University of Ottawa

Achieving Construction Material Traceability by Leveraging Blockchain Technology

by

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Thesis submitted to the University of Ottawa
in partial Fulfillment of the requirements
For the M.Sc. degree in
Digital Transformation and Innovation

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Abstract

Several researchers indicate that construction materials cost more than any other element of a construction project, reaching 50 - 60 % of the total cost. Materials go through different stages and complex exchanges in their life cycles, and the material's tracking is usually conducted manually (paper-based). Besides that, customers have little awareness of where the materials come from and how they are handled. In addition, construction projects often do not have a common system where they can share and manage material traceability information in a secure and trusted way. Many of the material traceability challenges in the construction chain come from relying on traditional tools and manual forms to gather tractable information, enter them in centralized databases, which lack interoperability between systems. Such measures cause a delay in the call back of defective materials, updated transportation information, as well as fraud, a lack of sharing due to privacy and security of information. A lack of focus on tracking within some stages and neglecting reverse logistics may also occur. This study aims to enhance material traceability by implementing blockchain technology, specifically Hyperledger Fabric, as a solution to address these issues. Blockchain, through its immutable, distribute, and secure storage of data, could provide a seamless collaboration platform with no boundaries to achieve traceability and unique material tracking. Also, the consensus mechanism of blockchain will allow all participants to be involved in each transaction, which could increase visibility, communication, quality of materials and reduce fraud, and disputes. A platform has been built according to obtained traceability requirements from the food industry due to the extensive research already conducted in the field along with the background analysis. The validity of blockchain in improving material traceability platform has been tested in a series of use cases and has been evaluated qualitatively to measure to what extent the use cases are workable and therefore usable, and to what extent the use cases are restricted.

Acknowledgements

My sincere appreciation and gratitude go to my supervisor, Prof. Tet Yeap, for his guidance, valuable suggestions, constant encouragement and precious advice during the fulfilment of this thesis. My appreciation also goes to Mr. Rahul Saini for his help and contribution toward completing the platform. I thank anyone at the University of Ottawa who played a role in my academic accomplishments. Finally, a big appreciation goes to my country, the Kingdom of Saudi Arabia, for the unconditional support during my academic studies.

Dedication

First, I'm grateful to Allah who has given me the strength to complete my thesis in a prescribed time. Also, I would like to dedicate this work to my parents for their continuous support and encouragement, you were both always the reason behind my success. A big thank you goes to my brothers, Khalid and Muhammad who accompanied me during my time in Canada. Also, would like to thank my little brothers, Mohanad, Ahmed and Yousef. Your love and support were always the light in my hardest time. My respect and love go to my two grandmothers, your prayers have always been by my side since I started this journey. Last, but not least, to all my friends for helping me survive all the stress.

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Chapter 1

Introduction

In our modern society, the construction industry is becoming bigger, more complex, and tracking materials through complex supply chains is challenging. Thus, the industry is looking at ways to ensure the quality and sustainability of the materials throughout the supply chain [48]. With many efforts have been accomplished to manage the complexity, supply chain management (SCM) practices [27] and using the right technologies [58] have proven their competence toward finding ways to improve traceability to verify and maintain quality of materials. Thus, the development of technology to fulfill construction supply chain needs is a current incentive for most companies.

A novel technology that might meet these criteria is blockchain. It has been a controversial topic since the launch of Bitcoin in 2008 by Satoshi Nakamoto [44]. However, companies and industries are now keen to find other fields of operation and new applications using blockchain. One particular area is the construction industry, it is believed that blockchain has the potential to improve material traceability in construction supply chains [59][60], which the author is trying to prove in this dissertation.

This study aims to develop a construction consortium platform by utilizing the capability of blockchain technology. Furthermore, to investigate whether blockchain can enhance material traceability to increase material quality (e.g. verify material origins) and reduce losses (e.g. counterfeit materials) in the logistics processes. In this chapter, a background to material traceability in the construction supply chain and blockchain technology is presented. Also, this chapter focuses on explaining the main points of the research problem, defining the thesis statement, and stating the research questions. The motivational for conducting this study is described, the objectives are specified, and the structure of the dissertation is laid out.

1.1 Motivation

Since I was a child, I have noticed that my family, and families in Kingdom of Saudi Arabia, avoid buying ready-built houses, and they tend to build their own houses under their own supervision. They also prefer purchasing material from suppliers directly and handing them to a contractor as they are afraid of material falsification and poorly constructed houses. I recall seeing my father watching workers mixing and pouring concrete as if he was the "superintendent". The decision to acquire a house in my country involves risks as many stories concern people who had been cheated or who had bought poorly constructed houses in multiple ways.

As discussed in Section 1.3, a current drawback that might cause these issues is the weak traceability of construction material in existing practices and software that did not apply the needed material traceability requirements in today's supply chain. Customers today, as a newcomer in the modern supply chain and construction chain partners, expect information about the provenance of materials. Not only they must have a complete project on time and within budget, but also when something goes wrong, and the material does not meet the quality, they want to have access to the cause of the problem and who causes it and who also has affected. According to Fan et al., [28] increasing traceability awareness of customers by adopting a new solution is a key to enhance the supply chain process. In line with these trends, as the traceability requirements develop, the current technology should adopt to keep up with changes by seeking new solutions.

A Blockchain as recent technology might be used to reduce the challenges mentioned in Section 2.1.4 of material traceability in the construction industry. With its characteristics, blockchain would enhance the material traceability by determining the provenance of materials, transforming the construction chain into an automated way, and strengthen interrelationship between partners and increase trust in a way that we could with it integrate material's information and provide up-to-date information about the material's status between partners that was hard to achieve before with centralized systems. Besides, blockchain is a secure, tamper-resistant, and immutable storage of information.

1.2 Material Traceability in Construction Supply Chain

A construction SCM deals with multiple challenges today because construction projects are increasingly engaged in globalization [17], where the material logistics chain has a long and complex journeys (sometimes in different geographic areas) before it becomes an end product. Each country has different requirements, laws, and regulations to ensure traceability standards are satisfied. However, this is not an easy feat, especially importing from international markets, due to counterfeit material and the quality of materials is questionable e.g. the case of importing steel from China to the UK [19].This could create a challenge because when a problem occurs, we have to trace it back to understand the issue, and identify whoever is affected e.g. suppliers, and their suppliers' suppliers. Currently, this is not achievable due to current regulations, in addition to practices and systems **lacking the requirements of modern supply chain**. Thus, preventing a trace back to the point in which the problem has occurred, and usually the available information is limited to some points in the chain, not the entire supply chain.

In addition, it is important to recognize that a construction project is a one-off prototype, where each customer has different requirements, and developed by partners who often come to work together for the first time and may never work together again [20]. This short-term relationship and uniqueness of the project increase the demand for material quality control in the entire supply chain.

There is also a new trend in the modern supply chain for consumers (e.g., governments) to be aware of the provenance and authenticity of a material they purchase. Customers want to trust companies and partners who do business by knowing where each material comes from, and in what conditions it is produced, to ensure that materials are manufactured with great attention to environmental impact, quality, and safety [30]. Thus, the entire supply chain of a material's journey must be governed, so accurate traceability and transparency to its customer can be achieved.

Therefore, optimizing construction SCM traceability is an incentive for companies to change its current practices to trace a material, from the initial phase until completion, because the development of a system that can enhance traceability is a necessity as it enables up-to-date information of material status, and provides trustworthy relationship among partners and their customers as well.

1.3 Problem Definition

As discussed in Sections 2.1.1 and 1.2, traceability of materials in construction SCM flows in all directions from raw material producer to the end customer. During its life cycle, material will go through roughly five phases, while some products have less than that e.g. bulk material. Typically, material related information recreates several times during manufacturing and shipping, and while moving from one point to another the owner is changed too. This scenario is not exclusive to construction industry, but products in other industries are mostly gone through the same.

The traditional approach, current practices, and existing software to handle materials have made material traceability in the construction supply chain logistics poor and insufficient. The improvement of material traceability in construction projects is the main objective of this thesis. However, there are multiple points in this improvement. Many have already been mentioned in Sections 1.2, 2.1.1, and 2.1.4, from which the following points are summarized as main categorization of challenges related to material traceability:

- **Information Limitation**.
- **Standard Limitation**.
- **Scope Limitation**.
- **Sharing Limitation**.

The actual problem with the previous points above shows that there is insufficiency when it comes to material traceability in the supply chains within the construction industry.

Researching of solution that can contribute to better material traceability and adds value to customers is a goal. Blockchain with its characteristics sounds a possible solution to be applied and investigated if it can be a valid solution to satisfy the requirements of traceability improvement in the flow of material in the construction chain logistics.

1.4 Blockchain as a Transformation for Construction Supply Chain

Blockchain is a shared, distributed, decentralized, and secured database. It was first deployed to use in an invented digital currency "Bitcoin" by Satoshi Nakamoto in 2008 [44] for keeping a permanent public record of transactions. The concept behind blockchain as a cryptographically secure chain of documents is not new as it is first originated from Haber and Stornetta [34]. Since then, industries have become enthusiastic about getting the benefit of technology that supports the characteristics of immutable, distributed, decentralized, and global networks.

Blockchain has a good analogy drawn by Chatterjee and Chatterjee [25] to make it understandable. Imagine a blockchain as a book where each page of the book refers to its previous page by a page. Each page contains sets of transactions. Once a page is filled with enough entries (approximately 10 min of transactions), it will get time-stamped, signed with a unique number, and added into the book. In this analogy, the book is the blockchain, pages are the blocks, and the unique number is the hash of the content in one page that linked to adjacent pages by a computational algorithm forming a hard chain that impossible to be broken. Hence, it is impossible to tamper a transaction without tampering the unique number of a specific page and also tampering the link between this specific page, the next page and all subsequent pages. Altering one of the blocks is nearly impossible because it is easy to notice whether a page is ripped off or not.

A construction supply chain is one of the areas the author believes that blockchain can bring prosperity to it. As discussed earlier, globalization has forced the construction industry to become more complex over the years, and materials have a more complicated and longer journey than ever before [17]. Increasing complexity is a natural outcome of supply chain development; however, it is not easy to deal with it, especially when the current practices or software cannot deal with the distributed nature of construction projects with other partners, resulting in difficulties of integrating information between them of materials in the construction supply chain [17].

Therefore, this dissertation will utilizie blockchain to improve the traceability of material in the construction industry, to enhance construction logistics processes and customer experience as well.

1.5 Objectives

The main objective of this dissertation is to investigate whether blockchain is a suitable approach to **improve material traceability** and reduce challenges that cause the insufficiency of traceability through the construction logistic chains, and also to determine the right requirements of traceability that can fit today's modern supply chain, and investigate whether blockchain can support them. This dissertation will determine if a blockchain can:

- Track where each material comes from, in which condition, and how a supplier delivers it, exchanges it, and how it is handled until it becomes an end product.
- Provide a secure communication channel that allows the dissemination of instantly up-to-date information where partners can share, query, and track the status of materials.
- Increase visibility from one end to another end in the logistics chain to have a global view of the chain and fast integration of data to avoid material fraud, reduce disputes, and allow early call back of defective materials.

1.6 Thesis Statement

The main objectives have been already identified in Section 1.5, to **improve material traceability by tracking the provenance and journey of materials, increase visibility from one end to another, improve information exchange, provide secure communication to increase trust of shared information**. Here, this dissertation focuses on investigating the material's traceability challenges, and whether blockchain can be used to solve such challenges and support traceability requirements. Therefore, the hypothesis this thesis defends is

"blockchain can make material traceability in construction logistics chain more efficient and effective ".

The research questions that will be answered to validate the thesis statement and achieve the objectives are:

RQ1: What are the challenges that prevent accurate and complete traceability of materials through the construction logistics chain?

RQ2: What are the requirements that would be considered most valuable to improve the traceability of materials in the construction logistics chain?

RQ3: Which kind of blockchain initiatives and tools can be chosen to design a platform for construction projects to apply the material traceability requirements?

RQ4: In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?

1.7 Methodology

The work of this dissertation was split into six steps following a design science research (DSR) approach in order to answer questions from Section 1.6. Theses steps are accomplished sequentially as shown in Figure 3.1, and each of them belongs to one of two main phases as divided by the author.

The first phase covers steps 1 and 2 in the DSR model and it is aimed to be the theoretical aspect of this dissertation. The second phase covers steps 3, 4, and 5 in the DSR model and it is aimed to be the design, demonstration, and evaluation of the proposed solution. Accomplishing the second phase and remaining research questions depend on the answer we reach from the second research question.

Below is a brief of the methodology of my work:

- Phase 1
  - Literature search to find a gap.
  - Literature search of chosen solution.
- Phase 2
  - Literature search to obtain traceability requirements.
  - Implementation.

1.8 Thesis Contribution

The main contribution is to develop a seamless platform with no boundaries using blockchain to enable B2B collaboration, leading to an improvement in material traceability in the construction logistics chain. Material's up-to-date information will be available and can be shared more efficiently in a reliable and secure network among the partners of a construction project, including customers as well.

Following are the contributions of my work:

1. Obtained traceability requirements.
2. Designed a blockchain-based material traceability system.
3. Designed an architecture to integrate the proposed system with other ERPs or internal traceability systems.
4. Defined a set of use cases to evaluate the functionality of the proposed system.

1.9 Delimitations

- The dissertation will focus on improving the traceability for materials in the construction industry.
- In a construction project, there are a variety of materials to be handled. Thus, in this study, materials will be narrowed down, and the focused in increasing traceability will be on a **bulk material** which lifecycle starts from downstream parties of the supply chain, as shown in Figure 2.1.
- The proposed platform will be evaluated if it could improve the traceability of a chosen type of bulk material(s).

1.10 Dissertation Structure

This dissertation has five chapters, in addition to the introduction:

Chapter 2 - This chapter is mainly a guide to provides background information about the current practice of material traceability in the construction industry and existing challenges. It also helps to understand the concept of blockchain and how it is used in the supply chain industry and current tools and frameworks. This chapter is divided into three main sections as the following. In the first section, this chapter features a literature review of material traceability in the construction industry to determine the gap that is preventing successful chain traceability. The second section includes concepts and definitions of blockchain from different perspectives. Blockchain architecture is described, and security implementation and categorization are presented. It also provides an analysis and comparison of the most popular frameworks. The last section of the chapter covers blockchain in the supply chain industry. The benefits and challenges of applying blockchain are described. Also, existing applications are examined, and steps for designing a similar application is included.

Chapter 3 - This chapter provides the proposed methodology to approach the research problem, questions, objectives, and the hypothesis. Then, this follows with an analysis of the traceability requirements in the food industry along with the background analysis to obtain traceability requirements, which uses as a basis to choose the best blockchain framework and design the proposed solution.

Chapter 4 - This chapter contains the chosen blockchain framework for the proposed solution, a detailed analysis of the traceability requirements for the the proposed solution that is obtained from chapter 3, the actual implementation of the proof of concept, and architecture for integrating the current proposed solution with other internal traceability systems or ERPs.

Chapter 5 - This chapter contains an empirical test through the designed platform based on the typical flow of material traceability in the construction supply chain that is shown in Figure 4.2. Then, it follows with a qualitative evaluation of the validity of the proof of concept on supporting the material traceability requirements in a series of use cases to reach a conclusion about the made hypothesis.

Chapter 6 - This chapter presents an overview of the work carried out to formulate a proposed solution, along with providing an answer to the problem and the thesis statement. The validity of work, Research contributions, difficulties, and future work are also put forward.

Chapter 2

Literature Review

This chapter contains background information on past research, including articles discussing material traceability in the construction supply chain, and blockchain. In the first section, literature representing material traceability in the construction industry's supply chain is presented to inform of current practices, technologies, and challenges. I then follow with a discussion of blockchain technology, including its concepts, principles, categorization and applications. In addition, I present the most popular blockchain frameworks, and a comparison of existing frameworks.

Finally, to demonstrate any potential advantages, disadvantages and impacts, both positive and negative, other industries use of blockchain in their supply chains is presented in the last section of this chapter. Moreover, similar projects that have tried to integrate blockchain as a solution to the supply chain industry are discussed, and key components for designing similar applications are listed, which will be later used as a solid ground in the design analysis and decision process.

2.1 Material Traceability in the Construction Supply Chain

The construction industry is a one-off prototype industry where each project has its material requirements, based on customer's preferences [20]. Along with globalization, these projects are becoming increasingly complex, and tracking elements through the supply chain is challenging [17]. The increased demand requires knowledge of material's provenance, quality control, and protection against counterfeit material from the beginning to the end in the logistic supply chain [30]. Therefore, continuous, up to date information on purchased materials and material status is important, particularly for the main contractor (project manager), as it can reveal whether the correct materials have been obtained and whether they can continue on schedule. The key to following material-related information, verifying it, and maintaining information associated with the material's life cycle as it moves along the supply chain is **traceability**.

This section acts as a reference to prior research on academic articles of material traceability in the construction industry. By presenting findings from a literature search, we can then understand current practices, including different concepts of traceability, technologies, and current challenges. Also, gaps in academic literature regarding material traceability can be identified.

2.1.1 Traceability in Construction Material

The construction industry is generally a group of partners entering a contract to work together to build an asset for a specific customer. The typical supply chain partners that carry out a construction project are architects, engineers, main contractors, subcontractors, and material suppliers [20]. Here, the "supply chain" acts as a linkage between partners to transform a range of services, resources, and materials into products or services consumed by customers [48]. It is important to understand that the construction industry has a difficulty in that each project has a unique prototype and is developed by partners who come together to work for the first, and possibly the last time, which means a unique construction supply chain would be created each time a new project started [20]. The only continuous, repetitive aspect in each supply chain link is the suppliers who offer the least bid for purchasing materials [20].

Materials are an integral element in the construction supply chain, and crucial as the amount spent on materials in construction projects is approximately 50 % - 60 % of the total project budget[52]. Therefore, managing material logistics is important, as it can have a direct impact on the timeline of construction work and the cost [49]. For example, hundreds of materials go through multiple stages before consumption, so if a problem occurs and the correct material is not delivered, this would then cause successive failures somewhere else in the construction project, leading to project delays and increased costs. Figure 2.1 shows the material and information flow of a typical construction supply chain, to highlight the complexity of traceability within this industry.

As shown in the figure below, the physical movement of materials from producers to end customers is the way partners are connected in the construction supply chain. Also, the flow of materials is accompanied by information coming from upstream and downstream partners. In real life, according to Pryke [48], the material's flow, associated information, and the relationship between partners are not always straightforward and simple as shown above, and might break down into several tiers of suppliers who would be involved in a specific product. The flow usually depends on the nature of a project, the decisions to be made, the processes, and partners involved. A material's life cycle starts down from the material extraction stage (or manufacturing) and goes up until having a finished product. Each link within the construction supply chain has its flow and might have a different endpoint. The path that is taken for the flow of information, materials, and resources is not the same at any given point as shown in the figure, it might go forward, backward, up, down, or overlap with other points. The set of activities each flow may go through are extracting raw materials, manufacturing, storage, transportation, installation, inventory tracking, distribution, and monitoring. As shown in Figure 2.1, Behera et al.,

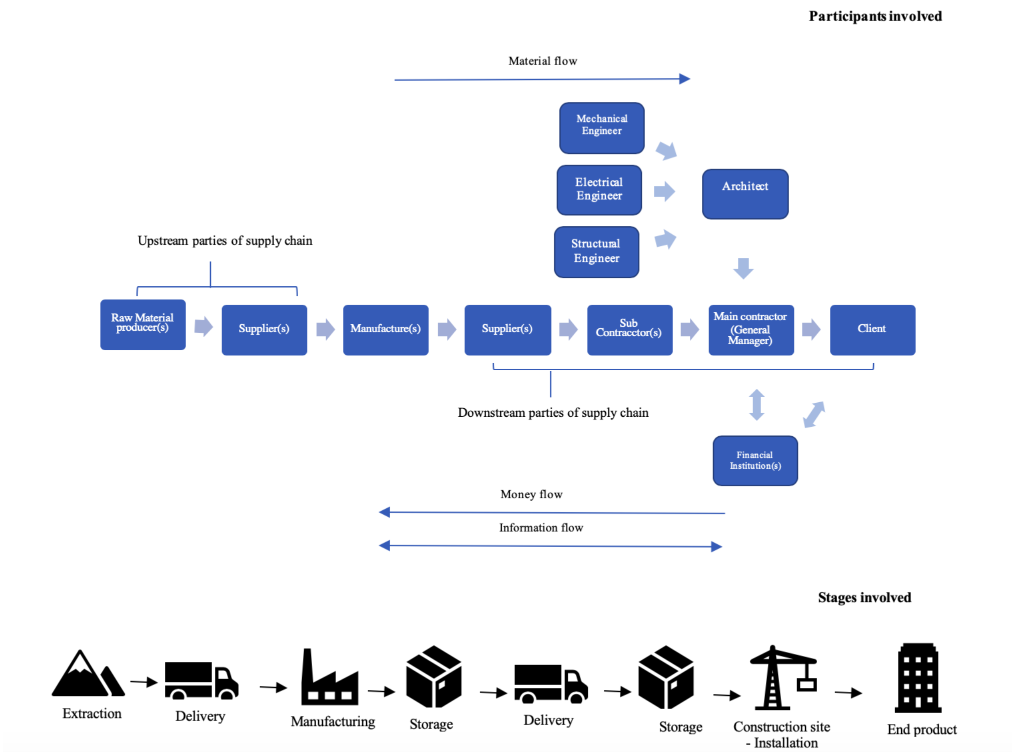

Figure 2.1: Traceability of Construction Materials (edited)[58].

[20] summarized those activities into five basic processes – plan, source, make, deliver and return.

At each activity level, construction SCM exists to manage and control all processes and flow of information between partners as well as enhancing the inter-operability relationship between them from one point to another and maintaining safety and quality [48]. **However, construction supply chains are becoming more complex, it is subject to constant changes with globalization and uniqueness, thus, tracing material becomes difficult.**

2.1.2 Traceability and Related Concepts

Unlike other industries, such as the food industry, traceability is still in its early stages in the construction industry. Rare studies have been found regarding traceability in relation to the quality of materials in the construction industry. A report published by the Business Roundtable [49] claims that the quality of the material is the responsibility of the purchasing department to assure that materials satisfy the purchaser's criteria and are available at the time needed. On the other hand, Stukhart [55] claims that quality objective is to control the flow of materials at the source, so counterfeit materials are prevented, and this is done through series of inspections along the supply chain. Such as: supplier and purchaser should agree on the condition of each transaction, requirements needed, how to verify that requirements are met, and compensation in case of material defects. Here, different traceability definitions and concepts are covered to understand how traceability has been processed in the industry.

Traceability Definition

As mentioned earlier, in the construction industry, traceability in relation to quality has been defined in a few papers. The report of BRE's Environmental & Sustainability Standard BEC 6001 provides a reference definition of traceability [31]. This reference definition is back to ISO 9000:2015 [14]. Upon my research, there is a lack of published studies in this industry, that come up with their own definition of traceability, and they always refer to standards such as ISO. Another, global organizations that show interest in traceability is GS1. The GS1 developed global traceability standards for product safety and quality, that are applicable to be applied in any supply chain, and also provide a referenced definition for supply chain traceability [32]. Table 2.1 shows both definitions.

Table 2.1: Definitions of traceability in the construction sector

Source	What to trace?	What to track?	Definition
BRE Global p.12 [31]	an object	-	"The ability to trace the history, application or location of an object" ISO 9000: 2015
GS1 Global Traceability Standard p.13 [32]	that which is under consideration	movement	"Traceability is the ability to track forward the movement through specified stage(s) of the extended supply chain and trace backward the history, application or location of that which is under consideration"

By analyzing both definitions, the ISO definition does not specify the stages where traceability should be implemented, while GS1 expects traceability to be implemented in specified stages, and not the entire supply chain. Both specify what details can be traced (e.g. history and location), however, GS1 extends the definition to track the movement as well. Also, both refer to the item to be traced with a generic word(s), 'object', and 'that which is under consideration', to show that the definition is suitable to apply traceability to any materials. This is important because each organization has its own objectives among other organizations and its own way of implementing traceability [32]. The GS1's definition of traceability is chosen next to ISO 9000:2015 as a theoretical reference for this dissertation for the following reasons:

- It develops Global Traceability Standards to improve safety, quality, efficiency, and visibility in the supply chain.
- It allows seamless information flow between partners.

- It uses global standards (ISO 9001:2000) as the reference of its definition which makes it flexible to address supply chain organizational objectives.
- GS1's definition is generic, and it could be applied to any business context, where it describes the "entity" of traceability with "that which is under consideration".
- In the definition, it refers to traceability as both the ability to track forward and trace backward which both are the essence of achieving full traceability.

The GS1's report contains not only traceability definition but also it delves deeper than ISO 9000: 2015, to classify traceability in term of tracking and tracing, Traceable Resource Unit (TRU), internal, external and chain traceability and traceability data. More detailed descriptions of what traceability is, are below.

Tracking and Tracing

Traceability is the ability to trace or track something. **Tracking, track forward, or descending traceability** is the capability of detecting the location of an item in the downstream direction of the supply chain based on a given criterion. On the other hand, **tracing, trace backward, or ascending traceability** is the capability of revealing an item's history and that includes the origin and its characteristics in the upstream direction of the supply chain based on a given criterion [32]. Here, both can be important for monitoring the quality of materials in the construction industry. For example, when a material does not meet quality standards, the tracking ability helps to recall defective materials at an early stage, while tracing can find the cause as well as everyone who was affected.

Traceable Resource Unit

The traceable resource unit (TRU) is a representation of the object in the supply chain that we want to trace or track [16]. Each TRU has a unique identifier and attributes (quality information of material at different times) that detaches one TRU from another. The TRU size varies depending on the industry and material and related attributes [32], so TRU can be a container, bag, item, etc. Aung and Chang [16] divides TRU into three types: batch unit, trade unit, and logistic unit. The documentation of GS1 standard [32] mentioned the same types; however, the GS1 report adds, any item other than those three is a TRU if "traceability partners agree is a traceable item" p.25 [32]. The **batch unit** is a quantity of items that are produced at the same time in the same processes. In some cases, a batch unit is a trade unit[32]. The **trade unit** is a unit that is exchanged from one company or partner to another in the supply chain (e.g. a box). The **logistic unit** is a type of trade unit that is established for transport and/or storage (e.g. pallet or container). Also, it made up by one or more TRUs, or one or more logistics unit(s) [32].

Internal and External Traceability

Traceability in the supply chain can be internal traceability, or external (chain) traceability [32]. Internal traceability refers to the traceability of an object within a supply chain entity (partner), to be processed to become one or more traceable outputs [32]. External or chain traceability refers to the traceability of the object outside the business entity. It takes place when a transaction of a traceable object happens from once traceability partner to another in the supply chain [32].

Traceability Data

The data that is relevant to a traceable system is the traceability data. It usually contains information that answers questions on who (e.g. partner), where (e.g. location), when (e.g. time), what (item), what happened (events). It can be divided into master or transaction (event) data [32]. The master data is consistent overtime and not related to the everyday activities. It usually contains general attribute information of TRUs e.g. name of a trade item, dimensions, country of origin, location, name of partners, and so on. On the other hand, event or transaction data is generated during the flow and process of TRU along the chain, and contains information such as shipment information, date of receipt, weight if variable and so on.

2.1.3 Technologies and Systems Applied in Relation to Material Traceability

Different identification technologies and information systems are used to improve logistic chain operation, particularly traceability. These **systems** have been built as a target for quality control, product recall, fraud detection, and getting real-time traceability data of materials flow in the construction logistics [36]. Today, such traceable systems are rarely used in construction supply chains, and researchers usually focus on material tracking and neglect reverse logistics (backward traceability). One of the core identification technologies that is used by researchers is RFID. It replaces previous identification technology such as bar code, QR-code because it enables effective tracking of materials [36]. Yet it does not reflect any significant performance in the industry as there have been rejected from some suppliers because of the cost associated with it [36].

Among these researches, Ikonen et al., [36] developed an RFlD-based information system to increase the traceability of concrete in the logistics, and communication among partners and reduce duplicated works caused by the traditional approach of collecting information. Their idea relies on the transfer of automated and collected information into a centralized information system that can be used for sharing information, quality inspection, connecting users and various information systems.

Song et al., [53] conducted a project to control material and information flow more effectively through continuous tracking by supporting communication between RFID and wireless sensor network (WSN) in construction SCM logistics processes.

Similarly, instead of using RFID, Dong et al., [26] developed a material quality inspection and tracking system using WSN and mobile phone to reduce the need to use paper-based for quality record inspection and increase information synchronization between the contractor's office and the construction manager.

2.1.4 Material Traceability Challenges

After having a glance at material traceability through the construction supply chain, it is now possible to mention the current challenges that face material traceability in the construction industry. Some of the challenges are identified by other researchers, while some points are identified by the author after reviewing existing technologies and systems of material tracking.

The first, and most pertinent issue that is noticed in the construction industry is that **the dissemination of information on construction materials has been managed by traditional tools**. Such includes inspection, status updates, quality records, defect, recalls and so on, in addition to, **manual forms (paper-based) along with data that is gathered and entered in different centralized databases**, and there is a risk of error and the information may remain on paper and get lost [36][58][59]. So, **instead of using an automatic method to exchange information in a secure, accurate, timely, and easily accessible way along the chain between construction chain partners**, information still marked down on paper, manager's queries are done through phone and email, and documents are scanned and sent via email or fax.

Another problem is **the lack of visibility** from one end to another through the construction supply chain. In the construction SCM, there are difficulties in interfacing between partners, where several problems arise e.g. inaccurate data, lengthy procedures to discuss changes, delay recalls, updates, and so on. **This is caused by the fact that each partner has its own interface where little collaboration, coordination, and communication happened with others during the material life cycle** [20]. This point brings another issue in the construction chain: if an unexpected issue happened, it is hard to update (synchronize) information immediately to all partners through the chain due to the **lack of interoperability between systems** [38]. This requires a long process to read data from one system and then added to another because each company is an enterprise of its own, with its own software and different **standard formats of transmitting data in the chain**.

Lack of sharing is a major source of the issue too, which prevents up-to-date sharing of information and causes duplication of work, delays, recalls, and errors. One possible scenario is that **the nature of construction projects and the short relationship between partners who work together for a certain amount of time, and may never work together again, causes poor information exchange** because there is no economic incentive for sharing information [20]. Also, another scenario that is associated with this issue is that **companies are strict with their privacy and security, and they do not want to disclose their information outside their own boundaries** except through secure channels. **The lack of standards of communicating in reliable**

and secure end-to-end delivery of information [38] **left companies without standards to decide what to, or not to share, what to trust or what not to trust, who to trust or who not to trust** is causing a limited degree of traceability [59].

Finally, the current technologies in the industry proposed by some studies [26][53][36] **do not translate any of traceability concepts explained in Section 2.1.2, in any kind of operational way. Also, instead of covering all stages of the construction supply chain, they focus on some stages and provide a very minimal detailed information about the provenance of the material or history**, where information possess by each partner is not complete, and it is hard to trace back and have a complete overview of material through the entire construction. Furthermore, these studies concentrated more on technical functions of the technologies and its integration with other technologies e.g. RFID and WSN, without considering the real issues of reliability of tracking information, data integration, and difficulty of sharing traceability information which causes insufficiency of material traceability between construction chain partners.

2.2 Blockchain Technology

This section acts as a guide to understanding blockchain technology, it presents blockchain from different perspectives and introduces blockchain principles, which are the core behind its applications. Then, it describes blockchain categorization that has emerged since the advent of Bitcoin, as well as opportunities for business applications, beyond Bitcoin. Next, it explains the security features, later, is an overview of existing frameworks for the implementation of blockchain, a comparison of frameworks, and its applicability to construction SCM is presented.

Therefore, the purpose of this section and the following sections is an introduction to blockchain and its application in the supply chain of other industries, which will provide insight on its potential use in supporting traceability in the supply chains of the construction industry when conducting the analysis later on.

2.2.1 Introduction

The "double-spend problem" and its related analogy the "Byzantine Generals problem" are a common issue in distributed computing systems that requires consensus. Both are extensively studied, and several solutions are proposed; however, until recently, these issues prevented having a fully reliable distributed system because coordination, consistency and availability between untrusted parties are still difficult to be fully achieved [40]. Therefore, finding a global consensus among partners is of phenomenal interest. In 2008, Satoshi Nakamoto [44] introduced a blockchain as a solution for the double-spend problem. The way Nakamoto constructed blockchain has become a working approach as it solve the consensus issue in a public network. Therefore, blockchain has become a useful technology for companies to run their applications on distributed systems.

Despite the popularity gained by Nakamoto[44], the concept behind blockchain is not new, and originated with Haber and Stornetta[34]. In 1991, Haber and Stornetta [34] published a paper called “How to Time-Stamp a Digital Document”. Their idea was to create a framework where the timestamped document could not be altered. Different sections of the study presented similar concepts of what we consider now as a blockchain, and most of the features involved about blockchain today were shown in their proposed system, such as, one-way hash function and secured chain of documents.

Years later, as a solution to the double-spend problem, and to enhance transactions by cutting of a trusted third party, Nakamoto built a blockchain as an underlying technology for the first digital cryptocurrency, "Bitcoin", and it was mostly used as currency and payments [44].

Since blockchain has become popular, more improvements have been introduced to it. One of the most recent developments is the creation of the very first blockchain application *smart contracts*, which found its way in areas other than finance, such as government, insurance, health, Internet-of-Things (IoT), supply chain, voting, etc. In these areas, multiple applications have been built and the blockchain has been applied to different cases such as provenance tracking, payment services, data storage, security, and much more [23]. The disruption in multiple areas is a result of the transparency provided, which will encourage new applications across new areas in the near future.

2.2.2 Defining Blockchain

Satoshi Nakamoto's Bitcoin whitepaper [44] is the original paper that contains implementation, principles and concepts of Bitcoin. As part of that paper, Nakamoto designed blockchain even though he did not mention the term blockchain, but the name derived from the technical structure of his idea because it was constructed on a chain of blocks: "Each timestamp includes the previous timestamp in its hash, forming a chain, with each additional timestamp reinforcing the ones before it"p.2 [44] Figure 2.2.

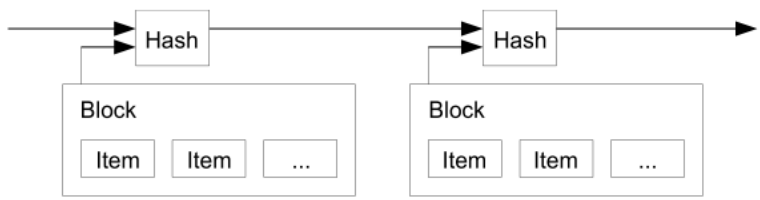

Figure 2.2: Blockchain Proposal [44].

In his paper, Nakamoto considers *consensus mechanisms* as the essence of his proposal, to overcome the double-spend problem, and as a part of his implementation, he maintains that blockchain transactions enable the peer-to-peer exchange of assets in the form of a digital currency. In addition, he explains his proposed system's main principles without defining blockchain explicitly. Therefore, the definition of blockchain is controversial, as researchers have defined it based on their own opinions of the main principles proposed in Satoshi Nakamoto's Bitcoin whitepaper. Merriam-Webster dictionary has defined blockchain as

"The technology at the heart of bitcoin and other virtual currencies, blockchain is an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way" This definition is quoted from [39].

Lakhani and Iansity [39] define blockchain as a vast spectrum, where blockchain-based applications can serve far beyond the spectrum of Bitcoin and other cryptocurrencies. Chatterjee and Chatterjee [25] agree with Lakhani and Iansity [39] definition, that blockchain as a system, can be widely adopted across all forms of transactions. On the other hand, Wust and Gervais [61] argue that blockchain can be constructed differently than the original Bitcoin's blockchain and rather, can be based on business requirement. Whereas Zheng et al., [64] claim that blockchain-based business applications can be built on the top of original Bitcoin's blockchain. Obviously, researchers' definitions of blockchain are similar; however, they differ, as listed in Table 2.2

Table 2.2: Blockchain Definition from Multiple Opinions

Nakamoto[44]	A peer-to-peer distributed network. A chain of a digital cryptocurrency. Block includes transactions, a timestamp, a hash of previous block and a block's hash. Proof-of-Work confirms transactions and documents new blocks to the chain in chronological order. Privacy is maintained by using a key pair.
Zheng et al[64]	A peer-to-peer transaction. Anonymous, persistent and a public ledger that stores a list of transactions. Immutable and decentralized ledger. Overcome double-spend by cutting out trusted third party.
Chatterjee and Chatterjee[25]	A peer-to-peer system. Decentralized and distributed data structure. The transaction is distributed in public network, but not copied. Like a book and it comprises of pages where each page references the previous page by a page number. Irreversibility of blocks. Immutability of blocks.
Lakhani and Iansity[39]	A peer-to-peer transmission, similar to TCP/IP. Open, distributed, transparent and shared database that store transactions in an immutable manner. Foundational technology. Transparency with pseudonymity. Irreversibility of records. Computational logic.
Wust and Gervais[61]	Peer-to-peer transactions of mistrusting entities. Immutable data storage to store a list of transactions. Permissionless blockchains or permissioned blockchains.

To summarize the above table, blockchain can be defined as a peer-to-peer technology for organizing and storing public, private, or semi-private digital ledgers in a distributed and decentralized manner. Blockchain consists of a persistently growing set of blocks of the latest transactions. It allows tracking, recording, or exchanging any kind of assets without relying on a trusted third party. As it shown in Figure 2.3, the first block is called the genesis block without a parent block, and it is created whenever the blockchain is initiated [43]. Additionally, each block is cryptographically hashed (which means the block is transformed into a digital representation and the hash is stored in the next block) and linked with other blocks in a single list (chain) across distributed nodes. However, before each block is appended to the ledger, each peer independently validates the blocks and must reach a consensus on the validity of the block.

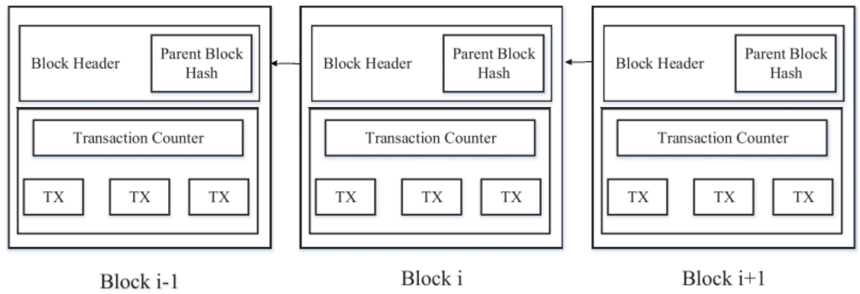

Figure 2.3: A Simple Visual Representation of Blockchain [64].

Furthermore, each block has a header and a body as it is shown in Figure 2.4, it typically has its own data, its own hash which is created by hashing all the transactions in the block (Merkle tree root hash), a referenced hash of the previous block (Parent block hash), a timestamp, and optionally a cryptographic mechanism to validate that the nodes stay legalized. Thus, each block cannot be tampered without the change of every subsequent hashed block which increases immutability, transparency, and security of the ledgers making blockchain tamper resistance. Later, some of Blockchain's internal elements will be explained in detail.

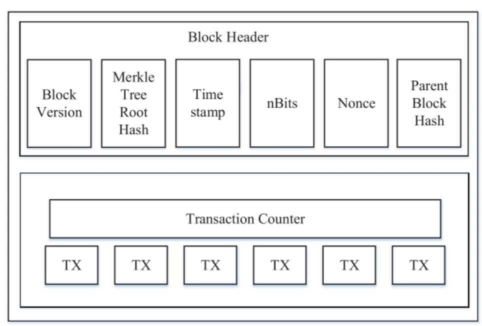

Figure 2.4: Block structure [64].

2.2.3 Blockchain Key Principles

Lakhani and Iansity [39] have divided blockchain's work principle into five basic principles:

Principle 1: Distributed Database or Distributed Ledger Technology

Distributed ledger technology (DLT) reflects the most common known feature that researchers know about blockchain, which ledgers are spread and shared across decentralized nodes [25][39][61][64]. Most of the researchers refer to ledgers as a distributed database [39][43][61], and some researchers refer to nodes as 'parties', 'peers' or 'users' [39] while others refer to them as 'entities' [61] or 'computers' [43]. The distributed and decentralized solution of Nakamoto [44] has allowed of secure, transparent, immutable, authentic, consistent transactions, and difficult to tamper because copies of a ledger are distributed among many participants where there is no master copy is kept by anyone. Every participant in the network receives a copy of the ledger, and they use it for adding a new transaction, validation, and verification [39][43]. The decisions for each transaction are made from decentralized nodes as a substitute of centralized network or authority [39][43]. The following Figure represents the different distribution of communication networks, Figure 2.5.

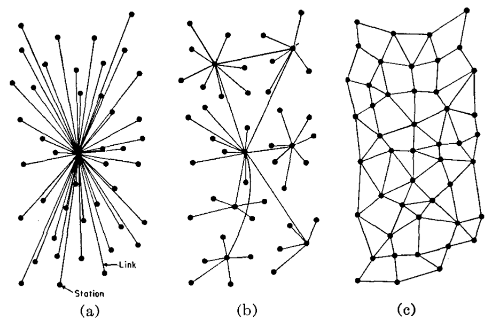

Figure 2.5: (a) Centralized. (b) Decentralized. (c) Distributed networks [18].

Principle 2: Peer-to-Peer Transmission

Instead of having a centralized node that dominates the chain and store information, the blockchain ledger is constantly copied and interchanged across multiple nodes on Peer-to-Peer network where each peer has a copy of the ledger to forward it to each other. According to Nakamoto [44], every transaction does not have to be delivered to all peers; however, it is enough for a transaction to reach the vast majority of users to be added to a new block in the network.

Principle 3: Transparency with Pseudonymity

Transparency is a property that Nakamoto had built it in a blockchain by eliminating the need of a trusted third party and making transactions available and accessible to anyone in a public network. Though miners are the only ones who can verify transactions and expand the chain, anyone can view the chain and check the validity of its content.

As transactions are done in a completely transparent network, the identity of users behind it is Pseudonymity [39] [44]. Anyone who joins the blockchain network can interact with every transaction and its associated value. A unique address is associated with each user or node where they use the address to interact with each other while their identity is kept secret, so users can choose whether to keep their identity secret or provide proof of identity to others as it is hard for anyone to track the identity of a person by the address.

Principle 4: Irreversibility of Records – Immutability

Blockchain is a sequence of blocks where each block is verified, documented, and deployed to a chain in chronological order using a variety of computational algorithms where each block is linked to the one before it and so one. This mechanism increases the integrity of blockchain and prevents any tampering among blocks once the transaction is stored in a chain. If anyone attempts to alter the content of a block, it no longer matches the hash of the block that follows it [44]. So, if we assume that a person wants to alter the content of the third block, he would have to change the hash of the following block to match. Now, the fourth block has been changed. So, the person would change the fifth block as well to match the hash of the fourth block, and so on until the end of the chain. This is the property of immutability. It is hard to break the chain manually and it is computationally expensive, and if that happens, it will be noticed by all nodes if the data has been tampered with, and will be verified using consensus mechanisms [39] [44].

Principle 5: Computational Logic

As blockchain is a digital ledger, any computational logic can be performed on transactions. Meaning that users or nodes can use algorithms and rules to invoke any kind of transactions automatically. Thus, blockchain can be programmed to handle any kind of information, contract or any business logic.

2.2.4 Categorization of blockchain

Witnessing the confidence individuals have in blockchain, it has encouraged developers to develop new blockchain initiatives for business applications beyond Bitcoin or any digital cryptocurrencies. Opposite to Bitcoin's **public blockchains**, developers have invested in **private blockchains**, and **semi-private** or **consortium blockchains**. All of them are categorized based on the level of authorization, who could take part in maintaining them, such as, consensus process, publish blocks, and so on [64].

Bitcoin is an example of **public blockchains**, which is fully decentralized and open for anyone who wishes to publish blocks without the need for authorization. Anyone can download it, join the network, read or validate the information in the blockchain, initiate transactions, and participate in the consensus process. Since there is no access control, it is vulnerable to attack where anyone may attempt to propagate malicious block to the network. Therefore, blockchain is secured by using consensus, which requires miners to consume extensive resources when attempting to publish blocks in the network and reward them with Bitcoin token as an incentive.

Private blockchains or Permissioned blockchains are open but only for limited and authorized participants who wishes to publish or validate blocks, it usually belongs to one organization (single group) where is regarded as a more centralized version of a blockchain network with a little decentralization. Unlike a public blockchain, read permission could be restricted for group of participants or opened, depending on organization needs. Usually, read permissions is opened for anyone, but write permissions is restricted. Private Blockchain is more efficient than the public Blockchains since permissioned blockchain uses consensus protocol in a faster way (more transactions processed per second) and with less computational power because it might not need cryptocurrency or incentive, and they have predetermined nodes who perform the consensus process.

Consortium blockchains are similar to private blockchains, both are permissioned blockchain category and more efficient than public blockchains. Read permission could be restricted or opened. However, consortium blockchains are partially distributed because they usually controlled by several organizations, and the consensus is done by predetermined nodes from all organizations.

In some articles, researchers divide blockchain roughly into two types: private and public blockchains [25][61] for the reason that consortium and private blockchains are quite similar in scalability and privacy level; however, the only difference is that in consortium blockchain several nodes are selected instead of a single group to verify the block and its transactions.

2.2.5 Blockchain Security Implementation

In the context of blockchain, implementation of security is based on three main technologies, cryptography, peer-2-peer transmissions (Section 2.2.3), and consensus mechanisms [43]. These technologies play a crucial job in maintaining the integrity of the chain, complete privacy of participants while keeping transparency of transactions [43][61].

Hash Cryptography

According to Tel [56], hashing is the process of taking the input of any length (called the "message") and converting it using a mathematical function to produce a fixed size of an array of numbers and letters, called "hash value", "hash", or "message digest". A Hash function was developed by the National Security Agency (NSA) and the National Institute of Standards and Technology (NIST) in 1993. The Hash function is a very secure algorithm although initial versions of the algorithms such as SHA-0 and SHA-1 had been cracked after five and seven years respectively. However, NIST provides much more complex hash functions SHA-2 that provide the highest level of security than the SHA-0 and the SHA-1. These algorithms are called SHA-224, SHA-256, SHA-384, and SHA-512. Additionally, NIST claims that because the complexity has been used no one can crack them in the near future.

Blockchain works by performing a transaction from Alice to Pop without relying on a trusted third party [44]. This transaction is not limited to currencies, but it can include any type of digital assets based on business requirements [39]. Alice and Pop can be users or entities as mentioned earlier in Section 2.2.3. For the scenario here, I consider Alice and Pop as users, and Alice want to transfer money to Pop via Bitcoin. In the blockchain, the transaction needed to be hashed is the input, the algorithm uses for hashing is SHA256, and the output is the hashed block (hash value). Here is an illustration of how Alice can transfer money to Pop as explained by Mueller et al., [43] and drawn by Chatterjee and Chatterjee [25] in Figure 2.6:

1. Both Alice and Pop have their own keys (public and private key).
2. Alice funds her wallet on Bitcoin.
3. Alice must sign the transaction with her private key and enter Pop's public key (bitcoin wallet address) before sending the asset.
4. Alice's transaction is represented in a "block" or "ledger" and is broadcast online to every node in the network.
5. Every participant in the network receives a copy of the transaction and validate it.
6. When the transaction approved by enough participants, it is added to other recorded transactions in a ledger. Then the block is appended it to the chain which cannot be changed.
7. Transaction gets executed and Pop receives the money.

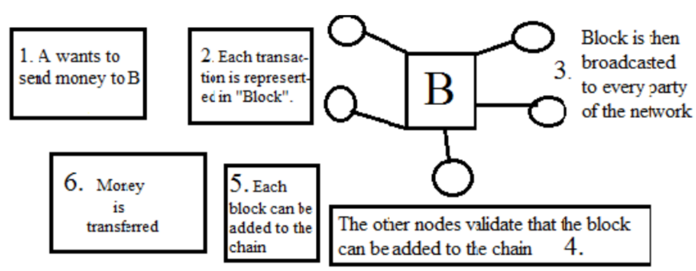

Figure 2.6: Workflow of the Blockchain Mechanism [25].

For blockchain, SHA256 and other hash algorithms are considered secure and useful because they built up the following characteristics [56]:

1. One-way: It means the algorithm is not reversible. The output cannot be reversed back to the original input.
2. Deterministic: It means the same input will always produce the same hash value.
3. Unique hash value: It means a slight change in the input cause a significant change and produce a new hash value.
4. Fast computation: Hash algorithm quickly can compute a hash for a given transaction.
5. Collision resistant: It means two input should not be hashed with the same output.

SHA-1 Algorithm

The mechanism of SHA algorithms is out of the scope of this study. However, as SHA algorithms play an important role in blockchain, the basic information of SHA-1 algorithm is provided. More information for its predecessor and successor, SHA-0 and SHA-2 respectively and working mechanism is in [56].

As it is shown in Figure 2.7, SHA-1 algorithm consists of bitwise operations, modular additions, and compression functions. It takes any input message up to 2^{64} -1 bits of length and produces a 160-bit of hash called a message digest. The top is the input and consists of five 32-bit registers A–E for round i. The bottom is the output values for the next round. In between, f represents functions where B, C and D are attracted to it, and E is module with the result of f. The square box is the addition modulo of 2^{32}. <<< and >>> denote shift operator. K_i is the round constant of round i. W_i is the expanded word message of round i.

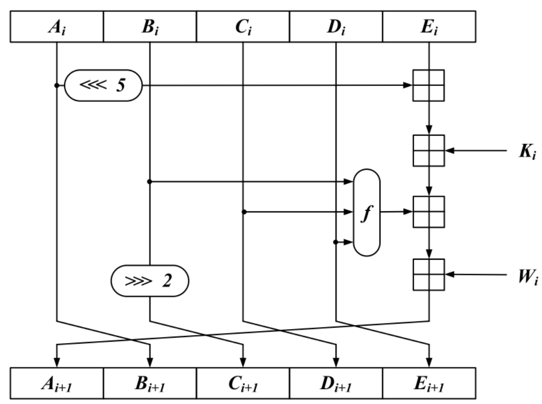

Figure 2.7: Schematic overview of a SHA-0/SHA-1 round [56].

Cryptographic Nonce

According to Zheng et al., [64], a nonce is a 4-byte random number that is used to generate variability in the hash while keeping the same data for the block. This field usually begins with 0 and goes up for every hash calculation. Nonce is utilized in the proof-of-work (PoW) consensus model as it is required calculating a hash value of the block header by each node in the system. Nonce is a part of block header as it is shown in Figure 2.4, and nodes would change the nonce frequently to generate different hash values. For these nodes, in order to accomplish a certain hash, it must be equal to or smaller than a target value that is set by the system. when a node found a hash (target value), it would create (mine) the block and broadcast it to other nodes to prove the correctness of the hash value. If the block is legalizing, then each node would append this new block to its blockchain. The PoW process is completely arbitrary and is called mining in Bitcoin, and nodes calculate the hash values are called miners.

Consensus Mechanism

As defined by Nakamoto [44], a consensus is a process of maintaining the consistency of a ledger by achieving agreement among nodes by enforcing certain rules and incentives. The challenge of consensus mechanism is to maintain integrity, legitimacy of the ledger and protect it from malicious attack and any conflict among nodes on the network [50]

In 2008, Satoshi Nakamoto [44] introduced an innovative way of using PoW as a consensus algorithm to overcome the double-spend problem and Byzantine Generals (BG) problem which was launched in [40]. In the BG Problem, there is a group of generals, and they want to attack a castle; the majority of generals have to come to a consensus on whether to attack or retreat [40]. A similar scenario of BG problem happens in the blockchain as the communication operates in a distributed network. So, if a new block is added to the chain, and to check its validity, the chain with the most PoW (most consensus) will consider to be true.

In blockchain peer-to-peer networks, nodes communicate and receive information between each other in a form of blocks. Each node must contain the same replica of the ledger, same blockchain structure, and information that they all agreed on based on the consensus algorithm.

In a public network, anyone can access the blockchain network, and perform several transactions. A group of nodes (miners) competes against each other to validate transactions and broadcast new blocks to the blockchain using PoW consensus algorithm to protect the network from different attacks. Miners cannot add blocks at the same time, instead, they must reach a consensus through the algorithm with others i.e. which nodes of which block should be added next to the blockchain to avoid desynchronization. Miners earn cryptocurrency token (Bitcoin) as an incentive for the hard work and to keep them honest.

This is one successful way to validate, verify, and store information on a blockchain. However, there are alternative consensus algorithms have used and developed with the advent of blockchain. Some of the algorithms, related blockchain type and platform is summarized in Table 2.3, cited from [64].

Table 2.3: Comparison between different consensus mechanisms

Consensus Algorithms	Overview	Blockchain Type	Typical Platforms, to name a few
Proof of work (PoW)	Multiple nodes or miners are competing against each other to publish the next block. A miner who can solve a mathematical puzzle win. The solution to this puzzle is the proof of work.	Public Blockchains	Bitcoin, Ethereum
Proof of Stake (PoS)	Nodes or validators have the chance to mine the next block based on the deposit they hold in the network.	Public blockchains, Consortium Blockchains	Under construction for Ethereum
Byzantine Fault Tolerance (BFT)	Multiple algorithms are available to achieve consensus using BFT in blockchain. one is Practical BFT which is set of approved nodes and ordered nodes used to approve transactions.	Private blockchains, Consortium blockchains	Hyperledger

2.2.6 Applications

According to Casino et al., [23], different taxonomies of blockchain business applications have created by researchers. Some have classified them as financial and non-financial applications, while others classify them based on blockchain versions, while he and his colleagues provide application-oriented classification. A **smart contract** is the first blockchain application for the financial industry. It is an agreement between partners who wish to conduct business in a trustless environment. It is used to define the business logic, stored in the blockchain, and many areas apply it today [23]. Below are some examples where blockchain and smart contacts have been used as solutions [23]. In-depth analysis of blockchain usage with respect to the **supply chains of other industries** is discussed in section in 2.4.

- Banking and Finance – Blockchain could be applied to enhance security, simplification and cost reduction, and transparency by cutting a trusted third party.
- Insurance – with smart contracts when certain conditions are met, insurance claims could be made automatically and faster with less dispute and error.
- IoT – relationship of blockchain and IoT could provide secure data exchange between multiple of interconnected smart objects.
- Voting – the anonymity and security features of blockchain are an optimal way of e-voting, it could increase trust and confidence in the voting process.
- Supply chain – blockchain could increase transparency, traceability in the supply chain network by enhancing visibility between participants including customer, reduce counterfeit products, and dispute.
- Healthcare – blockchain could solve the interoperability issue in healthcare records. distributed ledgers could be securely shared patients' medical data with all stakeholders and linked with other programs such as a smart contract to monitor patient status.
- Governance – Managing and holding the public official records in secure and automated way. This could help to make government services more efficient.

2.3 Blockchain Frameworks

Besides the Bitcoin blockchain, various Blockchain frameworks are available to build distributed application based on blockchain technology, plus to ready platforms to work on. Many blockchain platforms are available for companies and individuals as a starting point to deploy their application which does not require them to build a blockchain from scratch. Also, full-stack blockchain-as-a-service (BaaS) solutions are offered by big companies such as IBM, Amazon, and Microsoft where they can create, test, and deploy blockchain-based applications. The focus here is on well-known blockchain frameworks other than the Bitcoin blockchain. Ethereum and Hyperledger are already gaining the most popularity of public blockchain and permissioned (private) blockchain respectively. This section analysis these frameworks in details and explores its applicability. Features such as smart contracts, consensus algorithms, and performance are taken into consideration.

2.3.1 Ethereum

A successful blockchain initiative after the Bitcoin blockchain is Ethereum. The Ethereum is an open and public platform that features smart contracts that support creation of blockchain applications beyond digital currency. It is created and developed in 2014 by Vitalik Buterin [22]. Vitalik Buterin's ultimate goal is to introduce a new web era by providing developers with the needed tools that enable them to write any code in form of smart contracts and decentralized applications (DApps) on the Ethereum network. Buterin's white paper contains an explanation of Ethereum and the working mechanism and below are some of the important features of Ethereum.

Smart Contracts and Built-in Currency

Ethereum forms the base for creating blockchain applications in other areas than digital currency. This is achieved by incorporating a Turing-complete programming language with a blockchain, where the developer writes the source code that contains values, rules, and conditions in the **smart contracts** [22]. A smart contract contain transactions and values that is executed based on the terms of the contract or conditions [22].

Thus, smart contracts represent the logic and the predefined pattern that contain values, rules and conditions for particular application. Taking the example of cryptocurrency, a smart contract automates the transfer of the value of an asset and the owner whenever a transaction occurs. In Ethereum, smart contracts exceed the stage of the spent and unspent token, to more open domains of decentralized applications that can be run in Ethereum's blockchain framework [22]. Also, according to Buterin [22], Ethereum's blockchain is a "stateful" smart contracts which can hold other state information beside transactions, which allows for more complex decentralized applications than Bitcoin blockchain the one-off contracts. Anyone can build smart contracts with Solidity language that is run by Ethereum virtual machine (EVM).

Finally, just like the Bitcoin blockchain, within Ethereum network independent computers or nodes work together to execute smart contracts in peer-to-peer communication. Interacting with contracts requires high computational power which in turn requires nodes (miners) to be incentivized to do so. For each line of code in the smart contract that needs to be executed, a transaction fees must be paid for mining nodes for their contribution of computing power in the Ethereum network [22]. Thus, Ethereum has a cryptocurrency called, Ether, which serves as the "gas" or "fuel" to run apps.

Consensus Approach

The current implementation of Ethereum adopts PoW as a consensus strategy between participants, like to what is used in the Bicton blockchain, which consumes a huge amount of power and has performance issues as explained below. However, Vitalik Buterin and Vlad Zamfir have been working to solve these issues and move the Ethereum to alternative consensus algorithm, PoS, such as Casper [63]. PoS is a consensus strategy that is restricted to validator nodes (mining nodes in PoW) who have a security deposit in the network (e.g. cryptocurrency) as an assumption that validator nodes with more cryptocurrencies are trustworthy and increase the difficulty of attack the network [64]. In addition, compared to PoW, PoS uses less energy and more scalable as it does not let everyone to validate the next block, and also more decentralized and effective. In PoW, miners use a massive amount of electricity to solve a mathematical puzzle in order to mine the next block, and the first miner to find the solution gets the reward; however, all other miners are left with zero rewards, and all the used energy are wasted [64]. Also, it encourages the miners to use the mining pools which make the blackchin more centralized which could kill one of the main blockchain's principles [64].

Performance

Smart contracts allow the Ethereum to do more than just a cryptocurrency and to be more functional than the bitcoin blockchain; however, Ethereum's scalability related issues, **latency**, and **throughput** besides **data storage** are seen controversial whether they can deal with the increasing amount of data every day and scale-up for globalization or not.

The Ethereum's performance, as a public blockchain is measured by the average rate of proceeding transaction per second (TPS) – throughput. It is calculated by two parameters: **block size** and **block generation time** [51][64].

- **Block size**: unlike the 1MB Bitcoin block, Ethereum block size is not fixed as the platform uses the concept of paying in advance. The token unit "gas" or "fuel" is the limit of block size. In other words, a certain amount of gas for computation power has to be paid, and once the gas is consumed, the block reaches its size.
- **Block generation time**: This is the average time that is taken by mining nodes to propagate a new block into the network. In Bitcoin Blockchain, using PoW a block is processed in approximately 10 min, it usually takes this long for security reasons

to avoid the double-spent attack. However, Ethereum use different PoW algorithm called "Ethash" to reduce latency by using a small block time where a block is mined almost every 15 seconds [51].

The way these parameters affected performance is related to security too [51], e.g., with **block generation time**, the security is higher in a network that is validated by more nodes compared to fewer nodes in other networks. Hence, the tradeoff between the performance's parameters and security is a big challenge because of the correlations between them [64]. This means, any DApps that deploy in the public network have experienced scalability and performance issues in order to maintain security.

Additionally, with **block size**, if we intend to increase block size as a goal to increase network throughput, we need more nodes to increase security and speed up operations. However, in reality, the presence of a large number of nodes in the network corresponded by slower propagation in the network (latency) that in turn have a negative impact on security because delay may increase the possibility of chain forks and attack by dishonest miners to perform a double-spend attack [51][64]. Therefore, block size are stabilized in public blockchain to block the risk of such attacks. However, such risk can be avoided in private blockchain by scarifying some of the decentralization because the nodes are known and authenticated such as Hyperledger [51]. **In other words, private blockchain is more scalable than a public blockchain and can improve performance and scalability.**

Data storage is found to be another issue besides **latency** and **throughput**. The increasing amount of transactions every day makes blockchain becomes gigantic, which in turn is hard for nodes to keep up with the increasing size of the blockchain. Usually, mining nodes prefer small capacity blockchain with small transactions and high fees [64]. This could become a security issue in public blockchain and gradually could become far from decentralization as gradually fewer mining nodes want to validate, store, and maintain the gigantic blockchain.

Efforts to address the scaling issue have been proposed and tested by Buterin in the domains of sharding, layer-2 systems like Plasma and Raiden, and alternative consensus algorithm (PoS) as explained in consensus approach above. Some of these proposed solutions are summarized in Table 2.4

Table 2.4: Proposed solutions for Scalability related issues in Ethereum

Proposed Solutions	Overview
Sharding[51]	Sharding is one of several solutions being tested by developers to increase Ethereum's transaction throughput. It solves the biggest Ethereum scalability issue (every node has to process and store not only transactions but also the state of the whole blackchin as well) by spreading the workload where each node does not have to process the entire network. In other words, it works by splitting the Ethereum network into multiple chunks and dividing nodes where each subset of nodes is responsible for a subset of transactions. So, this will allow for concurrent (parallel) processing of the transactions, and this will increase the throughput of processing transactions and as a result increase scalability.
Plasma[54]	Plasma is another solution focuses on improving scalability –throughput. Plasma gets rid of unnecessary data in the main blockchain by using smart contracts to build smaller chains, which can be treated as children of the main blockchain. The main blockchain will have only the verified transaction that is received from its child blockchains. These chains work as the regular blockchain and can have their own configuration and children chain. Thus, implementing many of smaller chains can considerably increase the storage and scalability of the blockchain network.
Raiden[45]	Raiden's solution aims to provide scalable token transfer for Ethereum. The basic idea of Raiden is to allow off-chain token transfer without involving blockchain in every transfer by leveraging payment channel in securely way using digitally signed cryptography called Raiden balance proof. It works as the following: if Alice wants to send Bob tokens, a payment channel is opened, transaction is performed, then, the payment channel can be closed any time by request from Alice, and the transaction is submitted.

2.3.2 Hyperledger Fabric

Hyperledger is an open-source initiative of distributed ledger technologies that act as an incubator for blockchain and founded by Linux Foundation, which designs to meet different industrial standards by introducing a novel blockchain approach [15]. So far, Linux Foundation and alliance members have come up with the following different frameworks under the umbrella of Hyperledger: Hyperledger Sawtooth [5], Hyperledger Iroha [4], Hyperledger Fabric [15], Hyperledger Burrow [2] and Hyperledger Indy [3].

One of the frameworks, Hyperledger Fabric is led by IBM and Linux Foundation [1][6], to deal with challenges and limitations associated with the architecture of existing public blockchain frameworks, such as Ethereum blockchain. Hyperledger Fabric is a permissioned (private) blockchain for commercial adaptation without a cryptocurrency. Two versions of Hyperledger Fabric are released, first is Hyperledger Fabric v0.6, and the most recent one is Hyperledger Fabric v1.x in 2017 [15].

Chaincode

Chaincode is another form of smart contracts uses in Hyperledger to define the business logic of carrying out transactions [15]. Think of chaincode as a structure you would create to interact with the blockchain network's ledger to define assets, transactions and manage its state at the time of execution similar to Ethereum's smart contracts.

Chaincode runs in a Virtual Machine using a Docker container, thereby, isolated from the shared ledger (transaction log and the state). This feature makes it flexible for adding new chaincode programming languages compared to Ethereum that use its own language. Currently, chaincode applications are written in Go, Java, and Node.js. Therefore, programmers who are familiar with any of these languages can start using the blockchain framework without additional learning.

Each instance of chaincode is deployed in its own Docker container separately from other chaincode, this implementation allows of data privacy as only participants of each chainedocde are allowed to call transactions and make changes. Besides, chaincode holds business logic agreed by the network's participants.

Fabric Architecture and Consensus Workflow

As mentioned in section 2.3.2, two versions of Hyperledger Fabric architecture were released. The newer version, v1.x was released to address challenges and limitations encountered by the previous versions, up to v0.6 that obtained as a feedback of deployed applications, in addition to address significant issues of public blockchain technology [15].

According to Androulaki et al., [15], the limitations of previous permissioned blockchains has derived from public blockchains where both follow an order-execute architecture in which consensus and execution happen in the same order on all peers sequentially. Taking the example of Ethereum (PoW consensus) with order-execute architecture, after a block is mined and propagated to all nodes in the network, transactions will be performed sequentially by all nodes and it has to be deterministic. As this approach functions properly with public blockchains, but with permissioned blockchains like Hyperledger many limitations has encountered. In particular:

- Consensus is hard-coded: each consensus protocol in the platform has different features, performance and capabilities resulting in no "one-size-fits-all" which can not be adapt to other use cases.
- Non-deterministic transactions: deterministic cannot be guaranteed and can cause ledger "forks" and violates the basic premise of blockchain because all peers will not hold the same state.
- The sequential execution of all transactions: All peers are supposed to execute all transactions sequentially. This limits performance and causes a delay.
- Smart contracts language: smart contracts are written in a domain-specific language that limits wide adaptation of blockchain solutions.
- Confidentiality of execution: smart contracts run on all peers and are not restricted to some peers, which threatens confidentiality.

The new Hyperledger Fabric architecture, v1.x came into light and overcome these limitations. It "designed as **a modular consensus** and **extensible general-purpose permissioned blockchain**"[15]. In other words, Fabric is a ready blockchain framework that provides set of infrastructure, tools, libraries, and application building blocks that allows widespread adaptation of the technology. In addition, the architecture follows an execute-order-validate approach, which differs radically from the order-execute architecture. According to Androulaki et al., [15], this distinctive architecture is delivering a blockchain that allows **resilience**, **flexibility**, **scalability**, and **confidentiality**. The components the Fabric architecture have built on are:

- A membership service provider (MSP) acts as a security guard that protects the Fabric from intruders by providing credentials (cryptographic identity) to all types of nodes (clients, peers, and ordering service nodes) to participate in the Fabric network.
- An ordering service (Also known as orderer) acts as the communication backbone to peers for any updating state in the Hyperledger fabric, also it is responsible to maintain consistency by establishing consensus on the order of transactions.
- Peer maintains the ledger and manages the chaincode.
- An optional gossip protocol disseminates ledger data to all peers who have identified discrepancies in their own state compared to other peers.

- Assets represent any thing that has a value that can be exchanged in the Hyperledger network. The representation of the asset is in a key-value pair, and its state can change according to the transactions in the smart contract (chaincode).
- Chaincode defines the business logic of carrying out transactions. It is written in a general-purpose programming language (e.g., Go, Java, Node.js).
- Ledger is a data structure on the DLT framework that keeps track of all transactions and state changes.

Additionally, this architecture allows for a new level of privacy. Data and transactions are restricted, therefore participants who wish to interact with the network and submit transactions are required to enroll and obtain an identity (i.e., an enrollment certificate). The registration and identification process are provided by MSP of all kind of nodes. Besides obtaining the identity, Fabric introduces another level of data privacy using a **channel**. A channel allows for data privacy and confidentiality. In other words, a channel has peers as its members, and a ledger in a channel is shared across those peers, and those peers must be authenticated to be members of the channel and interact with it. Each channel has its rules that govern members and consensus happens within the channel and its members. For example, if three organization A, B, and C are engaged in carrying out a business on Fabric network; any transaction initiated by nodes in the network will be visible to all peers; however, if B and C tend to engage in some kind of business, then they can create their own private channel where the visibility of ledger, transactions and consensus is restricted to B and C.

In addition, another distinct feature of execute-order-validate architecture is the **consensus mechanism**. Nodes in a **consensus** take up one of three roles: peer nodes, ordering nodes and client applications [15]. **A peer** manages the ledger and chaincode and can either be a **committer**, which protects the network by endorsing transactions, or **endorser**, which verify endorsement policy and ensure consistency of the execution (deterministic transactions). The **client node** usually sends transaction invocation requests to endorsing peers. **The Ordering Service Nodes (OSN) or simply orderers** provide the communication layer for the Fabric through OSN which uses a pluggable consensus protocol to produce sequential endorsed transactions, create the blocks with them, and deliver the blocks to the committer peers. The ordering service can be implemented as a centralized or decentralized service. The three options available for OSN implementation are Solo, Kafka, and Raft (New as of v1.4.1). For more clarification, these nodes and each transaction are mainly involved in four phases in the consensus [15]. The following is a definition of each phase in the consensus approach:

Phase 1: Transaction proposal – a client, which usually an organization, submit a transaction proposal to endorsement peers, proposal contain information such as identity, content, transaction identifier, and so on. Once the transaction is endorsed, it broadcasted to ordering service.

Phase 2: Execute (endorsement) – set of endorser peers validate the transactions (e.g. certificate checks) from misbehaving or misconfigured nodes on the network, then decide whether to accept it or reject it. In case of acceptance, the transaction is endorsed (signed) and chaincode will be stimulated. In some cases, a transaction may require multiple checks by endorser peers.

Phase 3: Ordering – all transactions must get permission before appending to the ledger by ordering service nodes (OSN). OSNs support multiple channels, accept endorsed transactions, create blocks to group them, and specifies the order in which those transactions will be committed to the ledger.

Phase 4: Validation – verify if transactions are endorsed correctly with respect to endorsement policy in phase 1 and then verify that all transactions are deterministic (same outcome or result). A high-level step by step **workflow** of the **consensus** is outlined in Figure 2.8. First, the client sends transaction invocation requests to endorsing peers of its choice. Then, the endorsing peers validate a transaction and choose whether they endorse it valid or not. If they endorse it as a valid transaction, then endorsing peers simulate the chaincode, and sign the transaction and send it back to the client. Next, the client receives the endorsed transaction and sends it to OSN. Finally, new blocks get generated and send it out by ordering service to all peers (committer) to update the ledger and verify the endorsement policy.

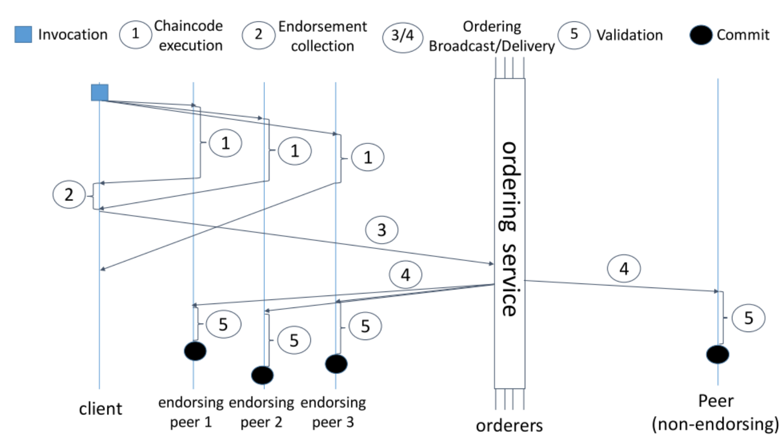

Figure 2.8: Consensus workflow in Hyperledger Fabric [15].

As it noticed from the explanation above, this consensus mechanism divides the workload between selected nodes in a similar fashion to mentioned solutions (e.g. Sharding) of scalability issues in public blockchain in section 2.3.1. By relying on trust on validating nodes, permissioned blockchain does not need a high computational power to increase the difficulty of attack the network as in public blockchains, which in turn eliminates the throughput issues. This is already proven by a comparison of **performance** between a blockchain that uses PoW such as Ethereum, and a blockchain that uses BFT such as Hyperledger by Pongnumkul, Siripanpornchana and Thajchayapong [47] and shown that Hyperledger achieves better latency and throughput over a public blockchain.

To sum up, using known and authenticated nodes, has shown that Hyperledger becomes faster and scalable than Ethereum. Also, issues of order-execute architecture is solved with the consensus mechanism of new architecture. Additionally, besides scalability, Hyperledger provides privacy through a channel by allowing data access to only authorized participants who belong to a channel to increase data confidentiality [51].

2.3.3 Comparison of Ethereum and Hyperledger Fabric

As explained in Section 2.3.1 and 2.3.2, both Ethereum and Hyperledger have a unique consensus mechanism, and provide a lot of features that can change the nature of businesses. However, at the end they both blockchain platforms, so how they do in comparison.

After having a glance overview at both platforms, **Ethereum** is a generic blockchain platform while **Fabric** is a modular architecture platform that is evolved as customized blockchain solutions for certain problems. Also, as seen in 2.3.2, hyperledger fabric might possess the qualifications that make it a good option to satisfy traceability requirements in the construction industry that is difficult to achieve in public blockchain such as Ethereum where anyone can access the network. Additionally, Fabric is more flexible than other frameworks in some ways, such as Fabric uses Java (popular programming language) where programmers can easily develop a smart contract. On the other hand, as seen in 2.3.1, controversial issues such as **scalability** and **data storage** might come as disadvantages to Ethereum in our comparison because the construction industry is kind of industry that is increasingly affected by globalization, where storage, performance, and scalability are crucial. Table 2.5 shows a comparison between these two blockchain platforms.

Table 2.5: Ethereum vs Hyperledger Fabric

Features	**Ethereum**	**Hyperledger Fabric**
Type	permissionless (public or private)	permissioned (private or consortium)
Pltform	generic blockchain platform	modular architecture platform
Performance	limited scalbility	more scalable
Accessibility	any one can access	restricted
Flexibility	not flexible requires more effort to learn	flexible to learn
Smart Contracts Language	written in Solidity	can be written in Go, Java, and Node.js
Cryptocurrency	Ether	none

However, such a comparison is not enough to decide one framework over another. Therefore, another important feature to distinguish is the difference in privacy between these frameworks:

- **Privacy** As mentioned in Section 2.3.2, Hyperledger's BFT algorithm and access control solve the privacy issue of permissionless blockchains (e.g. Ethereum), which makes it more applicable for any supply chain industry rather than Ethereum. This could come as a benefit for the construction supply chain industry that requires a secure channel as an incentive for companies to share material traceability information between authorized partners. **However, the difference in privacy is not enough reason to eliminate Ethereum from the competition. Therefore, performance has been chosen as significant criteria for the difference between these two:**

- **Performance** Even though they have the same functionalities, performance is the bottlenecks that might make us reach a decision to choose the best platform between Ethereum and Hyperledger that suits our requirements later on.

An experiment performed by Pongnumkul, Siripanpornchana and Thajchayapong [47] to measure the performance of these two platforms showed that Hyperledger's performance won the competition in every round of different measurements over the Ethereum (permissioned implementation). The evaluation metrics are **execution time**, **throughput**, and **latency**. For each metrics, the average is calculated based on five sets of experiments for each platform. In every round, Hyperledger Fabric had the lower Execution time, high throughput and lower latency which in general outperforms Ethereum. The results of experiment are in Figure 2.9 and 2.10. An interesting conclusion from both figure that there is a huge gap between both frameworks in performance. In other words, as the number of transactions grows at the same rate for both, Ethereum's latency and throughput are significantly worse than Hyperledger. For example, for the data set with one transaction, Ethereum's latency is about twice of Hyperledger's with larger throughput for Hyperledger, which means not only Hyperledger beat Ethereum in performance only, but its scalability is better too.

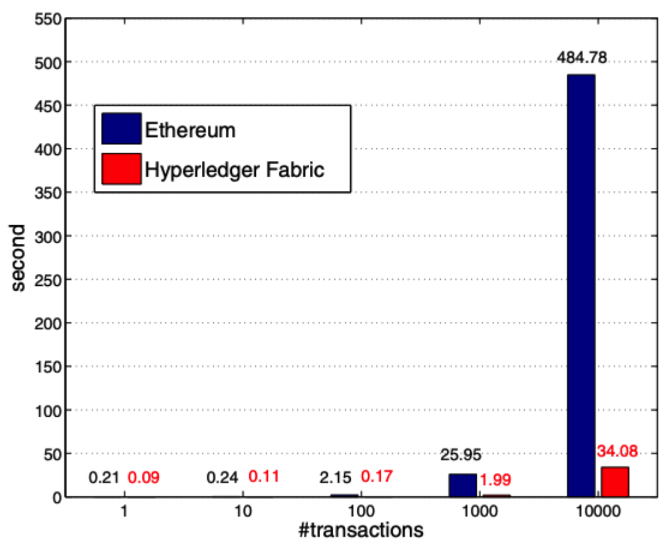

Figure 2.9: Comparison of average latency between Ethereum and Hyperledger[47].

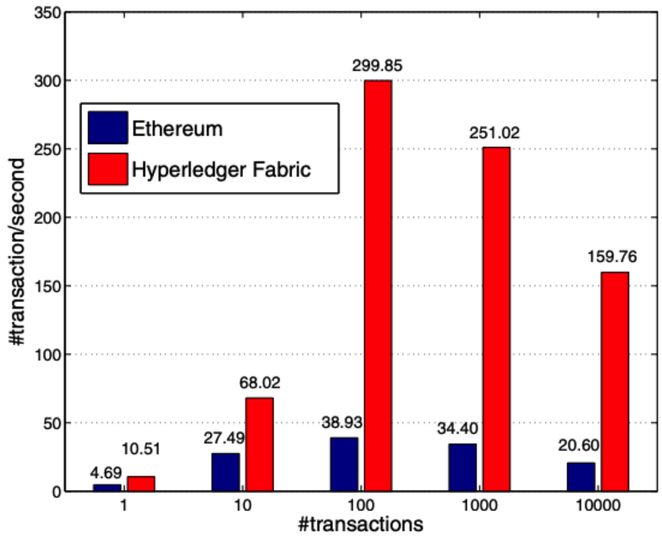

Figure 2.10: Comparison of average throughput between Ethereum and Hyperledger [47].

2.4 Blockchain in Supply Chains of other Industries

Blockchain has the potential to program business logic with the use of smart contracts in several domains as explained earlier in Section 2.2.6. In this section, we dive deeper into the confluence of blockchain and the supply chain of other industries to know if it a great addition to the construction industry later on. The benefits of applying blockchain in the supply chain industry are described. The challenges that might face companies who want to harness blockchain are also discussed. Also, current blockchain's use cases in the supply chain of other industries are also examined below. Finally, requirements to keep in mind when designing a blockchain-based **construction supply chain** later on are also included.

2.4.1 Key benefits of Blockchain for Supply Chain

Some of the benefits that blockchains carry to supply chain in particular according to derived benefits from previous related studies in Table 2.6 and that could apply to other industries in general are:

- **Reduce dispute**: immutable nature of blockchain incentives supply chain participants (e.g. suppliers) to input more accurate data because it is easy to figure out any attempt of fraud.
- **Reduce costs**: the cost associated with service or product can be dramatically reduced. For example, defective materials can be easily identified at early stages and knowing its source instead of recalling the entire chain.
- **Gaining consumer trust**: blockchain can be very useful for adding value to customers by allowing them to know the sources of materials. This could satisfy the new trend of the increasing demand of knowing the provenance of products by customers.
- **Boost real-time track and trace**: the ledger allows participants to track a material from its origin until the end of the chain. At any given time, material's status can be retrieved, and determine whether it is the correct one, to ensure that wrong or fake material is not delivered to us, and if it happens it is traceable.
- **Trust across the supply chain**: it is necessary to trust the information that comes from point to point in the supply chain. With blockchain, participants do not have to establish trust relationship between them as long as they trust the blockchain.
- **Cutting out intermediaries**: with smart contracts, agreements, detection, measurement, and tracking can be automatically validated through a blockchain without the need of intermediaries, therefore, reduce error, save time and money.

2.4.2 Challenges of Selecting a Blockchain Platform for Supply Chain

A blockchain through its benefits seems the perfect solution to many issues. However, it is still a new topic of research, and its disadvantages are real, therefore, we have to be thoughtful about applying the decision to embrace blockchain in any supply chain industry. Wang et al.,[59] have divided blockchain's main challenges into three main types of challenges:

Technical Challenges

The technical limitations facing a blockchain are **throughput**, **latency** and **size**. As discussed earlier in Section 2.3, different blockchain types have different **throughput** and **latency**, and in Section 2.3.3, we conclude that private deployments such as Hyperledger Fabric achieve better throughput and latency than a public one. However, the blockchain's performance can not compete of the current centralized systems in the supply chain in terms of latency and throughput which is much better than blockchain. [61]. As a result, blockchain would affect the performance and cause delays in the transactions in the supply chain. However, on the other side, blockchain provides better collaboration and trust that enhance sharing information of data between companies that we could not come to the agreement before because of the trust issues of centralized systems [57]. Moreover, the latency of transactions is important as well in the supply chain industry. Therefore, such an issue can be solved by applying permissioned blockchains such as Hyperledger which can provide low latency and process a high number of transactions as seen in Section 2.3.3.

Beside throughput and latency, **size** is a major concern as well. Applying blockchain in the supply chain industry could become a challenge due to the amount of transactions happening every day, which will become a big concern in the future as such transactions are gradually making the blockchain large in size. However, there are several attempts being made to find solutions for such issue.

Business-Related Challenges

Typically, in the supply chain industry, each company has its centralized database with defined format for storing data. In other words, each company maintains its business activities in its own ledger and it is hard for other companies to access information due to different standards each company have, which act as barriers in tracking needed information. Switch to a shared ledger might be difficult because involved companies need to develop a full system together and there are no common standards these companies can follow. Also, some industry such as the construction industry is a one-off prototype which requires a newly-developed blockchain platform for each project as it is hard to reuse existing blockchain solutions.

On the other hand, companies have invested in Enterprise Resource Planning (ERP) systems and other internal traceability systems, and there is a clash between these systems and blockchain due to the lack of interoperability in the internal ERP or traceability systems where companies designed them according to their data format, where other companies can not access data directly and they need to read it and entered it manually to their software because of a lack of standards between them, and on the other hand some of them rely on traditional methods.

Besides that, switching to blockchain ledger requires all the partners to be involved in every process of the supply chain which is hard to cope with, and it would be a great barrier [60].

Human-Related Challenges

Embracing blockchain is not only a technical challenge but a human one as well. The biggest obstacle to blockchain's success is society and unwillingness to rethink and renovate the way we do business. A few people know how blockchain works and enthusiastic about it while the majority keep the routine and resist the change.

For the people in the supply chain industry, the technology is still new, and most companies are in their trial and error learning phase to discover it and are still skeptical to embrace it because of the technical issues and the uncertainty surrounding it.

2.4.3 Existing Applications of Other Industries

In this section, some of the research papers and articles that use blockchain in SCM of other industries have been reviewed.

One big company that examines this technology is **Walmart, together with its partner IBM**. Controlling outbreaks of food poisoning or disease, and finding its source is a real challenge. Therefore, Walmart has created a food traceability system based on Hyperledger Fabric to trace the origin of over 25 products from 5 different suppliers. All data, including the transmission of products, is stored in the ledger, which is accompanied by the identity of the supplier as a proof of delivery. They use the GS1 standard to define and unified data format from and to the blockchain. At the same time, the products are tracked along the supply chain and information flow is accessible among all participants. One of the result shows that time needed to trace mangos provenance dropped from 7 days to 2.2 seconds. This application focuses more on tracking products by all participants and information integration, which both two important aspects of efficient supply chain management and better traceability [7].

Yoo and Won [62] deliver a solution to a new digital supply chain using blockchain and smart contracts. The complexity of product distribution in the supply chain has increased globally, and each company executes SCM autonomously with extra profits. Using smart contracts, processes and transactions are automated and integrated without any extra operational fees, and retail price information through the chain is available and transparent between all participants including customers. This technique not only gives access to transparent prices by all participants but also provides information that is validated and impossible to alter. Also, while it provides a new type of information sharing, it still able to keep the privacy of the supply chain. This new digital supply chain is very practical with the goals this dissertation seeks to achieve, which includes a new shared community where data is available, accessible, trackable, and privacy is strong. This solution specializes in price tracking as it moves from producers to final customers, and it operates on the Ethereum's smart contracts.

Tian [57] focuses on the tracking of quality and safety of the agri-food that transports from farm to dinner table. This approach uses blockchain along with Radio-frequency identification (RFID) to transfer quality metrics of food in real-time to the blockchain. It attempts to increase quality and restore customer confidence and minimize fake products. This application is only conceptual with the discussion of how blockchain can provide food traceability.

Figorilli et al., [29] experiments a blockchain using Microsoft Azure blockchain workbench together with Ethereum for the electronic traceability of wood from standing tree to the final user in order to eliminate fraud. This is another project similar to Tian [57] focusing on quality tracking with the use of IoT. The wood-related data is captured using RFID, loaded based on the smart contract, then it automatically recorded to the blockchain, and becomes accessible and visible to all participants. To facilitate the use of blockchain, they used ready blockchain services by Microsoft Azure with a cloud deployment. The Microsoft Azure ready deployment blockchain services is a designed services and tools to ease the process of creating and deploying blockchain applications to share business and data with other organizations. They use APIs service to integrate data with existing systems, IoT and blockchain. Also, they add a data manipulation software layer to ensure the compatibility between the central server (the supply chains' database) and blockchain smart contracts. Besides that to reduce resource consumption, they use off-chain storage to consolidate data before the permanent validation and storage in the blockchain, and to query the off-chain database system (supply chain central server) Instead of the blockchain which can be seen in Figure 2.11 through the use of 'security policy' element.

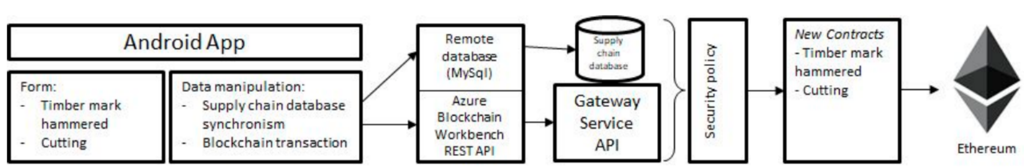

Figure 2.11: Interconnection diagram between the app developed (SmartTree; 2018) and the blockchain in the study of Figorilli et al., [29].

This solution focuses on the tracking of the products, allowing everyone to know how the products were produced and where the products came from. With this solution, a defect product can easily be recalled or removed. Both this solution and Tian [57] are specialized in a specific problem, however, both highlight that blockchain can be a good choice of quality tracking in the supply chain. Also, both use complementary technologies e.g. RFID beside blockchain to fulfill the need for real-time tracking.

Kim and Laskowski [37] present an ontology to design blockchain that supports provenance traceability using the Ethereum's smart contract. The proposed smart contract supports several supply chain operations (e.g. produce and consume) and has written based on traceability ontology axioms that could execute a provenance trace and enforce traceability constraints on the blockchain. This solution is mainly a guidance for those wishing to use ontologies to develop blockchain applications for tracing a product provenance. However, the defines functions and properties in the contract is limited to trace certain products and imposable to apply for other products while using the same resources.

Casino et al., [24] introduce a blockchain-based food traceability framework to help supply chain partners and customers tracking product origins, and automating supply chain processes. The proposed model aims to increase food safety and quality beside traceability. Also, the proposed model showed significant benefits over supply chain activities and current practices.

After examining previous studies [7][62][57][29][37][24], the key benefits identified by various researchers in the supply chain are marked in the Table 2.6 and summarized in Section 2.4.1.

Table 2.6: Key benefits of blockchain identified by some researchers in the supply chain

Articles	Benefits										
	Privacy	data availability	Fast Response	Increase Trust	Safety	Customer confidence	Immutability	Transparency	Tracking	Cut costs	Smart contracts
Walmart case study[7]			✓	✓	✓	✓	✓	✓	✓		
Yoo and Won[62]	✓	✓			✓	✓	✓	✓	✓	✓	✓
Tian[57]				✓	✓	✓		✓	✓	✓	
Figorilli et al[29]				✓	✓		✓	✓	✓		✓
Kim and Laskowski[37]					✓			✓	✓		✓
Casino et al [24]	✓			✓	✓	✓	✓	✓	✓	✓	✓

2.4.4 Essential Elements for Designing Similar App

Blockchains do not fit all scenarios, and when considering a blockchain app, there are subsidiary design choices. Therefore, before designing a system, the applicability of a blockchain needs to be assessed against some questions and needed requirements. This section provides important points drawn from reviewed previous studies [7][62][57][29][37][24] and other research articles, which should be taken into account in the decision making process when choosing and designing a blockchain in the supply chain, particularly in the construction industry. The common blockchain components applied by [7][62][57][29][37][24] in designing blockchain and achieving their goals are:

- **Evaluation of Suitability** – Wust and Gervais [61] provide a flow chart to determine whether a blockchain is the appropriate technical solution that can fulfill the need the dissertation is trying to prove. There are five main questions and other subsidiary questions.

- **Blockchain Selection and Integration** – as mentioned earlier in Section 2.3 and seen in [29], instead of starting from scratch, many blockchain platforms and services are available as a starting point for companies and individuals to create and deploy their application. This blockchain services such as Microsoft Azure Blockchain Workbench simplifies the creation of blockchain and enables developers to focus on creating business logic and smart contracts.

- **Smart Contracts** – in the reviewed applications, smart contracts were utilized to track products' provenance, change the holder of the product, and reduce the necessity of intermediaries and save time and money. It can also trigger events to notify organizations to take further steps, e.g., remove defective products or early recalls. Another feature is automated services, e.g., if the shipment exceeds the expected arrival date, the smart contract will automatically trigger fees against the shipping company or release payments when product status is changed to deliver, and many more functionalities. Thus, with smart contracts, new features can be built and developed the way we desire.

- **Complementary Technology** – with some scenarios a blockchain is required to be paired with a complementary technology, to name a few, RFID, sensors, GPS, IoT devices, in order to gather and track real-time information along the supply chain e.g. temperature and humidity of medical products.

Chapter 3

Methodology and Obtaining Traceability Requirements

This chapter's focus is on describing the research design used to conduct this study. It includes a description of the research approach used to determine whether the thesis statement is valid or not. It also demonstrates how the research questions will be answered, and how the traceability requirements will be obtained and then applied using blockchain for analysis later on.

In addition, having previously discussed the issues relating to material traceability in the construction industry, this chapter also focuses on reaching a conclusion about traceability requirements by doing an in-depth analysis of traceability in the food industry along with background analysis based on some points of focus. The analysis serves as a basis of the material's traceability requirements that later will be used to select the blockchain framework and design the proof of concept.

3.1 Approach

This study follows a design science approach, where the author identifies a problem and make a contribution toward designing a solution to overcome the problem. The capability and validity of the solution is determined by its utility in different contexts and its boundary [35]. The plan for accomplishing this study consist of six sequential steps as shown in Figure 3.1.

In order to address questions established in Section 1.6, below is written how each step in the figure below corresponds to a step within the research presented in this **dissertation**. The author divides these six steps into **two main phases**:

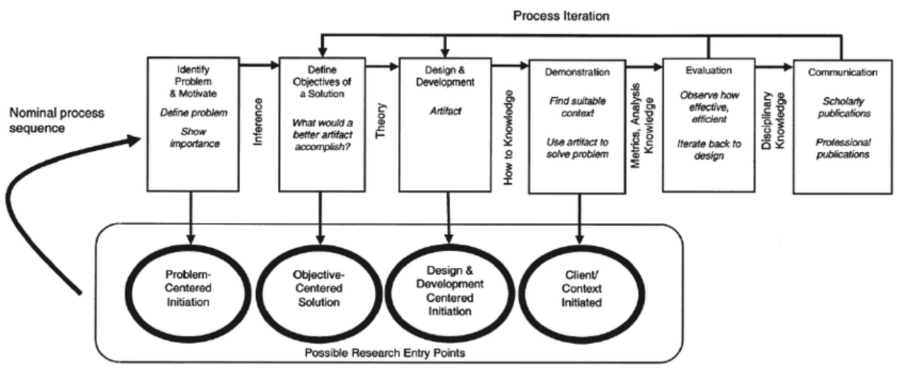

Figure 3.1: Design Science Research (DSR) Process Model[46].

3.1.1 Phase 1

The first phase covers step 1 and step 2 in the DSR model and aimed to be the theoretical aspect, this dissertation has built on.

This research starts with a motivation to increase customer awareness of the origin of materials as the material status along the construction supply chain is valuable not only for company involved but also for other partners, including customers. It begins by examining the current research in the two subjects, material traceability in construction supply chain, and blockchain as stand-alone subjects and then blockchain within the supply chain of other industries. Two databases are searched, Web of Science and Scopus. Web of Science and Scopus mostly contain the same research papers, therefore most of the papers are downloaded from Web of Science. Additionally, other articles are downloaded from different websites as the author see they are relevant for the theoretical part of this dissertation. The screening over the research papers was based on 1) relevance to the study, 2) recency, and 3) highly cited.

Literature Search to Find a Gap

To seek new insights on material's traceability through the construction supply chain, a **literature review** is conducted to find a **gap** by examining earlier studies in the current practice of material traceability in construction SCM, and the existing implementations of material tracking.

The **gap** that the many challenges in current practices cause the insufficiencies in the traceability of material within the construction supply chain answers the first question of the research questions. ***"What are the challenges that prevent accurate and complete traceability of materials through the construction logistics chain?"***. This question comprises a chapter (Chapter 2), and the main points of research problem summarized in Section 3.2.1.

Literature Search of Chosen Solution

As the finding indicates that there are insufficiencies in material traceability in construction supply chain, the chosen solution is to build a blockchain based platform that can improve traceability. To understand the technology and its applicability to the supply chain industry, a review conducted in Chapter 2 provides some information about the proposed solution.

3.1.2 Phase 2

The second phase covers steps 3, 4 and 5 in the DSR model and aimed to design, demonstrate and evaluate the proposed solution. Accomplishing this phase and answer the other research questions, depends on the answer we reach of the second research question.

Literature Search to Obtain Traceability Requirements

In order to reach a conclusion of the second question ***"What are the requirements that would be considered most valuable to improve the traceability of materials in the construction logistics chain?"***, several articles are searched to obtain traceability requirements that could be used as a basis to design the proof of concept. However, as mentioned earlier, traceability is still in its early stages in construction industry and rare studies have been found about traceability in relation to material traceability. Therefore, the sources are derived from food industry because of extensive research on food traceability. The two main sources that are used to obtain the traceability requirements of the main point of focuses are shown in Table 3.1. This question comprising a whole section (Section 3.2) in Chapter 3.

Table 3.1: Sources used to obtain traceability requirements from food Industry

Author	Year	Title
Aung and Chang	2014	Traceability in a food supply chain: Safety and quality perspectives
Bosona and Gebresenbet	2013	Food traceability as an integral part of logistics management in food and agricultural supply chain

Implementation

After obtaining the materials traceability requirements from answering the second research question, we can use them as a basis to answer the other two questions: ***"Which kind of blockchain initiatives and tools can be chosen to design a platform for construction projects to apply the material traceability requirements?"*** and ***"In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?"***.

The review conducted in chapter 2 provides information on the best tools and blockchain frameworks that can be used later through the analysis to find the suitable framework and answer the first of these questions. The decision will be made through analysis of the comparison of frameworks, obtained traceability requirements and a flowchart. Finally, to measure the success of blockchain and to answer the last question, a proof concept implementation is performed using the chosen platform and then tested it for its validity. This includes the work done in Chapter 4 and 5.

After elaborating of how phase 1 and 2 of this dissertation is conducted, now we can summarize its steps as the following:

1. **Identify current issues of material traceability** - through the literature review.
2. **Identify solution** - through implement a platform that can improve material traceability.
3. **Design and development**
   - Material traceability points of focus - through summarizing material traceability issues to main categories of challenges.
   - Obtaining traceability requirements - through the literature review of traceability in the food industry along with the background analysis based on points of focus.
   - Using the requirements - a blockchain framework is chosen, and a platform that supports the requirements is designed.
   - Implement the system according to the design in a chosen context.
4. **Demonstration** - the designed platform is tested in all use cases that implement different traceability requirements.
5. **Evaluation** - the results are evaluated qualitatively based on its effective, to measure to what extent use cases are workable and therefore usable, and to what extent the use cases are restricted.

   After reaching this step, and answering all research questions, we can reach a conclusion of the validity of the thesis statement.
6. **Communication** - the problem and the designed solution will be communicated through a conference paper.

3.2 Obtaining Traceability Requirements

The findings from examining earlier studies in Chapter 2 indicate that there are insufficiencies in material's traceability in construction supply chain. Also, at present there are rare studies for material traceability in construction projects as it is still at an emerging stage. So, in order to answer the second question ***"What are the requirements that would be considered most valuable to improve the traceability of materials in the construction logistics chain?"***, an in-depth analysis has been conducted in traceability of the **food industry** along with a **background analysis**. The reason for choosing the food industry is due to extensive research previously conducted on food tractability from where the food originated until it reaches customers. This analysis from food industry will be based on the points of focus summarized in Section 3.2.1. These analyses will help to obtain the requirements that would improve the current material traceability challenges and serve as the basis to build a proof of concept.

3.2.1 Traceability's Points of Focus

Having previously discussed the issues relating to material's traceability in the construction industry in Sections 1.2, 2.1.1, and 2.1.4, the author has summarized them into main categories of challenges related to material traceability as shown below:

- **Information Limitation**: Everyone can notice the results of digitalization in SCM enhancement over the years. Automation of information dissemination in construction projects instead of traditional forms such as email or phone would result in efficiency in logistics and better tracking information of materials, also would implement services that ensure fast and accurate tracking data and enhance coordination between partners, and process information in an effective way. Researchers in [36][58][59] believe **this issue is a result of**:
  - Relying on traditional tools and manual forms (paper-based) to gather data that is entered in different centralized databases.
- **Standard Limitation**: The combination of one-off prototype construction project and partners who gather only to complete a project and may never work again result in short relationship and poor information exchange and synchronization. Usually, each company shares and synchronizes information according to the format its software understands; any time the information is passed from one party to another, a data integration issue is happened because there is no common software where material related information can be shared and update automatically. **A loss of time**, **delay recalls**, **delay in identification of materials that does not compliance of quality standards** and **duplication of work** happens because in order for each party to access information, a lot of manual work must be done in order to read data from one system and added to another. Researchers in [38] believe **these issues are a result of**:

- Lack of common standards for software interoperability and integration between parties in the construction supply chain.
  - Having multiple third-party system that prevent having a common data storage technology where each company has its own interface to retrieve, read, and share data automatically and instantly.

- **Scope Limitation**: It is important to have a global view of the entire construction supply chain by each partner. Therefore, at each point in the chain we should trace back to the provenance to verify the true value of materials and track forward to control the quality associated with materials. For example, at any stage in construction supply chain, if a defect is found, or material that does not compliance of quality standards is shipped, the responsible party should be identified; however, the current practices lack major tracking information, e.g. no details information of tracked material (timestamp, standards, condition, etc.). For this reason, all materials related information should be stored and tracked from the beginning until consumption, as well as the conditions under which they are delivered and the transformations they have experienced. The author believes **these issues are a result of**:
  - Neglecting the reverse logistic over the forward tracking, and focusing on some construction chain stages over the others.

- **Sharing Limitation**: Companies are keen on their privacy and the information they share and compromising the confidentiality of information can stop them from sharing it with traceability partners. The short relationship with other partners and multi-tier supply chains leads to an untrustworthy relationship, and a waste of time and resources to discuss what details to share, e.g., who should be trusted to access information, what should be restricted, how a defect in materials can be identified and recalled, and so on. Researchers in [38] [59] believe **these issues are a result of**
  - Lack of standards of balancing between amount of visibility among the construction supply chain partners and the confidentiality of information exchange.
  - Lack of trust between companies along the construction logistics chain that act as a barrier for information integration.

3.2.2 Traceability's Points of Focus in the Food Industry

Within the food industry, traceability has always been used as a tool to ensure food safety and quality. Also, nowadays, the industry uses modern traceability requirements due to globalization such as giving information on origin of product as verifiable evidence of traceability [16][21]. Since a construction industry is a way behind that, this section adopts the traceability requirements from food industry to improve the current material traceability challenges and to use them later beside the background analysis to design and build a POC.

Information Limitation

Exchange of traceability data is a significant issue for ensuring consistency and a seamless flow of information between supply chain partners as stated by Aung and Chang [16]. Product recall, identification of non-compliance products and ensuring quality would be difficult and time consuming if traceability information does not design to be exchanged in electronic and timely manner [16]. Bosona and Gebresenbet [21] argue that some stages in supply chain would be greatly influenced by automated data capturing, and availability of timely and accurate information and could affect the overall quality of products such as inventory control and batch mixing of products from different suppliers. Therefore, in order to avoid this kind of issue, and make sure that each partner is communicating and sharing needed information outside their boundary in accurate and timely manner, Aung and Chang [16], and Bosona and Gebresenbet [21] both agree that each partner must maintain internal traceability as it is the way to achieve chain traceability, which in other words, each partner or company should shift to automatic methods to capture data and use software for sharing information from one end to another in the supply chain.

Therefore, we can conclude from that all supply chain stages (activities) particularly inventory relay heavily on information being both timely and accurate that can be exchanged in automatic and direct way in order to achieve traceability.

Standard Limitation

Exchange of information in an electronic manner results in diversity of software that makes the integration of information in the supply chain difficult because of inconsistency in formats of data capturing which requires a lot of manual work to be done in order to read data from one system and added to another. In Aung and Chang's [16] terms, p.176 "Traceability can only be achieved successfully if it is built upon global standards that enable interoperability between traceability systems across the whole supply chain". The GS1 global traceability standard provide globally unique identification of trade items, partners, location and so on. It is well suited to be used for traceability purposes in any industry for the reason mentioned in Section 2.1.2. The GS1identified standards to unify the data format and to integrate information quickly and seamlessly for system seeking to supply chain traceability as the following [32].

1. A unique identifier must be issued for each TRU with global standards and be labelled / marked / tagged at source. One of the standards is the Global Trade Item Number (GTIN) [33]. GTIN is used to provide items, pallet, and packages, with a serial number [33].
2. After assigning identifier to TRU(s), This GTIN is used to capture relevant data (properties) of TRU during process time, and along the chain.
3. Every traceability partner involved in the physical flow of products will receive the same information format.

4. If any kind of transformation happens, and processing TRU produce different TRUs. A new TRU should has a unique identifier and be linked with the old TRU and shared with other traceability partners.

From the information above, we can conclude that using global standards is essential for interoperability to quickly share up-to-date information between partners and achieve chain traceability. However, this could only solve part of the issue because the industry is still missing a common storage mechanism to maintain and authenticate traceability data. A centralized database that is run by a third party is recommended as a digitized method to store, share and query traceability information in food industry [16][21] though privacy and reliability of information could become a barrier for sharing traceability data and preventing a full end to end integration as stated by Lanko et al., [41].

Scope Limitation

As mentioned in Section 2.1.4, previous studies in construction industry considers tracking of material information in some stages in supply chain instead of covering all the stages. Also, the focus is only on forward tracking of location lacking important details of materials and the consumer as an important partner in the chain, is also lacking the reverse logistics. Beside that, as mentioned in Section 2.1.2, they still adopt the ISO 9001 definition as a base for material tracking and quality assurance, which only emphasizes knowing the location of material along the supply chain, and provide a certificate as a proof of quality and industry standards, without any further details on how to implement a traceability system, as addressed in the standard BES 6001 [31].

In the food industry, information available in certificate, or printed in product does not mean that it can guarantee its authenticity, its quality, or that it minimizes non-compliance products, or it provide complete view of what happen in the chain [16]. It has been realized in a modern supply chain that there is an increasing demand of verification of food quality in the entire supply chain, and to tackle this any traceability system should support product traceability information from the source until consume by customer, with the ability to trace the product back at any given point in the supply chain, and with the ability to keep the history associated with product movement. In other words, any traceability system could provide global overview by supporting backward tracking (tracing), forward tracking (tracking) and keeping records [16][21]. According to Aung and Chang[16], tracking and tracing are important traceability requirements for any information system. They both provide information to check whether each point is operating correctly according to quality standards which in turn allow for early recalls, and fast detect and response to any problems. However, effective tracking does not lead to effective tracing and vice versa [16], which means both tracing and tracking should be implemented as a separate requirement for any system seeking for traceability. Both are essential as tools for quality control, identification of non-compliance products, early recalls, and proof of authenticity, and from Aung and Chang[16], and Bosona and Gebresenbet [21] point of view, non-compliant products would be reduce if we are able to trace or track product at any stage of the supply chain when quality or standards are not met.

Therefore, we can conclude that an effective traceability system can provide successful asset management in global mode by enable both tracking and tracing capability at every stage in the supply chain while keeping records. Both tracking and tracing are essential for monitoring of quality, trace the origin, fast detect and response when quality or standard's requirements are break.

Sharing Limitation

An important point mentioned by Aung and Chang[16] that visibility between supply chain partners is crucial for exchange traceability data, where each partner is responsible to share information with others. In Aung and Chang's[16] terms, product's tracking information not only need to be exchanged in electronic manner but in effective way as well. They suggest that partners should agree on how they would balance between information sharing, amount of visibility and confidentiality of information.

Here, we can conclude that there is a need for a robust mechanism to ensure that each partner has enough visibility to access traceability data while keeping the privacy of each company or partner.

3.2.3 Traceability's Points of Focus in the state-of-the-art Projects

The projects examined in the state-of-the-art utilize different frameworks of blockchain, some of them are conceptual while the others are pilot projects. Also, all of them specialize only in enhancing traceability in SCM. Here, we will focus on the requirements that have helped researchers achieving traceability and how it can help the author by matching them with the points of focus of traceability improvements summarized in Section 3.2.1 later on.

Walmart case study [7], this Walmart's project focuses on having better traceability for safety purpose. In this project they focus in shorten the gap of information delivery between partners and uses **GS1 standards** to define traceability data attributes and store it in the blockchain and ease the integration with enterprise systems. **Speed of information delivery**, **fully digital process**, **interoperability between systems**, **trace the origin of product**, **fraud detection**, and **fast recalls** used as main requirements of having better traceability. Another interesting requirement is **decentralized database**, it is found out that it is one of the reasons why we have not been able to have successful traceability in the past. Says Yiannas, "(Walmart's) CEO, I had been hesitant about creating yet another traceability system – the ones we had tried in the past never scaled. Now I understand that was because they were centralized databases" Walmart case study [7] p.3.

Yoo and Won [62], this proposed tracing system focuses on **managing products** and storing them in a **secure storage**, and **tracing the origin** of a product to avoid tampering with tracking information, besides customers and partners become aware of all the details of products at every point in the supply chain. Also, it focuses on **product history**, **fraud detection**, **access control**, **automatic services (through smart contracts)**, and **non-editable records**, and **auditing the data** as requirements for efficient traceability. Also, Yoo and Won [62] consider **information reliability** as a crucial requirement to trust the information shared by partners in the modern supply chain, the immutable nature of blockchain prevent tampering and establish trust.

Tian [57], this project focuses on achieving efficient traceability through **information reliability**, **real-time tracking information**, **secure storage**, **managing products**, **automatic services** using RFID and **up-to-date information** that is opened of everyone to access in the blockchain, and **auditing the data**. Just like Yiannas (Walmart's CEO), Tian believes the losses of traceability come from the centralized storage which prevent trusted coordination. yet this project in paper, and it did not provide a proof of concept that applies traceability requirements to prove the efficiency.

Figorilli et al., [29] this project attempts to address security beside traceability. it tackles traceability by **gather traceability requirements** and **industry regulations** in one system. It focuses on **keeping reliable records** of transactions, **detect fraud**, **fully digital process**, and **interoperability between systems**, **secure data storage**, and **data integration using APIs**. The main activities of tracking from the origin until the final phase was coded in a **smart contract**.

Similar to Figorilli et al., [29] and Yoo and Won [62], Kim and Laskowski [37], use **smart contract** to impose traceability requirements on a product. The traceability requirements that are translated into more operational way in smart contracts are **managing products**, **trace the origin of the product**, and **enforceable verification**.

Casino et al., [24] this project focuses on achieving food traceability besides providing food safety through the use of smart contract. Multiple requirements and features are applied to manage products, such as, **automating methods**, **trace the origin**, **non-editable records** and **auditing the data**.

In summary, although all of these projects focused on traceability, however, the only project that focus on translating traceability concepts and requirements explicitly based on certain assumption is Kim and Laskowski [37]. Also, blockchain nature architecture and smart contract have used to satisfy traceability requirements. Additionally, there was an agreement that centralized storage is the major obstacle of having complete chain traceability.

3.2.4 Conclusion

After analyzing the main point of focus presented in Section 3.2.1 from both traceability in the food industry, along with the comparison of the state-of-the-art projects, it is now the time to answer the second question of the thesis: ***"What are the requirements that would be considered most valuable to improve the traceability of materials in the construction logistics chain?"***. Challenges that cause insufficiency in material traceability that summarized in Section 3.2.1 are **information limitation**, **standard limitation**, **scope limitation** and **sharing limitation**. These issues are a type of problem that was encountered before in the traceability process in the food industry as it shown in the analysis above. At each points of focus, some requirements must be met in order to improve them. Therefore, a matching between those points and needed requirements are shown in the Table 3.2 below as it gathered from the analysis above.

The next chapter will take these requirements as a basis for choosing the blockchain platform, designing the proof of concept for improving material traceability in construction supply chain, and answering the remaining research questions.

Table 3.2: Obtained Material Traceability Requirements According to Points of Focus

	Points of focus			
	Information limitation	**Standards limitation**	**Scope limitation**	**Sharing limitation**
Traceability Requirements	Automatic methods of data capturing and transmission	Regulatory standards and Global standards e.g. GS1	Auditing	Secure channel for exchange information
	Automatic services	Connection and communication from one system to another	Product management (material identification, details, partner identification, and so on)	Secure data storage that ensures data security and integrity
			Real time tracking information	Access control
			Fast update of tracking information	Real time exchange of information
			Fraud detection	Reliable information
			Quality control	
			Non- editable history records	
			Trace the origin	

Chapter 4

Implementation

After obtaining the traceability requirements from the previous chapter, now in Chapter 4 and 5 we can answer the remaining two questions of the research respectively: ***"Which kind of blockchain initiatives and tools can be chosen to design a platform for construction projects to apply the material traceability requirements?"*** and ***"In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?"***. The first question demands a decision about which framework will be chosen through obtained the criteria that must exist in the the traceability system. While the other question demands more details description of the obtained traceability requirements to design a platform using a chosen blockchain's framework. After that, in the next chapter, we can assess whether the PoC has succeeded in building all the requirements that aim to improve material traceability in the construction supply chain or not.

This chapter and the following chapter present how these two questions have been answered. The first section in this chapter begins with analysis to choose the best blockchain framework that suits material traceability requirements and ends with a decision of the chosen framework. The following sections focus on specifying the requirements by following recommended practice for software requirements specifications by IEEE, then the design of the platform, the actual implementation and the architecture are presented.

4.1 Framework Selection Criteria and Selection

In this section, the focus is to answer the third question of the research problem: ***"Which kind of blockchain initiatives and tools can be chosen to design a platform for construction projects to apply the material traceability requirements?"***. So, to reach a decision of the best framework, we need to translate the obtained requirements from Chapter 3 into operational means in the form of the main criteria, aspects, and services that must exist in the traceability system. Besides, the comparison from Section 2.3.3, and the first point of the key components of designing a blockchain application from Section 2.4.4 must be part of the analysis to reach a definitive decision of the suitable framework of this work.

4.1.1 Translate Traceability Requirements into Operational Means

To ease the process of making the decision towards selecting a framework. The main criteria and aspects that exist in the framework should be based on the obtained requirements form Chapter 3, Table 3.2. For the reason that these obtained requirements relate to the points of improvement of material traceability that summarized in Section 3.2.1. Therefore, the decision would likely go to the framework that has the criteria and the aspects that highly match the obtained requirements.

Beginning with the first area of improvement, **information limitation**, it was clear that automatic identification of materials and automatic transmission of traceability information is crucial for consistency and seamless flow of traceability information between construction chain partners. Also, supporting automatic services that is executed whenever certain conditions are met will help reduce error and dispute.

In the second area of improvement, **standards**, it was stated that successful traceability should be built on top of global standards to enable interoperability between systems. Therefore, the potential framework should provide easy integration with other construction chain systems to allow inserting and querying the tracking information instantly. As suggested, global standards and APIs will enable partners to be interoperated with existing internal traceability systems or ERP systems. This will support exporting and importing tracking information from and to the potential framework.

In the third area of improvement, **scope**, it was stated that a traceability system should provide a global overview of all activities that happen along the construction supply chain, where all partners can possess complete tracking information of products. The potential blockchain framework should track materials' movement along the construction chain, including partners, resources, materials, and information flow. The framework should also notify all actions about the changes that happen with the ability to trace back at any given point. Details of products, participants, and transactions should be available to query at any given time with intended partners. Additionally, fraud detection, audits by regulators should be implemented through a smart contract and other blockchain tools, as stated earlier in the state-of-the-art-projects analysis.

Finally, the last point of improvement, **sharing**, it was stated that there is still a concern of the amount of visibility from one point to another in the construction supply chain, and the privacy of partners, and whether the traceability information can be shared or trusted. These issues could affect the sharing of traceability information from partners. Therefore, a potential blockchain framework should run in a governed environment with only trusted partners and ensure the reliability of traceability information to meet one of the main requirements to improve material traceability.

by discussing the criteria the potential framework should support according to the obtained requirements, the criteria of the potential framework are listed in Table 4.1.

Table 4.1: Framework Criteria According to Points of Focus

	Points of focus			
	Information limitation	**Standards limitation**	**Scope limitation**	**Sharing limitation**
Traceability Requirements (Framework)	convert documents, forms into digitized means	Use unified format for traceability data	Audit trail for all transactions	Role-based access control
	Enforceable contract	Interoperability	Product management (asset registries, traceability partner registries, transactions registries)	Identity management
			Keep Non-editable records	Governed environment
			Events emitted	
			Enforceable verification	

4.1.2 The Potential Framework

From the previous section, a set of criteria are listed in the table above as the main criteria that the potential framework should support to improve material traceability in the construction industry. In Chapter 2, the interest was on two popular frameworks, but the choice has to be made to one of them. Therefore, from the table above, we can notice that there are two criteria give preference to one framework over the other. The need for authorized partners and the governed environment make **private or permissioned blockchain** is the right choice to design and build the blockchain-based material traceability platform.

To double-check the decision of choosing the right blockchain, Wust and Gervais [61] provide a flowchart to determine the appropriate blockchain. The flowchart consists of several questions, and each question lead to a different path until reaching the appropriate blockchain.

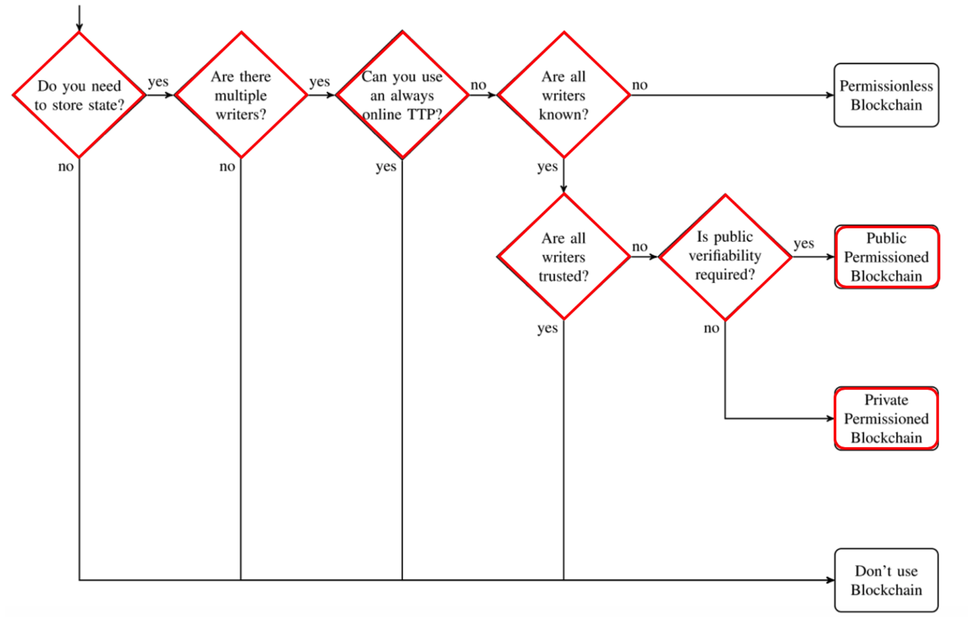

Figure 4.1: The decision path to decide what type of blockchain to use [61].

Based on the obtained traceability requirements that relate to control access of partners in a governed environment, the resulting blockchain that fits well is **permissioned blockchain (Figure 4.1, red path)**:

- Yes, we need to store state in the blockchain.
- Yes, we do have multiple writers from different companies in the construction supply chain.
- No, we do not need a trusted third party (TTP).
- Yes, all the writers are known.
- No, all writers are from different companies and they are not trusted.
- The answer could be yes or no because it depends if anyone can read blockchain state (public permissioned blockchain) or been restricted (private permissioned blockchain). However, the type would always be permissioned blockchain.

Based on the framework requirements that led to the suitable blockchain, now we can analyze it with the comparison of frameworks that are conducted in Chapter 2.

With **Ethereum**, anyone can access the network without the need for authorization which makes it misses one of the main functionality that must exist in the potential framework. Therefore, even Ethereum has been used before to improve traceability through smart contract functionality; however, it does not seem suitable for the environment of known partners who matters their privacy and confidently of shared information. On the other hand, **Hyperledger Fabric** is a private blockchain for only authorized partners, it also features different levels of permissions per user, and support smart contract functionality. This makes it the suitable framework that possesses the qualifications to satisfy traceability requirements in the construction industry that is difficult to achieve with Ethereum.

The framework requirements show that Hyperledger Fabric is the suitable choice as a framework. Besides that, the comparison conducted in Section 2.3.3, showed that Hyperledger Fabric has a better performance than Ethereum, and Fabric is flexible; the smart contract can be coded immediately using a known programming language such as Java and no need to learn a new language as in the case with Ethereum.

Therefore, we can come to a straight answer to the question: ***"Which kind of blockchain initiatives and tools can be chosen to design a platform for construction projects to apply the material traceability requirements?"***. So, based on the conclusion we reached from the analysis, Hyperledger Fabric along with chaincode's are the optimal framework and tool to use to design and implement an architecture that satisfies the requirements of improving material in the construction chain.

4.2 Platform Requirements Specifications

After making a definitive decision about the type of the blockchain framework for this project, now it is the time to use the obtained requirements from Chapter 3 to design and implement the platform. However, these requirements have to be broken down as sufficient detail description about platform characteristics is needed. The detailed description of the requirements follows the recommended practice for software requirements specifications of the IEEE organization - IEEE Std 830-1998 [8]. The requirements specification of the developed platform are divided as follow:

- **Introduction**: purpose of the work, scope of the work, and scope of the product.
- **Overall description**: users' categories and constraints.
- **Platform features and requirements**: functional requirements, non-functional requirements, data requirements, and platform tools.

4.2.1 Introduction

a. Purpose of the Work

This research is conducted to provide a proof of concept to evaluate the applicability of implementing blockchain platform with the typical construction supply chain to see how far the technology can support traceability requirements for materials using Hyperledger fabric v1.4.

b. Scope of the Work

The work presented in this dissertation is not a complete product. It is for a research purpose, and it is only a proof of concept and does not reflect how a real product would be.

The proof of concept focuses on improving the traceability of bulk materials according to the points of focus. This is mainly is done by converting all documents and forms into digitized means and verifying that material complies with quality standards and detecting non-compliances material. Also, by recording the movement of material with the ability to trace back at any given point in the chain, and increasing visibility between involved partners to allow them to insert, update and query traceability information while keeping the confidentiality of information and supporting an instant update for traceability information.

c. Scope of the Product

The PoC is developed locally using Hyperledger fabric v1.4 with lots of prerequisites being installed. It started with the development of Hyperledger fabric v1.4 network which includes the blockchain, ledger, peers, and CouchDB. The chaincode and blockchain will be designed to handle all the transactions to manage material traceability, actions, and the identities of construction project partners.

The transfer of material traceability information from and to internal traceability systems or ERP systems and blockchain has been applied to this study but in a simplified way. The architecture of the needed APIs and typical layers to interact with the blockchain network has been provided along with the use of global standards format to define data, to ease the process of integration with other systems and the blockchain.

4.2.2 Overall Description

a. User Categories

This work is dedicated to the construction industry that runs any supply chain, whether a simple or complex (spanned geographically), and wants to transform it into digitized solutions. Also, it is dedicated to construction company intends to integrate its internal traceability systems or ERPs with the blockchain to have a common platform with their partners in a secure network that transmits traceability information in a governed environment and keeps non- editable history records for all traceability transactions. In this section, all possible users who can benefit from this PoC if the platform is extended to include the upstream parties of construction supply chain are listed and then followed by the intended users (downstream parties of construction supply chain) for the proposed PoC.

users who can **benefit** from the proposed blockchain-based traceability system are:

- The construction company which includes general manager, inventory manager, employees from the purchasing department, engineers, and common employee. They will have visibility over material movement along the construction chain.
- Other construction supply chain partners such as suppliers, shippers, vendors, manufactures, distributers, suppliers' suppliers, and extractor, any of these companies will have access to material's information with their partner immediately, a material status update will be synchronized between them which will speed the delivery of correct material and increase trust between them.
- Authority organizations e.g. audit, regulator, or traceability certificate authorities (e.g. BRE Global) will have access to materials tracking information to check whether regulations are met and that materials are within quality standards. Also, they can perform inspections to check if there were any attempts of fraud of quality of materials between what has been ordered and what has been consumed.
- Customer can track the source and the history of the material they bought until it becomes an end product (e.g. a building) which increase their confidence.

Besides that, **other users** are:

- Blockchain network developer – to set up and deploy the blockchain network.
- Smart contract developer – to develop and deploy the smart contract.
- Client application developer - to export and import the data from and to the blockchain with the use of APIs.
- Network administrator(s) – they have control over the blockchain network in terms of assigning identity, assigning roles, revoking identity, to name few.

The **intended users** who would be registered with the proposed platform for bulk materials tracking are:

- Network admin(s)
- Developer(s)
- Regulator(s)
- Construction supply chain members
    - Construction company
        * General manager

    - ∗ Inventory manager
    - ∗ Purchase department employees
    - ∗ Foremen
  - – Supplier company
    - ∗ Supplier
    - ∗ Shipper
  - – Customers

b. Project Constraints

Constraints the project follow are:

- An asset (construction material) would be tested on bulk materials only, cement and pipes.
- The implementation starts from the downstream parties of the construction supply chain until having a finished product.
- The data format has to define based on a simplified way of GS1 standards.
- All tools and software that will be used in this project are open-source.
- This PoC will be developed locally using Hyperledger fabric v1.4.
- The deployment environment this project follows is the one for testing purpose, not production.
- A simple frontend and backend will be implmented to ease the integration between blockchain and other internal traceability systems or ERP systems.

4.2.3 Platform Features and Requirements

a. Functional Requirements

The **platform** is divided into a Hyperledger Fabric blockchain network (system), a smart contract or chaincode (application), authority organization (regulator), customer, and network admin. Next to each of them is an explanation, accompanied by the material traceability requirements based on the points of focus summarized in Table 3.2, with a number and a detailed description. It is important to understand that Hyperledger fabric uses some terminologies such as asset, participants, invoke transaction, and revoke identity.

Beginning with **Hyperledger Fabric blockchain network**, the system is decentralized distributed system that record, process, update all data and transactions in ledgers. This data and transactions are get verified through consensus before it is being updated in the ledger.

All types of peers and the construction chain members and regulator has to register to the system through a registrar (MSP), to provide credentials and a unique identity for each of them. Once the construction chain members and regulator are enrolled in the system, a public and private key are generated for them to interact with the blockchain network and to increase the trust of the network between them.

Once the network is created, an admin user attached to the network is get created, and we have to enroll it first to generate its credentials then we can use it to assign other credentials to construction chain members and regulators. Here, admin user act as the registrar of MSP to issue credentials to other users of the network.

The data should be visible for blockchain participants only, and they can invoke transaction, and add, update, check information based on the permission and the channel they have been enrolled in and as long as they still register as a user in the system or a channel. Also, the integration from and to other internal traceability systems to export and import data from and to the blockchain should be handled by the system to get proper credentials.

Therefore, having information in digitized means, authorization and authentication, secure channels, asset management, and consensus that would increase trust between construction chain members to exchange material traceability information are handled by the system. A more detailed description of what actually the system has to perform is described as follow:

1. The system shall provide the network administrator with credentials.
2. The system shall provide all peers and participants with credentials and identity.
3. The system shall allow each organization to have its own admin.
4. The system shall allow participants to edit their information.
5. They system shall define who can invoke transaction, read, update, and write in the blockchain.
6. The system shall record all actions and transactions that is invoked by users.
7. The system shall keep non-editable history records of all transactions and actions.
8. The system shall timestamp all transactions.
9. The system shall allow the deployment of chaincodes.
10. The system shall allow specifying policies around the execution of chaincode.
11. The system shall allow the creation of more than one channel to deploy the chaincode to support the information privacy of different organizations.
12. The system shall detect any fraud of the contents of blocks of the same information, e.g. if the information in pre-delivery inspection mismatch the information of pre-inventory inspection. Another example, if a material arrives in a different location than the expected one.

13. The system shall send a notification of events.

14. The system shall support the use of APIs to handle users' actions to the blockchain e.g. from the front end application to the blockchain.

15. The system shall impose access control and authentication on APIs from and to the blockchain.

16. The system shall support the invocation of multiple transactions at the same time.

Some of these functionalities are a built in Hyperledger fabric architecture, while others have to be programmed.

While the system shall ensure having a governed environment to share and integrate material traceability information between all construction chain partners and regulator, **Smart contract or chaincode**, will provide them other functionalities for material traceability requirements in the construction supply chain on the created channel but only registered members are allowed to invoke transactions. They can manage the material tracking along the construction chain by supporting automatic services, digital forms, enforceable contract, inserting new materials order, contact with suppliers, track material status updates, track delivery, track inventory, transfer material holder, track origins of materials, track materials on the work field, and so on.

All of these functionalities will provide a complete overview of all details of materials along the construction chain for all partners. Here, how material traceability in the construction supply chain can be supported by the functionality of smart contract in the proposed traceability system:

1. The smart contract shall allow the construction supply chain members to send invocation request on the chaincode for transactions.

2. The smart contract shall allow the construction supply chain members to create new assets (materials) record with all required key attributes.

3. The smart contract shall allow the construction supply chain members to read, update, or delete assets based on the permission that has been given to them.

4. The smart contract shall allow the construction supply chain members to create order and attached contract to it.

5. The smart contract shall allow the construction supply chain members to create delivery order and attached contract to it.

6. The smart contract shall allow the construction supply chain members to create good receipt order and attached contract to it.

7. The smart contract shall allow the construction supply chain members to create consumption order and attached contract to it.

8. The smart contract shall assign an automatically number for each contractual agreement between construction supply chain members.
9. The smart contract shall allow the construction supply chain members to create any contractual agreement.
10. The smart contract shall allow the construction supply chain members to query and track the history of information associated with an asset at any given time to trace the material back to the origin until the time of the query.
11. The smart contract shall allow the construction supply chain members to query to know the possessor of an asset.
12. The smart contract shall allow the construction supply chain members to query a shipment, and retrieve information such as the buyer, supplier, shipper, assets quantity, GTIN, and so on.
13. The smart contract shall allow the construction supply chain members to query inventory, and retrieve information such as the receiver, shipper, GIS, and so on.
14. The smart contract shall allow the construction supply chain members to query who consume certain materials, and retrieve information such as the consumer, quantity, consumed reason, and so on.
15. The smart contract shall allow the construction supply chain members to query the status of assets at any given time.
16. The smart contract shall allow the construction supply chain members to raise a dispute in case of damage.
17. The smart contract shall allow the construction supply chain members to raise a dispute if the asset does not comply with quality, regulations or standard.
18. The smart contract shall send notification of every actions on the chaincode to the general manager or regulator.
19. The smart contract shall link each asset to associated information along the supply chain.
20. The smart contract shall update the construction supply chain members with transactions they made e.g., check purchase order status, and so on.
21. The smart contract shall notify construction supply chain members if the shipment exceeds the expected arrival date.

Customer: The customer role in the construction supply chain is to track the history of material:

1. The smart contract shall allow the customer to track the history of an asset by entering the GTIN associated with to query and track the history to trace the material back to the origin.

Regulator: The regulator is part of any authority organization which its job requires to make sure that rules and regulations are met. The regulator can be chosen for monitoring purpose or can do more than that, e.g., detect fraud. A more detailed description of what actually the regulator can do is as follow:

1. The smart contract shall allow the regulator to query and track the history of information associated with an asset (material) at any given time to trace the material back to the origin.

2. The smart contract shall allow the regulator to perform assets (materials) inspection from one point to another in the construction chain, e.g., pre-delivery inspection, pre-inventory inspection, upon leaving inventory inspection and consumption inspection.

All Admin's functionalities are built in Hyperledger fabric architecture; however, the author list them below for the reader to understand the tasks the admin can perform.

Network administrator(s): As mentioned earlier, when a blockchain network is set up, an admin is created. The admin is the entry point for the MSP, to register other users, and grant them an authorization to interact with the blockchain. Admin acts as a security guard to keep a governed and secure environment from intruders and to maintain the network. The admin job is very crucial in achieving the obtained requirements to have governed and secure environment to incentives participants to exchange traceability information:

1. The admin shall be able to register participants and assign an identity to them through MSP.

2. The admin shall be able to revoke identity for participants e.g. expired certificate.

3. The admin shall be able to assign roles to participants.

4. The admin shall be able to change the roles of participants.

5. The admin shall be able to create channels and grant permission to participants on a channel level.

6. The admin shall be able to invoke transactions.

7. The admin shall be able to create, delete, and update assets.

b. Data Requirements

In the PoC, data is very crucial to satisfy the obtained requirements for material traceability. Having a unified data format, it will ease the integration between traceability partners along the construction supply chain. So, the goal is to use a global standard format to define the data in the PoC. Therefore, the data in the PoC will be built according to standards of **GS1** organization as it develops Global Traceability Standards as mentioned in Section 2.1.2 and 3.2.2. Again, this work is only for research purpose which will build only a minimum number of data attributes, however, in a real system these data attributes would have to be complete. Based on traceability data description in Chapter 2, the data in this project should be divided into two types:

- **Master Data:** the data contains general information for TRU (asset (material)) which includes participants, address, contact information and other attributes such as asset' model number or unique number (GTIN), location (GIS), weight and other material specifications.
- **Transactional Data**: The tracking data that is related to assets (materials) movement along the construction chain. This is the generated data based on transactions e.g. shipment information, time stamps, inspection information, and so on.

c. Non-Functional Requirements

The platform should follow the following non-functional requirements:

- **Usability** An interface should be clear for construction chain partners, customers, and regulators in the construction industry to use and navigate, also it should notify them for any upcoming request or update in the material status along the supply chain. A global data format should follow and use APIs. A read me file should be clear for developers to use them to integrate the blockchain with other internal traceability systems or ERPs to export and import the material traceability information from and to blockchain and from and to any ERPs.
- **Accuracy** The immutability nature of blockchain prevents any tamper with the data. However, blockchain cannot prevent the inserting of wrong data. The wrong data may be recorded in the ledger; however, any data must not update the blockchain world sate unless it is approved.
- **Security** Appropriate visibility between construction chain members should be maintained. In other words, the Hyperledger fabric provides multiple channels for data privacy. So, if some information needs to keep it confidential and important for the company internal traceability system, a new channel can be created to keep the confidentiality of the company' s information.

- **Performance** The platform should not fail or stopped, therefore it should not build on top of a single node (solo), other type is available such as (Kafka), this platform use only one order node, however, a real platform is expected to use more than once order nodes to avoid a single point of failure.

  Also, compared to Ethereum, Hyperledger fabric has shown better performance, but it is not better than a centralized database. But to look into the positive side, Hyperledger provides features to improve material traceability that could not achieve with the centralized database.

- **Portability** The platform is compatible to run on macOS; however, the Docker allows the platform to be compatible with another operating system. Also, the infrastructure requirements have been kept to the minimum, so the functionality can be transfer to other projects. on the other hand, all tools requirements have been listed, and read me file has been provided to ease the process of downloading and running the system.

- **Flexibility** The platform should be flexible to be scaled up with other stages in the construction supply chain for other materials types, e.g. engineered materials and prefabricated materials.

d. Tools Requirements

A sample Hyperledger Fabric Binaries and Docker Images is downloaded, and the author builds on top of them and customize a solution based on requirements. The sample and pre prerequisites are available here [12][13]. All the tools needed to build the proof of concept are listed below:

Hardware Requirements:

- PC – this project uses MacBook Pro, processor: 2.7 GHz Intel Core i5, Memory: 8 GB 1867 MHz DDR3

Software Requirements:

- Hyperledger Fabric v1.4.2

In order to develop or operate Hyperledger Fabric, the following prerequisites must be installed in the platform operating system:

- Docker and Docker Compose – v19.03.8
- cURL - latest
- NPM – latest
- nvm - latest
- Node.js - latest

- Python - v2.7.x
- Go - v1.13

Also, to develop and test the platform and the smart contract:

- Code editor - Visual Studio Code version 1.28, or higher.

For building user interfaces:

- React - v16.13.1

For the middleware:

- Nodes.js - v8.16.0
- Postman – API client
- MongoDB - v4.0.18

For Hyperledger Explorer:

- PostgreSQL - v12.3
- jq - v1.6

4.3 Platform Implementation

Building a blockchain framework does not have to start from scratch, Hyperledger fabric specific binaries and Docker Images have been downloaded as a starting point to configure a blockchain network to ease the process of implementation. The design blueprint will be based on the functional requirements, non-functional, and data requirements from Section 4.2.3. The implementation is divided into four parts:

1. Blockchain network set up.
2. Smart Contract (chaincode) design.
3. Access control design.
4. Middleware and frontend design.

For the implementation, the author follows an iterative design approach to accomplish them. In this section, the system model for material traceability in the construction industry is presented in a form of class diagram. The section starts with an overview of the platform, then implementation of the blockchain network, smart contract, data accessibility, middleware, frontend, and conclude with architecture for integrating the current proposed solution with other internal traceability systems or ERPs. So, in the following section along with next chapter, we will be able to answer the last question of this research: ***"In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?"***.

4.3.1 System Overview and Network Setup

The blockchain-based material traceability system includes the following actors as explained before, construction chain members, customers, and regulators. they all are connected through a decentralized network. The construction chain members are a construction company and common employees, suppliers, and shippers. Each of the actors of the system represents a peer in the network, where they can gain their identity and deploy the smart contract. The functions and roles of each peer are described below:

Construction Company: The **buyer** in the purchasing department places an order for materials with the supplier. The buyer will mention material type, quantity required and price the company is willing to pay. An **Inventory manager** creates goods receipt, and then places the materials in the storage. Also, he releases materials from inventory for the foreman for consumption in the construction site. The **general manager** track material movement to check whether the correct materials and quantities are being delivered or not. Also, track the activities along the supply chain and the work field. The **foreman** creates a consumption order for the materials that would be consumed in the working field. **In the real system, typically the construction company have many actors involved such as logistic engineer, inventory engineer, and so on, but**

this project is only a proof of concept that uses the minimum number of actors for implementing the basic functionality of the system.

Suppliers: The supplier is the holder or the owner of the material (asset). The material should be registered in the system by the supplier with a unique code, GTIN. So, the customer can trace back to the source of the materials. Additionally, the supplier receives the purchase order from the buyer in the purchase department at the construction company on their dashboard, does an internal stock check and dispatches the material to a shipper, and transfer the material possession to a new owner.

Regulators: The regulator authority as a peer in the network can monitor materials movement also does an inspection to check if materials as per requirements and regulations. Also, a regulator can dispute or do recalls if quality issues occurs.

Customers: The customer is the user who actually going to use the materials as an end product, e.g. house, building, and so on. The customer can be part of the network to query the source of materials.

The blockchain-based traceability system is shown in Figure 4.2 which include construction chain partners (construction company and suppliers), regulators, and customers which are connected through decentralized networks that are endorsed by the construction company, supplier company, and regulator authority.

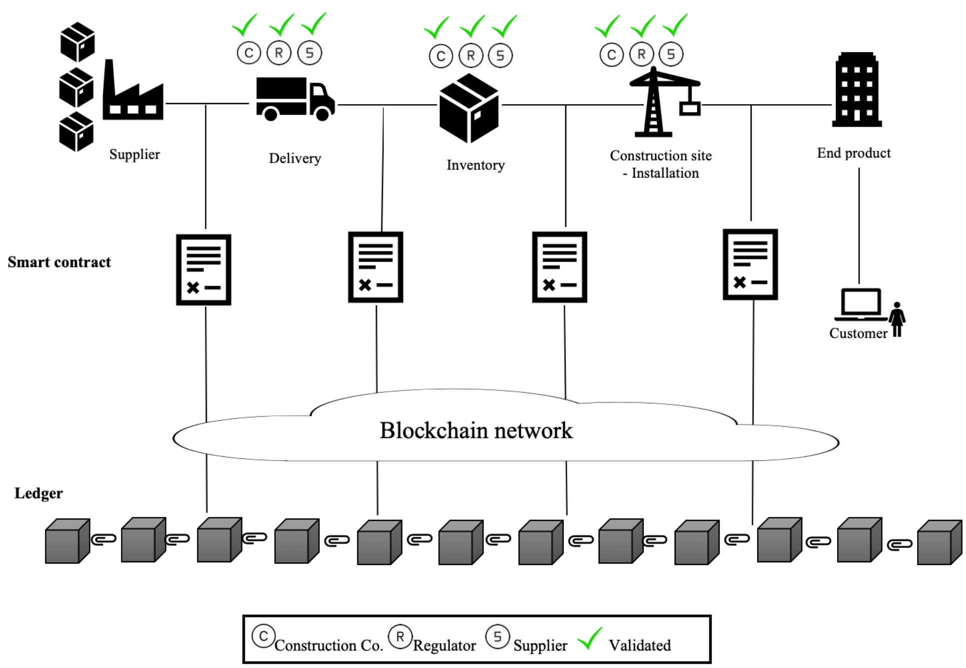

Figure 4.2: System Overview.

based on the project requirements and how to setup the blockchain network from Hyperledger Fabric documentation [10] and how to build it [11], the network was designed and built, below in Figure 4.3, **is the network topology for the three organizations that are a part of the configuration of material traceability system in the construction industry, R1, R2, and R3, for a construction company, supplier and regulator respectively**. As you can see the blockchain network infrastructure (trackbyfn) is exposed to all peers and the network configuration (NC) is governed by policies agreed by three organizations R1, R2, and R3 who made the network. The Regulator (R3) can be chosen to be a full peer to maintain the ledger or light peer just for monitoring, here regulator is a full peer. The ordering service (orderer.track.com) represents a single node (solo), and it gives the administrative rights to the three organizations. Each organization represents as peers in the network peer0.cst.track.com, peer0.sup.track.com, and peer0.reg.track.com, and each of them has a copy of the same ledger L1. Also, the network has one channel "mychannel" to deploy the chaincode "track". The channel "mychannel" is governed by rules agreed by the three organizations in my channel configuration MCC. In other words, transactions must approve (endorse) by the three organizations before accepting it by all of them and update all the ledgers. Additionally, each organization has a client peer or client application A1, A2 and A3 to perform transactions within channel "mychannel" from outside blockchain network, more about that in Section 4.3.4. In addition, each organization has a unique root certificate, ca.track, ca.cst.track, ca.sup.track and cs.reg.track for issuing and managing the identity of components to that organizations and orderer peer.

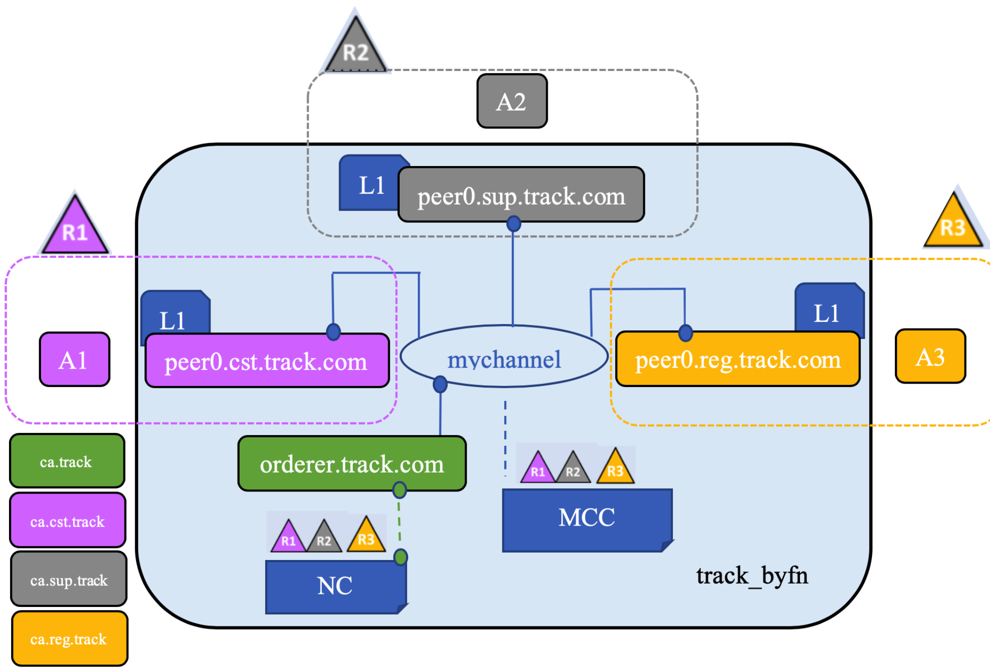

Figure 4.3: Fabric Network Topology for the three-organizations.

The network setup includes the specifications of **.yaml files** that generate network artifacts which include the creations of peers (organizations), identities (certificates and keys) of organizations and its components, genesis block, channel, chaincode and policies. After we run the **.yaml files** using specific tools, the generated contents and certificates will be parked in folders titled "crypto-config" and "channel-artifacts" as shown in the Figure 4.4 and 4.5. The full inputs of the content of .yaml files and all generated folders and files of the network can be found on GitHub:https://github.com/SofanaAlfuhaid/build-blockchain-based-material-traceability-system-in-the-construction-industry. The network is setup using Docker containers where peers hosted in Docker containers instances.

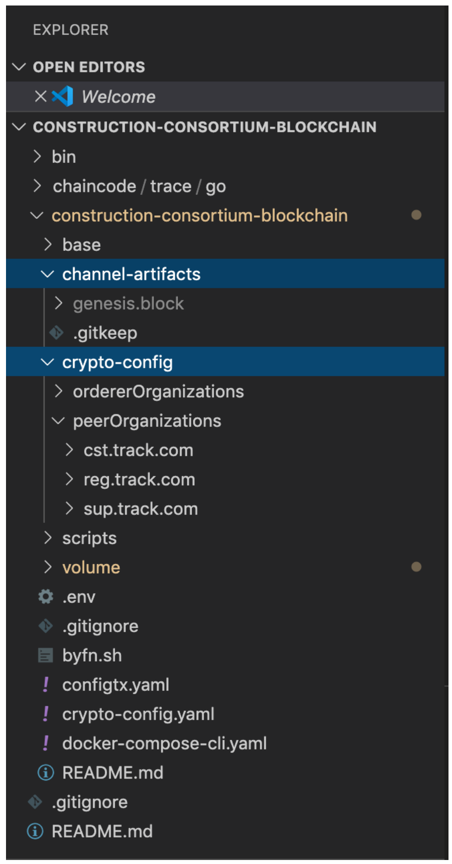

Figure 4.4: Screenshot of Multiple Folders and Files that make up the blockchain network artifacts.

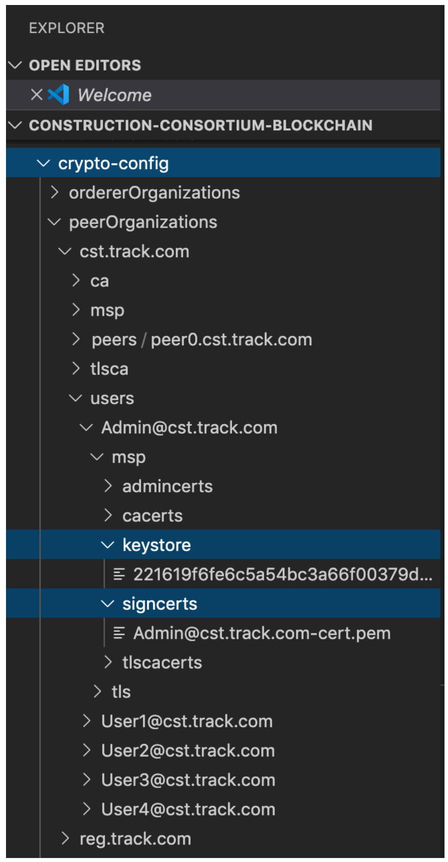

Figure 4.5: Screenshot of generated orderer and organization peers along with MSP and TLS that contain certificates and keys that allow participants to be part of the blockchain network and to access the application from and to blockchain network in a secure connection when tls is enabled. Each entity e.g. admin in the blockchain network will sign transactions and made communications with their private key ("keystore"), and then verified by a public key ("signcerts").

Join Peer, Create Channel, Install and Instantiate Chaincode

After running the network and creating peers (**construction company, supplier and regulator**) and its components, now we can access the peers to create a channel (mychannel) and install and instantiate the chaincode (track) to invoke transactions from the smart contract. Here, when we instantiate the chaincode we specify the **endorsement policy** where each transaction must be endorsed **by the three organizations** before accepting any changes to the blockchain by using the following command (Figure 4.6):

```
peer chaincode instantiate -o orderer.track.com:7050 --tls --cafile $ORDERER_CA -C
channel_name -n chaincode_name -v version -c '{"Args":["init"]}' -P "OR
('CSTMSP.peer','SUPMSP.peer', 'REGMSP.peer')"
```

Figure 4.6: Chaincode instantiate command and specifying endorsement policy.

Figure 4.7 shows an illustration of running the network up, joining the construction peer, create, install and instantiate Chaincode. The commands used in the Figure is the list command instead of create command because the channel has been created before, and same for the chaincode. The peer we join here is the construction peer (clicst) and we can do the same with other peers (clisup)(clireg), all environmental variables for each peer are specified in **docker-compose-cli.yaml file**.

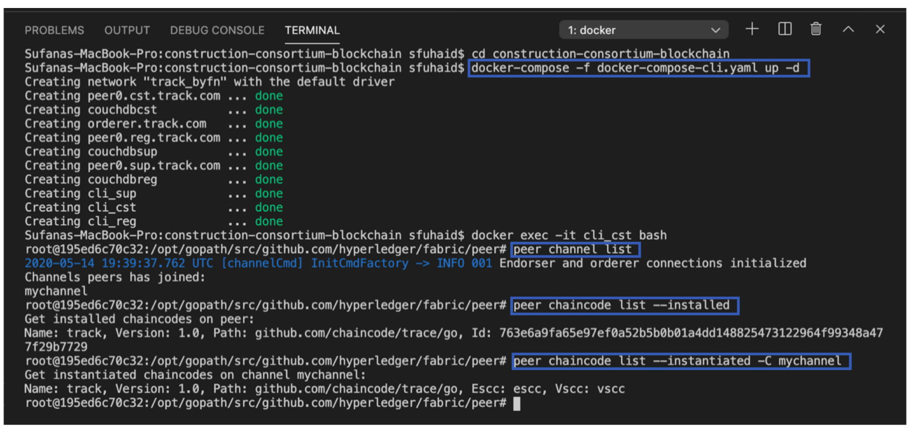

Figure 4.7: Running the network, join the peer and channel, install and instantiate Chaincode.

4.3.2 Smart Contract

Based on the requirements, the smart contract was designed and built using Go programming language. This includes the specifications of the **.go files**. It contains the chaincode functions (transactions) that users invoked to interact with the blockchain to query or update the ledger. Only main smart contract transactions and parameters will be explained, in addition to algorithms that author sees it is important for the theory part, full transactions and the business model that governed the interacting between construction supply chain partners can be seen from the class diagram below in Figure 4.8, and a full script can be found on GitHub: Here. The use of a UML diagram to help design the smart contract in the form of class diagram and the special notations of blockchain is derived from [42]. The smart contract components that will be explained in this section are **participants**, **assets**, **transactions**, and **queries**.

In order to achieve the material traceability process, the designed **smart contracts** is divided into **Purchase Contract (PO)**, **Delivery Contract (DO)**, **Pick up Contract** or **Goods Receipt contract (GR)**, and **Consumption Contract (CO)**. The DO contract contains PO number, and GTIN so all other contracts can be connected. The main components included in the design are **participants**, **assets**, **transactions**, **events**, **queries**, and **enumerations**.

Participants

Participants were defined earlier and had given identity when setting up the network. In the smart contract the following participants are given permission on the channel (mychannel) that deploy the smart contract to invoke transactions and interact with each other for managing materials along the construction supply chain:

- Regulator
- Customer
- Construction chain members
  - Purchase department employees (buyers)
  - General manager
  - Inventory manager
  - Foremen
  - Supplier
  - Shipper

These participants would be interacting with each other in the same channel in the network except customer (query only), and they have the same defined attributes in the smart contract as shown in Figure 4.8. The access control of each of them is explained in Section 4.3.3.

Assets

Construction materials and construction chain activities are the assets that is going to be stored in the ledger along with its status, and any changes that happen is based on smart contract transactions and participant's interaction. The assets of the construction business model are:

Material – represents materials owned by supplier and going to be exchanged. The attributes defined are Material ID (GTIN), type, description, and the current owner ID.

Purchase Contract – it represents the materials purchase order made by the buyer (purchase department) to a supplier. It includes all materials specifications needed for a specific project. It includes purchase order number, material type, quantity, description, status, location want to be shipped to, date and the ID for the person who made the purchase request, and the ID of the supplier. Whenever, this purchase order is accepted, there is a contract associated with it that made between the buyer and the supplier.

Delivery Contract – it represents the shipment the supplier prepared for the buyer. It includes the tracking information of materials, such as GTIN, truck number, shipment ID, shipment status, location, materials items, batch weight. Also, it includes the ID of the carrier (current holder or new owner), and ID of a regulator who do a pre-delivery inspection. Whenever, this shipment order is created and approved, there is a contract associated with it that made between the buyer and the supplier.

Pickup Contract – it represents the receipt of goods from the carrier by inventory manager. It includes the tracking information of received materials, such as, expected items, expected quantity, expected batch weight, status, expected location, and the GIS (the location the materials will be stored in inventory) also it includes the ID of the carrier and the receiver, and the regulator ID who perform a pre-inventory inspection. Whenever, the pickup order is created and approved, there is a contract associated with it that made between the inventory manager, the regulator, and supplier.

Consumption Contract – It represents releasing material from inventory to the work field for consumption by foremen from inventory manager. It includes the tracking information of using the purchased materials. It includes material ID (GTIN), quantity, Batch ID, Batch weight, status, the ID of the person who holds it (current owner), the ID of person who is going to consume it, and it the ID of the person who approves it for release from inventory.

Inspections are performed along the construction supply chain when materials arrive or leave a certain place to check if materials match the information in the purchase contract and regulations. Also, possible events of materials or possible fraud are emitted along the process of tracking materials.

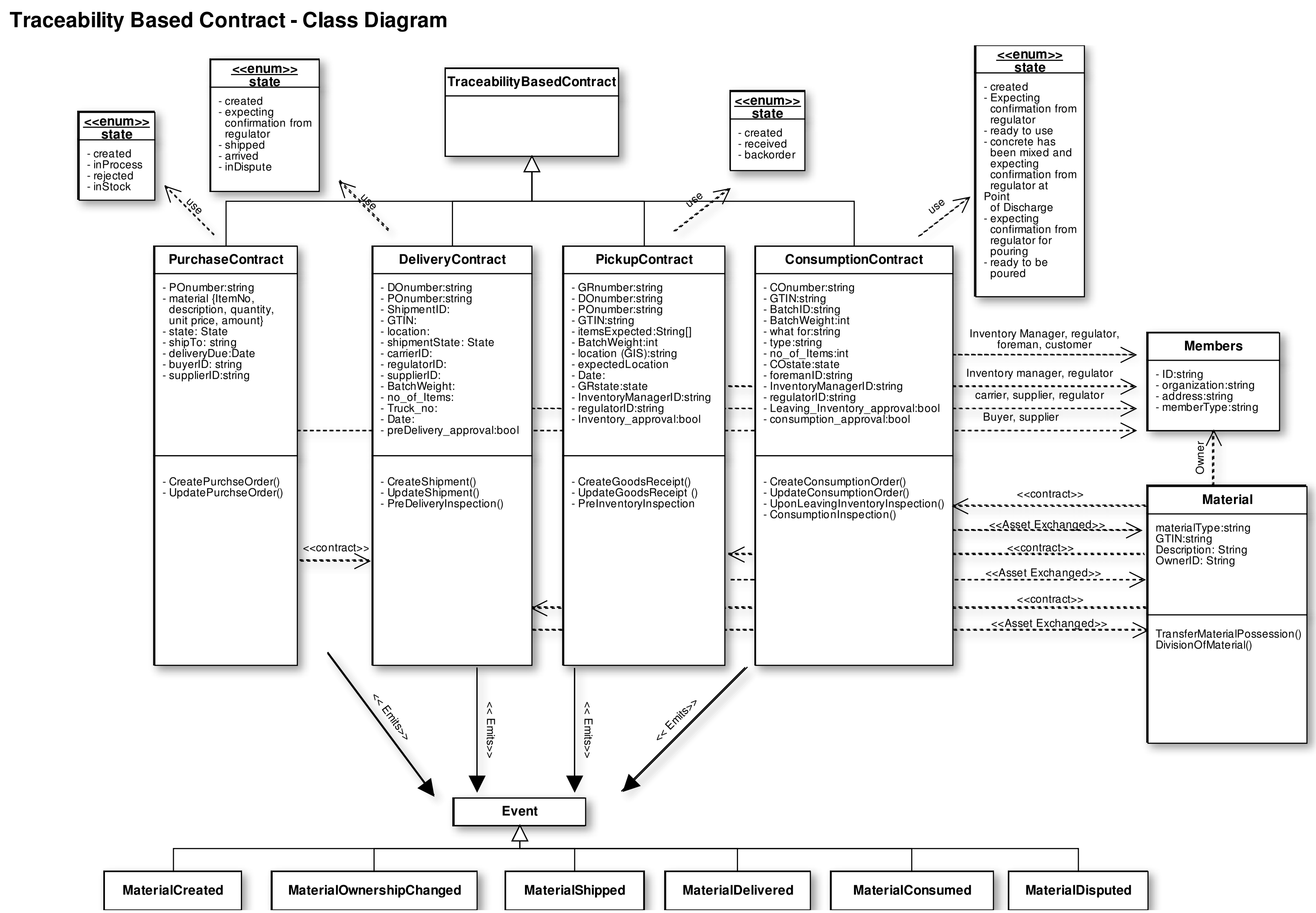

Figure 4.8: The Structure of Smart Contract of the Traceability System.

Business Logic – Transactions scripts

Through invoking (call) transactions, the participants made changes to the assets (construction materials). Transactions are smart contract functions in the construction network. Also, it controls the movement of materials (assets) between participants. Any material transaction invocation made by supplier or other participants along the construction chain is recorded as a block in the blockchain ledger.

All the business logic of materials traceability is modeled here in the form of transactions and their description:

CreatePurchseOrder - creates the purchase order and its contract simultaneously which includes all the parameters e.g. materials specifications, buyer, supplier, location, date, price willing to pay, and so on. The buyer will submit this order with their private key to the system, and then after the validation process (approve that all data needed is included before moving to the next phase in the supply chain) by authorized members from three organizations, it will be stored in the ledger and the first block will be created, and it will be moved to the supplier through their public key. Also, the general manager and regulator will get notified that an order has been placed. The new created block is timestamped and has information about the material that blockchain will keep track of it. Therefore, by registering the purchase order on the platform, all peers can see it through the platform. Algorithm 1 gives the he pseudo-code to create purchase order function.

Algorithm 1: PurchaseOrder()

Input(): The supplier ID, material {ItemNo, description, quantity, unit price, amount}, state, shipTo, DeliveryDue, BuyerID, POnumber(generated automatically by smart contract), current timestamp (now).

1. getInvokerIdentity **is set of authorized users to invoke smart contract transactions**
2. **If** cst.track.com ∈ getInvokerIdentity **then**
3. **If** all material parameters ≠ null **then**
4. Registries all input information to the blockchain, update status automatically, generate POnumber automatically and send order request to supplier.
5. **else**
6. Show an error "missing parameters"
7. **end**
8. **else**
9. show an error "Unauthorized Access"
10. **end**

UpdatePurchseOrder - update the status of ordered materials. The status of material is automatically updated based on the action of the supplier who received the order and the regulator who do the inspection, and the inventory manager who receives them. **Emits an event when the material order status is being updated**. Also, the purchasing department, general manager, and regulator will get notified of the updated status of the material.

CreateShipment - once the supplier accepts the purchase order, a purchase order status is updated automatically, and a shipment and associated contract is created which include the tracking parameters of materials shipment e.g. carrier, buyer, supplier, regulator, material items to include in the shipment, GTIN, batch weight, location, date, Shipment ID, Truck no, and so on. The general manager, the regulator will get notified that a delivery order is placed. The materials will not allow being delivered until it gets the approval from the regulator.

UpdateShipment - update the tracking status of the shipment that includes the ordered materials. The updated information includes passing the materials to a new holder, location, or passing the materials for inspection, and so on. **Emits an event when the shipment status is being updated**.

CreateGoodsReceipt - once a carrier delivers a shipment of materials, a goods receipt and the associated contract is created which include tracking information of delivered materials e.g. information of materials included in the shipment, quantity, batch weight, condition, and location in the inventory, and so on. The materials will not allow to be received and stored until it gets the approval from the regulator.

UpdateGoodsReceipt – update the tracking status of delivered materials, the updated information includes passing the materials to a new holder, location, or passing the materials for inspection. **Emits an "a dispute (penalty)" event if the shipment arrival day exceeds the expected day**. **This is done automatically if certain conditions do not follow**. **Also, emits an event when the goods receipt status is being updated**.

TransferMaterialPossession – transfer the holder or the ownership of the materials between construction chain participants. **Emits an event of changing the ownership or the holder of the materials**.

DivisionOfMaterial – this transaction happens if a batch of materials is going to be used (consumed). A new Batch ID will be associated with the material ID (GTIN). **Emits an event of creating a batch from bulk materials**.

Algorithm 2: DivisionOfMaterial()

Input(): The Inventory manager ID, GTIN, Batch ID, material {ItemNo, description, quantity}, current timestamp (now).

1. **If** cst.track.com ∈ getInvokerIdentity **then**
2. **If** quantity of material at consumption order < quantity of materials in stock **then**
3. Batch ID is added and linked to Material GTIN, and all inputs is added to blockchain, and material status updated automatically.
4. **else**
5. show an error "Unauthorized Access"
6. **end**

CreateConsumptionOrder – when the work starts in the construction site, a consumption material order and the associated contract is created which include types of materials to consume, quantity, material ID (GTIN), the new batch of material and its weight, location, the foremen will be handle it, and so on.

UpdateConsumptionOrder – update the tracking information of used materials. The updated information includes a new holder, location, passing it for inspection before releasing from inventory. **Emits an event of releasing materials from inventory for consumption. Also, emits an event when the consumption status is being updated**.

Blockchain cannot provide real-time information of the location of materials along the construction chain and our aim is to improve the material traceability, therefore **four counter check points** for **validation purpose** would be located between the main construction supply chain phases, to give information when the material leaves or arrives at a certain place to all participants as shown in the Figure below.

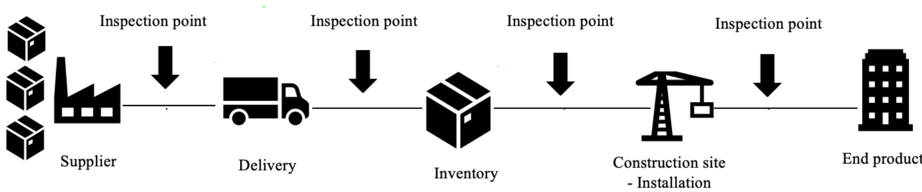

Figure 4.9: Inspection Points when Materiels arrive or leave a certain stage.

PreDeliveryInspection – a regulator will do the inspection for the prepared materials by a supplier. He will inspect materials according to weight, specifications, regulations, and general conditions. **Emits an event (dispute) of "possible fraud" or "damaged materials" if materials do not specify specifications**. According to regulator invocation request, shipment status, and purchase order status will be updated automatically, and the supplier will be notified that materials are approved for shipping.

PreInventoryInspection – once the materials delivered by a carrier, an inventory manager cannot receive it unless approved by a regulator. The regulator will do inspection for arrived materials, He will inspect materials according to weight, specifications, regulations, and general conditions. **If there were a conflict of information between the previous block and created block that contains inspection information of the same materials, an emit event of "possible fraud" will be generated automatically**. By this we can know where and when this fraud happened, and we can trace back to know where the issue happened and by whom.

UponLeavingInventoryInspection – once the materials are being requested in the construction work field. A regulator will do an inspection for the materials that are going to be used in the filed in terms of specification, weight, and general condition. Once the regulator approves it, the status of material will be changed automatically.

ConsumptionInspection – once the materials are used in the construction work field e.g. mixing concrete for pouring the foundation, foremen and workers will not be able to pour the concrete until the regulator do an inspection for the mixture and approves, then they can proceed with the work.

All the transactions with all parameters can be found in **traceability.go** file on GitHub: Here.

Queries

Query is to retrieve information from the ledger. After modeling the logic of material traceability in form of transactions, participants want to retrieve traceability information at any given point in the construction chain. For example, if the buyer wants to check the status of the purchased material, then a query has to be implemented. Hyperledger fabric uses CouchDB to store and retrieve information in a JSON format. So, we only need to provide the key or parameter for the thing we want to retrieve.

In this proof of concepts, some queries that ensure materials traceability is implemented in Table 4.2 or in the smart contract (**traceability.go**) on GitHub: Here.

Table 4.2: Implemented Queries for Material Traceability systems

Queries	**Retrieve Data**	**key**
getMaterialRecords	Transaction [ ]	none
getMaterial	Material	GTIN

From line 1177 – 1192 in the smart contract in Figure 4.10, it shows the query that enables the customer to retrieve material provenance by using GTIN from the blockchain. Also, from line 1194 – 1219 in Figure 4.11, it shows the query that enables the general manager of a construction project to retrieve material tracking information from the blockchain.

```
1177 // Customer query for Material by GTIN
1178
1179 func (tr *Trace) materialQuery(stub shim.ChaincodeStubInterface, args []string)  peer.Response {
1180     if len(args) < 1 {
1181                 shim.Error("Invalid number of argument provided")
1182         }
1183         var searchCriteria = `{
1184                 "obj" : "PurchaseOrder",
1185                 "gtin" : "%s"
1186                 }`
1187
1188                 orders := tr.retriveMaterial(stub, fmt.Sprintf(searchCriteria, args[0]))
1189
1190                 order,_ := json.Marshal(orders)
1191                 return shim.Success(order)
1192 }
```

Figure 4.10: Customer Query to retrieve Material Provenance by GTIN.

```go
// GM query for Material
func (tr *Trace) retriveMaterial(stub shim.ChaincodeStubInterface, criteria string, indexs ...string) []PurchaseOrder {

	var finalSelector string
	records := make([]PurchaseOrder, 0)

	if len(indexs) == 0 {
		finalSelector = fmt.Sprintf("{\"selector\":%s }", criteria)

	} else {
		finalSelector = fmt.Sprintf("{\"selector\":%s , \"use_index\" :\"%s\" }", criteria, indexs[0])
	}

	_TraceingLogger.Infof("Query Selector : %s", finalSelector)
	resultsIterator, _ := stub.GetQueryResult(finalSelector)
	for resultsIterator.HasNext() {
		order := PurchaseOrder{}
		recordBytes, _ := resultsIterator.Next()
		err := json.Unmarshal(recordBytes.Value, &order)
		if err != nil {
			_TraceingLogger.Infof("Unable to unmarshal Order retrived:: %v", err)
		}
		records = append(records, order)
	}
	return records
}
```

Figure 4.11: General Manager Query to Retrieve Material Tracking Information.

These queries are only examples of how construction chain members such as general manager can have a complete overview of the entire construction chain and trace back to the source of each material. Also, customers can query the material to know where the material comes from. However, in a real production more queries have to be implemented.

4.3.3 Access Control Design

By implementing the business logic of material traceability, we were able to build the requirements that ensure the traceability of materials in the construction industry. now, it is the time to build an important requirement, access control, as mentioned in Table 4.1 to ensure that material information is only shared with participants.

In Section 4.3.1 when we set up the network, it includes the creation of the identity of each participants of the network. Hyperledger Fabric uses access control lists (ACLs) for managing access to network resources by way of policies [9]. Resources here mean the system chaincode e.g. instantiated chaincode, or user chaincode (smart contract). For system chaincode, Fabric contains several default ACLs we can include them in a **configtx.yaml** file. However, these ACLs can be customized in terms of CRUD operations. For the smart contract, the transactions are programmed to check the identity of the person who invokes the transaction.

The default policy for ACLs for the system chaincode is kept to the default. The designed permissions in the smart contract level are shown below of who can invoke, create, read, update and delete transactions, and it has assigned only for the network participants only. However, all transactions in the previous section should have customized permission in terms of CRUD operations. These permissions in the current implementation are kept to the default. However, in real production they should be implemented.

- Only participants of the three organizations in the network are allowed to invoke transactions excluding customers. From line 1105 – 1120 in the smart contract in Figure 4.12, it shows that only participants of the network are allowed to invoke transactions.

```
1102 //Returns the complete identity in the format
1103 //Certitificate issuer orgs's domain name
1104 //Returns string Unkown if not able to parse the invoker certificate
1105 func (tr *Trace) getInvokerIdentity(stub shim.ChaincodeStubInterface) (bool, string) {
1106         //Following id comes in the format X509::<Subject>::<Issuer>>
1107         enCert, err := cid.GetX509Certificate(stub)
1108         if err != nil {
1109                 return false, "Unknown."
1110         }
1111
1112         issuersOrgs := enCert.Issuer.Organization
1113         if len(issuersOrgs) == 0 {
1114                 return false, "Unknown.."
1115         }
1116         isOK, msg := isValidDomainName(issuersOrgs[0])
1117         if !isOK {
1118                 return false, msg
1119         }
1120         return true, fmt.Sprintf("%s", issuersOrgs[0])
1121
1122 }
```

Figure 4.12: A Designed Permission that Allows only Participants of the Network to Invoke Transactions.

4.3.4 Frontend, Middleware, and Integration with Internal Traceability Systems or ERPs

The smart contract is one of the key components in designing a blockchain-based platform, and in order to invoke transactions and get a response to clients' applications to update the ledger, many things have to put into consideration. Because at the end all external applications of construction chain partners want to access blockchain, and import and export data smoothly and in a secure way to integrate material traceability information. The author has implemented simple frontend applications to build necessary requirements to access content from and to blockchain to test the system and provide typical architecture layers for all others applications to integrate with blockchain in the future.

In the implemented architecture blockchain is the first layer or bottom layer while other layers of applications would be on the top of the blockchain to invoke and get data from the blockchain. The main thing to put in mind is the access point between blockchain and other applications because all organizations will keep accessing and retrieving information from and to blockchain as long as it kept securely.

Figure 4.13 shows the typical architecture design for this project which follows "Model-View-Controller" design model. The bottom layer is the blockchain network, then followed by Nodes.js, it uses as a middleware or backend to build APIs to access blockchain contents, it includes all transactions invocation request and the identity (PK) of users. A mongoDB is used as a storage from and to blockchain. This then followed by the frontend that implements by React. Also, the architecture shows that this project is deployed locally using Docker images. The backend and frontend implementation can be found on Github: for backend https://github.com/SofanaAlfuhaid/construction-backEnd, for frontend https://github.com/SofanaAlfuhaid/construction-frontEnd. Additionally, a blockchain explorer tools has been used to view the blockchain content. It also can be found on Github: https://github.com/SofanaAlfuhaid/blockchain-explorer.

Integration with other Internal Traceability Systems or ERPs

Developers of other applications do not have to follow the same architecture layers below. Many options can be followed to integrate other internal traceability systems with blockchain. For example, they can replace users with each organization's internal traceability system or ERPs. Also, developers can design other middleware, or they can install the system to the user machine and connect directly to the network. Also, they can use ready blockchain services solutions and deploy them in the cloud. Here mongoDB has chosen as storage from and to blockchain, but they can choose any other database. Each organization can choose whatever suits their needs to access blockchain network and they could use the architecture below as a reference.

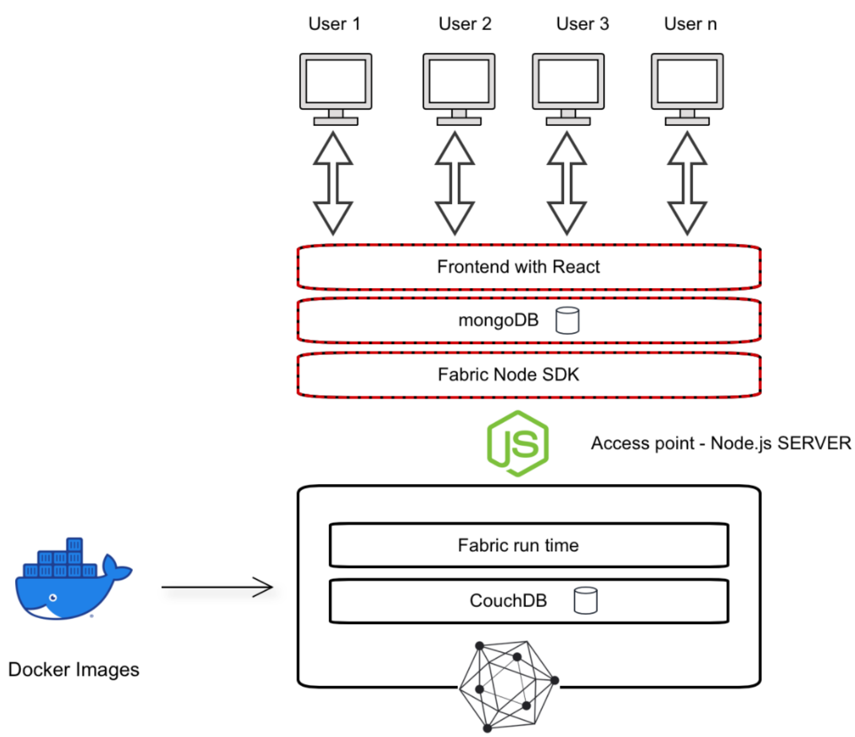

Figure 4.13: Typical Architecture Layers to Expose Blockchain with External Systems.

4.4 Conclusion

The chapter focuses on choosing the right framework, specifying a set of details materiel traceability requirements, and using the selected framework to design and build the system. Based on the requirements specification, we were able to design and build a blockchain-based traceability system. We also provided an architecture to ease the integration process between blockchain and other internal traceability systems and ERP systems. What remaining is to measure the degree of success of the implemented system in improving the material traceability in the construction industry and answer the last research question. Testing and evaluating the blockchain-based material traceability platform is performed in the following chapter.

Chapter 5

Platform Testing and Evaluation

After implementing the obtained traceability requirements into a blockchain-based solution in the previous chapter, this chapter first focuses on conducting an empirical test through the designed platform based on the typical flow of material traceability in the construction supply chain shown in Figure 4.2, in two **bulk materials**, **cement** and **pipes**. It then follows with a qualitative evaluation to measure the validity of the proof of concept on supporting the material traceability requirements in a series of use cases to reach a conclusion about the made hypothesis and to reach an answer to the last research question: ***"In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?"***.

5.1 Platform Testing

Assuming that construction designs are completed, and suppliers are chosen, we will begin testing the system from material procurement stage to delivery, storage, until consumption stage (end product).

Figure 5.1 shows the **home page** of the blockchain-based material traceability system. The home page shows the participants (peers) in the network which include construction chain partners (construction company and suppliers), regulators, and customers. The customer can only query the history of materials.

The platform was built to operate during the purchase order stage, delivery, inventory, and consumption stage. These are the downstream process in the construction supply chain as stated before, the focus is going to be on improving material traceability on **bulk materials**. The bulk materials are narrowed down into two types, that have been chosen for testing, which is **cement** and **pipes**. Each activity of the platform will be described below and will be represented in figures as well from **appendix** A.

- The **home page** allows selecting the stage to be executed. **By clicking on buyer**, buyer can either select **create a new order**, or **display order status**. **By clicking**

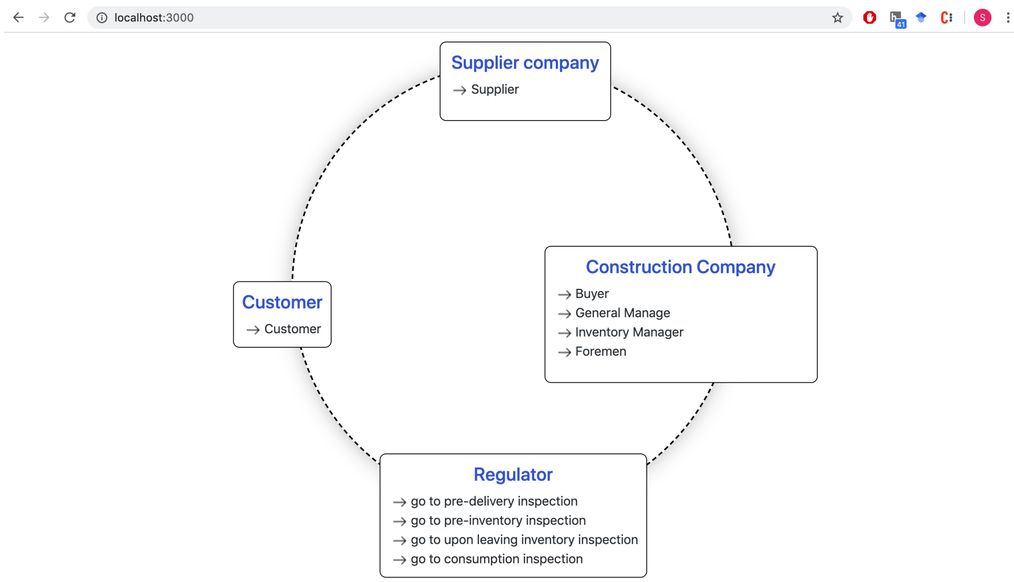

Figure 5.1: System Homepage.

on **create a new order**, the buyer can specify the purchase order agreement specifications that include all the parameters e.g. materials specifications, buyer, supplier, location, date, price willing to pay, and so on, as shown in Figure A.1. Once the buyer submitted the order, a purchase order number (PO) is generated automatically and the status is updated to "create" as shown in Figure A.2.

- **By clicking** on **display order status**, the buyer can track the status of each order, as shown in Figure A.3, there are two purchase orders for cement, and one purchase order for pipes, the first order has been rejected from the supplier, and the other two orders have recently created.

- Figures A.4, A.5, and A.6 show **blockchain content** for the recent transaction (**create purchase order for cement**) that is stored in **block 5**. Some important information is highlighted in red. Figure A.4 shows the creator's public key who created the purchase order and Figure A.5 is a continuation to Figure A.4 that shows a generated purchase order number (key) and other information such block hash, data hash, previous hash, to name a few. Figure A.6 shows the same information for block 5 and other blocks using Hyperledger Explorer.

- **A supplier** receives purchase requests on their dashboard, he will do an internal stock check and can either accept or reject the requests. If the supplier accepts the purchase order, the materials order status will be updated automatically. Figure A.7 shows the received orders from the construction company, and Figure A.8 shows orders status has been updated to "in progress" after being accepted by the supplier.

- After the supplier accepted the purchase orders of cement and pipes, the materials will be dispatched to a shipper with all the shipment information and the GTIN of requested materials, and the shipment will be on hold until the supplier gets a confirmation from a regulator. Figure A.9 shows the create delivery or shipment order by the supplier for the cements order, and Figure A.10 shows the delivery order after submitting where the delivery order status has been updated to "expecting confirmation from regulator". Figure A.11 and A.12 show the same but for the order of the pipes.

- **A regulator** receives a **pre-delivery inspection request** for a shipment. In case of cement, the regulator should weigh the whole batch of cement and compare it to the purchase order agreement, and either he can accept it or raise a dispute. If the regulator accepts it, the smart contract automatically will transfer the material possession to a new owner/holder (shipper), and the status of the material will be updated to "shipped". If the regulator disputes the shipment, the material status will be updated to "InDispute" for further adjustments. In the case of pipes, the same procedure happens except that the regulator should check four measurements, actual outside diameter, average inside diameter, pipe wall width thickness, and weight to ensure the quality of pipes. Figure A.13 shows the two inspections request for cement and pipes. Figure A.14 shows the status of the delivery order after the inspection, for the cement the shipment has been approved and the status updated to **"shipped"**, but for pipes, it shows an **error** because the measurements do not match the standards.

- Once shipment arrived at the expected location, an inventory manager creates **a goods receipt order** and specify the specifications of the arrived shipment. Once he submitted the form, the goods receipt order will be on hold until a regulator approves the materials and allows them to be stored. Figures A.15 and A.16 show the goods receipt order page.

- **A regulator** receives a **pre-inventory inspection request** for the received shipment. The same procedures for inspecting the cement and pipes will be performed again. if there were a mismatch between a pre-delivery inspection and pre-inventory inspection, the regulator will reject the received shipment. Otherwise, he will accept it, and the goods receipt order status, purchase order status, delivery order status and material possession will be updated, and they all will be notified on their dashboard. Figures A.17 and A.18 show goods receipt order status before and after the inspection. Figures A.18 and A.19 show the updated status of goods receipt order, purchase order status, and delivery order status on the participants' dashboard.

In the working field, materials will be consumed according to the end product design. Typically, the first thing that starts in any construction project is building the foundations. Here, cement will be requested and mixed to make the concrete.

- A foreman **creates a consumption order** for the amount of cements that will be consumed and specify why and where in the design the consumption would be. Figure A.20 and A.21 shows the consumption order.

- **The inventory manager** receives **a consumption order request** from the foreman and prepares the requested materials by doing an internal stock check. If the required quantity less than the actual quantity of materials, the inventory manager will add a batch ID and attach it to the GTIN of the requested material. Once the inventory manager submits the form to release materials from inventory, it will be on hold until the inventory manager gets a confirmation from a regulator. Figures A.22 and A.23 show a stock release order for cements by inventory manager.

- **A regulator** receives an "**upon leaving inventory inspection**" request and does the same inspection performed before to check if the whole batch of cement matches what has been ordered by the foreman. If the regulator accepts it, the foremen will be updated that the cements are ready to mix the concrete. Otherwise, he will reject it for further adjustment. Figures A.24 and A.25 show before and after "upon leaving inventory inspection" to confirm materials coming out from inventory.

- Once the foreman consumption order is approved and the order status updated to "ready to use" as shown in Figure A.26, the foremen can give the order to start mixing the concrete. However, he cannot give the order to pour them until he gets a confirmation from the regulator. Figure A.27, shows that the mixed concrete is on hold until the foremen get a confirmation from a regulator.

- **A regulator** receives **a consumption inspection request**. In case of concrete, the regulator should measure the density of the mixture, and if it was compatible with standards, the foreman will be updated that foremen can proceed with the pouring. Otherwise, the regulator will reject it for further adjustment. Figures A.28 and A.29 show the consumption order status before and after the concrete is approved to be poured.

A general manager can track the status of the steps through which a particular product has gone, the general manager can simply click in any order and track the status as shown in Figure A.30 and A.31. Additionally, the general manager and the regulator can track blockchain network, transactions, and so on using blockchain explorer as shown in Figures A.32, A.33 and A.34.

Finally, the customers also can query and track the history of the purchased materials through the GTIN of materials as shown in Figures A.35 and A.36.

All platform transactions can be seen in Figures from A.1 to A.36, from **appendix** A.

5.2 Platform Evaluation

In order to reach an answer to the last research question: : ***"In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?"***, we have to determine if the implemented blockchain-based material traceability platform has achieved the research objectives and material traceability requirements.

The followed methodology is to verify the detailed functional and non-functional requirements, and the high-level requirements from Table 3.2 in a qualitative manner as the following:

1. Each functional requirement will be referred to a use case in the platform and verify whether the system supports it in term of fulfilled, partially fulfilled, or not fulfilled.
2. For non-functional requirements, the author will write how each requirement has been applied in terms of whether they fulfilled the requirements, partially fulfilled or not fulfilled.

After evaluating both the functional and non-functional requirements, next, we will evaluate the high-level traceability requirements from Table 3.2 as they were the basis of chosen the blockchain framework and the platform design whether it fulfilled the requirements, partially fulfilled or not fulfilled.

Functional Requirements Verification

As it shown in Table 5.1, 5.2, 5.3, 5.4, and 5.5 most of the requirements were fulfilled while some of them were either partially fulfilled or not fulfilled.

Table 5.1: Functional Requirements Verification (system)

Functional Requirement ID#	**Functional Requirement (use cases)**	**Test Case Result**
Hyperledger Fabric blockchain network		
1	Verify if the system has generated certificate and keys for all admins from the three organizations.	fulfilled
2	Verify if the system has defined different permissions for the three organizations.	fulfilled
3	Verify if the system has created admin per organization.	fulfilled
4	Verify if the system has allowed each organization to edit number of users they want in the network.	fulfilled
5	Verify if the system has allowed to customize CRUD operation for each identity.	fulfilled
6	Verify if the system has recorded all actions and transactions happens in the network.	fulfilled
7	Verify if the system has kept immutable ledger of transactions.	fulfilled
8	Verify if the system has timestamped each transaction.	fulfilled
9	Verify if the system has allowed to deploy the chaincodes for transaction invocations.	fulfilled
10	Verify if the system has applied the endorsement policy in every transaction.	fulfilled
11	Verify if the system has allowed the creation of multiple channels and ledgers.	partially fulfilled
12	Verify if the system has detected a conflict in a fraud attempt.	fulfilled
13	Verify is the system has emitted notifications of events.	fulfilled
14	Verify if the system has allowed export and import of information from and to the blockchain with external systems.	fulfilled
15	Verify if the system has imposed authentication and authorization on APIs from and to the blockchain.	fulfilled
16	Verify if the system has allowed for submitting multiple transactions at the same time.	not fulfilled

From the above use cases, there were two unsatisfied requirements, the first one is not fulfilled and the other one is partially fulfilled. Here is an explanation:

For the **partially fulfilled requirement**, in the platform, the author has created and deployed the chaincode in one channel, while Hyperledger Fabric provides the functionality of creating more than one channel, but this functionality has not been performed in this project.

For the **not fulfilled requirement**, client applications can submit more than transactions at the same time, but it should be performed sequentially, this limitation is in the software itself.

Table 5.2: Functional Requirements Verification (construction supply chain members)

Functional Requirement ID#	**Functional Requirement (use case)**	**Test Case Result**
	Traceability Smart Contract	
1	Verify if construction supply chain members are able to invoke transactions.	fulfilled
2	Verify if construction supply chain members are able to create assets and related attributes according to their permissions.	fulfilled
3	Verify if construction supply chain members are able to read, update, and delete assets and related attributes according to their permissions.	fulfilled
4	Verify if purchase department (buyer) can create purchase order according to their permissions.	fulfilled
5	Verify if supplier can create delivery order according to their permissions.	fulfilled
6	Verify if inventory manager can create good receipt according to their permissions.	fulfilled
7	Verify if foreman can create good receipt according to their permissions.	fulfilled
8	Verify if smart contract automatically assign number for any contractual agreements between construction supply chain members when all specifications has specified including inspection.	fulfilled
9	Verify if smart contract automatically allows construction supply chain members to create any agreements.	not fulfilled

Functional Requirement ID#	Functional Requirement (use case)	Test Case Result
	Traceability Smart Contract	
10	Verify if smart contract allows construction supply chain members to query and track forward all the steps the bulk materials went throw and trace back to the origin.	fulfilled
11	Verify if the smart contract allows to query the current holder of the materials.	fulfilled
12	Verify if the smart contract allows to query the status of shipment and get information of who is the buyer, the shipper and related information.	fulfilled
13	Verify if the smart contract allows to query the status of inventory and get information of who receive the materials and related information.	fulfilled
14	Verify if the smart contract allows to query the status of consumption material and get information of who consume it, where and so on.	fulfilled
15	Verify if the smart contract allows to query the status of purchased materials at any given time.	fulfilled
16	Verify if the construction supply chain members can rise a dispute if damages found in materials	fulfilled
17	Verify if the construction supply chain members can rise a dispute if materials do not compliance with quality, regulations or standard.	fulfilled
18	Verify if the smart contract notifies general manager or regulates of every action happens in the construction supply chain. Also, notifies other supply chain members of any updates of status of assets.	fulfilled
19	Verify if the smart contract allows division of materials and link them together.	partially fulfilled
20	Verify if the smart contract allows members to check the status of made transactions.	fulfilled
21	Verify if the smart contract notifies if the shipment exceeds the expected arrival date.	fulfilled

Table 5.3: Functional Requirements Verification (Customers)

Functional Requirement ID#	Functional Requirement (use case)	Test Case Result
Traceability Smart Contract		
1	Verify if the customer can query all the steps of materials life cycle from the origin until consumption.	fulfilled

Table 5.4: Functional Requirements Verification (Regulators)

Functional Requirement ID#	Functional Requirement (use case)	Test Case Result
Traceability Smart Contract		
1	Verify if the regulator can query the steps the materials have gone through and trace back to the origin.	fulfilled
2	Verify if the regulator can do inspection from one point to another in construction supply chain and check material's standards.	fulfilled

Table 5.5: Functional Requirements Verification (Admin)

Functional Requirement ID#	Functional Requirement (use case)	Test Case Result
Traceability Smart Contract		
1	Verify if admin assign identity to participants	fulfilled
2	Verify if the admin can revoke participants identity.	fulfilled
3	Verify if admin can assign different roles to participants	fulfilled
4	Verify if admin can change different roles to participants	fulfilled
5	Verify if admin can create channels	fulfilled
6	Verify if admin can invoke transactions	fulfilled
7	Verify if admin can create, update, delete assets	fulfilled

From the above use cases there were two unsatisfied requirements, the first one is not fulfilled and the other one is partially fulfilled. Here is an explanation:

For the **not fulfilled requirement**, it is not possible to deploy contractual agreements between construction supply chain members than the already designed one. For any new contractual agreements, it has first to be designed and written then deploy for usage.

For the **partially fulfilled requirement**, sometimes it is challenging to divide bulk materials because they might come in shapes that hard to divide, inspect and compare to what we ordered or track where they consumed.

Non-Functional Requirements Verification

As it shown from Table 5.6, the result of verification the non-functional requirements and the explanation has been provided.

Table 5.6: Non-Functional Requirements Verification

Non-Functional Requirements	**Explanation**	**Result of Verification**
Usability	The developed platform act as a common platform that gather all construction supply chain members, regulators, and customer together, they can easily use it to increase collaboration and visibility to track materials from one point to another in the supply chain. Also, they can replace client APIs with their internal traceability systems or ERPs and use the provided architectural design as a starting point.	Fulfilled
Accuracy	The Blockchain immutability nature guarantee that no one can tamper the data, however, blockchain cannot ensure the entered data is correct. So, wrong information can be entered to the blockchain, therefore counter check to verify the validity of information is a solution that has been built in this project.	Partially Fulfilled

Non-Functional Requirements	Explanation	Result of Verification
Security	Access control and identity management has been implemented and a new channel could be created to main privacy of organizations. Besides that, no one can tamper with the recorded traceability information.	Fulfilled
Performance	The platform is built on top of single node (solo) which cannot tolerate single point of failure. However, this is acceptable for testing purpose, but it is not recommended for production. Also, though the performance measurement such as scalability does not physically test, however the assertion that Hyperledger fabric provide better performance has been gotten form the comparison which done earlier.	Fulfilled
Portability	The Hyperlaedger fabric has run on Docker containers instances which make it possible to run on another operating system than the used one. This is has not tested for this project, but the infrastructure requirements have been kept to the minimum, so little changes can be done to run it in another operating system.	Partially Fulfilled
Flexibility	The smart contract and the blockchain network have been made available for everyone, so other developer can continue the work and scale it to include other stages of construction chain for other types of materials.	Fulfilled

High-Level Traceability Requirements Verification

After verifying the functional and non-functional requirements, we are now able to verify if the platform supports the material traceability requirements. As it is shown in Table 5.7, the green background means the requirements is fulfilled, while the red means not fulfilled, and the orange means partially fulfilled.

Table 5.7: Verification of Material Traceability Requirements According to Points of Focus

	Points of focus			
Traceability Requirements	**Information limitation**	**Standards limitation**	**Scope limitation**	**Sharing limitation**
	Automatic methods of data capturing and transmission	Regulatory standards and Global standards e.g. GS1	Auditing	Secure channel for exchange information
	Automatic services	connection and communication from one system to another	Product management (material identification, details, partner identification, and so on)	Secure data storage that ensures data security and integrity
			Real time tracking information	Access control
			Fast update of tracking information	Real time exchange of information
			Fraud detection	Reliable information
			Quality control Non- editable history records Trace the origin	

From the table above we can notice that there were two unsatisfied requirements, blockchain can not provide a real-time tracking information e.g. you cannot query the current location of the shipment which means a blockchain needs a a complementary technology e.g. RFID in order to capture and transmit real-time material tracking information. This conclusion was reached by other researchers in some previous studies of other industries that a blockchain needs a complementary technology to improve material traceability in the entire construction chain.

In addition, blockchain cannot ensure the entered data is correct and counterfeit information might enter the system by supplier, and we will not know until it arrives. A complementary technology e.g. RFID could solve this issue; however, the author tried to solve this issue by adding inspection points along the construction chain whenever the material arrives or leaves a certain stage.

Finally, using a blockchain and smart contract, we were able to transform traceability forms into digitized means and review if all requirements have been fulfilled; however, if partners wish to deploy more forms and new agreements between them in the network; they can not, except for designed contracts and forms, and for the new one, it must be designed first by a developer and then deploy for usage, it cannot be immediately which might cause delay and increase the cost.

5.3 Discussion

Based on the platform testing and evaluation in the previous sections, blockchain supports reviewing material information and necessary documents in digitized way e.g. it automate the contractual agreement, processes and forms. A regulator or general manager by accessing a block content can easily review if all the necessary requirements has been filled, e.g., for purchasing materials. At the same time, smart contract provides automatic services where all partners get notified of the work progress along the construction supply chain which eventually replace the traditional methods that have been used for information dissemination between all construction supply chain partners, and reduce error and dispute.

This is due to the distributed database that gather all material tracking information and generate more visibility between construction chain partners and reduce the risk of non compliance materials, dispute, counterfeit materials. Also, blockchain helps strengthen the relationship with customers by providing a historical record of materials from the time of purchasing from suppliers until it became an end product. Customers, can query the materials and retrieve the information to be aware of the provenance and authenticity of a material.

Additionally, blockchain allow the sharing of up-to-date material traceability information between partners, and allow them to track any ongoing transactions in a governed environment. The construction chain partners and regulators can track materiel status at any given time and check if it satisfies quality standards whether at the time of purchasing, delivery, inventory, or at times of consumption. Here we can conclude that blockchain could replace third party organization e.g. ISO because even if suppliers provide certificates that materials comply with quality stands, or the suppliers claims that the documents they provided shows where the materials originated from, the construction company may not have the time to review all the documents and authenticate them. However, the implemented blockchain platform allows partners and regulators to track material information in every stage in the construction supply chain as shown through testing the platform. Also, they can track material history with just a click to retrieve all the information they want in case of damaging.

Furthermore, blockchain helps to build a construction consortium platform where all partners can trust and share their information. The provided architecture shows that blockchain can be applied and linked to existing apps. Internal traceability systems or ERP systems can be interoperated with blockchain to access data in secure infrastructure and import and export the data from and to the blockchain.

On the other hand, the author noticed that with the implemented blockchain platform, a supplier can enter incorrect information, and the blockchain cannot recognize that the entered data is incorrect. Also, no one would know about the issue until the materials arrive at the location because blockchain does not provide real-time information. Therefore, the author has added inspection points along the construction chain whenever the material arrives or leaves a certain stage to check the quality of materials. At each given point in the construction chain, a regulator can confirm the materials or dispute it, and all construction chain partners will get notified immediately of the current status of the material.

5.4 Conclusion

This chapter is completing the previous chapter by focusing on testing and evaluating the degree of success of the achieved work in enhancing the traceability of materials in the construction industry. The work in the previous chapter and this chapter is done to reach an answer to the last question of this research: ***"In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?"***.

Based on the work done in this chapter and the result of the performed evaluation, which is the key to reach an answer, we can say that the answer is **No**, Hyperledger Fabric does not succeed in supporting all the requirements of improving material traceability in the construction industry. Being unable to provide real-time material traceability information and guarantee the reliability of entered information could result in major losses of purchased materials such as fraud and delay callback of defective materials. **Though** this No does not mean Hyperledger Fabric does not succeed in building the majority of the requirements. The reason is that the Hyperledger Fabric alone cannot support all the requirements, and there is a need for complementary technology.

About the rest of the question, in practice, we were able to build a platform that support the majority of the requirements. The framework and other tools succeed in satisfying most of the requirements. Therefore, we cannot say a straight NO to this question because the satisfied requirements were more than unsatisfied requirements.

Chapter 6

Conclusions and Future Work

This chapter concludes the dissertation work. It discusses the findings to reach a conclusion of the research thesis statement. Then, it follows the contribution, the validity, and the difficulties of the work done. Finally, possible future works that may continue this dissertation is presented.

6.1 Recap

The ultimate objective of this dissertation is to examine previous works to find the gaps of the current practices of material traceability, and to obtain the traceability requirement that could help in improving material traceability in the construction industry, and see whether the hypothesis from chapter 1 is valid or not: ***"blockchain can make material traceability in construction logistics chain more efficient and effective"***. Therefore, in the process of the declaration of the thesis statement, four questions were prepared:

RQ1: What are the challenges that prevent accurate and complete traceability of materials through the construction logistics chain?

RQ2: What are the requirements that would be considered most valuable to improve the traceability of materials in the construction logistics chain?

RQ3: Which kind of blockchain initiatives and tools can be chosen to design a platform for construction projects to apply the material traceability requirements?

RQ4: In practice, can a chosen blockchain initiative and tools successes in building such a platform that supports all material traceability requirements?

Thesis Statement

As we have answered all the research questions, now we can reach a definitive decision about the thesis statement. Well, to decide if blockchain can make material traceability more efficient and effective, we have to evaluate if the implemented system provides better traceability of the material life cycle. Therefore, in chapter 5, the system was evaluated by the obtained traceability requirements.

In chapter 5, we concluded from the fourth question of the dissertation that a chosen framework has succeeded in achieving most but not all obtained requirements. Therefore, if the efficiency and effectiveness of material traceability mean satisfying all the requirements, then **NO**, we cannot say that blockchain can make material traceability in the construction chain efficient and effective. On the other hand, if the efficiency and effectiveness of material traceability mean providing better material traceability by satisfying the main requirements or requirements that improve traceability, then **YES**, we can say that blockchain can make material traceability efficient and effective. This can be seen by automating the contractual processes, forms, and registering transactions where accuracy and trail are essential, and providing up-to-date traceability information along the construction chain between partners and increase trust. So, blockchain has helped to underpin the increasing complexity of the construction supply chain and improve trust between partners, including customers, by saving cost and speeding up the delivery of the projects and tracking the source of materials. Therefore, we can say that blockchain can be used with other internal traceability systems and other complementary technologies e.g., RFID to improve material traceability.

6.2 Contributions

The entire process of the research that has been undertaken to reach the above conclusion has provided a valuable contribution to the construction industry.

Since the construction industry lacks a common software that brings together all the construction project partners to exchange material traceability in an automatic way. This dissertation provides a seamless collaboration platform that allows the sharing of up-to-date material traceability information and increases the visibility from one point to another in the construction chain to track materials besides reviewing all forms in digitized means in a secure and governed environment. Thus, this contribution would be a good incentive for people in the construction industry to invest in technological innovations and reconstruct the construction industry to keep up with the requirements of the modern supply chain.

Further, this dissertation contributes with an architectural design that could be used for further study to integrate the blockchain with other internal traceability systems or ERPs in the future.

6.3 Validity of Work

This dissertation began by examining earlier studies to find the gap in current practices of material traceability in the construction industry. Then, an in-depth analysis of traceability requirements from the food industry was conducted to obtain the needed requirements to solve the current issue based on the area of focus. Later, these requirements were used as a basis to choose the optimal framework and design a blockchain that can support the material traceability system. Then, the designed system was tested on a selected type of material and evaluated against the obtained requirements. Although the system was not tested on a real use case, and the author considered the work as a proof of concept, and cannot be used of actual production; however, in the author's opinion that the validity of the work can ensure through the whole process of answering the research questions which support the conclusion and produced valuable contributions to the industry.

6.4 Difficulties

One of the difficulties of this research is that few studies have been found on the possibility of traceability in the construction industry, so the author had to research other industries to obtain traceability requirements and apply them in the study.

Another difficulty is that the author has started implementing the platform using Hyperledger Composer, which is a tool provided to ease the process of building a blockchain network. However, this tool has been deprecated, and the author had to start from scratch with Hyperledger 1.4 as no tools were available to make the transition.

Finally, a difficulty that also might face construction companies in their way to adopt blockchain is that lots of dependencies have to be installed in order to build a blockchain network.

6.5 Future Work

As stated before this work is a proof of concept and not a complete product, the author obtained the needed requirements of material traceability from food industry because of extensive research done in this industry and applied them as a basis to design and develop a material traceability system in the construction industry for a selected type of bulk material. So, in order to continue exploring the blockchain in the construction industry, future works may include:

- Taking material traceability issues and the obtained traceability requirements and consult industry experts to validate the issues based on the area of focus that needs the most improvement, also validate traceability requirements to develop a framework that allows material traceability.

- Scaling up the system to include other stages in the construction supply chain for other materials types, e.g., engineered materials and prefabricated materials.
- Evaluating the system in a real use case to illustrate the challenges and demonstrate how the proposed solution could be improved.

APPENDICES

Appendix A

Cross Platform Testing

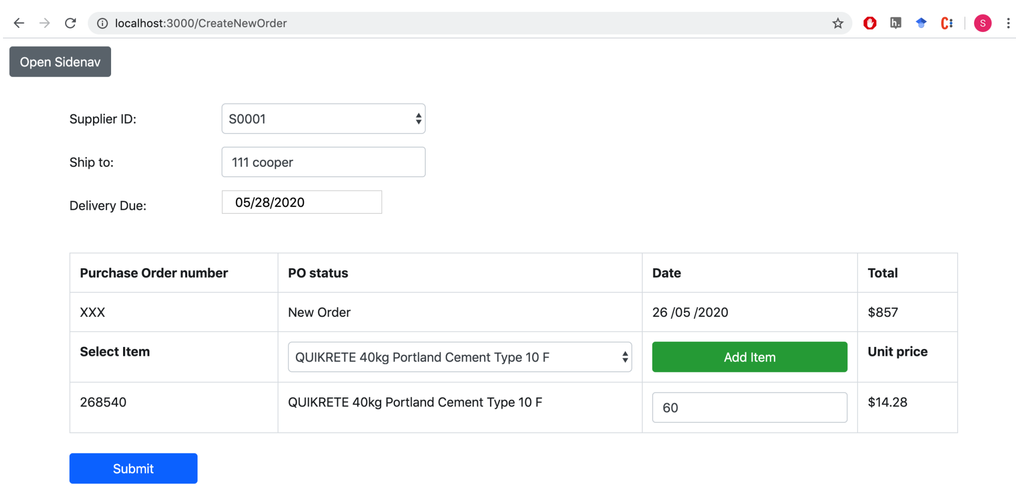

Figure A.1: Create Purchase Order Page.

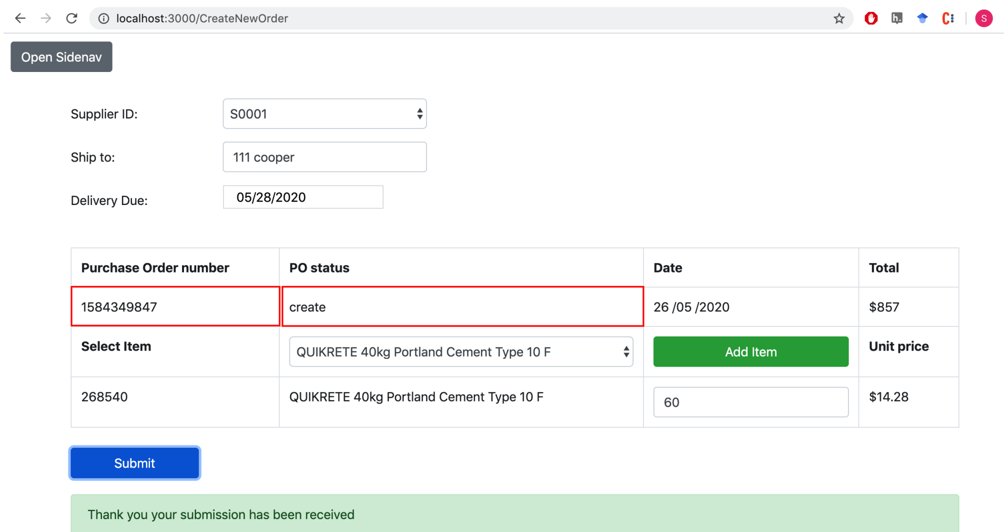

Figure A.2: Create Purchase Order Page (con't).

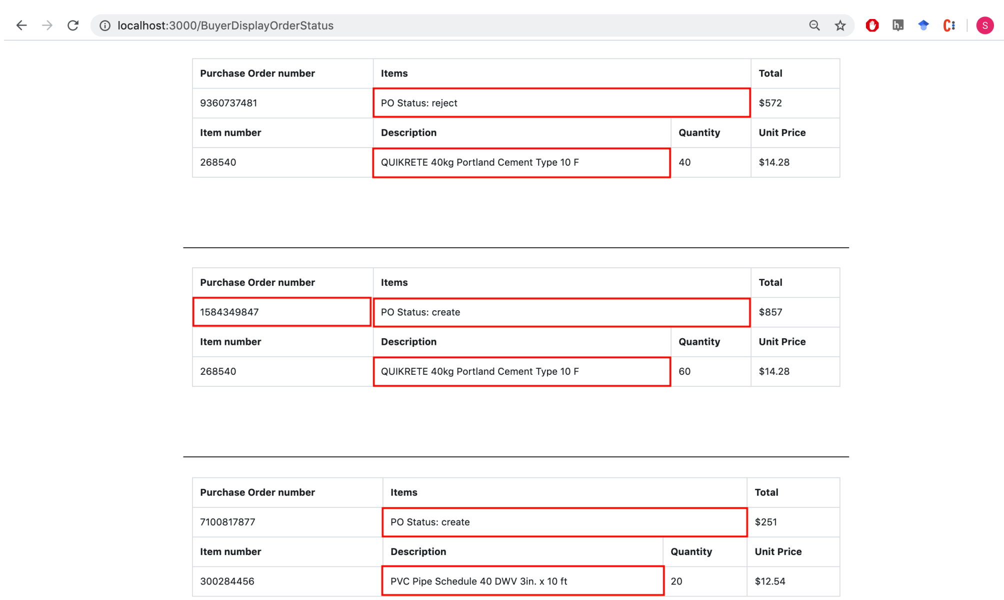

Figure A.3: Display Order Status Page.

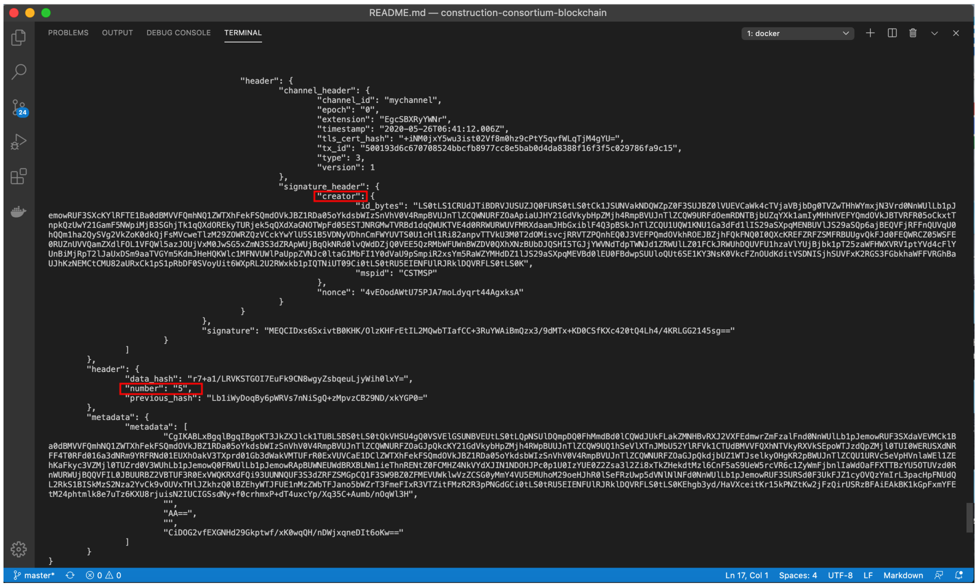

Figure A.4: Exploring Block 5 for the Create Purchase Order for Cements.

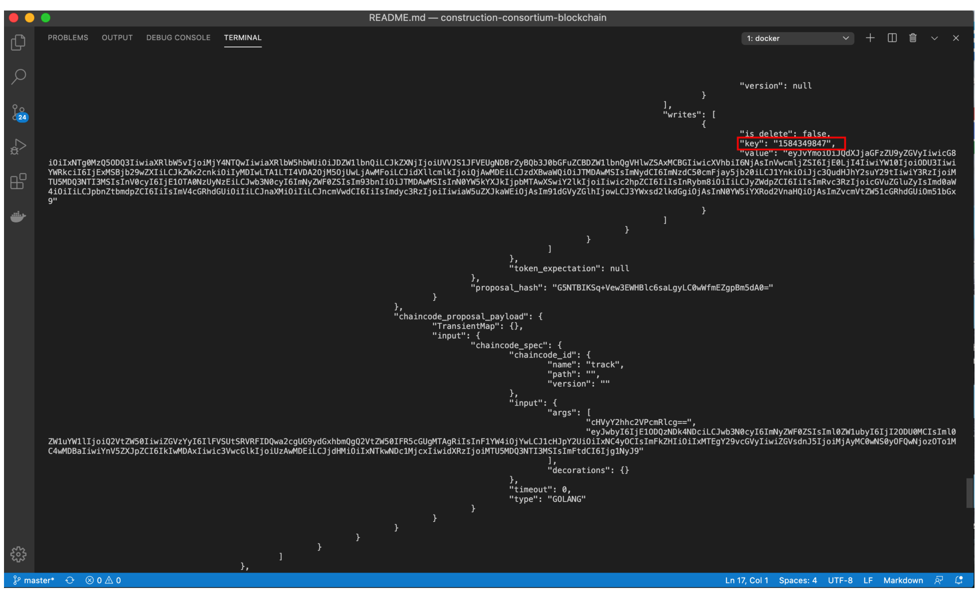

Figure A.5: Exploring Block 5 for the Create Purchase Order for Cements (con't).

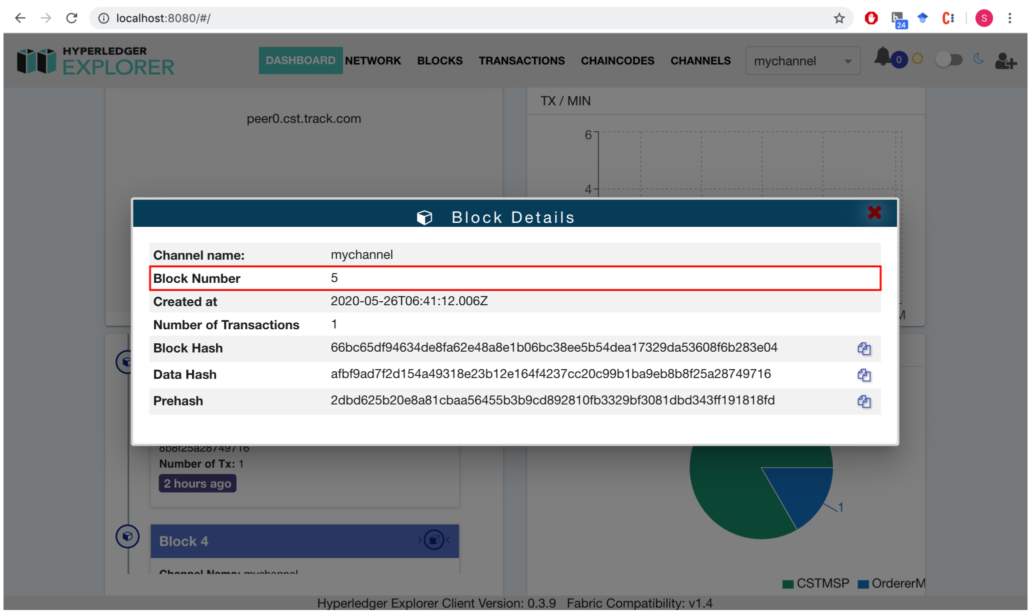

Figure A.6: Exploring Block 5 for the Create Purchase Order for Cements using the explorer (con't).

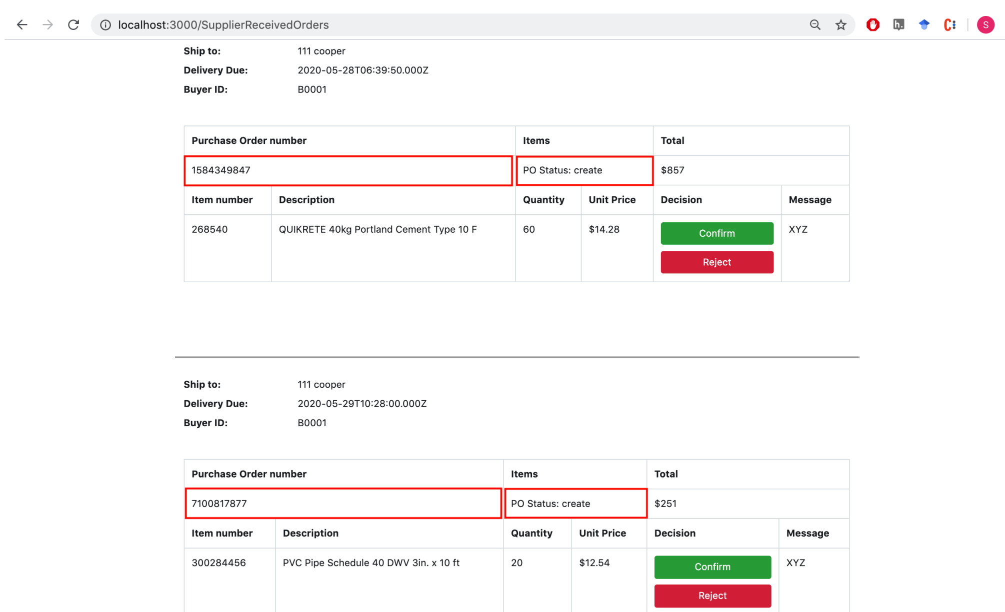

Figure A.7: Receive Orders Page.

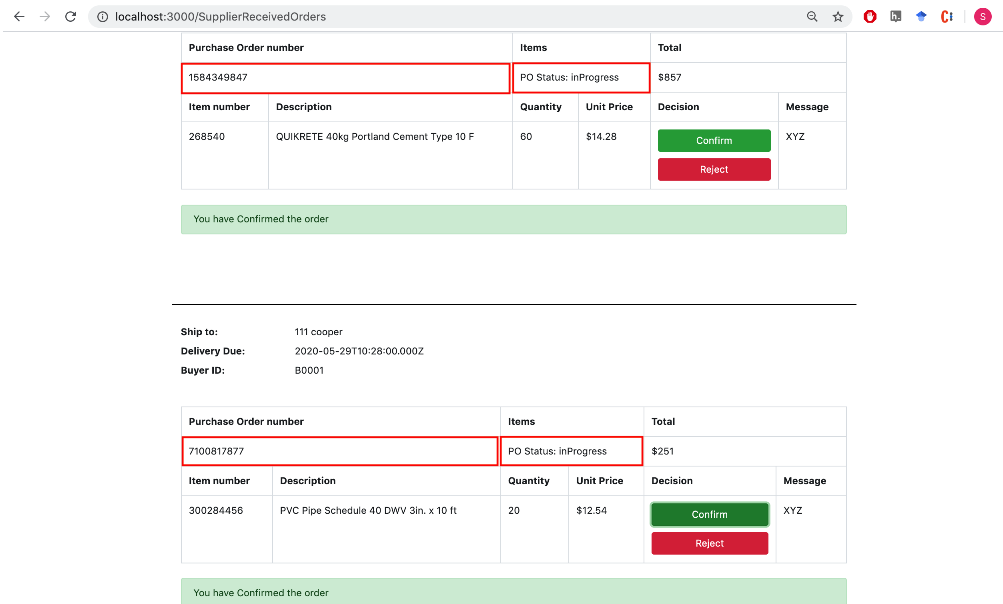

Figure A.8: Receive Orders Page (con't).

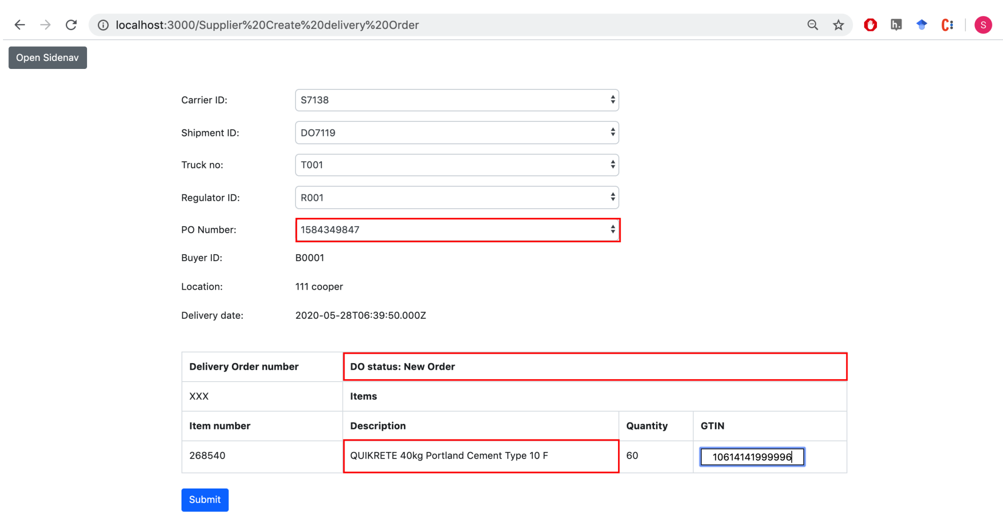

Figure A.9: Create Delivery Order for Cements.

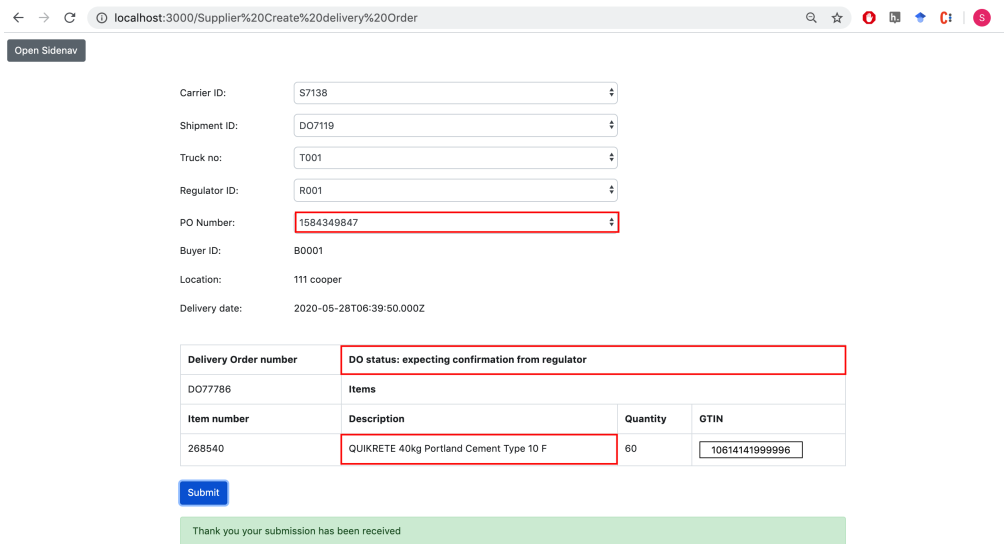

Figure A.10: Create Delivery Order for Cements (con't).

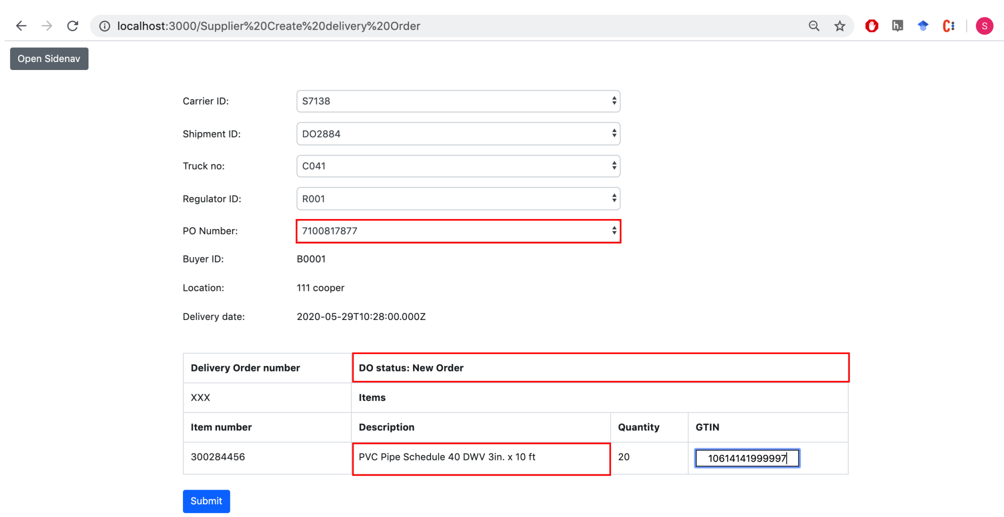

Figure A.11: Create Delivery Order for Pipes.

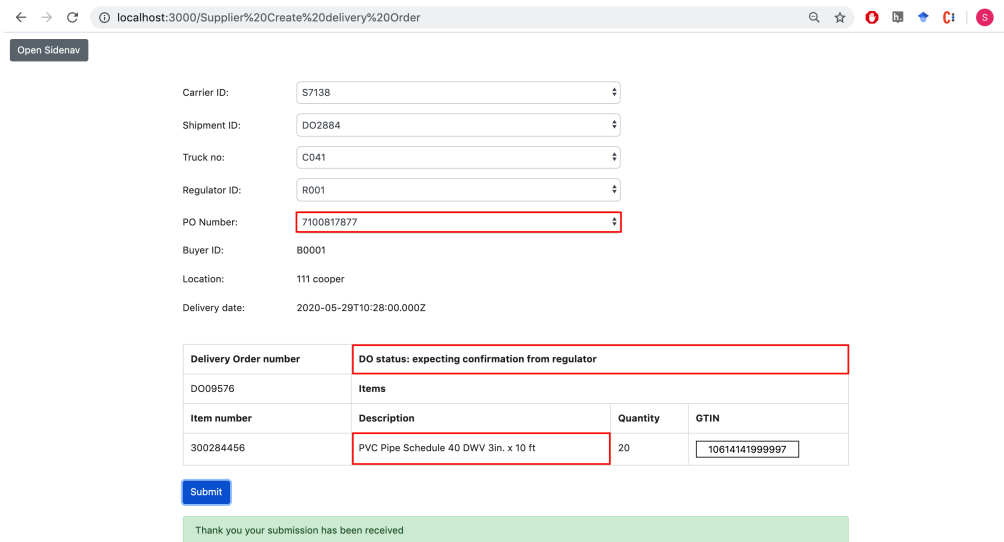

Figure A.12: Create Delivery Order for Pipes (con't).

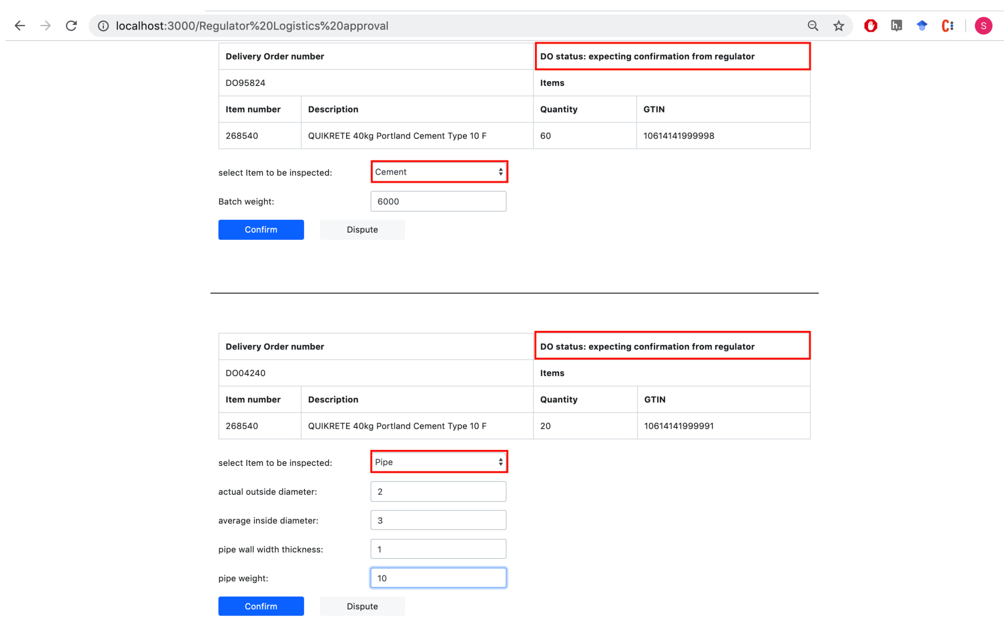

Figure A.13: Pre-delivery Inspection for Cements and Pipes .

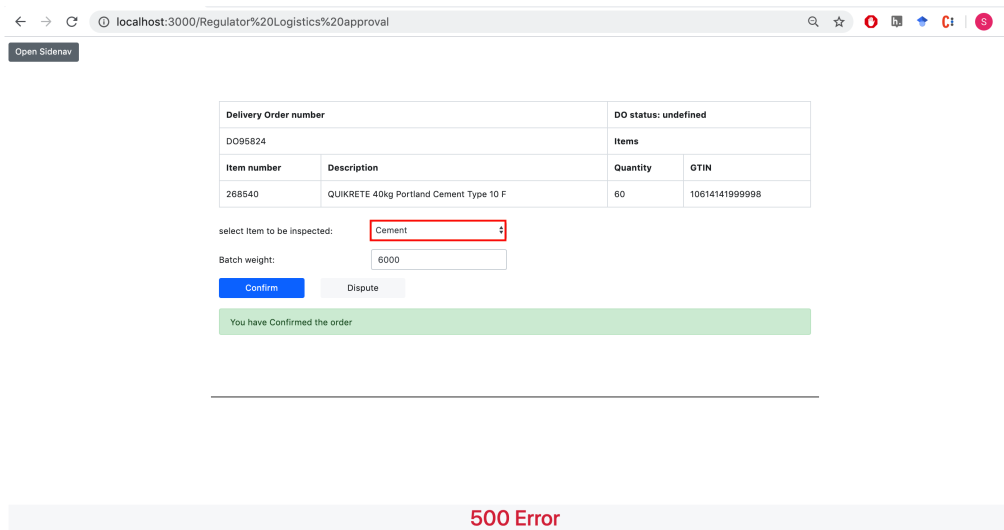

Figure A.14: Pre-delivery Inspection for Cements and Pipes (Con't).

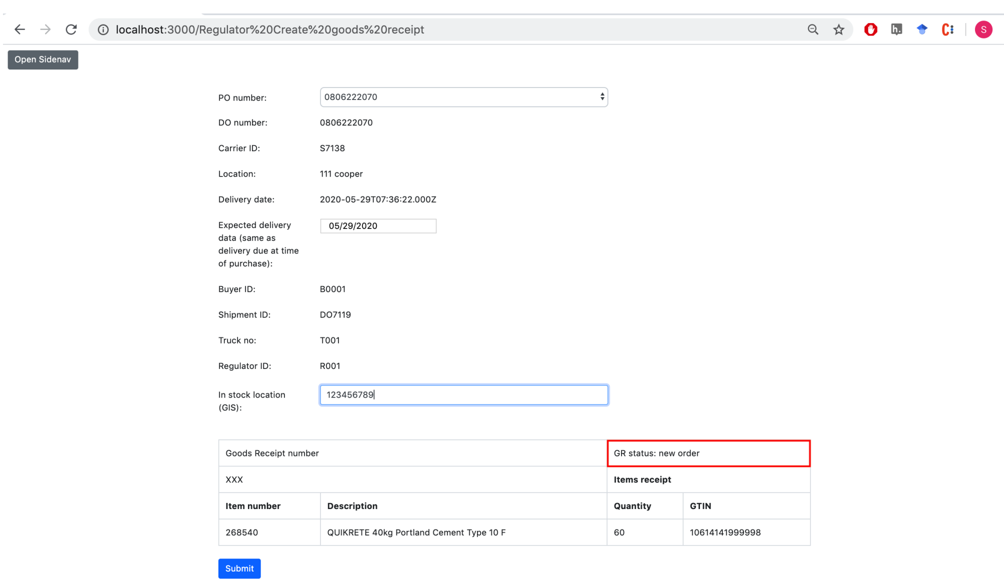

Figure A.15: Goods Receipt Order Page.

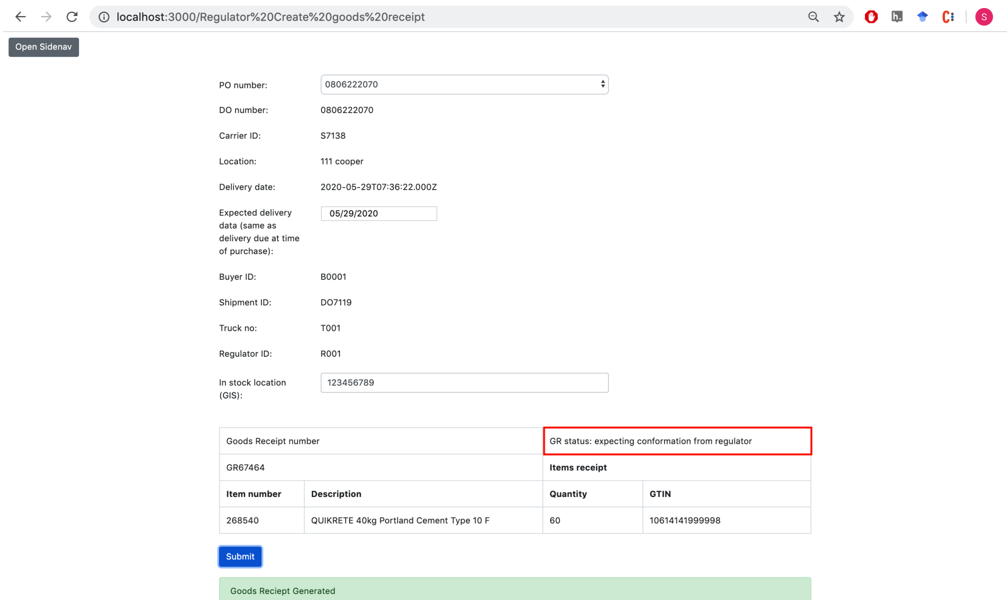

Figure A.16: Goods Receipt Order Page(Con't).

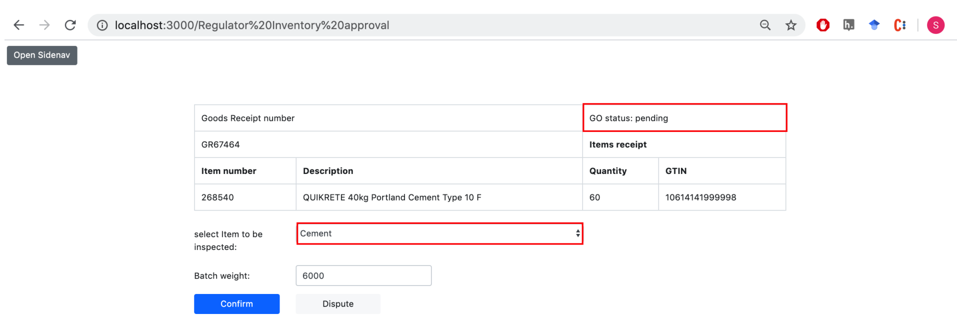

Figure A.17: Pre-inventory Inspection.

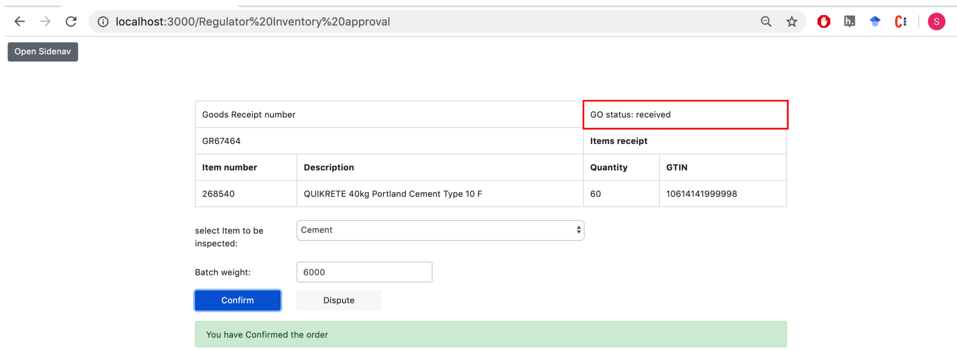

Figure A.18: Pre-inventory Inspection (Con't).

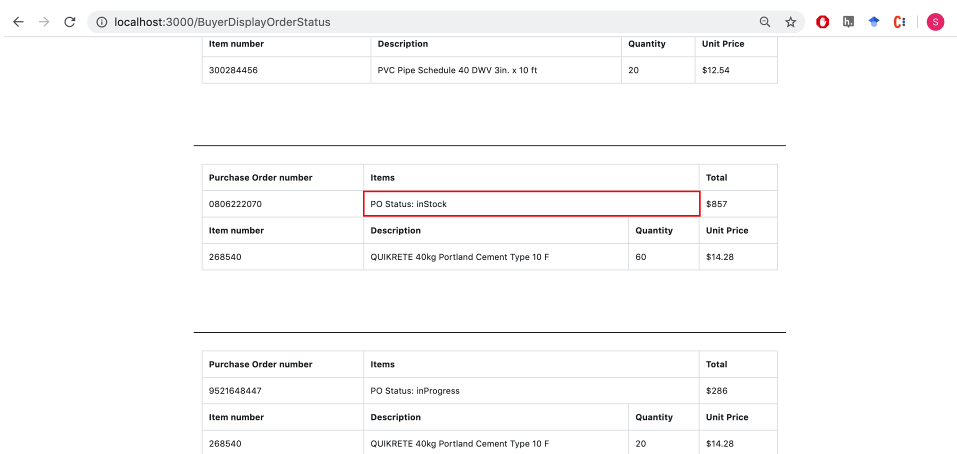

Figure A.19: Buyer's Dashboard Showed that the Materials are in Stock.

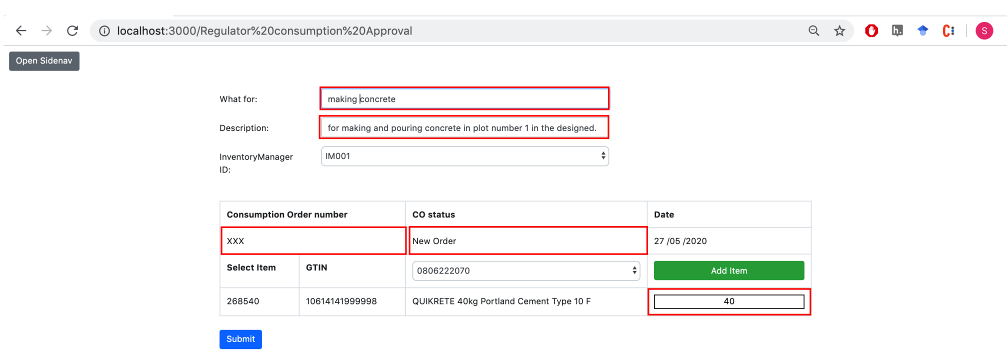

Figure A.20: Consumption Order Page.

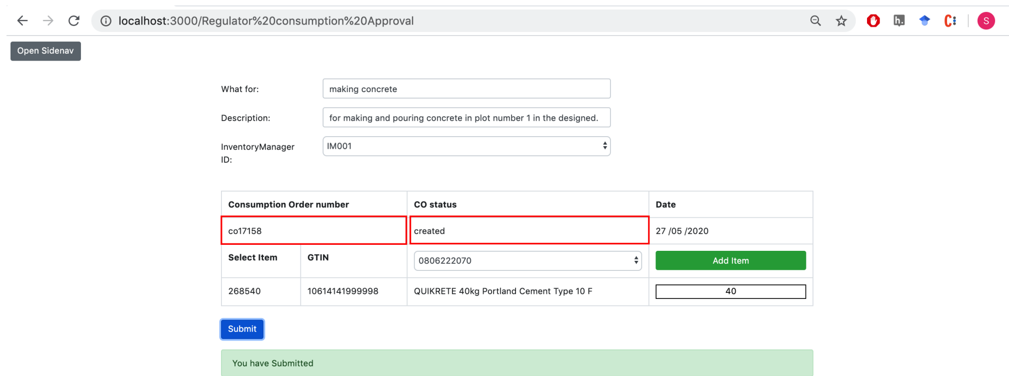

Figure A.21: Consumption Order Page (Con't).

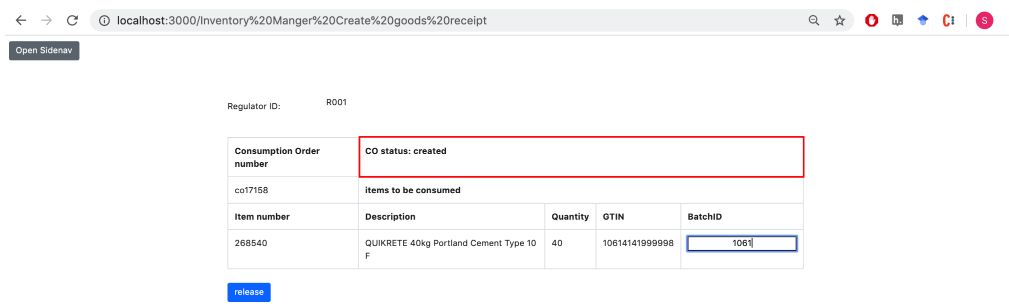

Figure A.22: Inventory Release Order.

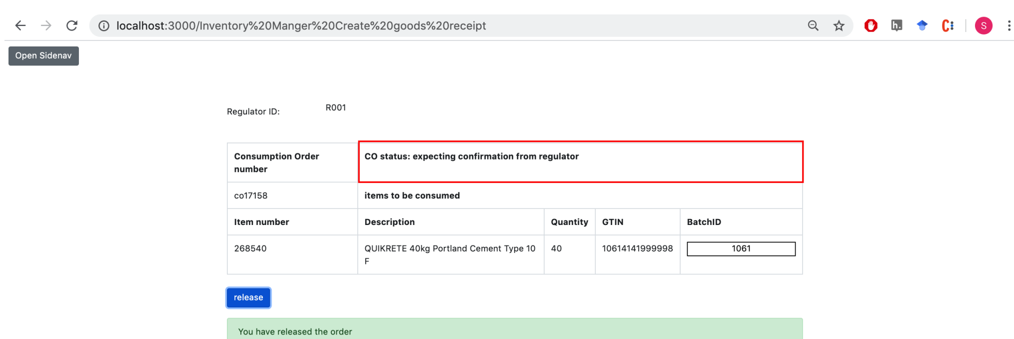

Figure A.23: Inventory Release Order (Con't).

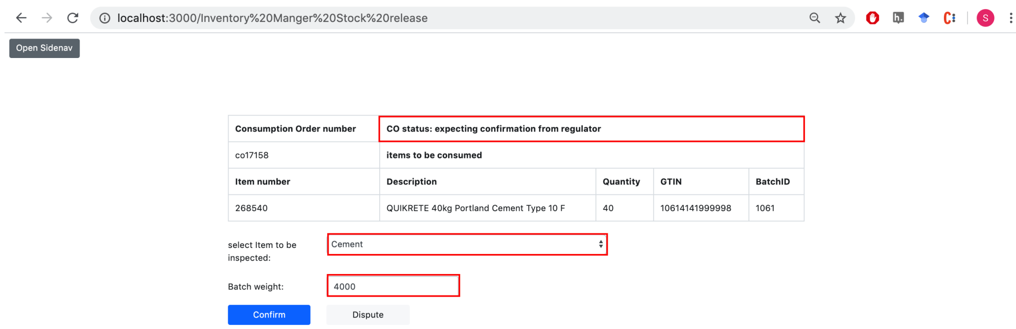

Figure A.24: Upon Leaving Inventory Inspection.

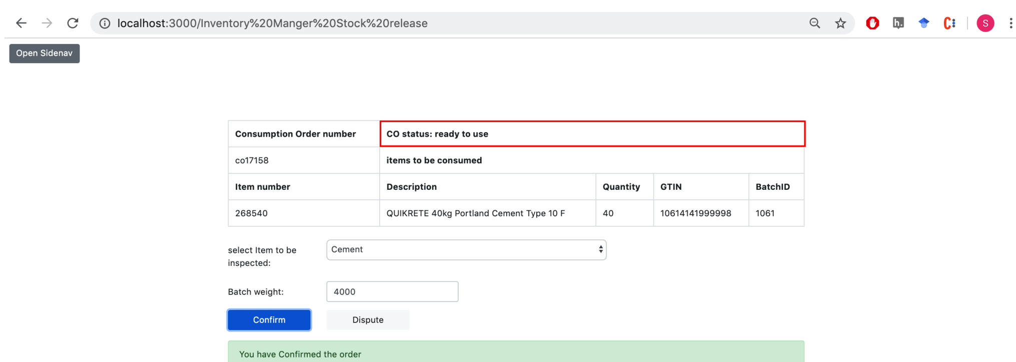

Figure A.25: Upon Leaving Inventory Inspection (Con't).

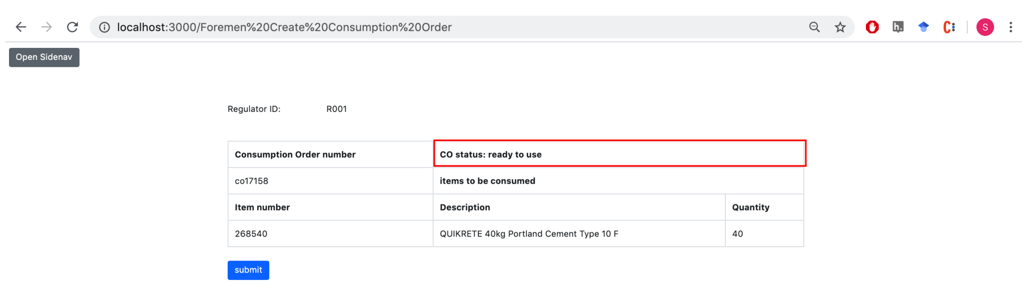

Figure A.26: Foreman's dashboard shows that Materials (cements) are ready to be use in the construction site.

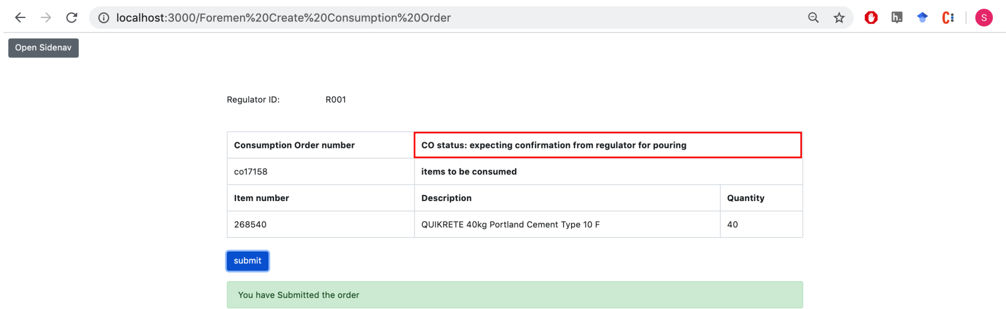

Figure A.27: Foreman's dashboard shows that concrete needs to be approved for pouring.

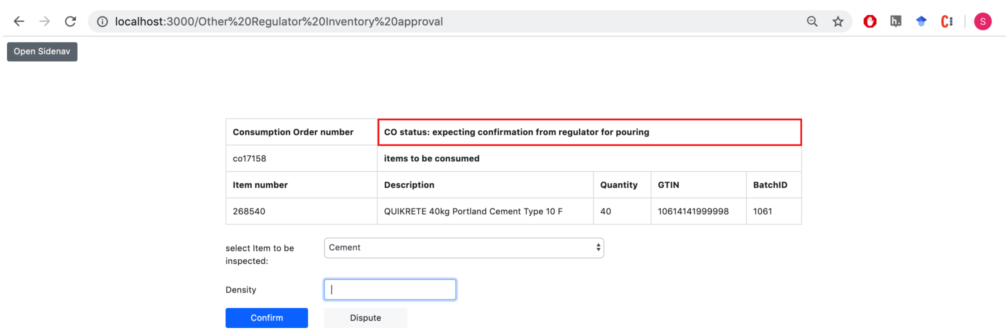

Figure A.28: Consumption Inspection for Concrete.

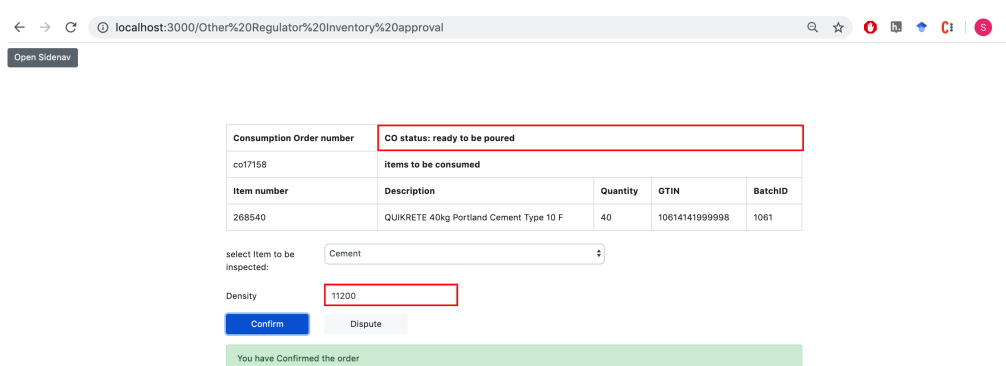

Figure A.29: Consumption Inspection for Concrete(Con't).

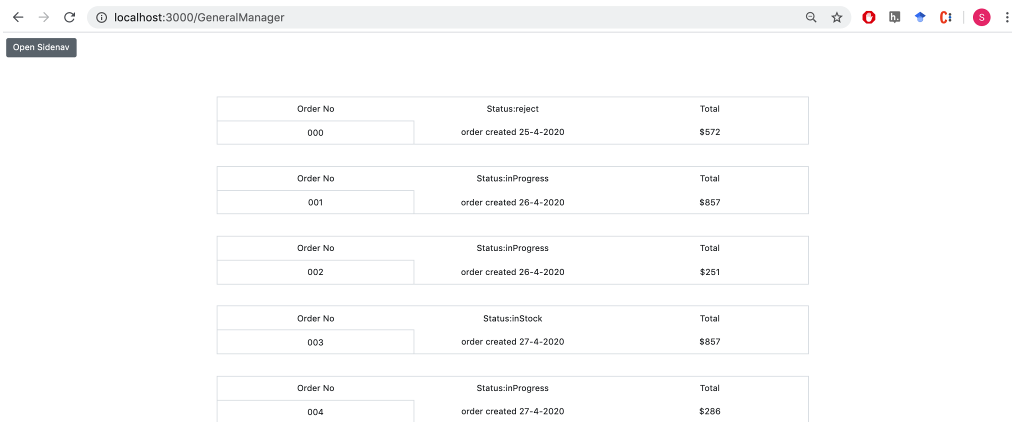

Figure A.30: Material Tracking Page by General Manager.

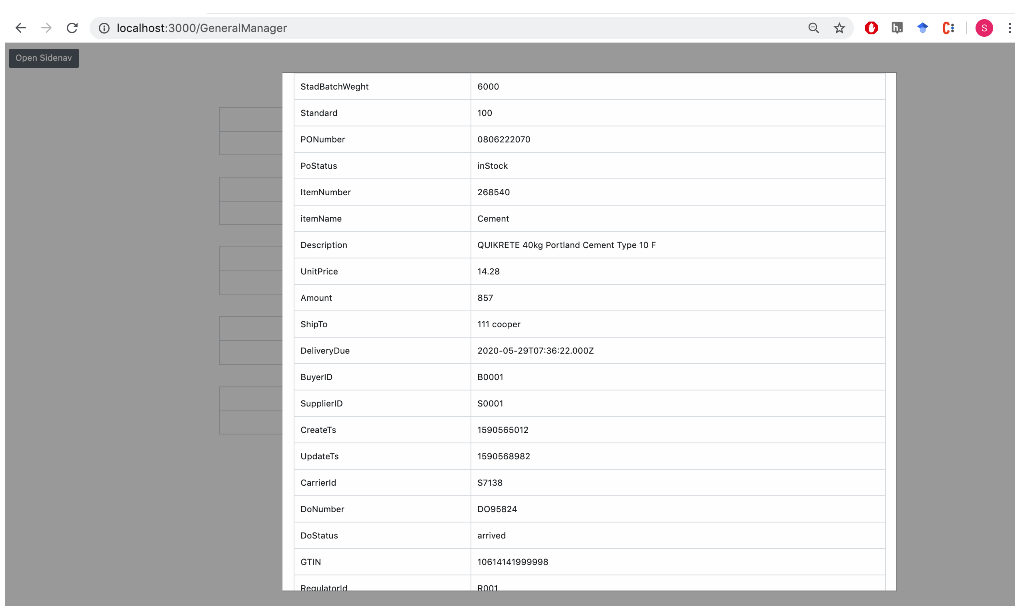

Figure A.31: Material Tracking Page by General Manager (Con't).

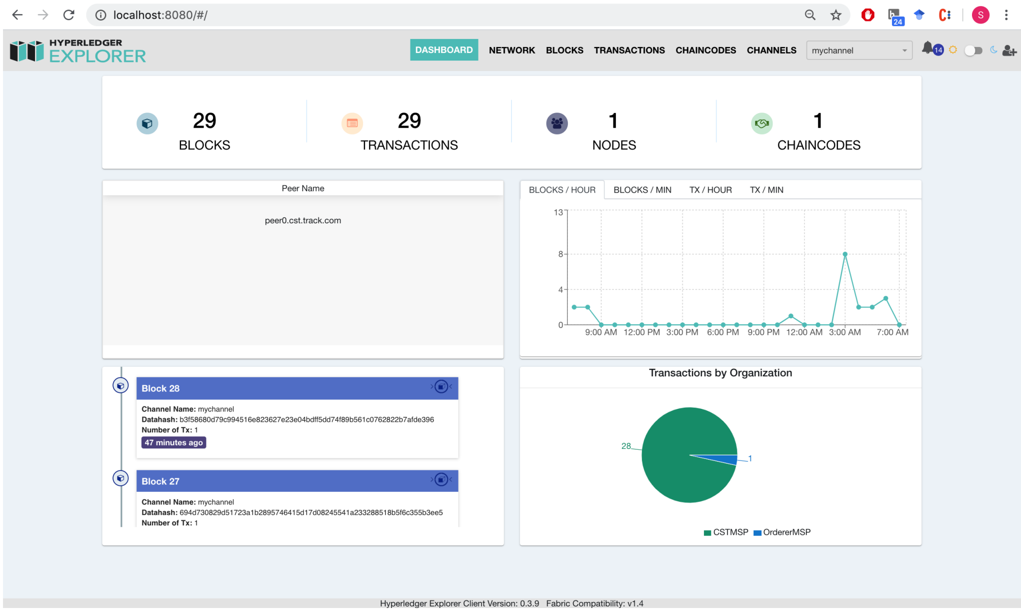

Figure A.32: Exploring Blockchain Network.

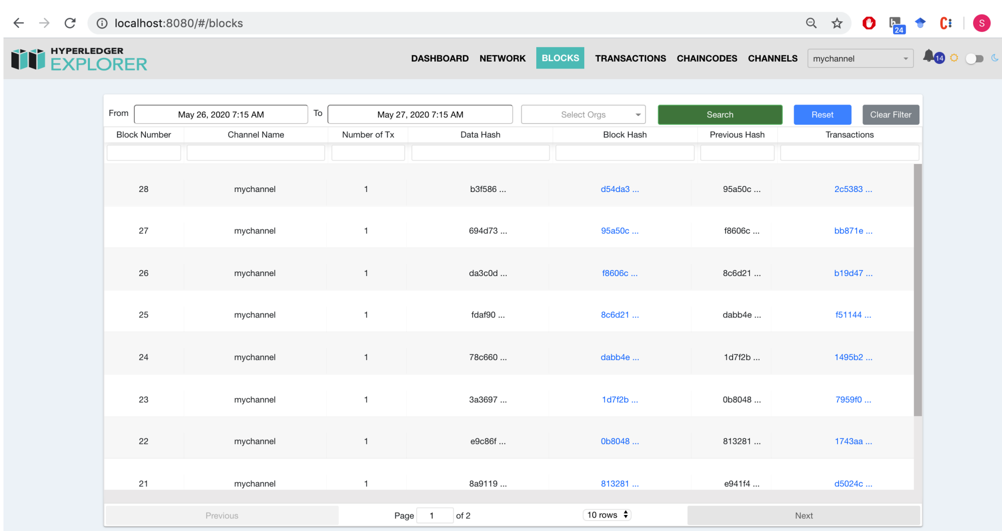

Figure A.33: Exploring Blockchain Network (Con't).

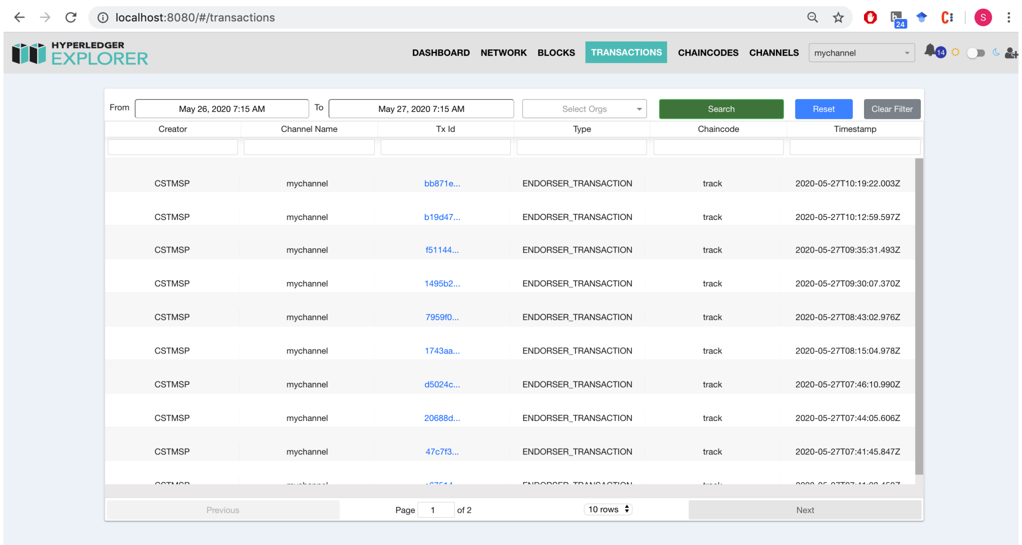

Figure A.34: Exploring Blockchain Network (Con't).

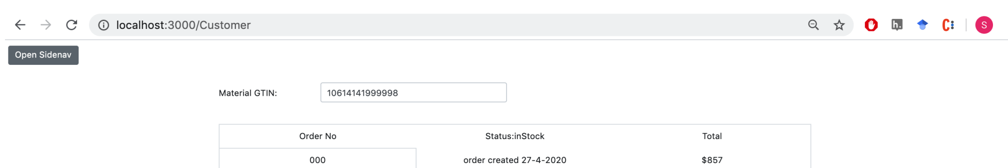

Figure A.35: Customer Page for Tracking Materials origins.

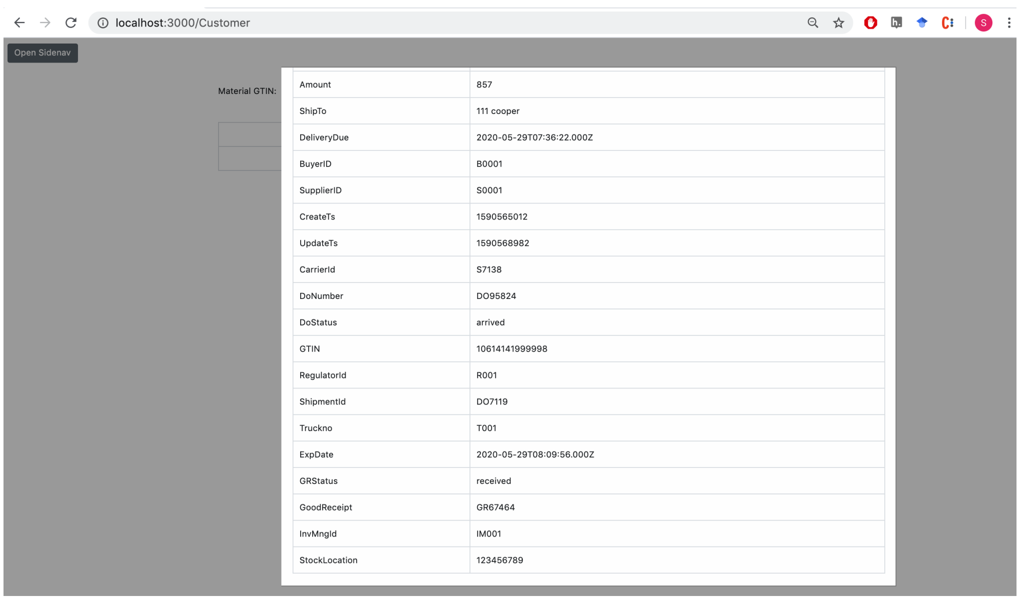

Figure A.36: Customer Page for Tracking Materials origins (Con't).

Appendix B

List of Acronyms

Acronyms

ERP Enterprise Resource Planning

B2B Business-to-Business

SCM Supply Chain Management

RFID Radio-frequency Identification

API Application Programming Interface

DSR Design Science Research

GTIN Global Trade Item Number

TRU Traceable Resource Unit

GIS Geographic Information System

References

[1] Hyperledger. https://www.hyperledger.org/.

[2] Hyperledger burrow. https://www.hyperledger.org/projects/hyperledger-burrow.

[3] Hyperledger indy. https://www.hyperledger.org/projects/hyperledger-indy.

[4] Hyperledger iroha. https://www.hyperledger.org/projects/iroha.

[5] Hyperledger sawtooth. https://www.hyperledger.org/projects/sawtooth.

[6] The linux foundation. https://www.linuxfoundation.org/.

[7] Walmart case study. https://www.hyperledger.org/wp-content/uploads/2019/02/Hyperledger_CaseStudy_Walmart_Printable_V4.pdf.

[8] Ieee recommended practice for software requirements specifications. *IEEE Std 830-1998*, pages 1–40, 1998.

[9] Hyperledger fabric v1.4, access control lists (acl). https://hyperledger-fabric.readthedocs.io/en/release-1.4/access_control.html?highlight=ACL, 2019.

[10] Hyperledger fabric v1.4, blockchain network topology. https://hyperledger-fabric.readthedocs.io/en/release-1.4/network/network.html?highlight=network%20topology, 2019.

[11] Hyperledger fabric v1.4, building your first network. https://hyperledger-fabric.readthedocs.io/en/release-1.4/build_network.html, 2019.

[12] Hyperledger fabric v1.4, install samples, binaries and docker images. https://hyperledger-fabric.readthedocs.io/en/release-1.4/install.html, 2019.

[13] Hyperledger fabric v1.4, prerequisites. https://hyperledger-fabric.readthedocs.io/en/release-1.4/prereqs.html, 2019.

[14] ISO 9000:2015(en). Quality management systems — fundamentals and vocabulary. https://www.iso.org/obp/ui/#iso:std:iso:9000:ed-4:v1:en:term:3.7.6, 2015.

[15] Elli Androulaki, Yacov Manevich, Srinivasan Muralidharan, Chet Murthy, Binh Nguyen, Manish Sethi, Gari Singh, Keith Smith, Alessandro Sorniotti, Chrysoula Stathakopoulou, Marko Vukolić, Artem Barger, Sharon Weed Cocco, Jason Yellick, Vita Bortnikov, Christian Cachin, Konstantinos Christidis, Angelo De Caro, David Enyeart, Christopher Ferris, and Gennady Laventman. Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains. In *Proceedings of the Thirteenth EuroSys Conference on - EuroSys '18*, 2018.

[16] Myo Min Aung and Yoon Seok Chang. Traceability in a food supply chain: Safety and quality perspectives. *Food Control*, 39(1):172–184, 2014.

[17] Ronald Ballou. The evolution and future of logistics and supply chain management. *European Business Review*, 19(4):332–348, 2007.

[18] Paul Baran. On Distributed Communications Networks. *IEEE Transactions on Communications Systems*, 1964.

[19] BBC. Steel imports from china investigated by european commission. https://www.bbc.com/news/business-35559540, 2016.

[20] Panchanan Behera, R. P. Mohanty, and Anand Prakash. Understanding Construction Supply Chain Management. *Production Planning and Control*, 26(16):1332–1350, 2015.

[21] Techane Bosona and Girma Gebresenbet. Food traceability as an integral part of logistics management in food and agricultural supply chain. *Food Control*, 33(1):32–48, 2013.

[22] Vitalik Buterin. A next-generation smart contract and decentralized application platform. *Etherum*, (January):1–36, 2014.

[23] Fran Casino, Thomas K. Dasaklis, and Constantinos Patsakis. A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics and Informatics*, 36(November 2018):55–81, 2019.

[24] Fran Casino, Venetis Kanakaris, Thomas K. Dasaklis, Socrates Moschuris, Spiros Stachtiaris, Maria Pagoni, and Nikolaos P. Rachaniotis. Blockchain-based food supply chain traceability: a case study in the dairy sector. *International Journal of Production Research*, 0(0):1–13, 2020.

[25] Rishav Chatterjee and Rajdeep Chatterjee. An Overview of the Emerging Technology: Blockchain. In *2017 3rd International Conference on Computational Intelligence and Networks (CINE)*, pages 126–127, 2017.

[26] Andy Dong, Mary Lou Maher, Mi Jeong Kim, Ning Gu, and Xiangyu Wang. Construction defect management using a telematic digital workbench. *Automation in Construction*, 18(6):814–824, 2009.

[27] John Egan. Rethinking construction (the egan report). *London: Department of the Environment*, 1998.

[28] Zhi-Ping Fan, Xue-Yan Wu, and Bing-Bing Cao. Considering the traceability awareness of consumers: should the supply chain adopt the blockchain technology? *Annals of Operations Research*, 2020.

[29] Simone Figorilli, Francesca Antonucci, Corrado Costa, Federico Pallottino, Luciano Raso, Marco Castiglione, Edoardo Pinci, Davide Del Vecchio, Giacomo Colle, Andrea Rosario Proto, Giulio Sperandio, and Paolo Menesatti. A blockchain implementation prototype for the electronic open source traceability of wood along the whole supply chain. *Sensors (Switzerland)*, 18(9):1–12, 2018.

[30] Toby Gardner, Magnus Benzie, Jan Börner, Elena Dawkins, Stephen Fick, Rachael Garrett, Javier Godar, A Grimard, Sarah Lake, Rasmus K Larsen, et al. Transparency and sustainability in global commodity supply chains. *World Development*, 121:163–177, 2019.

[31] BRE Global. Bes 6001: Issue 3.1 framework standard for the responsible sourcing of construction products,watford. http://www.greenbooklive.com/filelibrary/responsible_sourcing/BES-6001--Issue-3.1.pdf, 2016.

[32] GS1 Global Traceability Standard. Business Process and System Requirements for Full Supply Chain Traceability. (1.3.0):1–64, 2012.

[33] GS1 Standards in Construction. Transforming Construction Building the foundation for greater efficiency and sustainability. https://www.gs1.org/docs/technical_industries/Construction/GS1-Transforming-Construction-brochure.pdf.

[34] Stuart Haber and W Scott Stornetta. How to time-stamp a digital document. *Journal of Cryptology*, 3(2):99–111, 1991.

[35] Alan Hevner, Salvatore March, Jinsoo Park, and Sudha Ram. Design science in information systems research. *MIS Q.*, 28(1):75–105, March 2004.

[36] Jouni Ikonen, Antti Knutas, Harri Hämäläinen, Marko Ihonen, Jari Porras, and Tommi Kallonen. Use of embedded RFID tags in concrete element supply chains. *Journal of Information Technology in Construction*, 18(April):119–147, 2013.

[37] Henry Kim and Marek Laskowski. Toward an ontology-driven blockchain design for supply-chain provenance. *Intelligent Systems in Accounting, Finance and Management*, 25(1):18–27, 2018.

[38] Kari Korpela, Jukka Hallikas, and Tomi Dahlberg. Digital Supply Chain Transformation toward Blockchain Integration. In *Hawaii International Conference on System Sciences (HICSS)*, pages 4182–4191, At Big Island, Hawaii, 2017.

[39] Karin Lakhani and Marco Iansity. The Truth About Blockchain. *Harvard business review.*, 95(1):119–127, 2017.

[40] Leslie Lamport, Robert Shostak, and Marshall Pease. The Byzantine Generals Problem. *ACM Transactions on Programming Languages and Systems*, 4(3):382–401, 1982.

[41] Aleksandr Lanko, Nickolay Vatin, and Arturas Kaklauskas. Application of rfid combined with blockchain technology in logistics of construction materials. *MATEC Web Conf.*, 170:03032, 2018.

[42] Michele Marchesi, Lodovica Marchesi, and Roberto Tonelli. An Agile Software Engineering Method to Design Blockchain Applications. (Secr):1–8, 2018.

[43] Paul Müller, Sonja Bergsträßer, Amr Rizk, and Ralf Steinmetz. The bitcoin universe: An architectural overview of the bitcoin blockchain. *Lecture Notes in Informatics (LNI), Proceedings - Series of the Gesellschaft fur Informatik (GI)*, 283:1–20, 2018.

[44] Satoshi Nakamoto. Bitcoin: A Peer-to-Peer Electronic cash system. *Bitcoin.–URL: https://bitcoin. org/bitcoin. pdf*, 2008.

[45] Raiden Network. What is the raiden network? https://raiden.network/101.html#:~:text=Summary,%2C%20and%20privacy%2Dpreserving%20payments., 2017.

[46] Ken Peffers, Tuure Tuunanen, Marcus Rothenberger, and Samir Chatterjee. A design science research methodology for information systems research. *J. Manage. Inf. Syst.*, 24(3):45–77, December 2007.

[47] Suporn Pongnumkul, Chaiyaphum Siripanpornchana, and Suttipong Thajchayapong. Performance analysis of private blockchain platforms in varying workloads. *2017 26th International Conference on Computer Communications and Networks, ICCCN 2017*, 2017.

[48] Stephen Pryke. *Construction Supply Chain Management*, chapter 1, pages 1–19. John Wiley Sons, Ltd, 2009.

[49] Business Roundtable. *"Report on materials management," Construction industiy cost-effectiveness project.* Business Roundtable, New York, 1982.

[50] Lakshmi Siva Sankar, M. Sindhu, and M. Sethumadhavan. Survey of consensus protocols on blockchain applications. In *2017 4th International Conference on Advanced Computing and Communication Systems, ICACCS 2017*, 2017.

[51] Mattias Scherer. Performance and scalability of blockchain networks and smart contracts. Master's thesis, Umeå University, Department of Computing Science, 2017.

[52] Hari Singh. Materials management: the key to successful project management. *Essentials of Management for Healthcare Professionals*, 15(1):245–271, 1999.

[53] Jongchul Song, Carl T. Haas, and Carlos H. Caldas. Tracking the Location of Materials on Construction Job Sites. *Journal of Construction Engineering and Management*, 132(9):911–918, 2006.

[54] Josh Stark. Making Sense of Ethereum's Layer 2 Scaling Solutions: State Channels, Plasma, and Truebit. *Medium.com*.

[55] George Stukhart. Construction Materials Quality Management. *Journal of Performance of Constructed Facilities*, 3(2):100–112, 1989.

[56] Gerard Tel. *Cryptography in Context*, chapter 1. 2008.

[57] Feng Tian. An agri-food supply chain traceability system for China based on RFID & blockchain technology. In *2016 13th International Conference on Service Systems and Service Management, ICSSSM 2016*, pages 1–6. IEEE, 2016.

[58] Kalyan Vaidyanathan and William O Brien. Opportunities for IT to Support the Construction Supply Chain. In *Fourth Joint International Symposium on Information Technology in Civil Engineering*, pages 1–19, 2003.

[59] Jun WANG, Peng WU, Xiangyu WANG, and Wenchi SHOU. The outlook of blockchain technology for construction engineering management. *Frontiers of Engineering Management*, 4(1):67, 2017.

[60] Zhaojing Wang, Tengyu Wang, Hao Hu, Jie Gong, Xu Ren, and Qiying Xiao. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Automation in Construction*, 111:103063, 2020.

[61] Karl Wust and Arthur Gervais. Do you Need a Blockchain? In *2018 Crypto Valley Conference on Blockchain Technology (CVCBT)*, pages 45–54, 2018.

[62] Minjae Yoo and Yoojae Won. A study on the transparent price tracing system in supply chain management based on blockchain. *Sustainability (Switzerland)*, 10(11):1–15, 2018.

[63] Vlad Zamfir. Introducing casper "the friendly ghost". https://blog.ethereum.org/2015/08/01/introducing-casper-friendly-ghost/, August 2015.

[64] Zibin Zheng, Shaoan Xie, Hongning Dai, Xiangping Chen, and Huaimin Wang. An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends. In *Proceedings - 2017 IEEE 6th International Congress on Big Data, BigData Congress 2017*, pages 557–564, 2017.