefabrication supply chain was examined. Utilising a questionnaire survey for data collection, various communication platforms facilitating inter-organisational information sharing between prefabrication clients and contractors during project phases such as detailed design, construction, and handover were pinpointed. Subsequently, the importance of critical information attributes necessary for the prefabrication supply chain's success was confirmed. Lastly, the potential benefits of replacing traditional communication methods with blockchain technology, recognised as an effective information integration tool, were explored. The findings revealed that blockchain technology holds the potential to enhance supply chain information integration by guaranteeing traceability, transparency, and security. While this chapter provides insight into the technicality of information exchange and the benefits of blockchain technology, a great deal of further research using literature is still required to broaden the researchers and industry practioners' perspective on the applicability of blockchain technology in the prefabrication subsector of New Zealand's construction industry and provide them with a more rigorous background before introducing a practical framework in chapter 6. Thus, the next chapter acts as a consolidation of the previous chapters and an introduction to the following chapter.

Chapter 5: Blockchain technology in New Zealand's prefabrication supply chain

5.1 Prologue

A consolidation of literature used in previous chapters and a summary of the applicability of blockchain technology and its associated benefits in New Zealand's prefabrication supply chain are provided in this chapter, laying the groundwork for introducing a practical framework for integrating blockchain technology into the supply chain systems. Providing a transitional basis from literature to the development of a framework, this chapter is structured to present the key definitions and challenges in the prefabrication supply chain followed by the necessity of conducting research in that area. This chapter develops an understanding of how blockchain technology helps alleviate the complexities in New Zealand's prefabrication supply chain and establishes a foundation for further study and framework developments.

The current chapter is based on the following article:

Bakhtiarizadeh, E., Shahzad, W., & Rotimi, J. (2020). Applying secure information-based mechanism for prefabrication supply chain integration. *In Proceedings of the 5th New Zealand Built Environment Research Symposium (NZBERS)*, Auckland, New Zealand, 71 – 78.

5.2 Abstract

Various industries are taking advantage of innovations in their supply chain management practices. The construction industry, however, is considered a slow adopter of technologies and innovative practices due to poor information integration, which leads to a lack of collaborative interactions and, consequently, reluctance to utilise

technologies. Numerous studies have been conducted on supply chain practices in the construction industry, yet research on the prefabrication supply chain is limited, particularly where the effectiveness of supply chain management techniques is hindered as a result of the low level of information technology adoption. Therefore, this paper provides an intuition into the integration of prefabrication supply chain stakeholders. A literature review is employed to identify a newly introduced technology for information integration among supply chain stakeholders in prefabricated construction projects in New Zealand. The study indicates that using an effective and secure information-sharing mechanism for a prefabrication supply chain could enhance business interactions by generating a more collaborative and trustworthy environment among the partners.

5.3 Introduction

The concept of supply chain management is successfully used in different industries, but the use of this concept is very new for the prefabrication sub-sector of the construction industry. Prefabricated construction in New Zealand requires particular attention to the factors obstructing its efficiency and effectiveness, and lack of supply chain integration is observed to be a major issue limiting the performance of this sector (Shahzad, 2016).

Collaborative relationships leading to positive prospects of future cooperation among supply chain partners is a pivotal point that drives the integration of the supply chain within prefabrication construction (Akintoye, McIntosh, & Fitzgerald, 2000; Smyth & Pryke, 2008). The current practices of supply chain integration mainly suggest that the supply chain must be considered an integrated value-generating flow rather than merely a sequence of single activities (Vrijhoef, Koskela, & Howell, 2001). An integrated supply chain ensures the

processes of construction projects: design, planning, construction, and maintenance (Čuš-Babič et al., 2014). It also provides collaboration and trust among the delivery team as a uniform project team (Bankvall, Bygballe, Dubois, & Jahre, 2010).

For acquiring a collaborative and successful supply chain integration, efficient information sharing across stakeholders is essential (Konukcu, 2011). Prefabrication is considered an innovative technology in the construction industry that focuses on decreasing onsite construction activities as much as possible by transferring a significant portion of the events to an offsite controlled environment (Shahzad, 2016).

This research addresses the problem of relatively weak integration within New Zealand's prefabrication construction supply chain. The particular focus of the research is on information integration. The central point is that an effective and efficient exchange of information among supply chain stakeholders is imperative for enhancing supply chain integration in New Zealand's highly fragmented construction industry. Therefore, providing a secure and effective information integration-based platform for stakeholders involved in prefabrication projects will deliver integration improvement in the whole supply chain system.

5.4 Background

Prefabrication supply chain integration Construction Supply Chain Management (CSCM) encompasses all the processes involved in project delivery, from procuring necessary components to delivering the project to the end user (Behera, Mohanty, & Prakash, 2015). It is also defined as managing the flow of information, materials, processes, and activities between upstream and downstream organisations to deliver high-quality and reliable products to the end-user efficiently (Akintoye et al., 2000).

The concept of supply chain management includes an efficient flow of materials to the end-user and a flow of information to the supplier, employing integration, coordination, and cooperation among its members (Power, 2005). Still, this definition is continuously being revised by different authors in different industries and use cases (Luo et al., 2020). Nevertheless, the underlying premise of supply chain management can be founded in systems thinking, which magnifies the importance of considering all single parties involved in the cycle of delivering a product (or service) as significant collaborators to a more substantial system (Cai, Jun, & Yang, 2010).

Supply chains suffer from a lack of collaboration and coordination among stakeholders (Stadtler & Kilger, 2002). Within an organisation, inefficient integration of all supply networks hinders the sufficient flow of orders and products between suppliers and customers (Lambert & Cooper, 2000). Also, old-fashioned production methods are now being replaced by innovations and advanced technologies which require organisational integration (Konukcu, 2011).

Low transparency, traceability, and lack of trust can also be deemed as other difficulties resulting in the ineffectiveness of supply chain management systems (Mentzer et al., 2001). For successful supply chain management, a modification from individual roles to integrating key supply chain processes is required (Lambert & Cooper, 2000).

Supply Chain Integration (SCI) is a key to supply chain management (Konukcu, 2011). Implementing an efficient and effective inter and intra-organisational SCM requires integrating processes and flows (Cooper, Lambert, & Pagh, 1997; Prajogo & Olhager, 2012). Broadly, a supply chain comprises several distinctive organisations collaborating to accomplish a product or represent a service for customers to enhance the performance of a supply chain and improve

its integrity. Integration refers to the stability and uniformity of project delivery systems and collaborative relationships with adequate flows (Dainty, Millet, & Briscoe, 2001).

Suppliers' network complexity in the construction industry depends on the size of the projects; generally, in large projects, the number of suppliers can exceed hundreds (Shahzad, 2016). Consequently, this complexity of various actors leads to the vital need to improve the adaptability of SCM techniques with the latest technologies.

In New Zealand, there is a vital need to adopt innovation instead of traditional construction since the country is confronting a significant shortage of housing (Gordon & Curtis, 2018). For the next decade, Auckland alone requires approximately ten thousand new houses per year (PrefabNZ, 2018). This means that a more extensive area will face urban design problems, and the limitation of free land becomes more tangible. These constraints intensify the adoption of offsite construction rather than traditional construction (where construction sites accommodate site offices, machines, hangers, and material storage). In Canterbury, many buildings were damaged due to the earthquake in 2010, which means that there needs to be a vast effort to rebuild or repair the damaged houses (PrefabNZ, 2015). Moreover, there is a considerable number of low-quality and leaky buildings in New Zealand, for which innovative actions are required to prevent the rise of this crisis (Gordon & Curtis, 2018). Finally, supplying affordable housing is critically low in New Zealand due to geographical isolation and the high cost of materials and human resources. This also strengthens the need for adopting innovative construction practices (Shahzad, 2016).

As an innovative construction practice, prefabrication technology in New Zealand is snowballing in terms of its contribution percentage to the delivery of construction projects. Increasing demand for new houses and the lack of affordable accommodations

in New Zealand evolved the need for innovative and effective types of project delivery systems instead of conventional types. The prefabrication sub-sector is identified as leverage for eliminating the shortcomings of traditional construction systems. However, this sub-sector of the construction industry struggles with its challenges, such as low level of coordination and integration across its supply chain partners (Zhai, Zhong, Li, & Huang, 2016).

Prefabrication has been an innovative element of the New Zealand construction industry since colonisation in the early 18th century (PrefabNZ, 2013). Even though the construction industry in New Zealand is resilient enough to employ innovative methods of construction, the current use of prefabrication is relatively low (Shahzad, 2016). Prefabrication offers several functional benefits, including reduced onsite work, enhanced waste production, recycling and reuse opportunities, raised health and safety, better quality control, and a custom design (Kaufmann & Remick, 2009; PrefabNZ, 2015).

However, the construction industry, particularly in offsite manufacturing, is lagging in terms of supply chain integration (Bankvall et al., 2010; Shahzad, 2016). Complexities in prefabrication supply chains are higher in comparison with the traditional ones due to the broken working sites (Mostafa, Chileshe, & Zuo, 2014), and this fact raises the need for better collaboration and more transparent communication. Moreover, managing the flows of information and materials and responding quickly to any alteration in customers' demands or design requires dynamic concurrent management strategies as well as the flexibility of supply chain partners to ensure that the effective integration of the prefabrication supply chain is maintained (Gibb & Isack, 2003; Mostafa et al., 2014). As such, any challenges on the path of effective information integration need to be eliminated. Information integration Information exchange within supply systems requires integration to offer opportunities for fundamental improvement of supply chain integration.

Information integration refers to sharing information among supply chain partners, and its key goal is to attain real-time information transmission across the supply chain system (Prajogo & Olhager, 2012). Integration of information promises logistics integration, which is about coordinating the flow of materials and resources from suppliers to customers (Stock, Greis, & Kasarda, 2000).

Although numerous researchers proclaim that information integration is essential for effective supply chain management (Sahin & Robinson, 2022; Patterson, Grimm, & Corsi, 2003; Samarasinghe, Tookey, & Rotimi, 2013), it is not practically advanced in construction supply chain management (Cox & Ireland, 2002). Information exchange in the supply chain provides noteworthy improvement to business relationships and associated trust. As Yu et al. (2001) explain, while the supply chain is characterised by decentralisation, uncertainties appear when a person alters information inside a supply system, and others either remain uninformed or become aware late enough to respond to the change correspondingly. This can produce variations in products' delivery time and relative cost. Also, Čuš-Babič et al. (2014) prove that information that is made from various sources leads to scepticism, distrust and disintegration among parties involved in the supply chain.

With an efficient information flow and preservation of information related to projects in a secure platform, the concern of information alteration would be decreased, and supply chains could obtain better integration (Casino, Dasaklis, & Patsakis, 2018). employing a safe platform for trading information and engaging a secure storehouse for information could efficiently result in improved decision-making and collaborative and transparent relationships (Turk & Klinc, 2017). Also, all the information stored acts as

knowledge of the project upon completion of the project and could be used in future projects (Penzes, 2018).

Offsite construction is more feasible for isolated sites with low access (PrefabNZ, 2015). However, it resonates with a more complex supply chain since there are different sites and more people involved (Gibb, 1999). Maintaining efficient communication or information exchange throughout the process of completing a prefabricated project would substantially reduce this complexity (Hwang et al., 2018). The flow of information among prefabrication supply chain stakeholders is complex, and this may pose challenges to achieving effective collaboration and supply chain integration (Jaillon & Poon, 2010). The issue of inefficient prefabricated construction supply chains can be mitigated by adopting advanced information integration technologies as a solution.

5.5 Potentials of blockchain

Web or cloud-based supply chain management systems have recently been used worldwide to integrate supply chain networks (Ngai, Cheng, & Ho, 2004; Kuzlu et al., 2019). Information technology (IT) systems for SCM, such as Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), and Electronic Data Interchange (EDI), are changing their place with cloud-based technologies such as the Internet of Things (IoT), drone, and GPS receivers and RFID (Xing, Qian, & Zaman, 2016).

These technologies have enabled fast and effective real-time information exchange across supply chain partners. Also, with the help of these technologies, harmful human interventions in information databases have been decreased (Ngai et al., 2004). The adoption of information technologies in the supply chain, firstly, has reduced product development time by facilitating communication among the production team; Secondly, it has shortened the cost

and prices of products; and lastly, it has brought improved quality as per customers' expectations (Chou, 2004).

However, even though the application of cloud-based technologies could add value to SCM, there are a few associated issues. (Finch, 2004) explains that information/data security can be considered a significant issue about these systems since the risk of manipulation of stored contents or alterations by hackers is high. Meanwhile, these types of SCM systems provide all supply chain members, both inter- and intra-organisationally, with access to the information repository (Chou, 2004). In the construction supply chain, this can be hazardous since all of the information related to projects is susceptible to being changed either arbitrarily or intentionally by any user (Tse, Zhang, Yang, Cheng, & Mu, 2017). Which, in turn, can adversely affect organisations' market competitiveness and trust among partners.

Blockchain technology, on the other hand, can act suitably when it comes to security concerns. Distributed Ledger Technology (DLT), mostly known as "Blockchain," is a consensus-based ledger that facilitates transactions among its users by providing them with a secure and tamper-proof database (Penzes, 2018).

The first blockchain was originally invented in 2008 and introduced by Satoshi Nakamoto for crypto-currency transactions (Bitcoin) (Chen, Wang, & Zhang, 2018). It represents a network where various nodes perform their operations either publicly or privately without the intervention of a financial institution (Nakamoto, 2008). This technology would offer a peer-to-peer network where all the transactions are adhered to with a digital signature to deter double-spending when there is no supervision of a trusted third party. This network chronologically timestamps all the transactions using hashes in

an ongoing block and provides a record that is impossible to alter without the consensus of users (proof-of-work) (Li, Greenwood, & Kassem, 2018).

Blockchain is very similar to a cloud database on the internet. Still, the only difference is that blockchain is distributed, meaning the database is decentralised in multiple locations. Instead of having one source for information with various access, various scattered sources can be updated simultaneously (Penzes, 2018). Once new information or transaction is about to be added to the chain, the peer-to-peer consensus mechanism rises to validate the information without the interference of an intermediary (Lu & Xu, 2017). This can be helpful for organisations to hinder malicious attacks on their information databases.

Also, in the construction industry, where the number of disputes regarding payments is incredibly high (Sutrisna & Goulding, 2019), blockchain can function as a trustworthy and dependable contract administrator. Blockchain offers a reliable and error-free practice based on which the payments can be executed securely, and contracts can be created and monitored (Li, Greenwood, & Kassem, 2019). These capabilities and features can be found in neither traditional delivery systems nor web or cloud-based databases.

5.6 Applicability of blockchain in prefabrication supply chain

The prefabrication subsector of New Zealand's construction industry, in some cases, has more complexity in comparison with traditional construction (Jaillon & Poon, 2010). In the prefabrication supply chain, the distribution of information might be more complicated because more actors are involved in a given project. The separation of suppliers into two classifications of "direct" and "indirect" imposes a more significant challenge for the construction actors to exchange the required information or documents (such as drawings, calculations, schedules

and production details) in a quicker time and higher accuracy (Burgess et al., 2013; Shojaei, 2019).

Also, acquiring regulatory approvals and consenting procedures are complicated in prefabrication due to the diversity of worksites and time-consuming inspection processes (Shahzad, 2016). This can lead to higher project completion time. Moreover, in this industry, quality-based issues such as defects or reworks usually arise from ineffective traceability, coordination, and collaboration among prefabrication supply chain partners (Bell, 2009; Shojaei, 2019). This would adversely affect the development of integration within this subsector.

Trust is also a vital issue inhibiting the uptake of prefabrication in New Zealand (Shahzad, 2016). Most conflicts and trust problems emanate from inadequate information sharing and poor transparency in collaboration (Handfield & Bechtel, 2002). Lack of trust in prefabrication projects impedes future collaborations, adversely affects stakeholders' relationships, and deteriorates managers' viewpoint towards adopting innovations (Shahzad & Mbachu, 2012).

Although blockchain is a relatively new concept, New Zealand industries with the right policies and approaches could benefit socially, economically, and environmentally from this advanced phenomenon. New Zealand, despite being geographically isolated, is showing flexibility in adopting innovations for business development and is playing well in the global market (Burgess et al., 2013).

Blockchain technology has the potential to significantly impact the growth of domestic businesses, particularly in the prefabrication construction industry, where the technology is not practically being deployed. One of the foremost significances of blockchain in the prefabrication supply chain is the fact that by stacking all the

information in blocks, traceability is streamlined, and clients are capable of tracing back all the processes related to the completion of a project (Li et al., 2018). Thus, logistics efficiency, information flow, trust and transparency can be vastly enhanced (Zhao, Fan, & Yan, 2016). Also, by using this technology, interactions occurring among prefabrication supply chain organisations could follow an organised style of information exchange, which, in turn, leads to transparency of documentation and accountability of each organisation with respect to their trustworthy and accurate contribution to projects' deliveries (Chowdhury et al., 2018).

5.7 Conclusion

Construction is one of the biggest industries in New Zealand. However, this industry suffers from many inherent issues, including low productivity, poor quality of materials, and lack of collaboration and information sharing among all stakeholders (Virijhoef et al., 2001).

While traditional construction suffers from such issues, prefabrication is recognised as a useful innovation for tackling most problems by reducing defects, decreasing time and costs, and improving performance. The existing culture of prefabricated construction deters the adoption of advancements and makes the construction industry a sluggish user of supply chain information technologies (Shahzad & Mbachu, 2013). Therefore, for this industry, information technology platforms must be improved to effectively accommodate the knowledge and information of project-based supply chains.

A low level of effective information integration can be regarded as the underlying issue responsible for poor supply chain management. Inefficient information integration also leads to many other drawbacks, such as a poor collaborative and trustworthy supply chain environment (Cai et al., 2010). Employing blockchain technology as an information integration mechanism for improving security, trust, collaborative relationships, traceability, and

transparency can be helpful for dispelling complexities arising from prefabrication supply chain fragmentation. Applying this technology to New Zealand's prefabrication supply chain helps obtain a more effective and efficient integration.

5.8 Epilogue

This chapter summarised the relevant literature on the importance of implementing technological advances, namely blockchain technology, in the prefabrication supply chain in New Zealand. Integration of supply chains has long been the focus area of researchers, and this chapter outlined the requirements for supply chain integration through employing blockchain technology as an information integration tool for enhancing the effectiveness of the overall supply chain integration in prefabrication projects in New Zealand. Therefore, a bridge from the literature to the implementation of blockchain technology in New Zealand is required. The following chapter provides a comprehensive overview of the results from previous chapters, emphasising the need for applying this technology in prefabrication projects through a system design and framework development for integrating information exchange. As such, a framework with its associated interface system model is developed to target the feasibility of blockchain as a tool and, thus, fulfilling the last objective of this thesis and validation criteria.

Chapter 6: Blockchain framework for prefabrication supply chain integration

6.1 Prologue

In the previous chapters, relevant connections between clients and subcontractors were identified using interviews and a questionnaire. The analysis was then completed by reviewing the interconnectivity of stakeholders, determining prevalent communication channels, and exploring key information integration requirements that a technological tool must deliver, as perceived by industry experts. However, developing a practical framework for implementing blockchain technology was not explored in the previous chapters. This chapter presents a framework for utilising blockchain technology as a communication platform among the stakeholders. The literature review, pilot interviews, and question survey results from previous chapters were critically reviewed and analysed to develop an appropriate framework for integrating information flow among prefabrication stakeholders during the detailed design, construction (onsite and offsite), and handover phases. The proposed framework was presented to blockchain and prefabrication experts in a focus group meeting, and their inputs were captured using a validation survey to bring the study as closely as possible to practice within the New Zealand construction industry. The validation of the framework was carried out in two steps: 1) presenting the framework to the experts and 2) developing a survey for the experts to indicate their opinions and recommendations for improving the framework. The results of this approach ensured the validity of the proposed framework, addressing the last objective of the thesis.

6.2 Framework development

6.2.1 Workflow diagram

The prefabrication project life cycle involves various phases, and each phase generates many documents. The existing approaches of document management involve several processes, such as:

- Work Order Management, i.e. Change Orders (COs) or documents authorising specific work to be done, including details/changes on scope, timeline, and resources.
- Project Reporting, i.e. progress reports and financial reports.
- Design Collaboration, i.e. architectural plans, detailed drawings of the building's design., or specifications.
- Submission Management, i.e. permit applications and compliance documents.
- RFI (Request for Information) management.
- Inspection reporting and quality control management.
- Environmental, health and safety management.
- Operation and maintenance management.

Each of these processes plays a crucial role in ensuring that the construction project progresses smoothly, adheres to regulations, and meets the expectations of all stakeholders involved (Charoenngam, Coquinco, & Hadikusumo, 2003).

Documents are incoherently generated within these processes based on stakeholders' expectations and needs, drastically reducing the searchability of approvals and increasing information loss during a project life cycle and at the project completion phase (Ghnaya, Pourzarei, Rivest, & Boton, 2022). Providing integration methods using blockchain technology for an illustrative document within a certain life-cycle process allows generalisability in other document types and workflow processes. Figure 6-1 indicates an example of a logical workflow progression for one type of document mentioned earlier, i.e. Change Order (CO). In this example, the functionality of the proposed blockchain framework to facilitate processes such as Change Order Management is illustrated.

The Change Order workflow process consists of different steps, such as preparation of a Design Change Notification (DCN) by the client requiring alteration to the original design, reviewing the DCN by other stakeholders, preparing corresponding price and delivery programme changes, compiling a formal response to the notification for the client's approval (Bakhary, Adnan, & Ibrahim, 2015; Hardin & McCool, 2015). A DCN is typically a formal document that informs stakeholders about a modification in the original design of a prefabrication project (KV, V, & Bhat, 2019). This notification is crucial for informing all stakeholders, including architects, engineers, contractors, and project managers, about changes that may impact the project's scope, schedule, or budget. A DCN usually includes details such as the nature of the change, reasons for the modification, any associated impacts on the project, and the proposed solutions or adjustments. Also, DCNs are considered downstream communication or information flow triggered by clients and spread to all stakeholders (Koc & Gurgun, 2021; Koolwijk, Van Oel, Wamelink, & Vrijhoef, 2018). On the other hand, upstream

communications back to the approver and initiator of the DCN, i.e., the client, involves developing updates to the original Schedule of Price (SoP) and delivery programme.

As shown in Figure 6-1, it is the client's responsibility to issue the DCN and send it to the consultant (designer) for review. It is then the designer's responsibility to ensure the DCN is consistent with reference to the original design drawings and to request further information from the client if there is missing information or specifications before handing over to the next downstream party, i.e., the main contractor (builder). The main contractor, being in the core of a prefabrication project and acting as an intermediary by engaging subcontractors for on-site construction and assembly of prefabricated components and manufacturers for off-site construction of the components, is then tasked to disseminate the DCN to subcontractors and manufacturers and request their updated prices and schedules. In the end, when construction, design, manufacturing, and transportation price and programme changes are updated, it is the main contractor's responsibility once again to compile and integrate the updated schedules and prices in a document and generate a formal response to the client' DCN request. Upon the approval of the proposed pricing and programme updates, the client can then issue a formal variation/CO to notify all the stakeholders of the approved pricing pack and officially instruct the change.

This illustrative example demonstrates how multiple stakeholders and documents are integrated using the information flow logic in the proposed blockchain model.

6.2.2 Blockchain model

Most construction businesses (97.9 per cent) in New Zealand are small. Also, Medium-sized businesses (between 20 and 49 employees) make up 1.6 per cent of the total number of

construction businesses (Ministry of Business, Innovation, and Employment, 2022). Small and medium-sized businesses presently favour the utilisation of cloud-based applications like SharePoint and email platforms rather than investing in document management systems such as Aconex, primarily due to the substantial costs associated with the latter (Fernando, Hewavitharana & Perera, 2019).

Organisations that invest in document management systems, however, establish a common data source that is primarily restricted at the organisational level and customised for the key project stakeholders, disregarding smaller project participants (Song, Yang, & Tao, 2023). Also, the document repository created as a result of establishing document management systems will be a huge information storage with multiple user access types and limited transparency or traceability within countless threads of emails, attachments, documents, etc.

As a leading document management system, Blockchain supports secure information flow management. Security within information workflows involves ensuring the authenticity of users, meaning the ability to accurately verify the identities of different document approvers and confirm the workflow chain through an unalterable and clear logic (Naz et al., 2019). Additionally, auditability is crucial, emphasising the capability to document workflow events in an irreversible manner to establish accountability.

Blockchain utilises cryptographic hashing techniques and decentralised consensus procedures to guarantee the recording of information in a manner that is irreversible (Zhong et al., 2022). Blockchain can also be programmed by a smart contract with customisable functions to adjust and update blockchain ledgers.

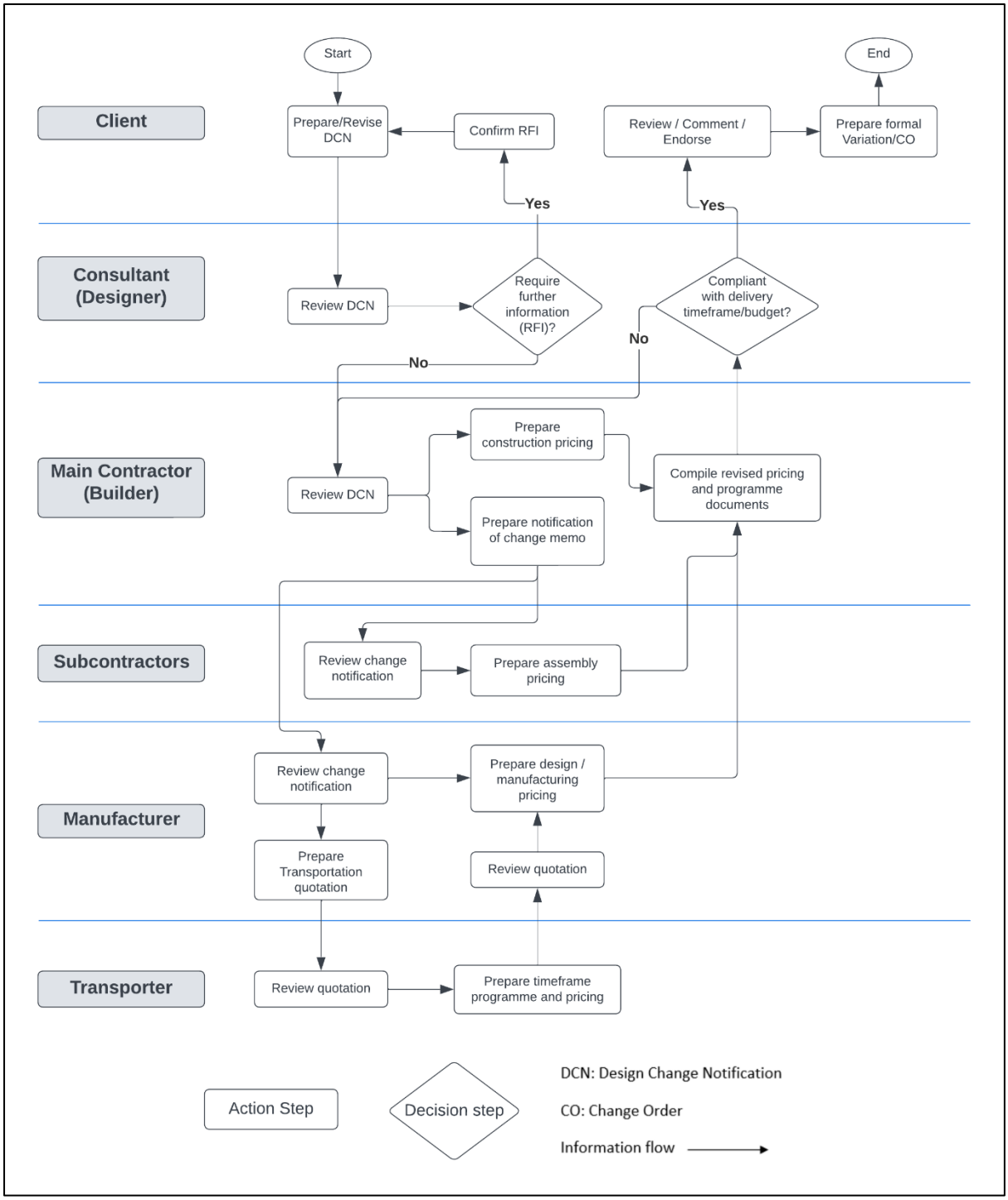

Figure 6-1: Information flow in technical design, construction (on-site & off-site), and handover phases

Blockchain technology is principally classified into two types: 1) public blockchain and 2) private (permissioned) blockchain. In a public blockchain, anyone can join and participate in the public network. No restrictions exist on who can access the network, validate

transactions, or participate in the consensus process (Nizamuddin, Salah, Azad, Arshad, & Rehman, 2019). In permissioned blockchain, however, access to a private blockchain is restricted. Only authorised entities or participants are granted permission to join the network, validate transactions, and participate in the consensus mechanism. Private blockchains are often used by businesses and organisations for specific purposes such as supply chain management, internal record-keeping, or collaborations where a controlled and known group of participants is involved (Nizamuddin et al., 2019).

While private blockchains such as Hyperledger Fabric or Mail Chain, which is operated on the Web3 platform, provide users with the capability to upload documents such as PDFs on the chain (Badr, Rafferty, Mahmoud, Elgazzar, & Hung, 2019), it is more common to hash the file content and store the hash on the blockchain and keep the entire document off-chain on a cloud storage or distributed file system such as Interplanetary File System (IPFS) (Naz et al., 2019). This is due to the latency associated with the transaction size and processing time. Latency is referred to as the average time elapsed to send and receive transactions/confirmations to the blockchain (Kuzlu, Pipattanasomporn, Gurses, & Rahman, 2019). The bigger the documents uploaded to the blockchain, the more it takes for the smart contract and blockchain to process the transactions.

On the other hand, the hash function, which refers to randomly converting the content of documents to fixed-size strings of characters and digits, creates a unique identity for the document that is tamper-proof. Any change to the document's content results in a completely different hash being generated for the same document name/number (Nizamuddin et al., 2019). Hashing is used to ensure the integrity of data stored on the blockchain. When data is added to a block, its hash is computed and included in the block. If the data is later altered, even by a

single bit, the hash will change, alerting the network to potential tampering. Also, smart contracts can manage the logic related to document handling. The smart contract can contain methods to validate document integrity (by comparing the hash), manage access control, and trigger events based on document-related actions (Sangeeta & Nam, 2023). An example of a hashing process is indicated in Table 6-1.

Table 6-1: Hash function

Input	Hash Function	Output example
PDF file content (Plaintext)	SHA-256 (Secure Hash Algorithm 256-bit)	1f92 f958 c572 46bb 2c48 a5a9 2bf9 d22d 72c2 492a 0800 d7c9 b106 3d75 980f 5c90

The proposed blockchain-based document management system in this study includes a blockchain-based smart contract framework to enable secure document retrieval and approval using stakeholders' unique identifiers and credentials and a permissioned ledger to record document transactions in an irreversible manner.

In Figure 6-2, the proposed blockchain platform showcases the integration of workflow information through security, i.e., assurance that only authorised users are in the chain and have access to the flow of data, irreversibility, i.e., certainty around version history and procedures that have been carried out for acquiring approvals of documents, and finally, transparency, i.e., document lifecycle transparency that this framework enhances throughout a project lifecycle.

As shown in Figure 6-2, the stakeholders, i.e., the client, designer, builder, subcontractor, manufacturer, and transporter, undergo authentication through their unique identifiers / cryptographic credentials stored on the blockchain using their individual smart contracts. For

instance, the subcontractor's smart contract contains the subcontractor's cryptographic identification with their associated alphanumeric private key that is kept confidential and used to sign or authorise transactions, proving ownership of the documents being transferred in the blockchain.

In the proposed framework, the client is the initiator of the transactions. In this example, the client prepares the DCN and transmits it downstream via a cloud-based application such as Outlook, SharePoint or Aconex. The designer's task is then to review the DCN and raise RFI with the client, if necessary, to ensure the implementation plan and documentation updates according to the previous versions of drawings before passing the notification on to the main contractor. As shown with the scattered arrows in Figure 6-2, all the corresponding information related to the change notification is exchanged among stakeholders downstream with the relevant documentation attached. Transporter, the last stakeholder to contribute to the pricing and programme updates, is tasked to use their cryptographic credentials via the smart contract to upload the hash of the relevant documents to the blockchain.

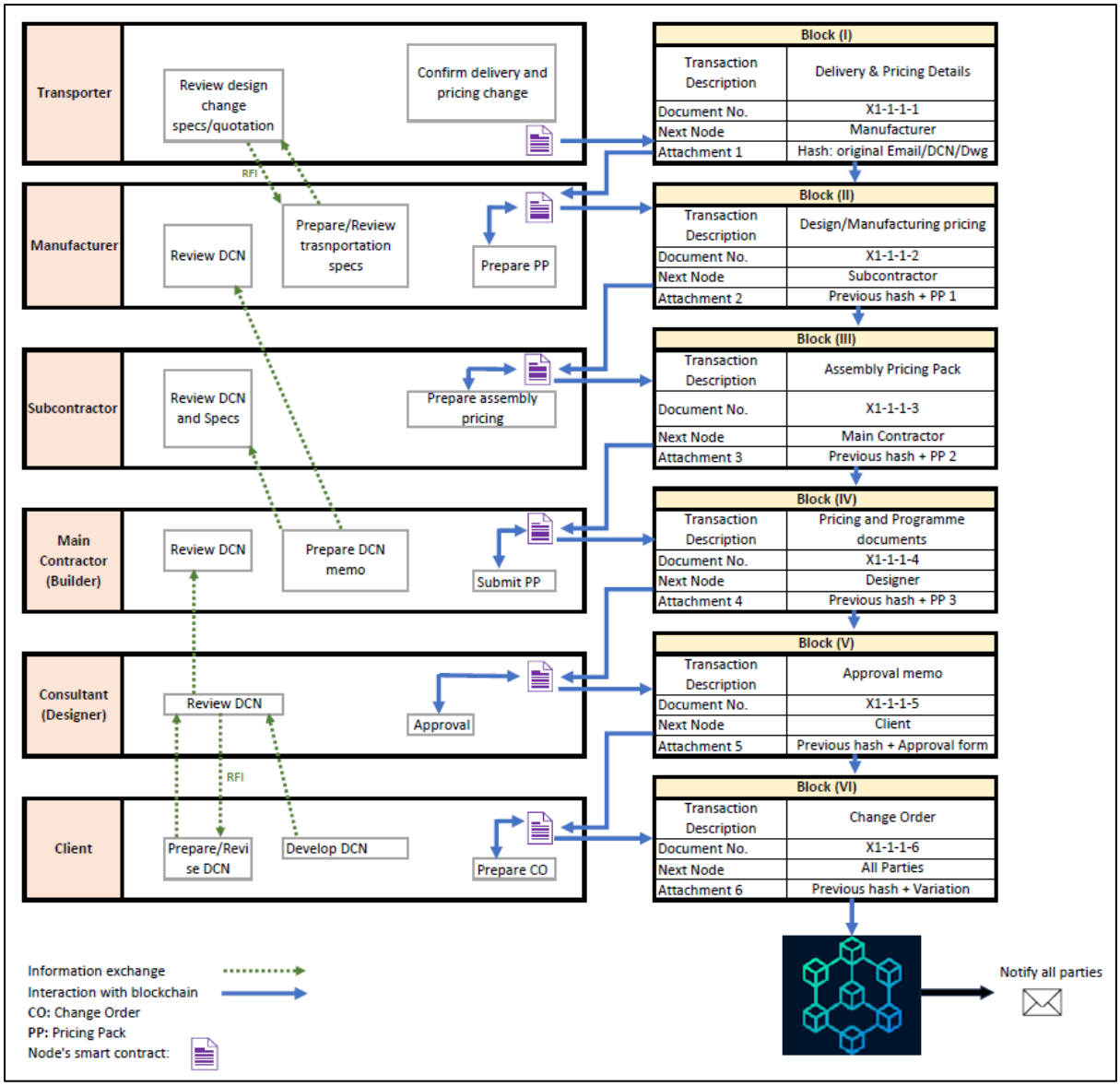

Figure 6-2: The proposed blockchain-based information integration framework

Blockchain then notifies the next node, i.e., the manufacturer of a document awaiting to be reviewed. Using the private key and smart contract, the manufacturer will be able to review the previous node's documentation stored off-chain by ascertaining and validating the integrity of the hash and then uploading the hash of manufacturing design, pricing, and programme updates to the blockchain. A simplified process of validating the hash is shown in Figure 6-3.

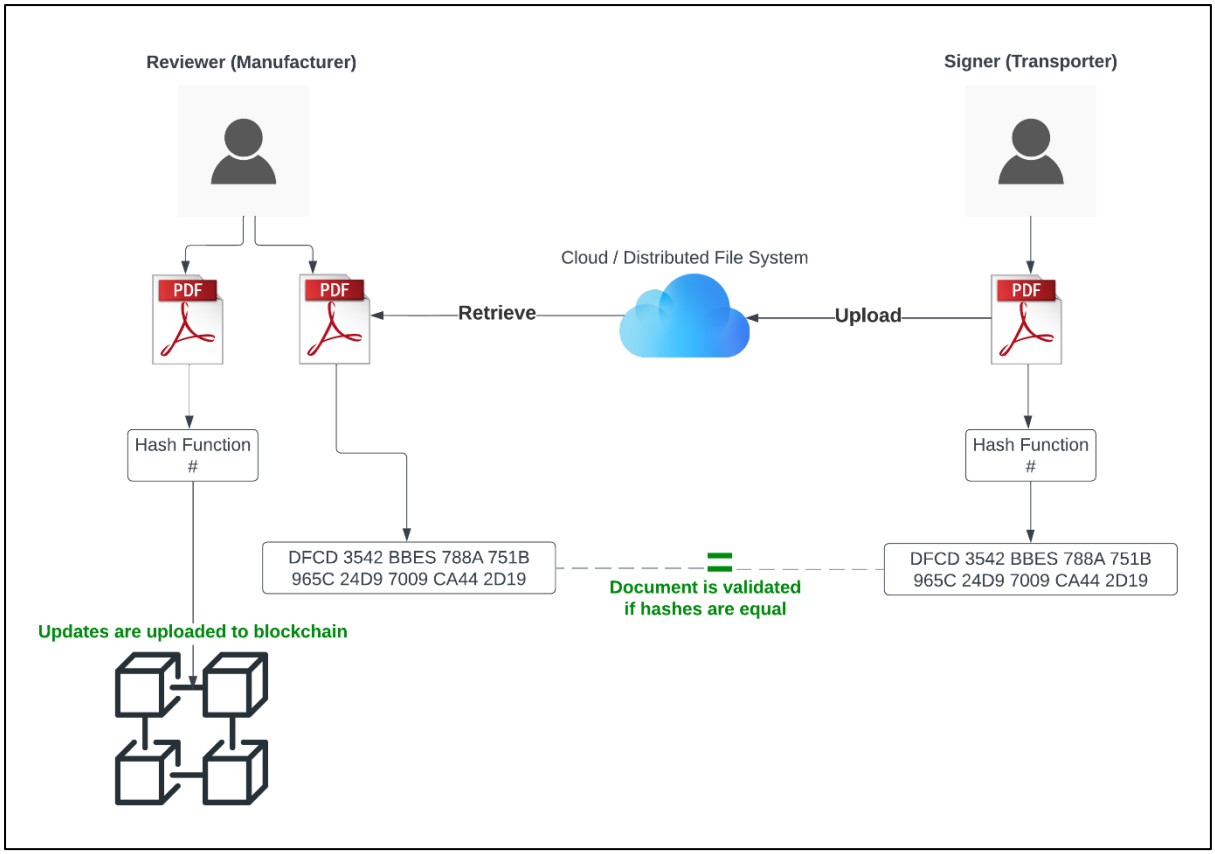

Figure 6-3: Hash validation process

As indicated in the proposed framework (Figure 6-2), the process continues until the updates to the scheduled prices and programmes resulting from the client's DCN are transmitted back to the client for endorsement. Upon the client's confirmation of the proposed changes, the blockchain is updated with the hash of the approval memorandum (formal Change Order) created by the client, and a notification email is generated to inform all the stakeholders of the approved change.

The document number shown in the blocks indicates the document's hash and the attachment is the document's name that is stored on the interplanetary file system. IPFS excels at decentralised storage and retrieval of large files or data, while blockchain excels at ensuring

data integrity and immutability. In the proposed framework, IPFS handles the storage aspect, while blockchain ensures that references to stored data are immutable and secure.

6.2.3 Systems interface design

Although cloud-based applications are commonly accepted by industry experts and construction organisations, Zhong et al. (2022) explain that cloud-based applications are centralised and prone to tampering. The InterPlanetary File System is a decentralised and distributed system designed to create a more efficient and resilient way of storing and sharing information on the internet. IPFS uses content-addressed storage, meaning that files and their contents are identified by a unique cryptographic hash. This hash is derived from the content itself, making it immutable and ensuring data integrity (Sangeeta & Nam, 2023).

This research proposes a hybrid approach using emails or cloud-based applications for information exchanged downstream and IPFS for the secure storage of Change Order documentation upstream. Cloud-based document storage applications or document management systems such as Aconex are primarily used for document management, collaboration, and stakeholder communication (Charoenngam et al., 2003). Aconex is well-suited for documenting information and has a proven track record in New Zealand's construction industry. Also, for the ease of information exchange, since the DCN created by the client may be followed by numerous Request for Information (RFIs) raised by the other stakeholders and, subsequently, one design change notification email may trigger several other threads of emails just as questions and answers relating to the client’s first request, applications such as Aconex can better and easier be adopted by the stakeholders, helping to reduce blockchain congestion or overload as a result of the high volume of activities that may exceed

its capacity and cause potential scalability issues. Moreover, information, i.e. DCN, raised by the client and handed over downstream to the other stakeholders contains unclassified documents that don't necessarily need to be treated confidential, as it may only include drawings, specifications, the intention of change, or the client's expectations of the result of the project. However, to reduce the need for a system admin (such as that needed for Aconex) and enhance certain aspects of a project, such as data integrity, decentralisation, security and trust, blockchain technology is better suited to be integrated into specific workflows, especially when confidential information such as pricing packs, detailed breakdown of costs, profit margins, and other sensitive financial information is transmitted upstream.

To enable stakeholders to upload documents to IPFS using blockchain, a decentralised application or a smart contract on a blockchain platform that interacts with IPFS must be created. There is also an option to develop a user interface for stakeholders to interact with the smart contract. The user interface can be a web application or a mobile app that connects to the blockchain and allows stakeholders to upload and retrieve documents. The interaction between the blockchain and IPFS can be illustrated through a sequence diagram, which depicts the flow of information and interactions between the two systems (refer to Figure 6-4).

First, the smart contract initiates document upload on IPFS through a transaction triggered by the user interface. Then, a unique hash is generated, and the smart contract stores the hash on the blockchain and uploads the document to the IPFS network, linking the blockchain to the content stored on IPFS. Later, the next node's user interface can initiate a request to retrieve the document with the IPFS hash, and finally, the smart contract returns the document content to the user interface from IPFS based on the provided hash. Integrating

blockchain and IPFS enables decentralised and secure content storage with cryptographic integrity.

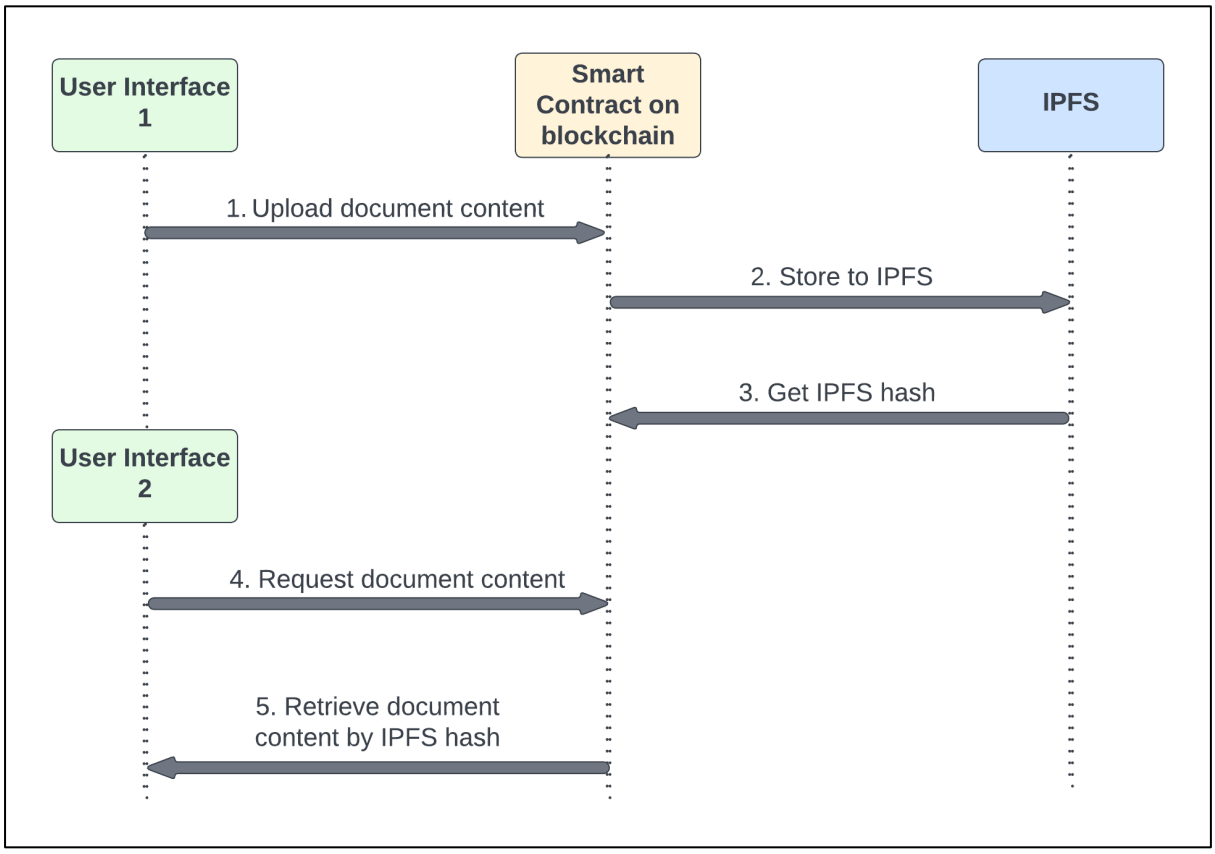

Figure 6-4: Systems interface diagram

A summarised version of systems interactions is shown in Figure 6-5 as a conceptual system design for the information flow among stakeholders using different systems. The system is designed to arrange technologies, i.e., blockchain, smart contract, and IPFS and assist in document approval, recording, and validating workflows. The initiator and the last node's workflows are represented by grey arrows, while the other stakeholders' workflows are represented by yellow.

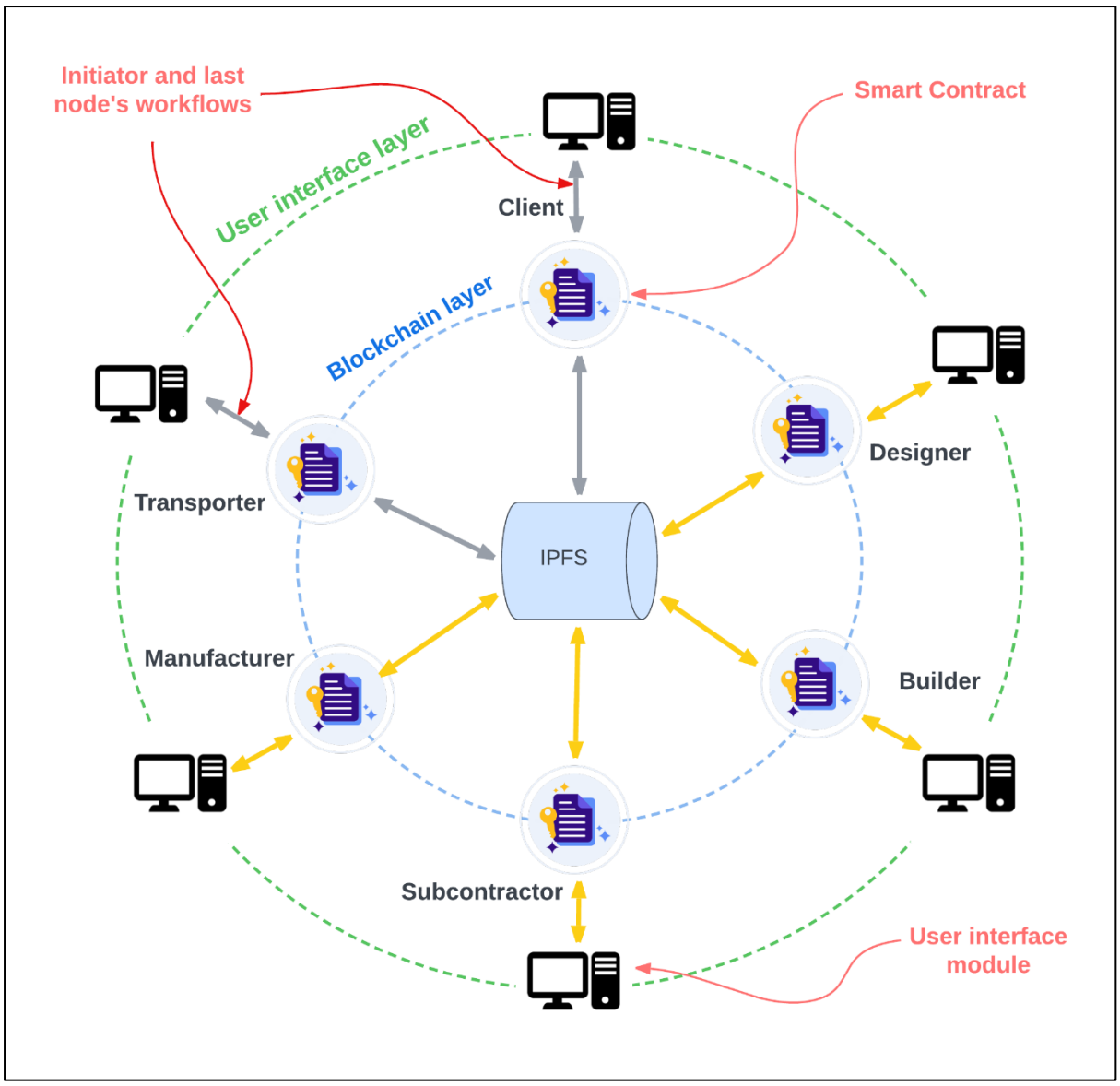

Figure 6-5: Conceptual system design

6.3 Validation results

To test the internal, external, construct, and content validity of the proposed framework and its practicality in the New Zealand context, four validation questions were asked following the presentation of the framework to the experts, and the responses were recorded. Respondents were given five qualitative choices to choose from (poor, average, good, very good, excellent) and a comment box at the end for their overall opinions and extra recommendations. 9 valid

responses to each question were returned, and the qualitative choices were converted to numerical values from 1 to 5, respectively. Table 6-2 shows the result of the validation survey.

As shown in Table 6-2, the average mean score for all four validity questions is 3.11, indicating that experts considered the framework's validity to be “good” overall.

Table 6-2: Validation result

No.	Questions	Expert Responses									**Mean**
		I	II	III	IV	V	VI	VII	VIII	IX	
1	Is the framework easy to comprehend and utilise for blockchain adoption?	2	4	4	2	2	3	3	3	2	**2.78**
2	Does the information flow among stakeholders appear feasible within a typical prefabrication supply chain setting?	2	5	4	4	3	2	3	4	4	**3.44**
3	Do the steps of implementing the framework follow a coherent sequence, allowing for its replication by researchers and practitioners?	2	3	3	3	2	3	4	3	3	**2.89**
4	Is the framework appropriate for practical adoption in the prefabrication supply chain in New Zealand?	2	4	4	3	3	3	4	4	3	**3.33**

Question 1, with a mean score of 2.78 for this question, indicates that the framework adequately covers the key aspects of blockchain adoption, focusing on the clarity and usability of the content and that the framework is averagely easy to comprehend and be utilised by industry practitioners. Blockchain is relatively new, and introducing a new and innovative technology may be perceived as a significant change, and industry experts might need time to adapt. An example of the expert's comments on question 1 is narrated below.

Question 1: Is the framework easy to comprehend and utilise for blockchain adoption?

Experts' comment:

The terms "direct flow" and "indirect flow" for the arrows are not too clear. Consider rewording the terms, perhaps "interaction/data flow with the blockchain" instead of "direct flow". I'm not sure of an alternative that would be suitable for "indirect flow". The framework could define the types of data that will be stored on the blockchain and those off-chain. For example, the initial discussions could be linked to the blockchain for reference. The framework would also benefit from a system architecture diagram to depict how the various software components will interact.

As indicated in Figure 6-2, the visual legend in the framework diagram, which lacked clarity during the initial presentation to the experts, has now been revised to facilitate an easier understanding of the framework's logic, providing clearer instruction. The terms direct and indirect flow have been replaced with clearer descriptions. Also, as shown in Figure 6-4 and Figure 6-5, a system interaction design has been prepared to help make the framework more comprehensive and easier to adopt, these figures were not part of the presentation and have been developed following the experts' recommendations around clarity of the technology adoption.

Question 2 was asked to evaluate whether the information flow aspect aligns with the theoretical construct of effective communication within a prefabrication supply chain setting. A mean score of 3.44 for this question shows that the experts consider the framework's validity "good", signifying the appropriateness and effectiveness of information flow among prefabrication supply chain stakeholders. An example of the experts' comments on question 2 is as follows:

Question 2: Does the information flow among stakeholders appear feasible within a typical prefabrication supply chain setting?

Experts' comments:

1. *The information flow has been clearly identified.*
2. *As a proof of concept, the research has considered all transactions and all necessary stakeholders.*
3. *Stakeholder collaboration is well described.*

One comment suggested that information flow should follow a non-linear approach. The proposed model is configured in a way that is easy to understand and practically followed by the researchers and industry experts. This comment has been noted, and supplementary articulation around the applicability of blockchain was provided earlier in this chapter. Collaborating through blockchain technology follows a non-linear sequence of information upload, consensus mechanism, approvals, and confirmation of transactions.

Question 3 addresses the validity of the framework's implementation steps, examining whether the observed outcomes result from the framework's design and sequence. A mean score of 2.89 for this question implies that implementing the framework follows a logical sequence, allowing for replication and general use in a broader industry scope and research.

Question 3: Do the steps of implementing the framework follow a coherent sequence, allowing for its replication by researchers and practitioners?

Experts' comment:

The inclusion of an architecture diagram and definitions of on-chain and off-chain data (mentioned in response 1) will add more clarity to the framework. Explicitly mentioning what type of blockchain is proposed will also be useful since the consensus mechanisms will differ.

As shown in Figure 6-4, an architecture diagram has been included to separate the off-chain and on-chain data using a distributed file system storage such as IPFS. Also, as explained in this chapter, the proposed framework considers utilising a permissioned (private) blockchain such as Hyperledger Fabric. Private blockchain offers restricted access that is typically limited

to specific participants or organisations in enterprise settings for specific use cases where a controlled and permissioned environment is essential, such as supply chain management, consortium networks, and inter-organisational processes (Song et al., 2023; Zhong et al., 2022). As such, the proposed framework is based on having the client, that is the end-user or customer of the project, as the pre-defined central authority of the private blockchain.

The other experts' comments on this question suggested that the information flow among stakeholders has been around change management, and the other types of data/information should also be considered in developing the framework. As articulated earlier, the proposed framework uses one example of many types of information exchanged regularly among different organisations involved in a prefabricated project to build a practical and easy-to-adopt model for industry practitioners. Finding a practical solution for the secure information integration and immutable data storage of only one type of information implies the generalisability of the framework to other types of data and its implementation in a larger network of participants. Also, some other comments recommended that features in the diagram and the framework should be enhanced with distinctive colours and descriptions, for which the updates have been implemented in the model, and the comments have been taken into account with the preparation of the system design, as shown in Figure 6-5.

Question 4 explores the validity of the framework and its practical use, assessing its applicability to the prefabrication supply chain in New Zealand. A mean score of 3.33 for this question signifies that the framework is appropriate for adoption in New Zealand. An example of the experts' comments on question 4 is as follows:

Question 4: Is the framework appropriate for practical adoption in the prefabrication supply chain in New Zealand?

Experts' comments:

1. *The framework will be appropriate for practical adoption once the points raised in the discussion and mentioned above are addressed, such as creating a policy for data storage on-chain and off-chain. Practical adoption will also need a system interface that allows the users to store and access the data easily without having to know too much about the blockchain.*
2. *The whole framework indicated the practicality of the project, but some modifications mentioned in the session are required to have a better implementation process.*
3. *The extent of the research, which can cover all necessary transactions, can be easily adapted.*

The comments indicate the appropriateness and suitability of the framework for practical deployment in the prefabrication supply chain in New Zealand. Suggested modifications to the framework have been incorporated into the articulation of the system design and visualisation of the framework. The other comments were around adding extra features and descriptive texts and design to the framework, which have been duly noted and incorporated into the system design development.

6.4 Epilogue

This chapter proposed a framework for addressing the prefabrication supply chain integration by applying blockchain technology to the information communication mechanism used frequently in the industry. In this chapter, a secure and hybrid document management system is developed (Figure 6-2) using blockchain technology, smart contracts, cloud-based applications, and the interplanetary file system. To depict the workflow and stakeholders' interactions in a typical prefabrication project in New Zealand, a workflow diagram coupled

with a private blockchain model and smart contract is designed to support the key purposes of document management approaches. Also, an architecture diagram is developed to demonstrate the validation criteria and the interface among various digital systems.

The proposed framework was validated in a focus group study with blockchain and prefabrication experts. Four validation questions were asked and answered by the experts in relation to the adoption of the framework in New Zealand, and nine valid responses were recorded, indicating that the framework with a system interface and architecture diagram is simply comprehensible and practical for adoption in the prefabrication supply chain.

Chapter 7: Conclusion and discussion

7.1 General introduction

This doctoral thesis tackles the challenge of limited integration in the prefabrication construction supply chain in New Zealand, with a specific emphasis on information integration. The primary argument posits that fostering an efficient and effective exchange of information among stakeholders within the prefabrication supply chain is crucial for improving overall integration in New Zealand's construction industry, which is characterised by significant fragmentation.

Prefabrication or Off-site Construction Supply Chain Management (OSCM) can help to oversee the activities of prefabrication stakeholders in terms of information exchange ((Prajogo & Olhager, 2012). Current prefabrication methods, nonetheless, were built using centralised systems, such as participants' local databases, which leads to the exposure of information to alteration, cyber-attacks, loss, and, finally, disputes among all prefabrication stakeholders (Zhong et al., 2022). Lack of trustworthy information management systems to verify construction compliance could also result in conflicts, unnecessary claims, and untrust in the upstream stakeholders and, finally, end-user customers (Harland et al., 2007). Therefore, a system that can integrate documents and document-related information (metadata) from existing document management systems, cloud-based repositories, and methods of correspondence and provide security against data tampering is desired.

Blockchain has the potential to act as a dependable and reassuring platform for information integration due to its immutability and decentralised nature. Distributed Ledger Technology (DLT), commonly referred to as "Blockchain," operates as a consensus-driven

ledger designed to enable secure transactions among users through a tamper-proof database (Lemieux, 2016). This technology establishes a peer-to-peer network wherein transactions are secured with digital signatures to prevent double-spending, even in the absence of oversight from a trusted third party (Penzes, 2018). The network systematically timestamps transactions using hashes in consecutive blocks, creating an unchangeable record that necessitates consensus from users for any alterations.
Despite being a relatively new concept, New Zealand industries have the potential to derive social, economic, and environmental benefits from blockchain with the right policies and approaches. New Zealand, despite its geographical isolation, exhibits adaptability in embracing innovations for business development and has a notable presence in the global market (Shahzad, 2016). Blockchain technology, although not widely implemented in the prefabrication construction industry, holds significant potential to profoundly influence the growth of domestic businesses in New Zealand.

However, the application of blockchain technology in the construction industry, particularly in its prefabrication subsector, lacks extensive testing of the underlying theory. The demand from clients to trace the origin of products used in construction projects, coupled with the need for effective integration among prefabrication supply chain partners, underscores the importance of this research. This dissertation suggests blockchain technology as a facilitator for information-sharing to enhance the efficiency and effectiveness of supply chain integration within the prefabrication subsector of New Zealand's construction industry.

This chapter is placed to summarise the key findings of this thesis. The following research objectives have been discussed and analysed in this thesis:

1. To identify the prefabrication project phases and stakeholders involved in New Zealand's prefabrication supply chain.
2. To determine the engagement of each stakeholder and explore their interconnectivity in New Zealand's prefabrication supply chain.
3. To identify, assess, and categorise the types and modes of interactions among stakeholders involved in the prefabrication supply chain in New Zealand.
4. To ascertain the applicability of blockchain technology in New Zealand's prefabrication supply chain from the identified interactions.
5. To develop a framework for enhancing supply chain integration in New Zealand's prefabrication subsector using blockchain technology.

7.2 Achievement of the research

7.2.1 Objective 1 development

For the first research objective, the study employs a qualitative research approach, aiming to enhance the portrayal and comprehension of real-world phenomena. This method involves extracting insights from practical contexts (Creswell & Creswell, 2017). Initially, a thorough examination of pertinent literature is conducted to establish a foundational understanding of prefabrication technology. This literature review aids in the identification of key stakeholders within the prefabrication supply chain and the various project stages. Subsequently, drawing on empirical knowledge and insights gained from the literature, the study identifies the inter-relationships among stakeholders within each stage, specifically focusing on the prevalent flow of information. Finally, observing information-sharing processes among partners in the prefabrication supply chain is utilised to chart the information-based inter-relationships.

The parties engaged in an offsite construction supply chain encompass various entities, including statutory bodies, clients or customers, consultants, builders or developers, subcontractors, manufacturers, direct and indirect suppliers, and transporters or distributors (Figure 2-1). Also, following the Royal Institute of British Architects (RIBA) Plan of Work 2013, construction project phases are structured into 12 stages, encompassing the entire prefabricated building processes from project inception to handover.

7.2.2 Objective 2 development

Understanding and insights gained through achieving the first objective led to developing the second objective, discussed in Chapter 3. This objective employed a literature review to discern and classify the interrelation of stakeholders at various stages of prefabrication projects. A pilot study was conducted to validate the identified stakeholders and understand the details of their relationships in specific project phases in New Zealand's context. Subsequently, a questionnaire survey was developed with three primary objectives: firstly, to gauge the importance of information integration among various organisations involved in prefabrication projects; secondly, to identify the attributes of information crucial for the success of the prefabrication supply chain; and finally, to determine the advantages of implementing blockchain technology. Through this objective, it was revealed that although prefabricated construction emerges as a superior approach for construction sites that are geographically dispersed, this method entails a supply chain with greater complexity compared to traditional construction approaches. Thus, the research aimed at bridging the gap by introducing an efficient system for information exchange throughout prefabricated projects to lessen this complexity.

7.2.3 Objective 3 development

To meet the third objective, as discussed in Chapter 4, this research employed an exploratory approach to uncovering the communication channels within the prefabricated construction supply chain in New Zealand. A questionnaire survey was developed with the dual objectives of identifying the modes of information exchange between clients and contractors and exploring the essential qualities of information crucial for improving the prefabrication supply chain. The channels were investigated in three phases of detailed design, construction (off-site and on-site), and handover and categorised into 11 distinct groups. The findings from achieving the third objective revealed that transparency, traceability and reliability are the most important attributes of information deemed to be critical for the successful impact of advanced information technology on the prefabrication supply chain integration. Also, the results indicated that the conventional and widely utilised communication modes in the prefabrication supply chain include email, meetings, telephone, and internet-based applications, all of which are cloud-based applications and susceptible to accidental or intentional tampering. Therefore, the prefabrication supply chain can benefit from the transparency and visibility connected to advanced information integration systems such as blockchain technology.

7.2.4 Objectives 4 and 5 development

Finally, this research's fourth and fifth objectives have been met in chapters 5 and 6, respectively. These chapters focused on developing a practical document management framework for improving information integration among prefabrication partners in New Zealand's prefabrication supply chain. In Chapter 6, a system design and framework have been

developed to demonstrate how blockchain technology can be applied to the context using the identified modes of interactions among the stakeholders and the capabilities of blockchain technology. The framework has been validated in a focus group meeting, and the experts' recommendations to enhance the features and applicability of blockchain have been applied to the framework. The life cycle of a prefabrication project encompasses diverse phases, with each phase generating a plethora of documents. The current methods of document management encompass numerous processes, and each process plays a vital role in ensuring the seamless progress of the construction project. Documents within these processes are inconsistently generated, diminishing the functionality of document management systems (Ghnaya et al., 2022). Therefore, information integration systems such as blockchain technology can play a vital role in this area. To develop a simple and comprehensible information integration system, a sub-section of multiple information types and processes (Design Change Notifications from the client and its accompanying Change Order) used regularly in the prefabrication projects was selected and then the framework was built and elaborated around that. Subsequently, the system design and its associated validation process were discussed in this chapter to bridge the technicality of the concepts and help industry practitioners with a practical tool to adopt for integrating information into their projects. Also, the validity and reliability of the research was tested using a validation survey. The result indicates that the experts considered the validity of the framework to be "Good" on a 5-point descriptive scale.

7.3 Research implications

7.3.1 Theoretical implications

The objective of this study is to formulate a framework that ensures the integration of the prefabrication supply chain through the application of blockchain technology. Despite extensive research conducted on supply chain management in the construction industry, there is a notable shortage of studies focusing on the prefabrication supply chain. This gap becomes particularly significant when considering the substantial obstacles hindering the efficiency of prefabrication supply chain systems. Therefore, this study offers valuable insights into supply chain integration within the prefabrication concepts.

In general, the findings of this thesis can help practitioners and academics understand the current research related to prefabrication and blockchain technology in the construction industry. This study stands out as one of the few that delves into the challenges within the prefabrication subsector and suggests innovative technologies within a specific context. This broadens the scope of utilising state-of-the-art technologies within the construction sector, aiding researchers in the construction industry in further investigating the subject using different approaches and various empirical studies in other fields and situations.

The framework and systems interface design provided in this thesis could be used by researchers and experts specialising in software development and programming to build a functionally encrypted platform or user interface using the proposed framework's specifics. Especially by considering: Integration Points to identify specific areas where blockchain can complement cloud-based applications such as Aconex rather than replacing it entirely, Interoperability to ensure seamless integration between the cloud and the chosen blockchain platform, and User Adoption to consider the ease of use for project stakeholders who may not be familiar with blockchain technology.

7.3.2 Practical implications

With the global exploration of blockchain technology, its application as a contemporary practice brings benefits to the prefabrication industry. Leveraging blockchain for enhancing information integration and stakeholders' interactions throughout the prefabrication supply chain holds considerable promise for both industry practitioners and researchers, providing a foundational understanding that will be instrumental for future framework developments.

The findings of this study offer insights into both blockchain technology and the integration of prefabricated supply chains. This understanding has proven valuable for stakeholders, aiding them in enhancing their managerial decision-making and refining supply chain strategies. Industry experts and managers can leverage the results of this study to comprehend the essential attributes of information and the prevailing communication channels within prefabrication supply chains.

The underlying data and analysis of this thesis can act as a decision-making tool for culture development, strategic planning, user management, sustainability solutions implementations, and collaborations within prefabrication organisations or, on a larger scale, in prefabrication supply chain systems.

7.4 Recommendations

7.4.1 Specific recommendations

The main aim of this study is to develop a practical framework aimed at evaluating and enhancing supply chain integration within prefabrication projects by employing blockchain technology. Specific recommendations to industry experts and researchers have been

mentioned below to ensure the effective implementation of the framework illustrated in this thesis.

- **Engagement Strategies for Small to Medium-sized Prefabrication Companies:** Develop tailored engagement strategies to encourage the adoption of blockchain technology and collaborative approaches among small to medium-sized prefabrication companies in New Zealand. This could involve offering incentives, providing training and support, or demonstrating the cost-effectiveness and benefits of blockchain integration.
- **Contractual Requirements and Technical Solutions:** Implement robust contractual requirements alongside technical solutions to ensure accurate and timely data input into blockchain systems. This may include clear guidelines for data upload responsibilities and consequences for inaccuracies, as well as user-friendly interfaces for easy adoption.
- **Survey Methodology Enhancements:** To address resource constraints and time limitations, consider supplementing survey methodologies with qualitative interviews combined with statistical analysis to gain deeper insights into the perceptions and experiences of participants in prefabrication projects in New Zealand.
- **Long-term Impact Assessment:** Conduct long-term studies to assess the practical implementation and impact of the formulated framework on various types of construction projects or organisations. This would involve quantifying the benefits of blockchain integration in terms of efficiency, cost savings, and stakeholder satisfaction over extended periods.

7.4.2 General recommendations

As integration in the construction industry continues to evolve, the use of innovative technologies becomes increasingly imperative for enhancing efficiency and effectiveness. In this context, the utilisation of blockchain technology holds immense potential for revolutionising traditional practices, particularly in prefabrication projects. However, beyond the immediate scope of the construction sector in New Zealand, there exist broader implications and opportunities for the application of this framework across various industries. Hence, it is essential to explore potential avenues for cross-industry application, conduct international comparative studies, and emphasise on continuous improvement and tailoring to ensure the framework's adaptability and effectiveness in diverse contexts. The following general recommendations outline key strategies for extending the utility and impact of the framework beyond its initial domain:

- **Cross-Industry Application:** Explore the applicability of the framework developed in this research to other industries. This could involve adapting the framework to suit the unique characteristics and requirements of different industries.
- **International Comparative Studies:** Conduct comparative studies in different countries and industries to evaluate the effectiveness and adaptability of the framework in diverse contexts. This would provide valuable insights into the transferability of the framework beyond the New Zealand construction industry and explore how factors like regulatory environments, stakeholder dynamics, cultural differences, and technological infrastructure impact the adoption and outcomes of blockchain.

- **Continuous Improvement and Tailoring:** Continuously refine and tailor the framework based on feedback from practical implementations and in-depth investigations. This iterative approach would ensure the framework remains relevant and effective in addressing the evolving needs and challenges of prefabrication projects and organisations.

7.4.3 Recommendations for future studies

This research is bound to the domain of prefabricated construction in New Zealand. The primary objective of this research is to formulate a pragmatic framework for assessing and augmenting supply chain integration in prefabrication projects through the utilisation of blockchain technology. The study narrows its focus specifically to prefabrication and the information exchange among its supply chain participants. In this context, blockchain technology serves as an innovative tool to integrate the data and information acquired throughout prefabrication projects. It is crucial that all initial information input into the first block (genesis block) is accurate, error-free, unaltered, and reflective of the truth. Therefore, it is assumed that the transporter, as the last stakeholder responsible for uploading the updated programme and prices based on the client's change request, correctly attaches all the information and necessary documents to the blockchain and IPFS to avoid confusion and additional RFI from the next node and, consequently, upstream stakeholders. A robust contractual requirement in parallel with technical solutions could act as a preventative measure required to prevent the upstream RFI.

Most prefabrication companies in New Zealand are small to medium-sized and are reluctant to adopt expensive information integration tools or document management systems such as Aconex or other cloud-based applications. One risk associated with utilising blockchain

is its initial cost of implementation. Developing and maintaining a private blockchain system specifically for construction can be costly, especially when considering the need for ongoing system updates, security audits, and staff training. Also, blockchain often involves collaboration among multiple stakeholders in a decentralised network and convincing all parties to adopt new collaborative approaches may be a hurdle in industries with pre-established practices. Moreover, blockchain platforms may not fully align with evolving regulations in the construction sector (such as labour laws, health and safety standards, and environmental regulations). Lack of regulatory guidance can make it difficult to ensure compliance.

Given that this study relies on a survey methodology, its validity is directly linked to the accuracy of opinions and responses supplied by practitioners and participants. Resource constraints and time limitations also impose restrictions on the number of interviews conducted and the number of questionnaire survey responses recorded.

Future studies could be conducted to build over the framework developed in this thesis by exploring the applicability of the framework in a different domain such as manufacturing, logistics, or renewable energy where communication and information exchange platforms act as pivotal tools in guaranteeing quality outcomes and products. Also, similar investigations in another country could be conducted for comparison purposes. For instance, comparing the applicability of this thesis's framework in a different country and industry with traditional information exchange applications. Also, long-term studies and practical implementation of the framework on a different type of construction project or organisation could help with quantifying the impact of the framework and in-depth investigations on improving or tailoring the framework for the respected organisation's purposes and needs.

A summary of the recommendations for future studies is put forth:

- **Expansion into Alternative Industries:** Investigate the applicability of blockchain-integrated supply chain frameworks in industries beyond construction, such as manufacturing, logistics, or renewable energy and explore how the unique characteristics and challenges of each industry influence the effectiveness of blockchain technology in enhancing supply chain integration.
- **Longitudinal Studies on Framework Implementation:** Undertake longitudinal studies to assess the long-term impact and sustainability of implementing blockchain-integrated supply chain frameworks. Also, track changes in efficiency, cost-effectiveness, and stakeholder satisfaction over time, capturing both short-term benefits and potential challenges that may arise with prolonged use.
- **Qualitative Investigations into User Experiences:** Conduct qualitative studies to gather insights into the experiences and perceptions of stakeholders involved in implementing blockchain-integrated supply chain frameworks. Explore factors influencing user acceptance, resistance to change, and the effectiveness of training and support programmes in facilitating adoption.
- **Integration with Emerging Technologies:** Explore synergies between blockchain technology and other emerging technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), or Web3. Investigate how combined solutions can further enhance supply chain visibility, traceability, and automation, driving greater efficiencies and integration.
- **Sustainability and Environmental Impact Studies:** Assess the environmental sustainability implications of adopting blockchain-integrated supply chain

frameworks, considering factors like energy consumption, carbon footprint, and waste reduction.

References

Abeyratne, S. A., & Monfared, R. P. (2016). Blockchain-ready manufacturing supply chain using distributed ledger. *International journal of research in engineering and technology*, *5*(9), 1-10. Doi: http://doi.org/10.15623/ijret.2016.0509001.

Achar, M., Chebii, P., & Mugo, J. (2021). The Role of Communication Channels on Implementation of Housing Construction Projects in Nairobi County, Kenya. *African Journal of Education, Science and Technology*, *6*(3), 282-298. Doi: https://doi.org/10.2022/ajest.v6i3.547.

Adedeji, A., Rapheal, O., & Opeyemi, O. (2018). An analysis of social media marketing of indigenous construction firms in Nigeria: A tool for sustainable growth. *International Journal of Construction Supply Chain Management*, *8*(2), 60-72. Doi: https://doi.org/10.14424/ijcscm802018-60-72.

Adetunji, I., Price, A. D. F., & Fleming, P. (2008, September). Achieving sustainability in the construction supply chain. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, *161*(3), 161-172. Thomas Telford Ltd. Doi: https://doi.org/10.1680/ensu.2008.161.3.161.

Akintoye, A., McIntosh, G., & Fitzgerald, E. (2000). A survey of supply chain collaboration and management in the UK construction industry. *European Journal of Purchasing & Supply Management*, *6*(3), 159-168. doi: https://doi.org/10.1016/S0969-7012(00)00012-5.

Alavi, M., & Leidner, D. E. (2001). Review: Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research Issues. *MIS Quarterly*, *25*(1), 107-136. doi: https://doi.org/10.2307/3250961.

Allison, N., & Warren, M. (2019). *Applying blockchain to product compliance and assurance in the construction industry*. Porirua, New Zealand: BRANZ.

Al-Ma'aitah, N. (2018). Green supply chain management (GSCM) practices and their impact on performance: an insight from the Jordanian construction sector. *Int. J. Constr. Supply Chain Manage*, *8*(2), 87-104. Doi: https://doi.org/10.14424/ijcscm802018-87-104.

Angeletos, G. M., & Pavan, A. (2004). Transparency of information and coordination in economies with investment complementarities. *American Economic Review*, *94*(2), 91-98. Doi: https://doi.org/10.1257/0002828041301641.

Anumba, C. J., Egbu, C., & Carrillo, P. (2008). *Knowledge management in construction*: John Wiley & Sons.

Attia, A. (2018). Knowledge management capability and supply chain management practices in the Saudi food industry. *Business Process Management Journal*, *24*(2), 459-477. doi: https://doi.org/10.1108/BPMJ-01-2017-0001.

Awasthi, A., & Grzybowska, K. (2014). Barriers to the supply chain integration process. *Logistics operations, supply chain management and sustainability*, 15-30. Doi: https://doi.org/10.1007/978-3-319-07287-6_2.

Badr, A., Rafferty, L., Mahmoud, Q. H., Elgazzar, K., & Hung, P. C. (2019). *A permissioned blockchain-based system for verification of academic records*. In 2019 10th IFIP International Conference on New Technologies, Mobility and Security (NTMS), IEEE, 1-5. https://doi.org/10.1109/NTMS.2019.876383.

Bakhary, N. A., Adnan, H., & Ibrahim, A. (2015). A study of construction claim management problems in Malaysia. *Procedia economics and finance*, *23*, 63-70. doi: https://doi.org/10.1016/S2212-5671(15)00327-5.

Bakhtiarizadeh, E., Shahzad, W., & Rotimi, J. O. B. (2019, November). A process map for supply chain relationships in prefabricated construction. In *43rd AUBEA Conference, Australia*, 112-123.

Bakhtiarizadeh, E., Shahzad, W., & Rotimi, J. O. B., (2020). Applying secure information-based mechanism for prefabrication supply chain integration: A review. In *the proceedings of the 6th New Zealand Built Environment Research Symposium (NZBERS)*, 65-83. Retrieved from http://nzbers.massey.ac.nz/index.php/2020-symposium.

Bankvall, L., Bygballe, L. E., Dubois, A., & Jahre, M. (2010). Interdependence in supply chains and projects in construction. *Supply chain management: an international journal*, *15*(5), 385-393. Doi: https://doi.org/10.1108/13598541011068314.

Behera, P., Mohanty, R. P., & Prakash, A. (2015). Understanding Construction Supply Chain Management. *Production Planning & Control*, *26*(16), 1332-1350. doi: https://doi.org/10.1080/09537287.2015.1045953.

Bell, E., Bryman, A., Harley, B. (2019). *Business Research Methods*. Oxford University Press: Oxford.

Bell, P. (2009). Kiwi prefab: Prefabricated housing in New Zealand: An historical and contemporary overview with recommendations for the future. Thesis, Victoria University of Wellington, New Zealand. Retrieved from http://researcharchive.vuw.ac.nz/handle/10063/1111.

Bidabadi Zahra, T., Hosseinalipour, M., Hamidizadeh Mohammad, R., & Mohebifar, A. (2016). Supply chain collaboration within the Iranian construction industry. *Organization, Technology and Management in Construction: An International Journal*, *8*(1), 1437-1445. doi: https://doi.org/10.1515/otmcj-2016-0004.

Biernacki, P., & Waldorf, D. (1981). Snowball sampling: Problems and techniques of chain referral sampling. *Sociological methods & research*, *10*(2), 141-163. Doi: https://doi.org/10.1177/004912418101000205.

Black, C., Akintoye, A., & Fitzgerald, E. (2000). An analysis of success factors and benefits of partnering in construction. *International journal of project management*, *18*(6), 423-434. Doi: https://doi.org/10.1016/S0263-7863(99)00046-0.

Blismas, N. G., Pendlebury, M., Gibb, A., & Pasquire, C. (2005). Constraints to the Use of Off-site Production on Construction Projects. *Architectural Engineering and Design Management, 1*(3), 153-162. doi: https://doi.org/10.1080/17452007.2005.9684590.

Blismas, N., Arif, M., & Wakefield, R. (2009). Drivers, constraints and the future of offsite manufacture in Australia. *Construction Innovation, 9*(1), 72-83. doi: https://doi.org/10.1108/14714170910931552.

Bradley, E. H., Curry, L. A., & Devers, K. J. (2007). Qualitative Data Analysis for Health Services Research: Developing Taxonomy, Themes, and Theory. *Health services research, 42*(4), 1758-1772. doi: https://doi.org/10.1111/j.1475-6773.2006.00684.x.

BRANZ. (2022). *Durability evaluation framework for new building materials*: BRANZ Research Now Materials 2022. https://www.branz.co.nz/pubs/research-now/materials/durability-evaluation-materials/

Briscoe, G., Dainty, A. R., & Millett, S. (2001). Construction supply chain partnerships: skills, knowledge and attitudinal requirements. *European journal of purchasing & supply management*, *7*(4), 243-255. Doi: https://doi.org/10.1016/S0969-7012(01)00005-3.

Burgess, J. C., Buckett, N. R., & Page, I. C. (2013). Prefabrication Impacts in the New Zealand Construction Industry. BRANZ. Retrieved from https://www.branz.co.nz/pubs/research-reports/sr279/.

Cai, S., Jun, M., & Yang, Z. (2010). Implementing supply chain information integration in China: The role of institutional forces and trust. *Journal of operations management*, *28*(3), 257-268. Doi: https://doi.org/10.1016/j.jom.2009.11.005.

Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics and informatics*, *36*, 55-81. Doi: https://doi.org/10.1016/j.tele.2018.11.006.

Charoenngam, C., Coquinco, S., & Hadikusumo, B. (2003). Web-based application for managing change orders in construction projects. *Construction Innovation, 3*(4), 197-215. doi: https://doi.org/10.1108/14714170310814936.

Chen, S., Wang, H., & Zhang, L. J. (Eds.). (2018). *Blockchain-ICBC 2018*. Springer International Publishing.

Cheng, J. C., Law, K. H., Bjornsson, H., Jones, A., & Sriram, R. (2010). A service oriented framework for construction supply chain integration. *Automation in construction*, *19*(2), 245-260. Doi: https://doi.org/10.1016/j.autcon.2009.10.003Get rights and content.

Chinyio, E., & Olomolaiye, P. (2009). *Construction stakeholder management*. John Wiley & Sons.

Chou, D. C., Tan, X., & Yen, D. C. (2004). Web technology and supply chain management. *Information management & computer security*, *12*(4), 338-349. Doi: https://doi.org/10.1108/09685220410553550.

Chowdhury, M. J. M., Colman, A., Kabir, M. A., Han, J., & Sarda, P. (2018, August). Blockchain versus database: A critical analysis. In *2018 17th IEEE International conference on trust, security and privacy in computing and communications/12th IEEE international conference on big data science and engineering (TrustCom/BigDataSE)*, 1348-1353. IEEE. doi: 0.1109/TrustCom/BigDataSE.2018.00186.

Chowdhury, S., Rodriguez-Espindola, O., Dey, P., & Budhwar, P. (2023). Blockchain technology adoption for managing risks in operations and supply chain management: evidence from the UK. *Annals of operations research*, *327*(1), 539-574. https://doi.org/10.1007/s10479-021-04487-1.

Christopher, M. (1994). *Logistics and Supply Chain Management: Strategies for Reducing Costs and Improving Services*. J. Oper. Res. Soc. *45*(11), 1341.

Commerce Commission New Zealand. (2023). Https://comcom.govt.nz

Cooper, M. C., Lambert, D. M., & Pagh, J. D. (1997). Supply chain management: more than a new name for logistics. *The international journal of logistics management*, *8*(1), 1-14. Doi: https://doi.org/10.1108/09574099710805556.

Costa, A. A., & Tavares, L. V. (2012). Social e-business and the Satellite Network model: Innovative concepts to improve collaboration in construction. *Automation in Construction*, *22*, 387-397. Doi: https://doi.org/10.1016/j.autcon.2011.09.017.

Cox, A., & Ireland, P. (2002). Managing construction supply chains: the common sense approach. *Engineering, construction and architectural management*, *9*(5/6), 409-418. Doi: https://doi.org/10.1108/eb021235.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*: Sage publications.

Creswell, J.W. (2005). Educational Research. Planning, Conducting, and Evaluating Quantitative and Qualitative Research. *Upper Sadle River*, United States, Pearson Education.

Čuš-Babič, N., Rebolj, D., Nekrep-Perc, M., & Podbreznik, P. (2014). Supply-chain transparency within industrialized construction projects. *Computers in Industry*, *65*(2), 345-353. doi: https://doi.org/10.1016/j.compind.2013.12.003.

Dainty, A. R., Millett, S. J., & Briscoe, G. H. (2001). New perspectives on construction supply chain integration. *Supply chain management: An international journal*, *6*(4), 163-173. Doi: https://doi.org/10.1108/13598540110402700.

Darlow, G., Rotimi, J. O., & Shahzad, W. M. (2022). Automation in New Zealand's offsite construction (OSC): a status update. *Built Environment Project and Asset Management*, *12*(1), 38-52. Doi: https://doi.org/10.1108/BEPAM-11-2020-0174.

Deep, S., Gajendran, T., & Jefferies, M. (2021). A systematic review of 'enablers of collaboration'among the participants in construction projects. *International journal of*

construction management, 21(9), 919-931. https://doi.org/10.1080/15623599.2019.1596624

Deng, H., Xu, Y., Deng, Y., & Lin, J. (2022). Transforming knowledge management in the construction industry through information and communications technology: A 15-year review. *Automation in Construction, 142*, 104530. https://doi.org/10.1016/j.autcon.2022.104530

Devine, P. (2015). Blockchain learning: Can crypto-currency methods be appropriated to enhance online learning? *In Proceedings of the ALT Online Winter Conference, Online, 7–10 December 2015*, 1–7.

Doran, D., & Giannakis, M. (2011). An examination of a modular supply chain: a construction sector perspective. *Supply Chain Management: An International Journal*, *16*(4), 260-270. Doi: https://doi.org/10.1108/13598541111139071.

Enz, M. G., & Lambert, D. M. (2023). A supply chain management framework for services. *Journal of Business Logistics*, *44*(1), 11-36. https://doi.org/10.1111/jbl.12323.

Evborokhai, M., & Shittu, A. (2020, November). Assessment of Communication Channels in Use by Professionals on Construction Projects in Abuja, Nigeria. *Proceedings of the 5th Research Conference of the NIQS (RECON 5).* Nigerian Institute of Quantity Surveyors. Federal University of Technology, Minna, Nigeria.

Fawcett, S. E., & Magnan, G. M. (2002). The rhetoric and reality of supply chain integration. *International Journal of Physical Distribution & Logistics Management*, *32*(5), 339-361. Doi: https://doi.org/10.1108/09600030210436222.

Fellows, R. F., & Liu, A. M. (2015). *Research methods for construction*: John Wiley & Sons.

Fernando, H., Hewavitharana, T., & Perera, A. (2019, July). Evaluation of Electronic Document Management (EDM) systems for construction organizations. In *2019 moratuwa engineering research conference (mercon)*, 273-278. IEEE. doi: 10.1109/MERCon.2019.8818768

Finch, P. (2004). Supply chain risk management. *Supply chain management: an International Journal*, *9*(2), 183-196. Doi: https://doi.org/10.1108/13598540410527079.

Frohlich, M. T., & Westbrook, R. (2001). Arcs of integration: an international study of supply chain strategies. *Journal of operations management*, *19*(2), 185-200. Doi: https://doi.org/10.1016/S0272-6963(00)00055-3.

Gan, X., Chang, R., & Wen, T. (2018). Overcoming barriers to off-site construction through engaging stakeholders: A two-mode social network analysis. *Journal of Cleaner Production*, *201*, 735-747. Doi: https://doi.org/10.1016/j.jclepro.2018.07.299.

Ghnaya, O., Pourzarei, H., Rivest, L., & Boton, C. (2022, May). Role of electronic document management systems in the design change management process. In *Canadian Society of Civil Engineering Annual Conference*, 673-685. Cham: Springer International Publishing. doi: https://doi.org/10.1007/978-3-031-34593-7_41.

Gibb, A. G. (1999). *Off-site fabrication: prefabrication, pre-assembly and modularisation*: John Wiley & Sons.

Gibb, A., & Isack, F. (2003). Re-engineering through pre-assembly: client expectations and drivers. *Building research & information*, *31*(2), 146-160. Doi: https://doi.org/10.1080/09613210302000.

Gielingh, W. F., & Tolman, F. P. (1991). Information integration in the building and construction industries. *Computer-Aided Civil and Infrastructure Engineering*, *6*(4), 329-334. Doi: https://doi.org/10.1111/j.1467-8667.1991.tb00263.x.

Girard, J., & Girard, J. (2015). Defining knowledge management: Toward an applied compendium. *Online Journal of Applied Knowledge Management*, *3*(1).

Golafshani, N. (2003). Understanding reliability and validity in qualitative research. *The qualitative report*, *8*(4), 597-607.

Gordon, G., & Curtis, M. D. (2018). *Building-quality issues: A literature review*. BRANZ. Retrieved from https://d39d3mj7qio96p.cloudfront.net/media/documents/SR375_Building-quality_issues_-_A_literature_review.pdf.

Gray, C., & Al-Bizri, S. (2007). Modelling trade contractor information production. *Architectural engineering and design management, 3*(1), 39-48. Doi: https://doi.org/10.1080/17452007.2007.9684628.

Grix, J. (2002). Introducing students to the generic terminology of social research. *Politics*, *22*(3), 175-186. doi: https://doi.org/10.1111/1467-9256.00173.

Hackius, N., & Petersen, M. (2017). Blockchain in logistics and supply chain: trick or treat?. In *Digitalization in Supply Chain Management and Logistics: Smart and Digital Solutions for an Industry 4.0 Environment. Proceedings of the Hamburg International Conference of Logistics (HICL), 23*, 3-18. Berlin. doi: 10.15480/882.1444.

Handfield, R. B., & Bechtel, C. (2002). The role of trust and relationship structure in improving supply chain responsiveness. *Industrial marketing management, 31*(4), 367-382. Doi: https://doi.org/10.1016/S0019-8501(01)00169-9.

Hannabuss, S. (1987, May). The concept of performance: a semantic review. In *Aslib Proceedings*, 39(5), 149-158. MCB UP Ltd. Doi: https://doi.org/10.1108/eb051048.

Hardin, B., & McCool, D. (2015). *BIM and construction management: proven tools, methods, and workflows*: John Wiley & Sons.

Harland, C. M., Caldwell, N. D., Powell, P., & Zheng, J. (2007). Barriers to supply chain information integration: SMEs adrift of eLands. *Journal of operations management*, *25*(6), 1234-1254. Doi: https://doi.org/10.1016/j.jom.2007.01.004.

Hatmoko, J. U. D., & Scott, S. (2010). Simulating the impact of supply chain management practice on the performance of medium-sized building projects. *Construction*

Management and Economics, 28(1), 35-49. Doi: https://doi.org/10.1080/01446190903365632.

Höök, M. (2006). Customer value in lean prefabrication of housing considering both construction and manufacturing. In *Annual Conference of the International Group for Lean Construction.* 583-594. Catholic University of Chile, School of Engineering.

Huang, T., & Wilson, R. A. (2020). *Auckland's Construction Sector: Industry Snapshot and Trends to 2019*. Auckland Council, Te Kaunihera o Tāmaki Makaurau. Retrieved from https://knowledgeauckland.org.nz/media/1714/tr2020-002-aucklands-construction-sectortrends-to-2019.pdf.

Humphreys, P., Matthews, J., & Kumaraswamy, M. (2003). Pre-construction project partnering: from adversarial to collaborative relationships. *Supply Chain Management: An International Journal, 8*(2), 166-178. Doi: https://doi.org/10.1108/13598540310468760.

Hwang, B. G., Shan, M., & Looi, K. Y. (2018). Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. *Journal of cleaner production, 183*, 183-193. Doi: https://doi.org/10.1016/j.jclepro.2018.02.136.

Jagtap, M., & Kamble, S. (2020). The effect of the client–contractor relationship on project performance. *International journal of productivity and performance management, 69*(3), 541-558. Doi: https://doi.org/10.1108/IJPPM-05-2018-0205.

Jaillon, L., & Poon, C. S. (2010). Design issues of using prefabrication in Hong Kong building construction. *Construction Management and Economics, 28*(10), 1025-1042. Doi: https://doi.org/10.1080/01446193.2010.498481.

Jayashri, N., Rampur, V., Gangodkar, D., Abirami, M., Balarengadurai, C., & Kumar, A. (2023). Improved block chain system for high secured IoT integrated supply chain. *Measurement: Sensors, 25*, 100-633. Doi: https://doi.org/10.1016/j.measen.2022.100633.

Jennex Murray, E. (2009). Towards a consensus knowledge management success definition. *VINE*, *39*(2), 174-188. Doi: https://doi.org/10.1108/03055720910988878.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational researcher*, *33*(7), 14-26. Doi: https://doi.org/10.3102/0013189x033007014.

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of mixed methods research*, *1*(2), 112-133. Doi: https://doi.org/10.1177/1558689806298224.

Kadefors, A. (1999). Client-contractor relations: How fairness considerations and interests influence contractor variation negotiations. In *Proceedings IGLC*, 7, 231-240. Gothenburg, SWEDEN.

Kalian, A., Watson, A., Agbasi, E., Anumba, C., & Gibb, A. (2004). Modelling the building cladding attainment processes. *Business Process Management Journal*, *10*(6), 712-723. Doi: https://doi.org/10.1108/14637150410567893.

Kaufmann, M., & Remick, C. (2009). *Prefab green*. Gibbs Smith.

Kazi, A. S. (2005). *Knowledge management in the construction industry: A socio-technical perspective*. Igi Global.

Khalfan, M. M., McDermott, P., & Swan, W. (2007). Building trust in construction projects. *Supply chain management: an international journal*, *12*(6), 385-391. Doi: https://doi.org/10.1108/13598540710826308.

Khanuja, A., & Jain, R. K. (2020). Supply chain integration: a review of enablers, dimensions and performance. *Benchmarking: An international journal*, *27*(1), 264-301. https://doi.org/10.1108/BIJ-07-2018-0217.

Kirchherr, J., & Charles, K. (2018). Enhancing the sample diversity of snowball samples: Recommendations from a research project on anti-dam movements in Southeast Asia. *PloS one*, *13*(8), e0201710. Doi: https://doi.org/10.1371/journal.pone.0201710.

Koc, K., & Gurgun, A. P. (2021). Stakeholder-associated life cycle risks in construction supply chain. *Journal of Management in Engineering*, *37*(1), 04020107. doi: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000881.

Konukcu, S. (2011). *A knowledge chain framework for construction supply chains.* Doctoral dissertation, Loughborough University. Retrieved from https://hdl.handle.net/2134/9155.

Koolwijk, J. S. J., van Oel, C. J., Wamelink, J. W. F., & Vrijhoef, R. (2018). Collaboration and integration in project-based supply chains in the construction industry. *Journal of Management in Engineering*, *34*(3), 04018001. doi: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000592.

Korpela, K., Hallikas, J., & Dahlberg, T. (2017). Digital supply chain transformation toward blockchain integration. *50th Hawaii International Conference On Systems Science*, United States. Doi: https://doi.org/10.24251/HICSS.2017.506.

Kuzlu, M., Pipattanasomporn, M., Gurses, L., & Rahman, S. (2019). Performance analysis of a hyperledger fabric blockchain framework: throughput, latency and scalability. In *2019 IEEE international conference on blockchain (Blockchain)*, 536-540. IEEE. doi: 10.1109/Blockchain.2019.00003.

KV, P., V, V., & Bhat, N. (2019). Analysis of causes of delay in Indian construction projects and mitigation measures. *Journal of Financial Management of Property and Construction*, *24*(1), 58-78. doi: https://doi.org/10.1108/JFMPC-04-2018-0020.

Lambert, D. M., & Cooper, M. C. (2000). Issues in Supply Chain Management. *Industrial Marketing Management*, *29*(1), 65-83. doi: https://doi.org/10.1016/S0019-8501(99)00113-3.

Lee, K., & Lim, C. (2001). Technological regimes, catching-up and leapfrogging: findings from the Korean industries. *Research policy*, *30*(3), 459-483. Doi: https://doi.org/10.1016/S0048-7333(00)00088-3.

Lemieux Victoria, L. (2016). Trusting records: is Blockchain technology the answer? *Records Management Journal*, *26*(2), 110-139. doi: https://doi.org/10.1108/RMJ-12-2015-0042.

Li, J., Greenwood, D., & Kassem, M. (2018, December). *Blockchain in the built environment: analysing current applications and developing an emergent framework*. Diamond Congress Ltd., Budapest University of Technology and Economics.

Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in construction*, *102*, 288-307. Doi: https://doi.org/10.1016/j.autcon.2019.02.005.

Li, X., Shen, G. Q., Wu, P., & Yue, T. (2019). Integrating building information modeling and prefabrication housing production. *Automation in Construction*, *100*, 46-60. Doi: https://doi.org/10.1016/j.autcon.2018.12.024.

Li, Z., Wang, W. M., Liu, G., Liu, L., He, J., & Huang, G. Q. (2018). Toward open manufacturing: A cross-enterprises knowledge and services exchange framework based on blockchain and edge computing. *Industrial Management & Data Systems*, *118*(1), 303-320. Doi: https://doi.org/10.1108/IMDS-04-2017-0142.

Love, P. E., Irani, Z., & Edwards, D. J. (2004). A seamless supply chain management model for construction. *Supply chain management: an international journal*, *9*(1), 43-56. Doi: https://doi.org/10.1108/13598540410517575.

Lu, Q., & Xu, X. (2017). Adaptable blockchain-based systems: A case study for product traceability. *IEEE Software*, *34*(6), 21-27. Doi: 10.1109/MS.2017.4121227.

Lu, W., Chen, K., Xue, F., & Pan, W. (2018). Searching for an optimal level of prefabrication in construction: An analytical framework. *Journal of Cleaner Production*, *201*, 236-245. Doi: https://doi.org/10.1016/j.jclepro.2018.07.319.

Luo, L., Jin, X., Shen, G. Q., Wang, Y., Liang, X., Li, X., & Li, C. Z. (2020). Supply chain management for prefabricated building projects in Hong Kong. *Journal of management in engineering*, *36*(2), 05020001. Doi: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000739.

Mack, N. (2005). *Qualitative research methods: A data collector's field guide.* Family Health International Publications, USA.

Mannaro, K., Pinna, A., & Marchesi, M. (2017, September). Crypto-trading: Blockchain-oriented energy market. In *2017 AEIT International Annual Conference*, 1-5. IEEE. Doi: https://doi.org/10.23919/AEIT.2017.8240547.

Mantravadi, S., & Srai, J. S. (2023). How impocrtant are digital technologies for urban food security? A framework for supply chain integration using IoT. *Procedia Computer Science*, *217*, 1678-1687. https://doi.org/10.1016/j.procs.2022.12.368.

Meng, X. (2012). The effect of relationship management on project performance in construction. *International journal of project management*, *30*(2), 188-198. Doi: https://doi.org/10.1016/j.ijproman.2011.04.002.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (2001). Defining supply chain management. *Journal of Business logistics*, *22*(2), 1-25. doi: https://doi.org/10.1002/j.2158-1592.2001.tb00001.x.

Ministry of Business, I. a. E. M. (2022). *Building and construction sector trends annual report*. New Zealand: Ministry of Business, Innovation and Employment (MBIE) Retrieved from https://www.mbie.govt.nz/dmsdocument/25439-building-construction-sector-trends-annual-report-2022.

Moon, S. A., & Kim, D. J. (2005). Systems thinking ability for supply chain management. *Supply Chain Management: An International Journal*, *10*(5), 394-401. Doi: https://doi.org/10.1108/13598540510624214.

Mostafa, S., Chileshe, N., & Zuo, J. (2014). A synergistic supply chain enhancing offsite manufacturing uptake in Australian house building. In *Proceedings of the 30th Annual Association of Researchers in Construction Management Conference ARCOM 2014*, 1143-1152. Association of Researchers in Construction Management. Portsmouth, UK.

Naderifar, M., Goli, H., & Ghaljaie, F. (2017). Snowball sampling: A purposeful method of sampling in qualitative research. *Strides in development of medical education*, *14*(3). Doi: https://doi.org/10.5812/sdme.67670.

Nakamoto, S., & Bitcoin, A. (2008). A peer-to-peer electronic cash system. *Bitcoin.* Retrieved from https://www.klausnordby.com/bitcoin/Bitcoin_Whitepaper_Document_HD.pdf.

Nassaji, H. (2015). Qualitative and descriptive research: Data type versus data analysis. *Language teaching research*, *19*(2), 129-132. doi: https://doi.org/10.1177/1362168815572747.

Navaratnam, S., Satheeskumar, A., Zhang, G., Nguyen, K., Venkatesan, S., & Poologanathan, K. (2022). The challenges confronting the growth of sustainable prefabricated building construction in Australia: Construction industry views. *Journal of Building Engineering*, *48*, 103935. https://doi.org/10.1016/j.jobe.2021.103935

Naz, M., Al-zahrani, F. A., Khalid, R., Javaid, N., Qamar, A. M., Afzal, M. K., & Shafiq, M. (2019). A secure data sharing platform using blockchain and interplanetary file system. *Sustainability*, *11*(24), 7054. doi: https://doi.org/10.3390/su11247054.

Nesarnobari, S., Shahzad, W., Jelodar, M. B., & Sutrisna, M. (2024). Unlocking the Full Potential of Offsite Construction by Optimising its Procurement and Delivery. *Routledge Handbook of Construction Project Procurement and Delivery* (pp. 350-370). Routledge.

Ngai, E. W. T., Cheng, T. C. E., & Ho, S. S. (2004). Critical success factors of web-based supply-chain management systems: an exploratory study. *Production Planning & Control*, *15*(6), 622-630. Doi: https://doi.org/10.1080/09537280412331283928.

Nicholas, J., & Edwards, D. J. (2003). A model to evaluate materials suppliers' and contractors' business interactions. *Construction Management and Economics*, *21*(3), 237-245. Doi: https://doi.org/10.1080/0144619032000049692.

Nizamuddin, N., Salah, K., Azad, M. A., Arshad, J., & Rehman, M. (2019). Decentralized document version control using ethereum blockchain and IPFS. *Computers & Electrical Engineering*, *76*, 183-197. doi: https://doi.org/10.1016/j.compeleceng.2019.03.014.

North, K., & Kumta, G. (2018). *Knowledge management: Value creation through organizational learning*: Springer.

O'brien, J.A., & Marakas, G.M. (2005), *Introduction to information systems*, vol. 13, McGraw-Hill/Irwin New York City, USA.

Oranga, J. (2023). Tacit Knowledge Transfer and Sharing: Characteristics and Benefits of Tacit & Explicit Knowledge. *Journal of Accounting Research, Utility Finance and Digital Assets*, *2*(2), 736-740. https://doi.org/10.54443/jaruda.v2i2.103

Pan, Y., Zhang, X., Wang, Y., Yan, J., Zhou, S., Li, G., & Bao, J. (2019). Application of blockchain in carbon trading. *Energy Procedia*, *158*, 4286-4291. Doi: https://doi.org/10.1016/j.egypro.2019.01.509.

Papadonikolaki, E., Vrijhoef, R., & Wamelink, H. (2016). The interdependences of BIM and supply chain partnering: empirical explorations. *Architectural Engineering and Design Management*, *12*(6), 476-494. Doi: https://doi.org/10.1080/17452007.2016.1212693.

Papetti, A., Marconi, M., Rossi, M., & Germani, M. (2019). Web-based platform for eco-sustainable supply chain management. *Sustainable Production and Consumption*, *17*, 215-228. Doi: https://doi.org/10.1016/j.spc.2018.11.006.

Patterson, K. A., Grimm, C. M., & Corsi, T. M. (2003). Adopting new technologies for supply chain management. *Transportation Research Part E: Logistics and Transportation Review*, *39*(2), 95-121. Doi: https://doi.org/10.1016/S1366-5545(02)00041-8.

Patton, M. Q. (2015). *Qualitative research & evaluation methods : integrating theory and practice* (Fourth edition): Sage Publications.

Penzes, B. (2018). *Blockchain Technology in the Construction Industry*. https://doi.org/10.13140/RG.2.2.14164.45443.

Power, D. (2005). Supply chain management integration and implementation: a literature review. *Supply chain management: an International journal*, *10*(4), 252-263. Doi: https://doi.org/10.1108/13598540510612721.

Prajogo, D., & Olhager, J. (2012). Supply chain integration and performance: The effects of long-term relationships, information technology and sharing, and logistics integration. *International Journal of Production Economics*, *135*(1), 514-522. doi: https://doi.org/10.1016/j.ijpe.2011.09.001.

PrefabNZ. (2013). *Roadmap for Prefab in New Zealand.* Retrieved from http://www.prefabnz.com/Downloads/Assets/7641/1/PrefabNZ%20Roadmap%20for%20Prefab%20in%20New%20Zealand%20(2013).pdf.

PrefabNZ. (2015). *levers for prefabNZ*. Retrieved from http://www.prefabnz.com/Downloads/Assets/7645/1/PrefabNZ%20Levers%20for%20Prefab%20(2015).pdf.

PrefabNZ. (2018). *Good Offsite Guide FINAL*. Retrieved from http://www.prefabnz.com/Downloads/Assets/9743/1/PrefabNZ%20Good%20Offsite%20Guide%20FINAL%20(1). Pdf.

Rahimian, F. P., Goulding, J., Akintoye, A., & Kolo, S. (2017). Review of motivations, success factors, and barriers to the adoption of offsite manufacturing in Nigeria. *Procedia engineering*, *196*, 512-519. Doi: https://doi.org/10.1016/j.proeng.2017.07.232.

Rebs, T., Brandenburg, M., & Seuring, S. (2019). System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach. *Journal of cleaner production*, *208*, 1265-1280. Doi: https://doi.org/10.1016/j.jclepro.2018.10.100.

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International journal of production research*, *57*(7), 2117-2135. Doi: https://doi.org/10.1080/00207543.2018.1533261.

Sahin, F., & Robinson, E. P. (2002). Flow coordination and information sharing in supply chains: review, implications, and directions for future research. *Decision sciences*, *33*(4), 505-536. Doi: https://doi.org/10.1111/j.1540-5915.2002.tb01654.x.

Samarasinghe, A., Tookey, J., & Rotimi, J. O. B. (2013). Supply chain collaboration in New Zealand house construction. *The 38th Australasian Universities Building Education Association Conference*. Faculty of Engineering, The University of Auckland, Auckland, New Zealand.

Sangeeta, N., & Nam, S. Y. (2023). Blockchain and Interplanetary File System (IPFS)-Based Data Storage System for Vehicular Networks with Keyword Search Capability. *Electronics*, *12*(7), 1545. doi: https://doi.org/10.3390/electronics12071545.

Saunders, M. N. (2011). *Research methods for business students, 5/e*: Pearson Education India.

Saunders, M., Lewis, P., Thornhill, A. (2009). *Research Methods for Business Students*, 5th ed. Pearson Education India: Edinburgh, UK.

Segerstedt, A., & Olofsson, T. (2010). Supply chains in the construction industry. *Supply chain management: an international journal*, *15*(5), 347-353. Doi: https://doi.org/10.1108/13598541011068260.

Shahzad, W. M., & Mbachu, J. (2012). *Productivity enhancement of construction industry using prefabrication: Impact levels of the underlying constraints and improvement measures*: LAP Lambert Academic Publishing.

Shahzad, W. M., & Mbachu, J. (2013). Prefabrication as an onsite productivity enhancer: analysis of impact levels of the underlying constraints and improvement measures in New Zealand construction industry. *International Journal of Project Organisation and Management, 5*(4), 334-354. Doi: https://doi.org/10.1504/IJPOM.2013.058382.

Shahzad, W. M., Hassan, A., & Rotimi, J. O. B. (2022). The challenges of land development for housing provision in New Zealand. *Journal of Housing and the Built Environment, 37*(3), 1319-1337. Doi: https://doi.org/10.1007/s10901-021-09896-z.

Shahzad, W. M., Rajakannu, G., & Kordestani Ghalenoei, N. (2022). Potential of Modular Offsite Construction for Emergency Situations: A New Zealand Study. *Buildings, 12*(11), 1970. https://doi.org/10.3390/buildings12111970

Shahzad, W., Mbachu, J., & Domingo, N. (2015). Marginal productivity gained through prefabrication: Case studies of building projects in Auckland. *Buildings, 5*(1), 196-208. Doi: https://doi.org/10.3390/buildings5010196.

Shahzad, W.M. (2011), *Offsite manufacturing as a means of improving productivity in New Zealand construction industry : key barriers to adoption and improvement measures*. Master's thesis, Massey University, Auckland, New Zealand.

Shahzad, W.M. (2016), *Comparative analysis of the productivity levels achieved through the use of panelised prefabrication technology with those of traditional building system*. Doctor of Philosophy (PhD) thesis, Massey University, Auckland, New Zealand. Retrieved from http://hdl.handle.net/10179/11207.

Shojaei, A. (2019). Exploring applications of blockchain technology in the construction industry. In *Proceedings of International Structural Engineering and Construction Management*, 1-6. Mississippi State University, Mississippi, USA. Doi: https://doi.org/10.14455/ISEC.res.2019.78.

Smith, R. E. (2016). Off-site and modular construction explained. *National institute of building sciences*. Retrieved from https://www.wbdg.org/resources/site-and-modular-construction-explained.

Smyth, H., & Pryke, S. (2008). Collaborative relationships in construction. *Collab. Relationsh. Constr*, *14*, 245. Retrieved from https://onlinelibrary.wiley.com/doi/book/10.1002/9781444301069.

Song, H., Yang, Y., & Tao, Z. (2023). Application of blockchain in enterprise financing: literature review and knowledge framework. *Nankai Business Review International*, *14*(3), 373-399. doi: https://doi.org/10.1108/NBRI-08-2022-0080.

Sooriyamudalige, N., Domingo, N., Shahzad, W., & Childerhouse, P. (2020). Barriers and enablers for supply chain integration in prefabricated elements manufacturing in New Zealand. *International Journal of Construction Supply Chain Management, 10*(1), 73-91.

Stadtler, H., & Kilger, C. (2002). *Supply chain management and advanced planning*. Springer.

StatsNZ (2019), *Gross domestic product overview for March 2019 quarter*. Retrieved from https://www.stats.govt.nz/information-releases/gross-domestic-product-march-2019-quarter/#:~:text=Economic%20activity%2C%20as%20measured%20by,this%20quarter%2C%20up%202.0%20percent.

StatsNZ (2023), *Gross domestic product overview for September 2023 quarter*. Retrieved from https://www.stats.govt.nz/news/home-building-in-auckland-lifts-construction-activity/

Stock, G. N., Greis, N. P., & Kasarda, J. D. (2000). Enterprise logistics and supply chain structure: the role of fit. *Journal of operations management*, *18*(5), 531-547. Doi: https://doi.org/10.1016/S0272-6963(00)00035-8.

Sundram, V. P. K., Bahrin, A. S., Abdul Munir, Z. B., & Zolait, A. H. (2018). The effect of supply chain information management and information system infrastructure: The mediating role of supply chain integration towards manufacturing performance in

Malaysia. *Journal of Enterprise Information Management*, *31*(5), 751-770. Doi: https://doi.org/10.1108/JEIM-06-2017-0084.

Sutrisna, M., & Goulding, J. (2019). Managing information flow and design processes to reduce design risks in offsite construction projects. *Engineering, construction and architectural management*, *26*(2), 267-284. Doi: https://doi.org/10.1108/ECAM-11-2017-0250.

Tan, K. C. (2001). A framework of supply chain management literature. *European Journal of Purchasing & Supply Management*, *7*(1), 39-48. Doi: https://doi.org/10.1016/S0969-7012(00)00020-4.

Tezel, A., Febrero, P., Papadonikolaki, E., & Yitmen, I. (2021). Insights into blockchain implementation in construction: models for supply chain management. *Journal of management in engineering*, *37*(4), 04021038. Doi: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000939.

Thanasegaran, G. (2009). Reliability and Validity Issues in Research. *Integration & Dissemination*, *4*, 35-40. Retrieved from http://ezproxy.massey.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=43899561&site=eds-live&scope=site.

Tse, D., Zhang, B., Yang, Y., Cheng, C., & Mu, H. (2017, December). Blockchain application in food supply information security. In *2017 IEEE international conference on industrial engineering and engineering management (IEEM)*, 1357-1361. IEEE. Doi: 10.1109/IEEM.2017.8290114.

Turk, Ž., & Klinc, R. (2017). Potentials of blockchain technology for construction management. *Procedia engineering*, *196*, 638-645. Doi: https://doi.org/10.1016/j.proeng.2017.08.052.

Vilasini, N., Neitzert, T., Rotimi, J., & Windapo, A. (2012). A framework for subcontractor integration in alliance contracts. *International Journal of Construction Supply Chain Management*, 2(1), 17-33.

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European journal of purchasing & supply management*, *6*(3-4), 169-178. Doi: https://doi.org/10.1016/S0969-7012(00)00013-7.

Vrijhoef, R., L. Koskela, and G. Howell. (2001). Understanding construction supply chains: An alternative interpretation. In *Proceeding of the 9th Int. Group for Lean Construction Conference*, 185–199. Singapore: National University of Singapore.

Walliman, N. (2017). *Research methods: The basics*. Routledge, London.

Wang, J., Wu, P., Wang, X., & Shou, W. (2017). The outlook of blockchain technology for construction engineering management. *Front. Eng. Mana, 4(*1), 67-75. Doi: https://doi.org/10.15302/J-FEM-2017006.

Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X., & Xiao, Q. (2020). Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Automation in construction*, *111*, 103063. Doi: https://doi.org/10.1016/j.autcon.2019.103063.

Wisner, J. D., Tan, K.-C., & Leong, G. K. (2014). *Principles of supply chain management: A balanced approach*: Cengage Learning.

Wong, P. S., Kanellopoulos, M. P., & Edmonson, L. (2018). An empirical analysis of the effect of prefabrication on fostering sustainable construction. In *Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate* (pp. 185-195). Springer Singapore. https://doi.org/10.1007/978-981-10-6190-5_18.

Xing, K., Qian, W., & Zaman, A. U. (2016). Development of a cloud-based platform for footprint assessment in green supply chain management. *Journal of cleaner production*, *139*, 191-203. Doi: https://doi.org/10.1016/j.jclepro.2016.08.042

Yang, R., Wakefield, R., Lyu, S., Jayasuriya, S., Han, F., Yi, X., ... & Chen, S. (2020). Public and private blockchain in construction business process and information

integration. *Automation in construction*, *118*, 103276. Doi: https://doi.org/10.1016/j.autcon.2020.103276.

Yeo, K. T. (1993). Systems thinking and project management—time to reunite. *International journal of project management*, *11*(2), 111-117. Doi: https://doi.org/10.1016/0263-7863(93)90019-J.

Yu, Z., Yan, H., & Edwin Cheng, T. C. (2001). Benefits of information sharing with supply chain partnerships. *Industrial management & Data systems*, *101*(3), 114-121. Doi: https://doi.org/10.1108/02635570110386625.

Yue, X., Wang, H., Jin, D., Li, M., & Jiang, W. (2016). Healthcare data gateways: found healthcare intelligence on blockchain with novel privacy risk control. *Journal of medical systems*, *40*, 1-8. Doi: https://doi.org/10.1007/s10916-016-0574-6.

Zhai, X., Reed, R., & Mills, A. (2013). Factors impeding the offsite production of housing construction in China: an investigation of current practice. *Construction Management and Economics*, *32*(1-2), 40-52. doi: https://doi.org/10.1080/01446193.2013.787491.

Zhai, Y., Zhong, R. Y., Li, Z., & Huang, G. (2017). Production lead-time hedging and coordination in prefabricated construction supply chain management. *International Journal of Production Research*, *55*(14), 3984-4002. Doi: https://doi.org/10.1080/00207543.2016.1231432.

Zhang, C., Xiao, H., Gursoy, D., & Rao, Y. (2015). Tacit knowledge spillover and sustainability in destination development. *Journal of Sustainable Tourism*, *23*(7), 1029-1048. Doi: https://doi.org/10.1080/09669582.2015.1032299.

Zhang, P., & Ng, F. F. (2012). Analysis of knowledge sharing behaviour in construction teams in Hong Kong. *Construction Management and Economics*, *30*(7), 557-574. Doi: https://doi.org/10.1080/01446193.2012.669838.

Zhao, J. L., Fan, S., & Yan, J. (2016). Overview of business innovations and research opportunities in blockchain and introduction to the special issue. *Financial innovation, 2*, 1-7. Doi: https://doi.org/10.1186/s40854-016-0049-2.

Zhong, B., Guo, J., Zhang, L., Wu, H., Li, H., & Wang, Y. (2022). A blockchain-based framework for on-site construction environmental monitoring: Proof of concept. *Building and Environment, 217*, 109064. doi: https://doi.org/10.1016/j.buildenv.2022.109064.

Zhou, H., & Benton Jr, W. C. (2007). Supply chain practice and information sharing. *Journal of Operations management*, *25*(6), 1348-1365. https://doi.org/10.1016/j.jom.2007.01.009.

Appendices

Appendix 1: Human Ethics Approval form

Appendix 2: Pilot interview questions

Appendix 3: Questionnaire survey

Appendix 4: Validation interview survey

Appendix 5: Statement of Contribution forms

Appendix 6: Data Analysis

Appendix 1: Human Ethics Approval

From: humanethics@massey.ac.nz <humanethics@massey.ac.nz>
Sent: Tuesday, July 30, 2019 8:56:32 AM
To: Ehsan.Bakhtiarizadeh.1@uni.massey.ac.nz <Ehsan.Bakhtiarizadeh.1@uni.massey.ac.nz>; Rotimi, James <J.Rotimi@massey.ac.nz>; Shahzad, Wajiha <W.M.Shahzad@massey.ac.nz>; james.rotimi@aut.ac.nz <james.rotimi@aut.ac.nz>
Cc: Human Ethics <gmhumeth@massey.ac.nz>
Subject: Human Ethics Notification - 4000021397

HoU Review Group

Ethics Notification Number: 4000021397
Title: Developing a framework for supply chain integration in the prefabrication subsector of construction using blockchain technology

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low-risk notification for this project is valid for a maximum of three years.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research. If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Professor Craig Johnson, Director (Research Ethics), email humanethics@massey.ac.nz."

Please note that if a sponsoring organisation, funding authority or a journal in which you wish to publish require evidence of committee approval (with an approval number), you will have to complete the application form again answering yes to the publication question to provide

more information to go before one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

You are reminded that staff researchers and supervisors are fully responsible for ensuring that the information in the low risk notification has met the requirements and guidelines for submission of a low risk notification.

If you wish to print an official copy of this letter, please login to the RIMS system, and under the Reporting section, View Reports you will find a link to run the LR Report.

Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)

Appendix 2: Pilot interview questions

Prefabrication project phases, stakeholders, and their interactions

Based on the existing literature and observations, I have identified the stakeholders involved in the supply chain of prefabricated projects in New Zealand and the sequential phases that a typical prefabrication project progresses through. I've created a mapping that illustrates the correlation between these phases and the participation of stakeholders in each stage. I would greatly value your time in reviewing this mapping with me.

Q1. What is your general opinion about this process map?

Q2. What is your opinion about the identified stakeholders? Is there a stakeholder missing or one that might not fit in New Zealand's prefabrication projects?

Q3. What are your thoughts on the identified project stages? Is there a stage missing or one that might not fit in New Zealand's prefabrication projects?

Q4. What are your thoughts on the interaction arrows (information flow) shown in the process map? Do you see any potential correlations that may have been overlooked or ones that might not align with a typical prefabrication project?

Q5. In which stage of the process and among which stakeholders do you observe noticeable complexity and believe there is room for improvement in information flow?

Appendix 3: Questionnaire survey

Invitation to participate in a research survey.
Research title: Developing a framework for prefabrication supply chain integration in New Zealand using blockchain technology.

Hi,

Thank you for taking the time to discuss my PhD research today.

I am a researcher at Massey University undertaking PhD research entitled: "Developing a framework for prefabrication supply chain integration in New Zealand using blockchain technology", and I would like to invite you to participate in a survey as part of the research, which aims to investigate the applicability of blockchain technology in New Zealand prefabrication construction projects. The survey should take about 10-15 minutes to respond to. Please find a link to the survey questions below.

Information obtained from the questionnaire will be treated as confidential and used for academic purposes only.

Your contribution to the survey will be highly appreciated. If you have any queries, please do not hesitate to contact me.

Yours sincerely,

Ehsan Bakhtiarizadeh
PhD Candidate,
School of Built Environment,
Massey University, New Zealand
Phone: 0272459021
Email: e.bakhtiazadeh@massey.ac.nz

Questionnaire Survey

Prefabrication Supply Chain Integration using Blockchain Technology

Start of Block: Introduction

Thank you for participating in this questionnaire survey.

This survey is being conducted for a PhD research project at the School of Built Environment, Massey University, Auckland, New Zealand.

Survey Objectives:

- To explore the interconnectivity of stakeholders in New Zealand's prefabrication supply chain.
- To identify, assess, and categorise types and modes of interactions among stakeholders involved in the prefabrication supply chain in New Zealand.
- To ascertain the applicability of blockchain technology in Prefabricated construction supply chain.

Benefits of Participation:

- The survey will shed light on the recent developments in "advanced Information Technology (IT) for the prefabrication sub-sector of New Zealand's construction industry".
- In addition, this survey provides insight into the relationship between Prefabricated projects' development phases and their supply chain integration criteria.

Confidentiality Statement:

Massey University Research Ethics Committee has approved this project. The information provided by participants will be used for research purposes only. All information will remain confidential, and any distribution or publication of information collected in this survey will be in aggregate form and will not reflect any individual contribution.

The questionnaire should take about 7-12 minutes. Please feel free to contact Ehsan Bakhtiarizadeh or his supervisory team for any further queries.

* Please note that this survey seeks responses considering the pre-COVID-19 scenarios.

Contact Information:

Ehsan Bakhtiarizadeh: ehsan.bakhtiazadeh@massey.ac.nz (Contact No: 0272459021)
Associate Professor. James O. B. Rotimi: j.rotimi@massey.ac.nz
Dr. Wajiha Shahzad: w.m.shahzad@massey.ac.nz

Do you consent to participate in this survey?

- ○ Yes (1)
- ○ No (2)

Skip To: End of Survey If Do you consent to participate in this survey = No

End of Block: Introduction

Start of Block: Pre-survey Definitions

Pre-survey Definitions:

***Supply Chain Integration:** is the integration of key business processes from initial raw material extraction to intermediate processing, transportation, storage, and final sale to the end-product customer.

***Information Integration:** Information integration refers to the exchange of information among supply chain partners, and its primary purpose is to achieve real-time and collaborative transmission of information throughout the supply chain system.

***Distributed Ledger Technology (Blockchain):** Blockchain is a distributed consensus-based ledger which facilitates transactions among its users by providing them with a secure and tamper-proof database. Blockchain is very similar to the cloud database, but the only difference is that Blockchain is distributed, which means that the database is decentralised in multiple locations, and instead of having one source for information with various users, there are various sources that can be accessed simultaneously by all users.

End of Block: Pre-survey Definitions

Start of Block: Demographic information

Q1. You are responding to this survey from:

- ○ Client's perspective
- ○ Contractor's perspective

Q2. How many years of work experience do you have in the construction industry?

○ 0-5 years ○ 5-10 years ○ 10-15 years ○ More than 15 years

Q3. How many years of work experience do you have in **Prefabrication** subsector of New Zealand's construction industry?

○ 0-4 years ○ 4-8 years ○ 8-12 years ○ More than 12 years

Q4. What type of prefabrication deliverables does your organisation offer? (select all that apply)

- ☐ **Component-based prefabrication:** units and components such as precast beams and columns
- ☐ **Panelised prefabrication:** such as precast floor or wall panels
- ☐ **Modular prefabrication:** such as pods or modules
- ☐ **Hybrid prefabrication:** combination of panelised and modular prefabrication
- ☐ **Complete building prefabrication**
- ☐ **Other**

Q5. To what extent do you have knowledge about Blockchain technology?

○ Excellent ○ Good ○ Average ○ Poor ○ Very poor

End of Block: Demographic information

Start of Block: Introduction to next page

The next three blocks of questions will be regarding information flow between clients and contractors engaged in prefabricated construction industry. You will be answering to three relatively identical questions with different headings pertaining to three different development phases of a project, namely "Detailed Design", "Construction" (including off-site preparation/assembly of components, transportation to construction site, and on-site construction), and "Handover" phase.

End of Block: Introduction to next page

Start of Block: Detailed Design

Project development phase: Detailed Design

Q6. Please indicate the type(s) of information that is exchanged between Client and Contractor at the **Detailed Design** phase of your projects. (select all that apply)

- ☐ Design drawings and specifications
- ☐ Construction schedules and cost estimates
- ☐ Meeting minutes
- ☐ As-builts and survey reports

- ☐ Gantt charts
- ☐ Quality assurance records
- ☐ Reference literature
- ☐ Manufacturing plans
- ☐ Cash flow and cost reports
- ☐ RFI (Request for Information)
- ☐ Photographs and videos
- ☐ Timesheets
- ☐ Newsletters
- ☐ Journals and magazines
- ☐ Advertising materials
- ☐ Documents for statutory approvals
- ☐ Other ----------

Q7. Please indicate the main channel(s) for exchanging information between Client and Contractor at the **Detailed Design** phase of your projects. (select all that apply)

- ☐ Email
- ☐ Meeting
- ☐ Telephone
- ☐ Cloud database/ Internet
- ☐ Intranet and Extranet
- ☐ GIS (Geographic Information System)
- ☐ BIM (Building Information Modelling)
- ☐ Video conference
- ☐ Verbal or informal communication
- ☐ Workshops
- ☐ Social media
- ☐ Forums
- ☐ Other ----------

End of Block: Detailed Design

Start of Block: Construction

Project development phase: Construction (Off-site, Transportation, On-site)

Q8. Please indicate the type(s) of information that is exchanged between Client and Contractor at the **Construction** phase of your projects. (select all that apply)

- ☐ Design drawings and specifications
- ☐ Construction schedules and cost estimates
- ☐ Gantt charts
- ☐ Quality assurance records
- ☐ Reference literature
- ☐ Manufacturing plans
- ☐ Cash flow and cost reports
- ☐ RFI (Request for Information)
- ☐ Photographs and videos
- ☐ Meeting minutes
- ☐ As-builts and survey reports
- ☐ Timesheets
- ☐ Newsletters
- ☐ Journals and magazines
- ☐ Advertising materials
- ☐ Documents for statutory approvals
- ☐ Other ----------

Q9. Please indicate the main channel(s) for exchanging information between Client and Contractor at the **Construction** phase of your projects. (select all that apply)

- ☐ Email
- ☐ Meeting
- ☐ Telephone
- ☐ Cloud database/ Internet
- ☐ Intranet and Extranet
- ☐ GIS (Geographic Information System)
- ☐ BIM (Building Information Modelling)
- ☐ Video conference
- ☐ Verbal or informal communication
- ☐ Workshops
- ☐ Social media
- ☐ Forums
- ☐ Other ----------

End of Block: Construction

Start of Block: Handover

Project development phase: Handover

Q10. Please indicate the type(s) of information that is exchanged between Client and Contractor at the **Handover** phase of your projects. (select all that apply)

- ☐ Design drawings and specifications
- ☐ Construction schedules and cost estimates
- ☐ Gantt charts
- ☐ Quality assurance records
- ☐ Reference literature
- ☐ Manufacturing plans
- ☐ Cash flow and cost reports
- ☐ RFI (Request for Information)
- ☐ Photographs and videos
- ☐ Meeting minutes
- ☐ As-builts and survey reports
- ☐ Timesheets
- ☐ Newsletters
- ☐ Journals and magazines
- ☐ Advertising materials
- ☐ Documents for statutory approvals
- ☐ Other ----------

Q11. Please indicate the main channel(s) for exchanging information between Client and Contractor at the **Handover** phase of your projects. (select all that apply)

- ☐ Email
- ☐ Meeting
- ☐ Telephone
- ☐ Cloud database/ Internet
- ☐ Intranet and Extranet
- ☐ GIS (Geographic Information System)
- ☐ BIM (Building Information Modelling)
- ☐ Video conference
- ☐ Verbal or informal communication
- ☐ Workshops
- ☐ Social media
- ☐ Forums
- ☐ Other ----------

End of Block: Handover

Start of Block: Confidential information

Q12. From your point of view, how <u>important</u> is the management/transmission of confidential information?

○ Extremely important	○ Very important	○ Moderately important	○ Slightly important	○ Not at all important

End of Block: Confidential information

Start of Block: Information channels

Q13. Please indicate to what extent you agree or disagree with the followings:

	Strongly agree (1)	Somewhat agree (2)	Neither agree nor disagree (3)	Somewhat disagree (4)	Strongly disagree (5)
Internet of Things (IoT) is frequently used in my organisation	○	○	○	○	○
Enterprise Resource Planning (ERP) is frequently used in my organisation	○	○	○	○	○
BIM & 3D modelling is frequently used in my organisation	○	○	○	○	○
Document Management System is frequently used in my organisation	○	○	○	○	○
Geographic Information System (GIS) is frequently used in my organisation	○	○	○	○	○
Smart phones or tablets are frequently used in my organisation	○	○	○	○	○
Global Positioning System (GPS) is frequently used in my organisation	○	○	○	○	○
RFID and bar codes are frequently used in my organisation	○	○	○	○	○

Blockchain is frequently used in my organisation	○	○	○	○	○
Information Technology (in general) is frequently used in my organisation	○	○	○	○	○

End of Block: Information channels

Start of Block: Information quality

Q14. To what extent do you agree or disagree that lack of information integration/exchange creates the following drawbacks in your organisation?

	Strongly agree (1)	Somewhat agree (2)	Neither agree nor disagree (3)	Somewhat disagree (4)	Strongly disagree (5)
Scattered (Decentralised) information	○	○	○	○	○
Slow information flow	○	○	○	○	○
Untraceable information	○	○	○	○	○
Information loss	○	○	○	○	○
Conflicting information	○	○	○	○	○
Misinformation	○	○	○	○	○
Unsecured/Unreliable information	○	○	○	○	○
Mutable (susceptible to manipulation) information	○	○	○	○	○
Non-auditable information	○	○	○	○	○

End of Block: Information quality

Start of Block: The main survey

Q15. Technology is often used/applied for **facilitating information exchange** in my organisation.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q16. Utilisation of technology is important to the success of **prefabrication construction** projects.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q17. **Document management systems** prevent the swift flow of information across partners involved in prefabrication projects.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q18. **Transparency of information** is important to the success of the prefabricated construction industry.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q19. **Information Traceability** is important to the success of the prefabricated construction industry.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q20. **Security (reliability) of information** is important for the success of prefabricated construction projects.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q21. **Integrated information exchange** impacts positively on prefabricated construction supply chain performance/integration.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q22. **Blockchain technology** positively impacts prefabricated construction supply chain performance/integration.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q23. **Real-time information exchange** impacts positively on the success of prefabricated construction supply chain performance (on-time and on-budget delivery).

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q24. Retaining project information is important to the success/integration of the prefabricated construction supply chain.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

Q25. Generally, **"New Zealand's prefabricated construction industry"** would benefit from such research that explores the types and modes of interactions among its stakeholders and introduces secure network-centric platforms for enhancing real-time communication and collaboration of numerous partners involved in its supply chain.

○ Strongly agree	○ Somewhat agree	○ Neither agree nor disagree	○ Somewhat disagree	○ Strongly disagree

End of Block: The main survey

Appendix 4: Validation survey

Blockchain technology in New Zealand's off-site construction

Kindly select a suitable rating for each validation question to signify the degree of your contentment with each question.

Use the space below each question to provide any comments regarding each question and, at the end, to provide any general comments/feedback.

Q1. Is the framework easy to comprehend and utilise for blockchain adoption?

- Poor
- Average
- Good
- Very good
- Excellent

Reasons for your answer to this question

Q2. Does the information flow among stakeholders appear feasible within a typical prefabrication supply chain setting?

- Poor
- Average
- Good
- Very good
- Excellent

Reasons for your answer to this question

Q3. Do the steps of implementing the framework follow a coherent sequence, allowing for its replication by researchers and practitioners?

- Poor
- Average
- Good
- Very good
- Excellent

Reasons for your answer to this question

Q4. Is the framework appropriate for practical adoption in the prefabrication supply chain in New Zealand?

- Poor
- Average
- Good
- Very good
- Excellent

Reasons for your answer to this question

General comments/feedback

Appendix 5: Statement of Contribution

1. Doctoral research contribution for the paper used in chapter 2.
2. Doctoral research contribution for the paper used in chapter 3.
3. Doctoral research contribution for the paper used in chapter 3.
4. Doctoral research contribution for the paper used in chapter 4.
5. Doctoral research contribution for the paper used in chapter 5.

As stated in the attached statements.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Ehsan Bakhtiarizadeh
Name/title of Primary Supervisor:	Professor James Rotimi
In which chapter is the manuscript /published work:	Chapter 2

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

A process map for supply chain relationships in prefabricated construction

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:
- The percentage of the manuscript/published work that was contributed by the candidate: 80.00
- Describe the contribution that the candidate has made to the manuscript/published work:

Participated in the research to investigate the solutions through data collection and analysis. Conducted literature review and prepared the first draft of the manuscript.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Ehsan Bakhtiarizadeh Digitally signed by Ehsan Bakhtiarizadeh Date: 2023.12.12 20:21:06 +13'00'
Date:	12-Dec-2023
Primary Supervisor's Signature:	James Olabode Bamidele Rotimi Digitally signed by James Olabode Bamidele Rotimi
Date:	30-May-2024

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

GRS Version 5 – 13 December 2019
DRC 19/09/10

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Ehsan Bakhtiarizadeh
Name/title of Primary Supervisor:	Professor James O.B. Rotimi
In which chapter is the manuscript /published work:	Chapter 3

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Blockchain technology applicability in New Zealand's prefabricated construction industry

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

Participated in the research to investigate the solutions through data collection and analysis. Conducted literature review and prepared the first draft of the manuscript.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Ehsan Bakhtiarizadeh Digitally signed by Ehsan Bakhtiarizadeh Date: 2023.12.12 20:23:06 +13'00'
Date:	12-Dec-2023
Primary Supervisor's Signature:	James Olabode Bamidele Rotimi Digitally signed by James Olabode Bamidele Rotimi
Date:	30-May-2024

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

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UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Ehsan Bakhtiarizadeh
Name/title of Primary Supervisor:	Professor James O.B. Rotimi
In which chapter is the manuscript /published work:	Chapter 3

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Applicability of Blockchain technology in New Zealand's prefabricated construction industry: A potential solution

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

Participated in the research to investigate the solutions through data collection and analysis. Conducted literature review and prepared the first draft of the manuscript.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Ehsan Bakhtiarizadeh Digitally signed by Ehsan Bakhtiarizadeh Date: 2023.12.12 20:24:23 +13'00'
Date:	12-Dec-2023
Primary Supervisor's Signature:	James Olabode Bamidele Rotimi Digitally signed by James Olabode Bamidele Rotimi
Date:	30-May-2024

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

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Name of candidate:	Ehsan Bakhtiarizadeh
Name/title of Primary Supervisor:	Professor James O.B. Rotimi
In which chapter is the manuscript /published work:	Chapter 4

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Blockchain and information integration: Applications in New Zealand's prefabrication supply chain.

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

Participated in the research to investigate the solutions through data collection and analysis. Conducted literature review and prepared the first draft of the manuscript.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Ehsan Bakhtiarizadeh Digitally signed by Ehsan Bakhtiarizadeh Date: 2023.12.12 20:25:04 +13'00'
Date:	12-Dec-2023
Primary Supervisor's Signature:	James Olabode Bamidele Rotimi Digitally signed by James Olabode Bamidele Rotimi
Date:	30-May-2024

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Name of candidate:	Ehsan Bakhtiarizadeh
Name/title of Primary Supervisor:	Professor James O.B. Rotimi
In which chapter is the manuscript /published work:	Chapter 5

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Applying secure information-based mechanism for prefabrication supply chain integration: A review

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

Participated in the research to investigate the solutions through data collection and analysis. Conducted literature review and prepared the first draft of the manuscript.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Ehsan Bakhtiarizadeh Digitally signed by Ehsan Bakhtiarizadeh Date: 2023.12.12 20:25:45 +13'00'
Date:	12-Dec-2023
Primary Supervisor's Signature:	James Olabode Bamidele Rotimi Digitally signed by James Olabode Bamidele Rotimi
Date:	30-May-2024

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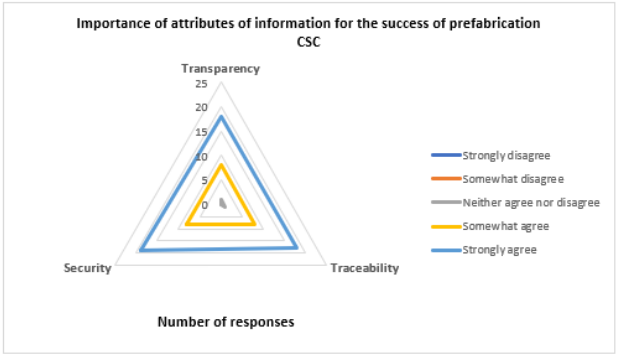
Appendix 6: Data Analysis

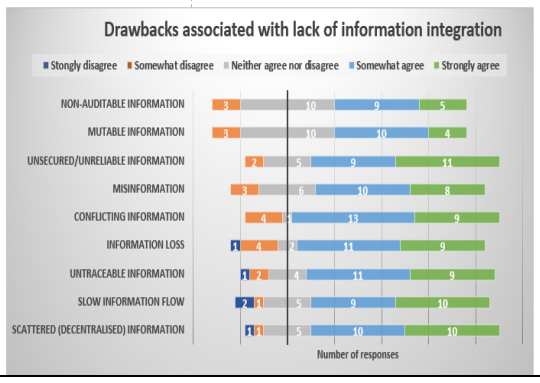
#	Question 18 **Transparency** of information is important to the success of prefabricated construction industry	Question 19 Information **Traceability** is important to the success of prefabricated construction industry	Question 20 **Security** (reliability) of information is important for the success of prefabricated construction projects
1	Strongly agree	Strongly agree	Strongly agree
2	Somewhat agree	Strongly agree	Strongly agree
3	Strongly agree	Strongly agree	Strongly agree
4	Strongly agree	Strongly agree	Strongly agree
5	Strongly agree	Strongly agree	Strongly agree
6	Strongly agree	Strongly agree	Strongly agree
7	Somewhat agree	Neither agree nor disa	Somewhat agree
8	Strongly agree	Strongly agree	Strongly agree
9	Strongly agree	Strongly agree	Strongly agree
10	Strongly agree	Somewhat agree	Strongly agree
11	Strongly agree	Strongly agree	Somewhat agree
12	Somewhat agree	Somewhat agree	Somewhat agree
13	Neither agree nor disa	Somewhat agree	Strongly agree
14	Strongly agree	Strongly agree	Strongly agree
15	Strongly agree	Strongly agree	Somewhat agree
16	Strongly agree	Strongly agree	Strongly agree
17	Strongly agree	Somewhat agree	Strongly agree
18	Somewhat agree	Somewhat agree	Strongly agree
19	Somewhat agree	Strongly agree	Strongly agree
20	Strongly agree	Strongly agree	Strongly agree
21	Strongly agree	Somewhat agree	Somewhat agree
22	Strongly agree	Strongly agree	Strongly agree
23	Somewhat agree	Somewhat agree	Somewhat agree
24	Strongly agree	Strongly agree	Strongly agree
25	Strongly agree	Strongly agree	Strongly agree
26	Somewhat agree	Strongly agree	Somewhat agree
27	Somewhat agree	Somewhat agree	Somewhat agree

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Transparency	0	0	1	8	18
Traceability	0	0	1	8	18
Security	0	0	0	8	19

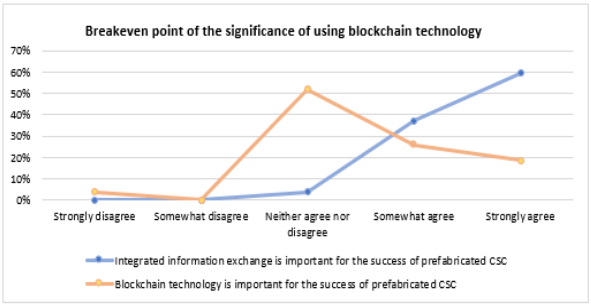


Scattered (Decentralised) information	Slow information flow	Untraceable information	Information loss	Conflicting information	Misinformation	Unsecured/Unreliable information	Mutable (susceptible to manipulation) information	Non-auditable information
Strongly agree	Strongly agree	Somewhat agree	Somewhat agree	Somewhat agree	Neither agree nor disagree	Somewhat agree	Neither agree nor disagree	Neither agree nor disagree
Somewhat agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Somewhat agree	Somewhat agree
Strongly agree	Somewhat agree	Neither agree nor disagree	Strongly agree	Somewhat agree	Strongly agree	Somewhat agree	Somewhat agree	Neither agree nor disagree
Somewhat agree	Somewhat agree	Strongly agree	Strongly agree	Somewhat agree	Strongly agree	Somewhat agree	Somewhat agree	Somewhat agree
Strongly agree	Strongly agree	Somewhat agree	Somewhat agree	Strongly agree	Somewhat agree	Somewhat agree	Neither agree nor disagree	Neither agree nor disagree
Somewhat agree	Somewhat agree	Somewhat agree	Somewhat disagree	Somewhat disagree	Somewhat disagree	Somewhat disagree	Somewhat disagree	Somewhat disagree
Somewhat agree	Somewhat agree	Neither agree nor disagree	Somewhat agree	Somewhat agree	Neither agree nor disagree	Somewhat agree	Neither agree nor disagree	Neither agree nor disagree
Somewhat agree	Neither agree nor disagree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree
Strongly agree	Strongly agree	Somewhat agree	Somewhat agree	Strongly agree	Somewhat agree	Strongly agree	Neither agree nor disagree	Somewhat agree
Strongly agree	Strongly agree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Strongly agree	Strongly agree	Strongly agree
Somewhat disagree	Neither agree nor disagree	Somewhat disagree	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Somewhat agree	Neither agree nor disagree
Neither agree nor disagree	Strongly disagree	Strongly disagree	Somewhat disagree	Somewhat disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Somewhat disagree
Strongly disagree	Strongly disagree	Somewhat disagree	Somewhat disagree	Somewhat disagree	Neither agree nor disagree	Neither agree nor disagree	Somewhat agree	Somewhat disagree
Neither agree nor disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Somewhat agree	Neither agree nor disagree	Somewhat agree	Neither agree nor disagree	Somewhat agree
Strongly agree	Somewhat agree	Strongly agree	Somewhat agree	Somewhat agree	Somewhat agree	Strongly agree	Somewhat disagree	Neither agree nor disagree
Strongly agree	Somewhat agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree	Somewhat agree
Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
Neither agree nor disagree	Neither agree nor disagree	Somewhat agree	Somewhat disagree	Somewhat agree	Somewhat disagree	Somewhat disagree	Somewhat disagree	Neither agree nor disagree
Somewhat agree	Neither agree nor disagree	Somewhat agree	Neither agree nor disagree	Somewhat agree	Somewhat agree	Strongly agree	Neither agree nor disagree	Somewhat agree
Neither agree nor disagree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree
Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree
Somewhat agree	Somewhat agree	Strongly agree	Strongly agree	Somewhat agree	Somewhat agree	Strongly agree	Somewhat agree	Somewhat agree
Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Somewhat agree	Somewhat agree	Strongly agree
Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree
Somewhat agree	Strongly agree	Somewhat agree	Somewhat agree	Strongly agree	Somewhat agree	Strongly agree	Somewhat agree	Somewhat agree

	Strong	Somew	Neithe	Neithe	Somew	Strong
Scattered (Decentralised) information	1	1	2.5	2.5	10	10
Slow information flow	2	1	2.5	2.5	9	10
Untraceable information	1	2	2	2	11	9
Information loss	1	4	1	1	11	9
Conflicting information	0	4	0.5	0.5	13	9
Misinformation	0	3	3	3	10	8
Unsecured/Unreliable information	0	2	2.5	2.5	9	11
Mutable information	0	3	5	5	10	4
Non-auditable information	0	3	5	5	9	5



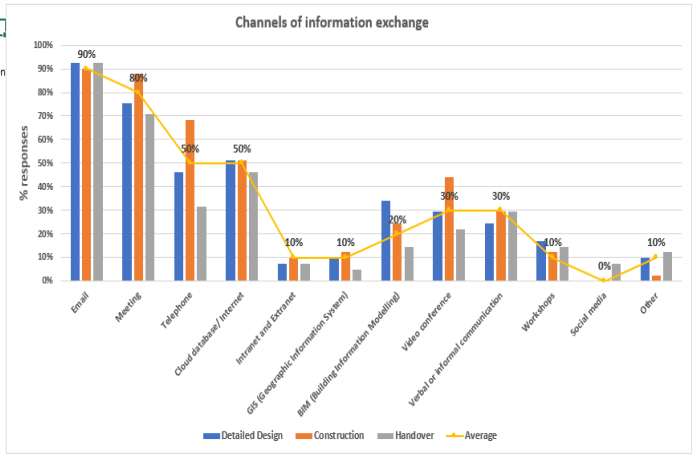
#	Q21 Integrated information exchange impacts positively on prefabricated construction supply chain	Q22 Blockchain technology impacts positively on prefabricated construction supply chain performance/integration
1	Strongly agree	Neither agree nor disagree
2	Neither agree nor disagree	Neither agree nor disagree
3	Strongly agree	Neither agree nor disagree
4	Strongly agree	Neither agree nor disagree
5	Strongly agree	Neither agree nor disagree
6	Strongly agree	Neither agree nor disagree
7	Strongly agree	Neither agree nor disagree
8	Strongly agree	Strongly agree
9	Somewhat agree	Somewhat agree
10	Somewhat agree	Somewhat agree
11	Strongly agree	Somewhat agree
12	Strongly agree	Somewhat agree
13	Somewhat agree	Somewhat agree
14	Somewhat agree	Neither agree nor disagree
15	Strongly agree	Strongly agree
16	Strongly agree	Somewhat agree
17	Somewhat agree	Neither agree nor disagree
18	Strongly agree	Strongly agree
19	Somewhat agree	Strongly disagree
20	Strongly agree	Somewhat agree
21	Somewhat agree	Strongly agree
22	Somewhat agree	Neither agree nor disagree
23	Somewhat agree	Neither agree nor disagree
24	Somewhat agree	Neither agree nor disagree
25	Strongly agree	Strongly agree
26	Strongly agree	Neither agree nor disagree
27	Strongly agree	Neither agree nor disagree



	Strongly disagree	Somewhat disagree	Neither agree nor	Somewhat agree	Strongly agree
Integrated informati	0%	0%	4%	37%	59%
Blockchain technolog	4%	0%	52%	26%	19%

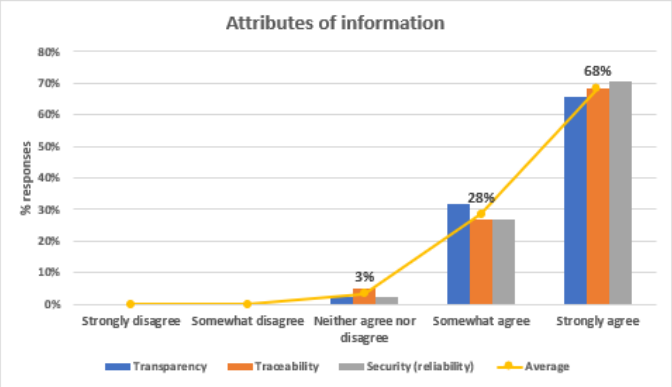
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	Question 7																				
2	Please indicate the main channel(s) for exchanging information between Client and Contractor at the Detailed Design phase of your projects. (select all																				
3	Email	Telephor	Cloud da	BIM (Buil	Video co	Verbal o	Other														
4	Email	Meeting	Video co	Workshops																	
5	Email	Meeting	Cloud da	BIM (Building Information Modelling)																	
6	Other																				
7	Email	Telephor	Cloud da	BIM (Buil	Video co	Workshops															
8	Email	Meeting	Telephor	Cloud da	Video conference																
9	Email	Telephone																			
10	Email	Meeting	Cloud da	Intranet	Other																
11	Email	Meeting	Cloud database/ Internet																		
12	Email	Meeting	Telephor	Cloud da	GIS (Geo	Verbal o	Workshops														
13	Email	Meeting	Telephone																		
14	Email	Meeting	Telephor	BIM (Buil	Video co	Verbal or informal communication															
15	Email	Meeting																			
16	Email	Meeting	Intranet	BIM (Buil	Video conference																
17	Email	Meeting																			
18	Email	Telephor	Cloud database/ Internet																		
19	Email	Meeting	Telephor	BIM (Buil	Video co	Verbal o	Workshops														
20	Video conference																				
21	Email	Meeting	Telephor	Cloud da	BIM (Buil	Video co	Verbal o	Workshops													
22	Email	Meeting	Cloud da	BIM (Building Information Modelling)																	
23	Email	Meeting	Telephone																		
24	Email	Meeting	Telephor	Verbal or informal communication																	
25	Email	Meeting	Telephor	GIS (Geographic Information System)																	
26	Email	Meeting	Telephor	Cloud database/ Internet																	
27	Email	Meeting	Telephor	Cloud da	GIS (Geo	Video co	Verbal o	Workshops													
28	Email	Meeting																			
29	Email	Meeting	BIM (Buil	Workshops																	
30	Email	BIM (Building Information Modelling)																			
31	Meeting	Cloud database/ Internet																			
32	Email	Cloud da	Verbal or informal communication																		
33	Email	Meeting	Telephor	Cloud da	Video conference																
34	Email	Telephone																			
35	Email	Meeting	Cloud da	Intranet	Other																
36	Email	Meeting	Cloud database/ Internet																		
37	Email	Meeting	Telephor	Cloud da	BIM (Buil	Video co	Verbal o	Workshops													
38	Email	Meeting	Cloud da	BIM (Building Information Modelling)																	
39	Email	Meeting																			
40	Email	Meeting	BIM (Buil	Workshops																	
41	Email	BIM (Building Information Modelling)																			
42	Email	Meeting	Cloud database/ Internet																		
43	Email	Meeting	Telephor	Cloud da	GIS (Geo	Verbal o	Workshops														

		Email	Meeting	Telephone	Cloud data	Intranet an	GIS (Geogr	BIM (Buildi	Video conf	Verbal or in	Workshops	Social med	Other
Question 7	Detailed Design	0%	83%	63%	49%	10%	12%	22%	41%	29%	15%	0%	0%
Question 9	Construction	0%	71%	27%	41%	7%	5%	12%	22%	27%	15%	7%	12%
Question 11	Handover	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Average	0%	50%	30%	30%	10%	10%	10%	20%	20%	10%	0%	0%



Q18	Q19	Q20
Transparency of information is important to the success of prefabricated construction industry	Information Traceability is important to the success of prefabricated construction industry	Security (reliability) of information is important for the success of prefabricated construction projects
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Neither agree nor d	Somewhat agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Somewhat agree	Strongly agree
Strongly agree	Strongly agree	Somewhat agree
Somewhat agree	Somewhat agree	Somewhat agree
Neither agree nor d	Somewhat agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Somewhat agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Somewhat agree	Strongly agree
Somewhat agree	Somewhat agree	Strongly agree
Somewhat agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Somewhat agree	Somewhat agree
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Somewhat agree	Somewhat agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Strongly agree	Somewhat agree
Somewhat agree	Somewhat agree	Somewhat agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Strongly agree	Neither agree nor disagree
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Neither agree nor d	Somewhat agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Somewhat agree	Strongly agree	Somewhat agree
Somewhat agree	Somewhat agree	Somewhat agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Strongly agree	Strongly agree
Strongly agree	Somewhat agree	Strongly agree

	Strongly disagree	Somewhat disagre	Neither agree nor d	Somewhat agree	Strongly agree
Transparency	0%	0%	2%	32%	66%
Traceability	0%	0%	5%	27%	68%
Security (reliabi	0%	0%	2%	27%	71%
Average	0%	0%	3%	28%	68%



#	1. Is the framework easy to comprehend and utilize for blockchain adoption?	2. Does the information flow amongst stakeholders appear feasible within a typical prefabrication supply chain setting?	3. Do the steps of implementing the framework follow a coherent sequence, allowing for its replication by researchers and practitioners?	4. Is the framework appropriate for practical adoption in prefabrication supply chain in New Zealand?
1	Average	Average	Average	Average
2	Very good	Excellent	Good	Very good
3	Very good	Very good	Good	Very good
4	Average	Very good	Good	Good
5	Average	Good	Average	Good
6	Good	Average	Good	Good
7	Good	Good	Very good	Very good
8	Good	Very good	Good	Very good
9	Average	Very good	Good	Good

1	2	2	2	2
2	4	5	3	4
3	4	4	3	4
4	2	4	3	3
5	2	3	2	3
6	3	2	3	3
7	3	3	4	4
8	3	4	3	4
9	2	4	3	3
	25	31	26	30
Average	**2.78**	**3.44**	**2.89**	**3.33**