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IMPROVE FOOD SUPPLY CHAIN TRACEABILITY USING BLOCKCHAIN

A Thesis in

Industrial Engineering

by

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ABSTRACT

The central problem to be addressed in this thesis is to investigate how blockchain technology can be used to provide greater asset traceability in today's food supply chains. Blockchain is a shared, distributed ledger that uses cryptography to validate and record transactions and track assets in a business network. The goal is to create a blockchain model that can be implemented across food supply chains and present the benefits and limitations in its implementation. Food provenance is one of the most challenging problems that FSC companies face today. A global supply chain network with multiple operating procedures and asymmetrical food regulations between countries makes end-to-end food tracking incidental to the food industry. A detailed literature review on the current challenges in food tracking, food safety regulations and food supply chain design is also discussed in this research. Analysis of food illness outbreak dataset in the US between 2007-2016 is also presented to focus on two key results. Firstly, to focus the blockchain model development on food products with highest food illness outbreak incidents and secondly, to increase IoT scanning points in certain stages of the supply chain that have recorded more than 50% of the total contamination incidents. Finally, a blockchain model is created using Hyperledger Sawtooth, and its benefits over conventional information technology systems and global food tracking methods are presented. Future research studies can focus on using blockchain enabled models to replace ERP systems, reduce food waste and improve supply management between stages in the food supply chain.

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Chapter 1

Introduction

We consume food products every day based on the trust that they are produced, transported and stored according to the internal and government food safety regulations. Food products flow through an extensive network of different players ranging from the supplier to the retailers before reaching the end consumer. These intermittent stages participate in the design, production, delivery, and sales of the product. Although food safety regulators conduct periodic food safety inspections and provide quality certifications, it is often unreliable when examining a supply chain scaling across continents with uneven technology distribution. For example, United States discontinued meat imports from Brazil in June 2017 due to food inspectors in Brazil accepting bribes, the horse meat scandal in Europe in 2013, the 2008 baby milk powder scandal in China, and the rising food adulteration problem in India. These incidents have been occurring periodically over the past decade, forcing consumers and governments to demand more transparency throughout the food supply chain.

Based on Food and Drink Research Report 2016 from Lloyds bank [Retrieved April 3, 2018, from http://www.lloydsbankinggroup.com/globalassets/documents/media/press-releases/lloyds-bank/2016/lb-food-and-drink-report-2016.pdf], 54% of the organizations see the growing focus on food provenance as a challenge for the business, and 67% consider that the increased awareness on public health as a business opportunity. The 2016 estimates are significantly higher, almost doubled from 2015 estimates, showing a clear trend that consumers are concerned about the authenticity of their food products but hesitate to act upon through their purchasing decisions. It is partially due to the absence of an alternative that guarantees that they are getting a product as advertised and information asymmetry in the fragmented supply chain that makes the tracking process cumbersome for the buyer. Customers are increasingly looking for products from verified sources, and leading supermarkets have long realized the competitive advantage of open, transparent supply chains and sustainable manufacturing. For example, fish suppliers like John West are inserting QR codes on all cans of their tuna fish products, enabling product traceability back to the fisherman's location. This initiative alone added £17m to the brand's sales. As of February 2018, Walmart has successfully conducted pilot studies with IBM to test if they can ensure the safety of the food products they sell as part of their retail stores. However contemporary silo databases for each supply chain stage is ineffective in providing unforgeable trust to the customer since they are not tamper proof. Most of the today's food supply chains track their products only at the end of each supply chain segment and still are unable to map their products to its source and the stages it went through in between.

Manufacturing, transportation, and consumption of food products have many potential adverse outcomes like irreversible environmental damage, exploitation of labor conditions, unsafe sourcing practices, counterfeiting and vast amounts of food waste due to imbalanced supply and storage strategies. However, end consumers continue to use these systems without understanding the ramifications it causes through its footprint and food supply chains are conveniently held secret with minimal effort being made to provide end-to-end visibility for its stakeholders. Despite these challenges, the notion of having a central body to provide data and transaction transparency in the food chain was the only possible alternative, until recently, when a new technology called blockchain demonstrates a whole new avenue to address food provenance.

1.1 Motivation

Though the challenges in implementing a transparent supply chain are enormous, the advantages of implementing FTSs far outweigh the disadvantages (initial capital investment cost and maintenance). The benefits of an active FTS can be categorized broadly as a Social benefit, Authorities' benefits and Food companies' benefits. However, for the sake of simplicity the benefits can be categorized as an increase in customer satisfaction, improvement in food crises management, improvement in Food Supply Chain Management (FSCM), competence and technological contribution and, contribution to agricultural sustainability. There is an existing rich network of devices and sensors that create a data rich ecosystem for efficient asset tracking and analysis, which had been impossible in supply chains ten years ago. This evolution has now enabled us to utilize this ecosystem and build a blockchain network which provides a lot of potential benefits as discussed in this research.

1.2 Problem definition

The central problem to be addressed in this research is to find how blockchain technology can be implemented to provide greater asset traceability in today's food supply chains. The blockchain is a shared, distributed ledger that utilizes cryptography to verify and record transactions and track assets in a business network. The goal is to analyze if blockchain, along with IoT devices, provide any benefits to the modern supply chain networks in the form of increased efficiency, greater traceability or improved customer trust, when compared to the existing systems.

1.3 Brief description of the methodology

Previous studies on food tracking systems concentrate on exploring the definition of food tracking, the common challenges, and limitations in using technology to identify the provenance of the products. The challenges faced in food tracking is different for different supply chains. Hence an initial study was conducted on the food outbreak online dataset from Center for Disease Control and Prevention (CDC) to identify the target food products that have the highest number of food illness incidents in the USA during the period 2007-2016. Further analysis is then performed to identify the different stages in the supply chain of the target products and identify the food safety regulations that have been imposed by the United States Department of Agriculture (USDA) to ensure its safe commerce. By incorporating these food safety rules and assessment tools in a supply chain network design formulated based on the background research, a blockchain environment is developed to using IoT information to conduct product transactions as a food product moves down the chain. Here each stage or stakeholder in the target FSC would act as a node communicating and transacting to multiple other nodes inside the FSC. A private blockchain model is then created using Hyperledger Sawtooth, in which every transaction (movement of food products, food processing, value addition, packing, manufacturing or assembly) performed on every product and its raw materials is recorded. It enables a clear line of communication between multiple players in the supply chain starting from the raw material supplier or farmer to the end customer. This information is immutable and hence serve as a high starting point to establish fool-proof quality systems to identify and remove defects and food safety rules violations. It also provides a considerable time advantage in controlling food outbreaks due to the existing chain of information regarding every product ever sold and consumed.

1.4 Results

A blockchain network is developed based on the information from the food outbreak analysis to find out if it can be the game-changing technology that provides increased efficiency, higher traceability, and improved customer trust. A detailed comparison between blockchain and traditional databases is also presented to identify reasons why food corporations must capitalize this opportunity by investing in this technology to enjoy a considerable market advantage.

1.5 Organization of the thesis

The construction of this thesis is as follows. Chapter 2 summarizes the basic introduction to food supply chain and blockchain, as it is required to understand the subsequent chapters. Research published in the areas of food tracking systems, food safety and regulations, food supply chain design and potential gaps are addressed in chapter 3. Chapter 4 discusses the methodology and technologies used for carrying out this research. This chapter also presents the final model results and outlines the benefits and limitations of the blockchain model. Conclusions and scope for future work are discussed in chapter 5.

Table 1-1. Structure of thesis

Chapter	Content
Chapter 1	Introduction
Chapter 2	Background
Chapter 3	Background Literature
Chapter 4	Methodology & Analysis
Chapter 5	Conclusion and Future Work

Chapter 2

Background

2.1 Food Supply Chain (FSC)

In a food supply chain, a network of stakeholders transacts with each other in the form of growing, processing or selling food to the end customer. Transportation companies function as links that connect these stages and ensure that the right quantity and quality product reaches the right destination at the right time as depicted in the figure 2-1.

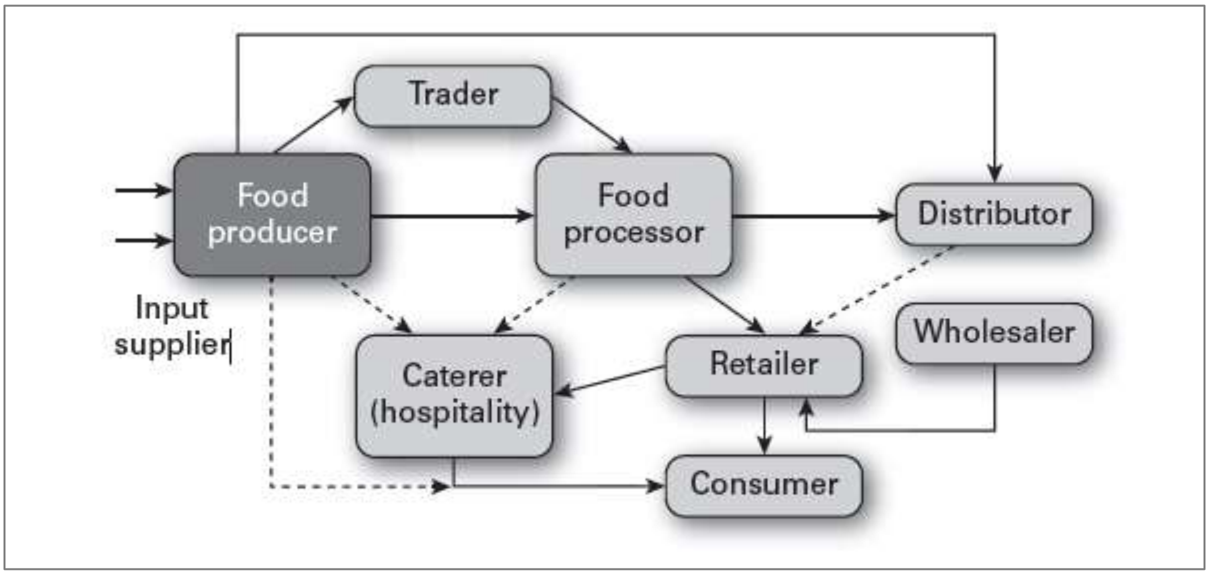

Figure 2-1. Stages in a typical food supply chain network (from Dani, Samir, 2015)

The stakeholders include:

1. The food ingredient suppliers to food producers or food farmers.
2. The food producers or farmers involved in growing the food.
3. The food processors or manufacturers involved in manufacturing and sometimes processing the food products.

4. The distributors involved in distributing the manufactured food product to end customers and retailers.
5. The end consumers involved in shopping the food products, comprising of individuals and restaurants.
6. Government and non-governmental organizations (NGOs) administering policy creation and development programs for food sustainability and security.
7. Food Inspectors or regulatory bodies involved in overseeing and managing the entire food value chain from the supplier to the end consumer.
8. Logistics companies involved in moving, storing and managing food products throughout the value chain.
9. Financial organizations such as banks and private investment firms furnishing monetary assistance to the entities within the food supply chain.

2.1.1 Food producer

The food producing sector has been a vital employment and income generator for centuries. Based on 2015 GDP sector composition data, agriculture sector contributes 6.1% of total world's GDP. China and India account for 21.06% and 7.68% of total global agricultural output, followed by the United States at the third place. The output of farms in the United States contributed to only 0.67% of its GDP. The actual contribution of the agriculture sector to the country’s GDP is higher than this because several sectors related to agriculture like food, beverages, tobacco products, fishing, textiles and apparel, leather, food service industry, forestry; rely on agricultural output to provide their share of value addition to the economy.

The top 6 producers of agricultural products together constitute 42.43% of total Agriculture GDP of the world. This data implies the sophistication of today’s global FSC in moving food and food-related products between continents and the growing requirement to make this process safe and traceable from its point of origin to its point of consumption. Any FSC starts with the food ingredient supplier whose inputs are in the form of fertilizers, machinery, seeds, labor, and so on. And any disruption to this stage has severe implications in food quality and availability. These are large corporations who have invested a lot in food innovation (seeds, pesticides, and so on). The next stage is the farmers, which is the most important aspect of the entire chain since this is where the food is grown or managed (livestock, fish, meat) according to the availability of resources. Farmers can be segmented based on farm size, crops grown, and level of agriculture tech used in the production process ranging from small scale individual farmers to large corporations operating greenhouses in hundreds of acres. There is also an urban farming boom in developed countries with startups using soil sensors, hydroponics, LED lighting and aeroponics, negating the need for natural sunlight or soil to grow food products. With an ever-changing landscape of food production methods, food traceability and quality assurance are immense challenges faced by the policymakers.

2.1.2 Food processor

This stage is responsible for transforming the raw food produced into the final product that can be consumed by the end customer. Few reasons for food processing are preservation, food safety, creating variety, creating convenience and fortification for nutrition. This transformation is simple when fruits and vegetables are sold as the final product. For example, performing quality checks, size, color, and shape, or value addition activities like packaging, for transit. It becomes complex with frozen foods which typically gets frozen, processed, packed and refrozen multiple times as it travels through multiple players from different countries. In fish supply chains, there is an intermittent step in the value chain that involves a detour through China, to perform food processing like filleting, before the product is re-exported to various continents. Raw meat undergoes much transformation before it becomes ready-to-consume meals for the retail stores. Majority of this stage for all raw meat products are commodity chains that are not structured to establish a track system for food provenance or to verify the sustainability of their production practices.

Most of the food producers are food manufacturers who procure raw food from the producers to make flavored edible products. These products need to adhere to the strict safety regulations enforced by the government for production, logistics and the retail environment. Another kind of food processors includes the catering sector like restaurants, food service agents, hotels, airlines, passenger trains, hospitals and takeaway places where they transform the food to suit the requirements of the end customer. It is an essential entity in the FSC, as it contains the most significant number of employers ranging from highly skilled chefs to people working in manufacturing units making frozen food for supermarket shelves.

2.1.3 Food retailer

Food retailing is one of the important steps in the FSC as the food reaches the end consumer after this stage and the entire fulfillment of the supply chain depends upon the ability of the retailer to sell the product to the end customer, which in turn initiates the cash flow cycle in the supply chain. In addition to the end retailers, there are other players in this segment - distributors purchase products from the manufacturers and sell or distribute them to retailers and food service companies, and wholesalers buy in large quantities from the distributor or manufacturer and sell it to the retailers or customers. Large retailers own their distribution centers and truck fleet, ensuring efficient movement of products through the network, not only to control the transportation cost, but also to control perishability and product damage. Before getting a product to the retail shelf, many requirements must be satisfied by the manufacturer such as barcodes, labeling, and product packaging.

2.2 The Blockchain

A blockchain is a decentralized ledger, that was initially intended to record the cryptocurrency transactions that happen within a digital currency network. Cryptography and blockchain are the backbone technologies behind the first decentralized digital currency developed by Satoshi Nakamoto in 2009 called “Bitcoin.” It is a form of a Peer-to-Peer (P2P) network, where unlike server-based systems it doesn’t need a central server to host the blockchain and store the transaction history. Instead, it saves a copy of the blockchain on all participants (or nodes) of the network, thus providing a decentralized public ledger. For example, torrent file sharing.

Each node within a blockchain contains a public and a private key, and every transaction initiated includes some necessary information related to the sender, recipient, asset information, time and an identifier for the previous transaction of the sender. An asset could be any product within a supply chain or a transaction between a buyer and seller. A cryptographic hash function named SHA-256 (Secure Hash Algorithm 256) generates a 16-digit hexadecimal string called the “hash,” using the sender’s public key and the transactional information. The hash made is unique to a public key and a transaction information combination. A group of transactions grouped together randomly is a block. This encrypted transaction information is decoded to verify the authenticity of the transactions and its sender, and it can be decrypted only by brute force (randomly trying different possible combinations). The process of solving the hash is called mining and nodes who verify these transactions are called miners. Once the network creates a block from the pool of unverified transactions, available miners would compete to verify the transactions by solving the cryptographic hash.

The process of selecting a miner in a blockchain is governed by a consensus algorithm (for example, Bitcoin uses “Proof of Work”). It is different for other blockchain platforms like Ethereum and Hyperledger frameworks. Each block in a blockchain consists of 3 critical components - a hash (a unique digital identifier), a timestamp, and the hash of the previous block (to compute the account balance). The hash of the previous block links the entire chain of blocks together and hence preventing any block from being updated or introduced between two validated blocks. Once a transaction is verified, it gets recorded in the blockchain. A change in a published transaction value is very hard in a public blockchain network like Bitcoin since an attacker must acquire 51% or more of the entire computing power available in the system. Hence each subsequent block strengthens the verification of the previous block and therefore blockchain as the whole. This mechanism makes the blockchain immune to malicious activities, leading to the critical attribute of immutability.

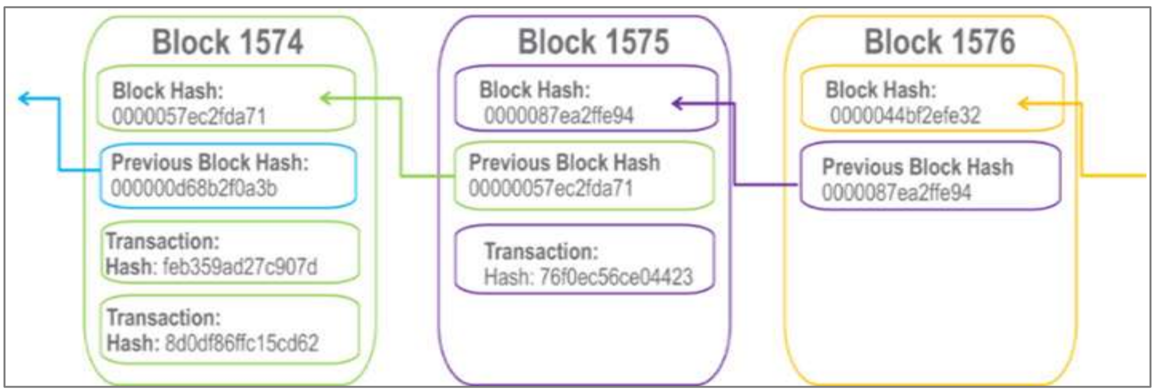

Figure 2-2. Blockchain recording mechanism

The miners are rewarded in bitcoins depending upon the amount of computing power they are contributing to solving the hash. The hashing algorithm periodically changes the difficulty by updating the required minimum/maximum hash value (nonce), so that the miners do not receive too many bitcoins as a reward when new blocks are created, especially when the network computation power increases as new users join. In figure 2-3, the hash rate denominations are in PH/s (10^{15}), and it continuously increases over time. It is also evident that this curve is almost proportional to the price trend of bitcoin over last 12 months in figure 2-4. A comparison between the two graphs shows that the system increases the difficulty of solving a hash, as more users join the network. Currently, the average time to verify a bitcoin block starting with 18 zeros and to use the combined processing power of all the miners in the system takes approximately 9.8 minutes.

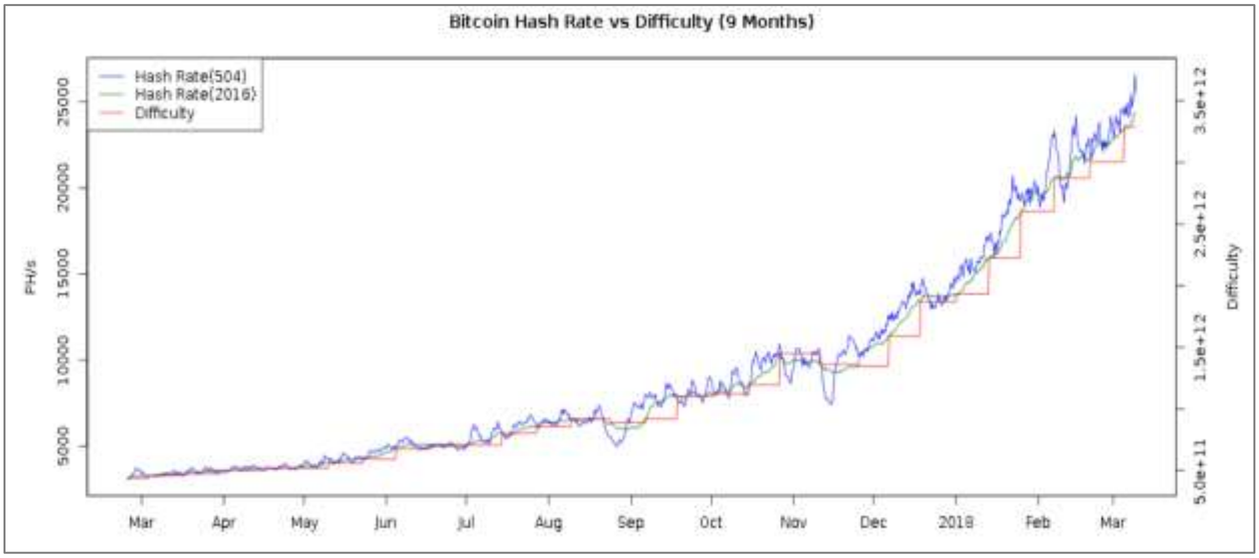

Figure 2-3.Bitcoin Hash Rate (in Peta Hashes per second) vs. Difficulty
(Source - https://bitcoinwisdom.com/bitcoin/difficulty)

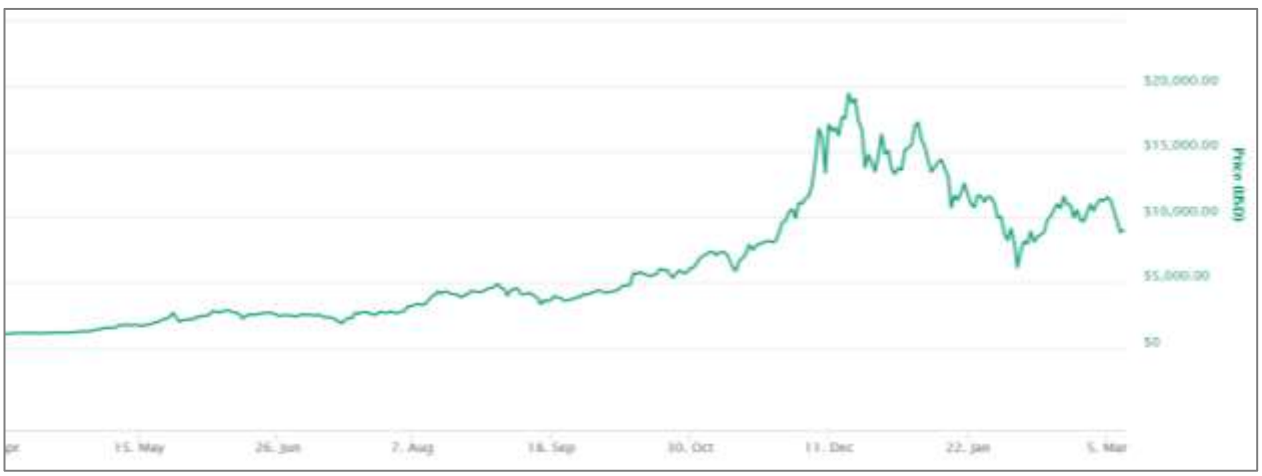

Figure 2-4. Bitcoin value (USD) over last one year
(Source - https://coinmarketcap.com/currencies/bitcoin/#charts)

In Ethereum, the blockchain system is governed by rules agreed on by the network participants in the form of smart contracts and was initially introduced for operating the shared accounting ledger in Bitcoin. Beyond this initial financial application, it is widely used when many players with little or no trust are part of a transaction; for example, fragmented supply chains. The three critical characteristics of blockchain that makes it an attractive alternative for supply chain asset tracking are,

- **Distributed processing**: Requires no central controlling structure. The process is distributed to all the embedded processors or participants in the network.
- **Synchronized records**: The ledger is distributed to all players thus making it fraud-proof.
- **Smart information**: We can create cloud applications that run on top of the blockchain architecture, enabling us to customize the format of the data visible to each stage in the supply chain.

2.2.1 Blockchain platforms

Before exploring the difference between extended blockchain platforms, it is critical to understand the difference between Public vs. Private blockchains and Permissioned vs. Permission-less blockchains. Public blockchains do not have any control over who can participate in the network, while in a private blockchain all users or a predefined set of users have control over who can join the network. For example, Bitcoin and Ethereum are public blockchains, and enterprise-grade blockchains created for internal business purposes are private blockchains. Two characteristics differentiate Permissioned and Permission-less blockchains – firstly, whether the participants in the network can determine who can take part in the consensus mechanism and secondly, who can create smart contracts and or perform transactions in the network. The ideal use case for Permissioned blockchains is supply chain management since it needs extensive vetting before they agree to execute transactions between companies in a blockchain.

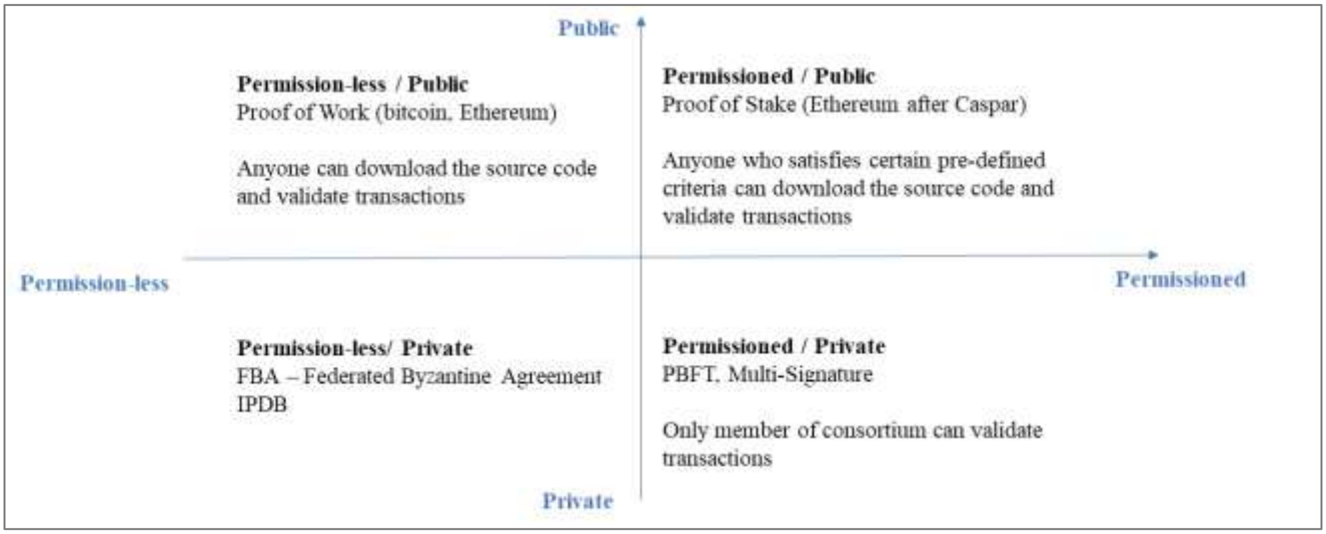

Figure 2-5. Types of blockchains (adapted from Pavel Kravchenko 2016)

The Consensus algorithm ensures that the data on a blockchain is synched with all the nodes in the network and hence making it almost impossible for hackers to tamper with its existing state. Some of the consensus algorithms used are Proof of Work in Bitcoin, Proof of Stake in Ethereum, Apache Kafka in Hyperledger Fabric, Proof of Elapsed Time (PoET) in Hyperledger Sawtooth, RBFT in Hyperledger Indy, Tendermint in Hyperledger Burrow, and Yet Another Consensus (YAC) in Hyperledger Iroha. Due to its default consensus algorithm (PoET) and scalability features, Hyperledger Sawtooth has been used to facilitate supply chain asset tracking in this research. Proof of Elapsed Time (PoET) was developed by Intel, which allocates a random waiting time to each validator for a block to be verified and select the validator with the shortest waiting time. This algorithm is based on a Trusted Execution Environment (TEE) to make sure the blocks are generated at random but without any Proof of Work. The significant disadvantage with this approach is that it requires us to trust the TEE system to uphold the randomness property in generating the waiting time lottery for the validators. Proof of Authority (PoA) consensus contains a set of 'authorities,' which are designated nodes that can create new blocks and execute the validation. Ledgers using PoA require sign-off by most of the authorities for a block to be built. It makes it ideal for Permissioned or Private blockchain networks. Most of the Hyperledger blockchains are private blockchains, which means that the parties that join the network are authorized to participate in the system.

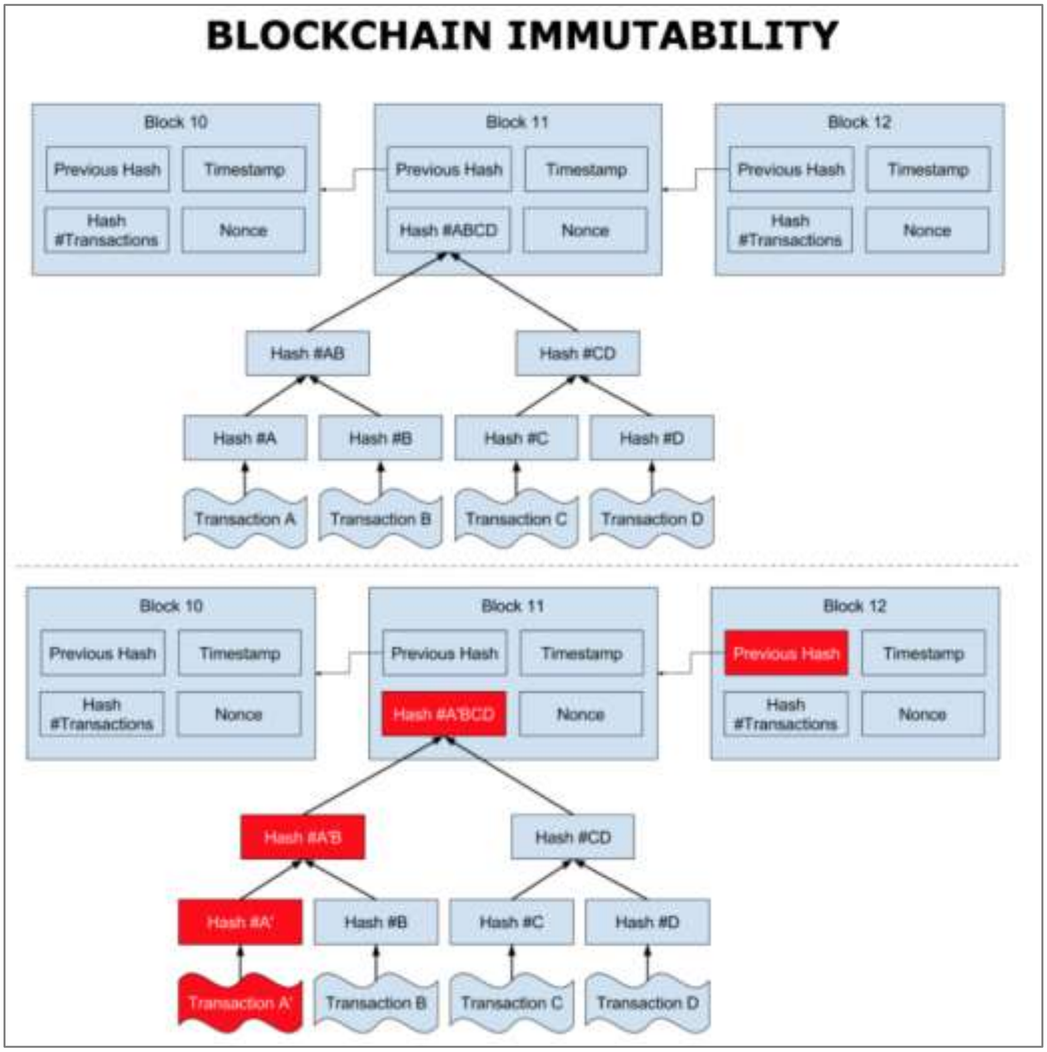

Figure 2-6. Blockchain immutability

Smart Contracts are computer algorithms that verify certain predesigned constraints and execute a set of commands upon verification. When a predefined triggering event like expiration date or shipments received occurs, smart contracts get activated to facilitate, verify and enforce the negotiation of a legal agreement according to the business logic pre-coded. Ethereum uses a more expansive set of programming languages and tools to allow for many other types of programs and applications to be created. The core invention of Ethereum is EVM or Ethereum Virtual Machine. The EVM runs on the Ethereum network, and it runs a Turing-complete software. Some of its key features include the immutability of data, to make corruption and tamper-proof applications that are decentralized and secured with cryptography. It is also designed with zero downtime since the applications on the network are decentralized. As a result, smart contracts are created to utilize the Ethereum platform to execute a predefined set of computer codes when required contract conditions are met by all the parties involved in the transaction.

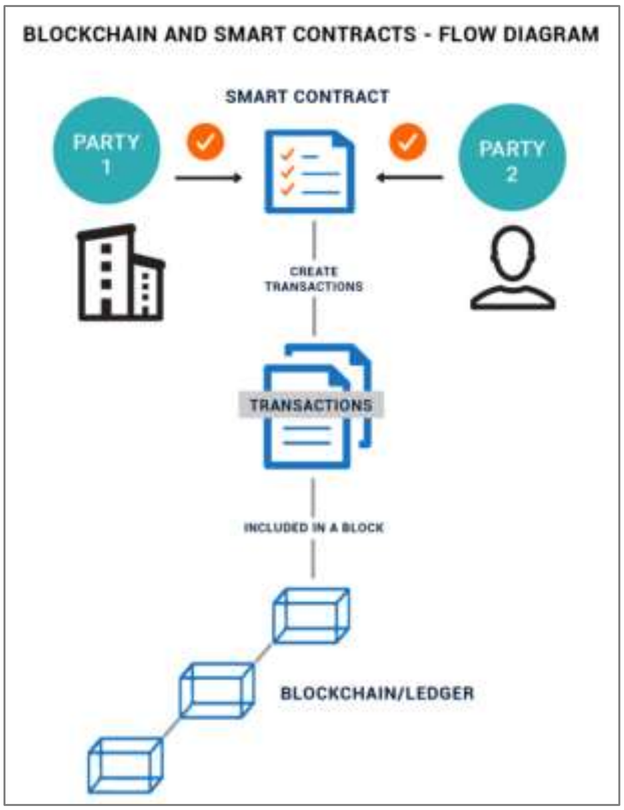

Figure 2-7. Smart contracts and blockchain

Quorum, created by JPMorgan is a deviation from the Ethereum public blockchain. It uses a consensus algorithm called Quorum, and it provides a distributed ledger framework predominantly for enterprise businesses and also a development platform to create smart contracts. Data privacy inside the network is achieved by providing access to data based on access requests.

2.2.2 Hyperledger frameworks

The number of projects under the Hyperledger umbrella has been steadily increasing with eight fully functional projects. We would be discussing only three projects which are used in this research or believed to enhance the findings of this research. Hyperledger sawtooth is a blockchain platform created to provide distributed ledgers and smart contracts for enterprise utility and hence is designed with business scalability in mind without any high energy consumption as in Bitcoin. It is developed to accommodate the growing market conditions for companies with a capacity for potentially thousands of different nodes on the network while ensuring uptime, operations integrity and greater flexibility. By default, Sawtooth uses Proof of Elapsed Time (PoET) consensus algorithm with support for both private and public blockchains. However, PoET can be replaced with a different algorithm, provided the new policy to replace the default consensus algorithm in the network is approved by all the participants. Sawtooth stands out due to its two distinctive features - Proof of Elapsed Time (PoET) and transaction families. PoET is a consensus mechanism, which takes advantage of some unique features on Intel's chips. Transaction family is an approach to smart contracts, where a set of acceptable templates are predefined for smart contracts that, then, the rest of the network can use. Moreover, that is a safer approach to make smart contracts than a fully programmable, general purpose programming language. Hyperledger Sawtooth allows for private transactions, without passing information through a central authority.

Hyperledger Explorer is a visualization tool designed to create a user-friendly web application, that can be used to edit or view blocks, transaction information, smart contracts and other relevant information stored in the ledger. Hyperledger composer is a JavaScript developer toolkit for building enterprise blockchain networks. It allows us to model the blockchain network and create API (Application Programming Interface) that interacts with the blockchain.

The blockchain considered for this project under the Hyperledger framework contains the following,

- An append-only distributed ledger using Hyperledger Sawtooth
- Smart contracts to process transaction requests
- A consensus algorithm (PoET) to maintain immutability
- Privacy of transactions through permissioned access

2.2.3 Why Hyperledger Sawtooth?

Hyperledger Sawtooth is ideal for a food supply chain because of its ability to track an asset's (in this case any food product) provenance and journey. The ability to batch transactions together allows for all final goods produced by a producer to be entered as a block. The distributed state agreement, novel consensus algorithm, and decoupled business logic from the consensus layer allow the consumers to be confident that they are buying the food items that are legal and sustainable. It is incredibly scalable and able to withstand high throughput of data, which makes it an excellent option for production supply chain scenarios. Proof of Elapsed Time (PoET) consensus algorithm randomly selects the transaction validators to execute transactions. Since this consensus method relies on trusted computing, as opposed to manual labor, PoET allows nearly limitless network scalability. Another modular feature is that of the transaction families. It encapsulates business logic for the network and helps define architectural differences between data control logic and application logic.

For example, let us consider a meat producer who sells to multiple retailers and restaurants. Through a mobile or web application, any private business can gain entry to the Hyperledger Sawtooth blockchain network comprised of numerous meat producers, input suppliers, meat processing plants, regulators, retailers and end customers. Except for the regulators and end customers, all will have the ability to add information to this ledger as the meat passes through the supply chain, while regulators and end customers will have read-only access to the ledger.

2.2.4 Sawtooth terminology

- Node: Every participating supply chain stage/individual in the Hyperledger Sawtooth network runs at least one node to interact with the system and receive transactions from other stages. Each node runs at least a main validator process, a REST service listening for requests and one or more transaction processors.
- Transaction validators: They validate transactions, transaction blocks and ensure that transactions result in state changes that are consistent across all participants in the network.
- Transaction families: It defines the operations that is performed in the back end when a transaction is executed.
- Transaction processor: It is the server-side business logic of transaction families that act upon network assets. Each node within the Hyperledger Sawtooth network runs a transaction processor. This transaction processor processes incoming transactions submitted by authorized nodes.
- Transaction batches: They are clusters of transactions that are either all published to the global state of the ledger if validated or are all not published to the global state if not validated.
- Global state: It contains the current state of the ledger and a chain of the transaction to be verified. The state for all transaction families is represented on each validator.
- The network layer: It oversees the communication between validators in a Hyperledger Sawtooth network. That includes performing initial connectivity, peer discovery, and message handling.

- The journal: It maintains and extends the blockchain in the network. Transaction batches arrive at the journal, where they are evaluated, validated, and added to the blockchain. Additionally, the journal resolves disagreements over who validates a block. Once blocks are completed, they are delivered to the "Chain Controller" for validation and conflict resolution. Another key feature is its flexibility in allowing consensus algorithms other than PoET.
- Forks: They are conflicts that occur in a blockchain when different participants propose multiple rules of engagement and fail to arrive at a universal agreement. For example, in Bitcoins, a fork is a situation when two miners have validated the same block at the same time. This situation is resolved by letting them solve subsequent blocks, and the miner with the most extended chain of blocks gets to append them to the blockchain. Similarly, in Sawtooth, this could arise when two winners propose.

2.2.5 Challenges in blockchain adoption

International Organization for Standardization (ISO) have established a committee for Distributed Ledger Technologies (ISO/TC 307) in 2016 with the scope of standardizing blockchain and other distributed ledger technologies. Areas for future standardization (Clare Naden, 2017) includes designing taxonomy and software ontology, security and privacy terms, smart contracts, governance, and business use cases.

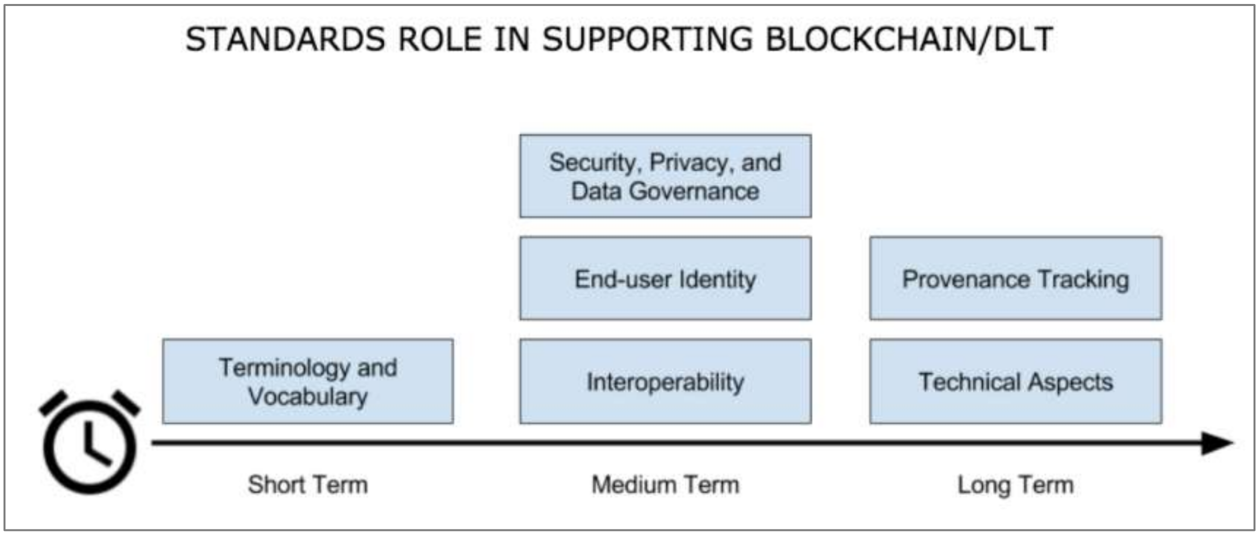

Figure 2-8. Role of standardization for blockchain applications

Another huge challenge is the absence of any regulation around the transactions in a blockchain, creating an environment of considerable uncertainty for its participants. Highly regulated industries like banking and finance are investing in stealth startups to develop individual blockchain use cases. The United States Securities and Exchange Commission (SEC) has clarified that as of Dec 11, 2017, it has not approved any cryptocurrencies to be listed and traded (Jay Clayton, 2017). The Chinese government has, in fact, banned all ICOs, while top 60 ICO platforms are being investigated (Saheli Roy Choudhury, 2017).

No regulations are governing smart contracts, causing much anxiety among various players like lawyers, regulators, programmers, and businesses. The lack of regulatory guidelines along with a lack of industry standards makes rapid adoption of DLT very difficult. The scarce availability of experts in the area is also a significant challenge in the adoption of blockchain technologies. The growing trend of blockchain searches in Google (Figure 2.3), shows the rising popularity of developers and experts in creating blockchain business use cases.

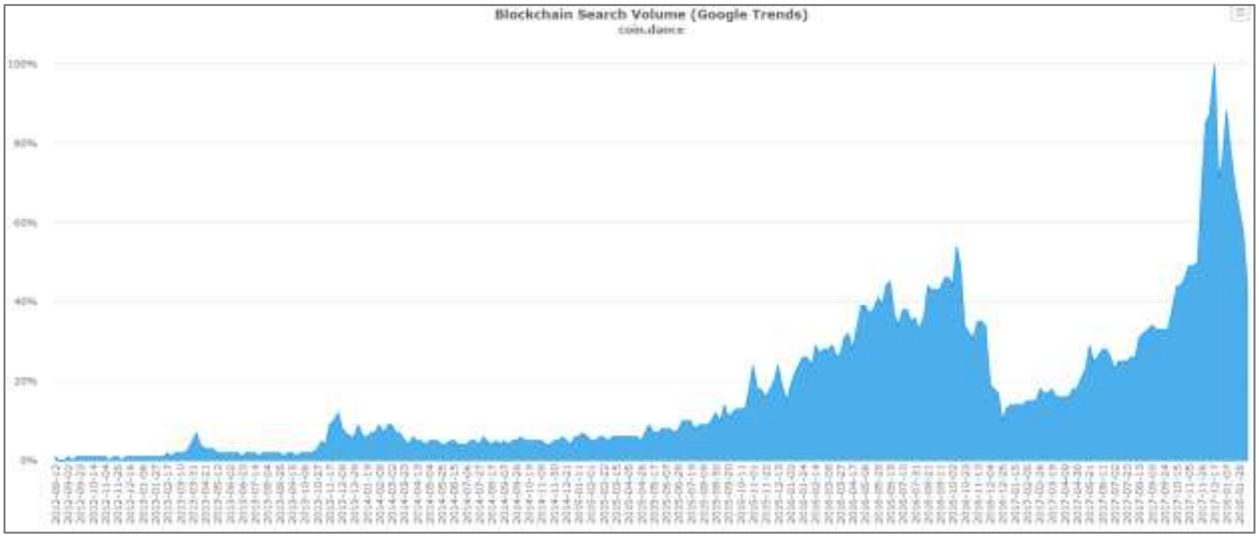

Figure 2-9. Blockchain Google Search Volume (Source - https://coin.dance/stats/blockchain)

Chapter 3

Background Literature

A framework outlining the scope of a literature review on food traceability shown in figure 3.1. It encompasses different aspects that must be analyzed to implement a food traceability software system. Research works regarding definitions of food traceability, driving forces for food traceability, technologies used, different ontologies for new technology adoption, benefits regarding supply chain performance improvement and current barriers for implementation are discussed in detail in this chapter. The gap in research work on using blockchain in food supply chain management is also discussed with potential applications.

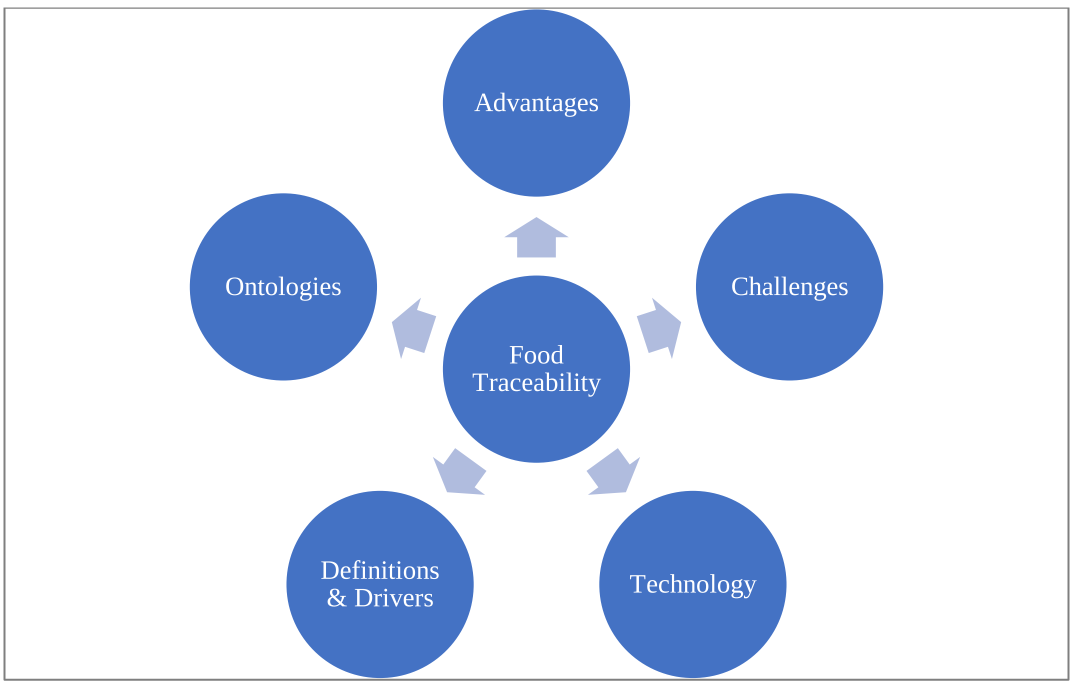

Figure 3-1. Literature review framework on food product traceability

3.1 Definitions and drivers of traceability

Previous studies show that there is no standard definition for product traceability. According to Bulut et al. (2008), The International Standards Organization of standards (ISO 9001: 2000) defines traceability as “the ability to trace the history, application, or location of an entity using recorded identifications”. Bosona, T., & Gebresenbet, G. 2013, have defined food traceability with three different interpretations: tracing, tracking and product movement history information. Tracing refers to backward follow-up of products and tracking relates to the forward monitoring of products. Few researchers (Manos & Manikas, 2010) have also mentioned that food traceability is mostly connected with food quality and safety assurance but rarely connected with business development and logistics improvement. However, the ability to combine the qualitative product information with logistics information has been consistently missing in the existing food supply chain infrastructure. Using sensors and IoT devices installed at every checkpoint (value addition on the product) throughout the supply chain, this issue can be addressed by continuously tracking both quality information and physical product movement. In a blockchain network, every product becomes an asset, and every IoT update serves as transactions performed on the asset. Thus, with a unique product ID, any food product can be traced and tracked for quality assurance and logistical activity.

Food traceability studies have been performed for more than two decades, and they reveal different drivers that contribute to the continuous attempts to improve traceability in the food supply chain. Increased pressure due to food safety regulations from the government is explored in Liao et al. (2011), forcing the business partners to share product information to establish a traceability system. Concerns from customers regarding safety and quality have also been a significant factor for businesses to introduce traceability. The correlation between food traceability systems and fear of large-scale food disease outbreak, contamination due to radioactivity, bioterrorist attacks, and product forging have been explored in Schroeder and Tonsor (2012). Visibility over the regular administration of vaccination to animals and animal welfare in meat, poultry and egg product production is crucial to prevent foodborne illness (Engelseth 2009). Increase in customer purchase power and more awareness over product quality and calorie consumption has forced businesses to introduce specific tags like organic, cage-free or gluten-free in its products. Advancements in technology is a massive player in pushing food traceability deep in a supply chain, as companies have identified the potential for improving supply planning, logistics performance and overall operations (Salampasis et al. 2012).

3.2 Technology in FSC

E-commerce has put enormous challenges for the food retailers to rethink how they could provide an omnichannel retail environment to its customers while efficiently operating their supply chain. Omnichannel requires that the retailer must enable operations (browsing, purchasing and returns) in multiple channels – online, mobile, store, click and collect and so forth. Hence, retailers are the first to experiment and adopt new technologies and new management systems in the entire supply chain to create a more efficient, responsive and transparent distribution channel. FSCs have inspired many leading technologies for supply chain operations like Electronic Data Interchange (EDI), Collaborative Planning Forecasting and Replenishment (CPFR) and Radio-Frequency Identification (RFID) (Kelepouris et al. 2007). These technologies have helped in enhancing product traceability, reduce paperwork and control the bull-whip effect in the food supply chain.

Background literature provides evidence for the potential benefits of using technology to enhance product identification, food safety and quality measurement, packaging and software development. Most common types of data capturing in product identification are paper copies, bar codes, RFID tags and electronic systems. Some of the technologies introduced to meat industry include bar codes, microchips, RFID tags, transponders, voice recognition enabled systems, bio coding and chemical markers (Bosona, T., & Gebresenbet, G. 2013).

Another important reason for adopting technology is to attract customers and simplify their shopping experience. Next generation concepts like the Amazon go store in Seattle does not feature a cashier or checkout lines. Instead, it uses camera, sensors and a sophisticated AI software to charge the customers via their amazon app on their smartphone. In-store services like a bakery (bakery sales will approach $18.4 billion by 2020, a 45 percent increase over 2010 (the Madison, Wis.-based trade group estimates).

Currently, there are 21 and growing number of companies using blockchain for asset management, identity management and critical document authentication like passports, birth certificates, online account logins creating a digital ID, which combines decentralized blockchains with identity management (Elena Mesropyan, MEDICI, 2017). However, very few companies like Provenance, Hijro, Blockverify, QuickBooks, Everledger, and Skuchain are focusing on improving product provenance in a wide range of products like fish, luxury goods like diamonds, expensive handbags and tracing the origin of pharmaceutical drugs.

An IT-enabled food tracking system was also proposed (Theuvsen, & Hollmann-Hespos, 2012), which utilizes all the logistics information to improve the supply planning and overall logistics operations. The current architecture that has been predominantly used in today's food chains as shown in figure 3-2 uses a centralized database that collects information regarding product characteristics only when it reaches the distributor and then subsequently to the retailer. It is primarily applicable in a centralized retail supply chain where the retailers own their distribution network and logistics. Information regarding the product in upstream stages from processor until the farm is maintained as database silos in the form of excel sheets and hard copies. Streamlining data capturing, data sharing and data security is a prerequisite to constructing an end-to-end tracking system, could be either a conventional IT system or a blockchain.

3.3 Benefits and challenges of implementation

Bosona et al. (2013) have broadly classified the different benefits of implementing an efficient food tracking system as Social benefits, benefits for authorities and profits for food companies. More detailed literature analysis shows evidence that food provenance can reduce quality issues, reduce customer complaints and hence improve consumer satisfaction Liao et al. (2011). It dramatically improves the response cycle during food crises; enabling regulators to trace hazardous food products and detect counterfeiting Azuara et al. (2012). It reduces the number of recalls due to enhanced vulnerability deduction in the early supply chain stages. For food companies, an efficient food tracking system translates into a reduction in the cost of logistics, inventory, procurement, and reduces information asymmetry (Karlson et al. 2013). Studies also show that competition in capturing market share can lead to development in traceability capacity among food companies. Availability of useful data would also encourage research communities to understand patterns and create more sophisticated applications to enhance safety and security of the food supply chains and prevent unsustainable sourcing practices.

One of the common barriers to implementing a food tracking system is that it is expensive regarding capital and operating cost and often is not cost effective and user-friendly. The complexity of its implementation due to increased paperwork, change in current operating and ERP systems, additional effort and training required makes it hard for downstream stages to initially pushing this to the upstream stages. The challenges mentioned above are compounded when including scalability for multiple business partners with current IT-enabled traceability systems. Since IoT or data collection devices are a prerequisite for an effective FTS, designing food packages and integrating it with the

IoT devices for data capturing is also a considerable challenge in establishing IoT base architecture, upon which the blockchain environment would thrive. Also, there is difficulty in tracking production and harvest conditions at upstream supply chain stages when it is not packed for fresh produce.

Francisco et al. (2018) studied the blockchain technology adoption using a Unified Theory of Acceptance and Use of Technology (UTAUT), discussing implications due to pre-existing system behavior, end-user acceptance and physiological factors, scalability, environmental influences and motivation for broad spread adoption. Kim et al. (2016) developed an ontology-based blockchain modeling approach with the integrating of IoT devices for data capturing and data sharing. A study by Kim et al. (2016) also addresses the issue of having common data standards between different stages in the supply chain, when using a decentralized blockchain network, as discussed in chapter 2.2.3. Chen, Si, et al. (2017) have proposed a preliminary systems approach by constructing four layers that accommodates both the technological and supply chain complexity in adopting blockchain using IoT devices in supply chain management. The study by Chen, Si et al. (2017) has been used a foundation in this research, to create a blockchain application for a supply chain and analyze its performance using the simulated data and compare it against the conventional database systems.

3.4 Food safety in the USA

United State Department of Agriculture (USDA) had estimated the cost of foodborne illness at $15.6 billion in annual health-related expenses for 2014, with 15 pathogens causing 95% of the foodborne illness incidents they examined. Food supply chains are distinct from supply chains of other sectors due to the unique characteristics of their network design like perishability, seasonality in production, diversity in product assortment, edibility, and information asymmetry between stages. (i.e.) The seller has more information regarding the product than the buyer. Four major federal agencies administer the majority of the food safety systems in the US –

- Food Safety and Inspection Service (FSIS) overseeing labeling and packaging for meat, poultry, and egg products, is an agency of USDA.
- Animal and Plant Health Inspection Service (APHIS), is an agency of USDA that monitors health and welfare of animals and plants.
- Food and Drug Administration (FDA) is responsible for both safe labelings of foods other than meat, egg, and poultry, and for monitoring safety of medical drugs and devices.
- Center for Disease Control and Prevention (CDC) is involved in investigating, monitoring and preventing foodborne illness.

Starbird et al. (2000) have examined the ineffectiveness of food safety standards without regulations and recommended using a quantifiable and measurable performance standard, a reliable inspection procedure and an economic penalty for noncompliance to improve overall food quality in a supply chain. Though the reliability of the inspection methods and financial penalties are heavily criticized during a foodborne illness outbreak, very few research has been done to provide an alternative. The end customers are buying the food products based on the trust in safety regulations and regulatory compliance by food manufacturers. Only recently, with the increased popularity and more funding to build custom Blockchain applications, there is a potential solution to address the problem of trust between stages in the food supply chain by presenting immutability, scalability and universal access to information as its key selling points.

Earlier events and the Canadian and US BSE cases have changed the perspective on traceability of the government and industry in the United States. Hence a team composed of experts representing the industry and state and federal authorities created the United States Animal Identification Plan (USAIP). This effort is currently conducted by the National Identification Development Team, and it has implemented the traceability systems in phases with premise identification at 2004, individual identification for commerce at 2005-2006, and enhanced technology for tracking at 2005-2006. It is not clear whether the system is voluntary or mandatory (Clapp 2003a and 2004). There are currently no mandatory meat traceability systems in the United States. However, private, voluntary traceability systems are widespread in the industry (Golan et al. 2003a). In August 2003, USDA launched the voluntary Beef Export Verification (BEV) program that assures Asian buyers that products shipped overseas come from animals slaughtered in the United States. Under this program, the Agricultural Marketing Service of USDA conducts process verification audits for operators eligible to export to Japan under the program (Clapp 2003b). However, this market had been closed since the 20 confirmations of the first BSE case in December 2003. Overall interest in traceability systems is growing throughout the supply chain, particularly for the export market and for serving specific consumer segments within the United States. In the US both public and private authorities are now promoting the introduction of traceability systems. They are responding to concerns of international or domestic business partners; hence we would expect supply chain dynamics and global demand to be the drivers of traceability in the US.

Chapter 4

Methodology & Analysis

The background literature denotes that many state-of-the-art tracking technologies are being used in the food supply chain, but only in few vertically integrated downstream stages. Also, the product information is stored in data silos along the chain, making it difficult to create an end-to-end tracking solution. Very few publications and business case studies discuss the use of blockchain in food provenance. However, a comparison between existing data architecture and an advanced blockchain model is absent, preventing us from having a holistic idea of its advantages and disadvantages. This section aims to address the above-discussed problem by 1) Conducting an initial study on the food illness outbreak dataset to identify the target food products with the highest number of outbreak incidents in the US from 2007-2016. 2) Model the current data architecture that is used for food traceability 3) Create an integrated data model incorporating blockchain, smart contracts and IoT devices for Hyperledger Sawtooth and 4) Compare traditional data tracking mechanism and integrated blockchain mechanism regarding cost, efficiency, and utility.

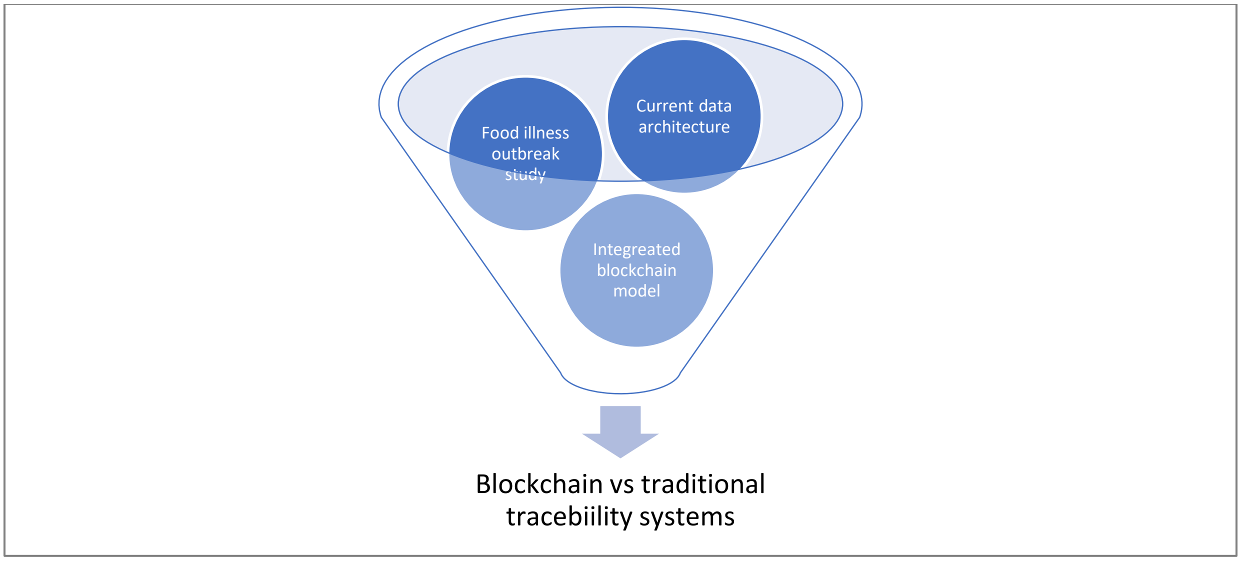

Figure 4-1. Research Methodology

4.1 Foodborne illness

This section aims to 1) explore the distribution of foodborne illness in the US by the state to identify multistate or single state food outbreaks 2) determine the food product frequently contaminated by pathogens 3) examine the number of foodborne illness cases reported throughout various stages in food supply chain. All statistics provided in this section are based on the dataset from National Outbreak Reporting System (NORS) from the Center for Disease Control and Prevention. The dataset proved to be a perfect fit for this research since it contains around 8800 disease outbreaks in the US between 2007-2016 capturing the total number of illnesses, hospitalizations, deaths, food vehicles and ingredients causing contamination. California, Illinois, and Ohio are the top 3 states with a maximum number of outbreak incidents (independent of the population) as shown in Figure 4.2. Multistate disease outbreaks are not captured in Figure 4.2, which has the highest number of incidents in the US at 19,190 events.

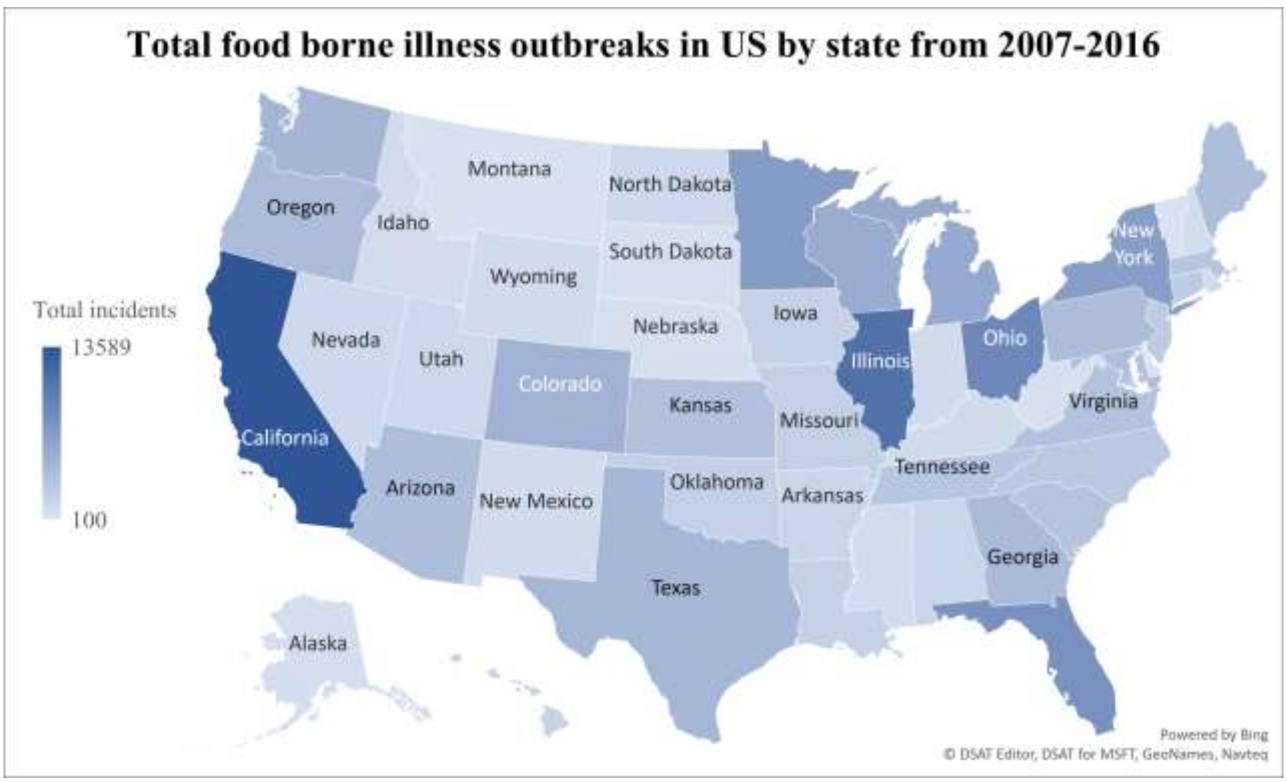

Figure 4-2. Amount of food outbreak incidents in the US from 2007-2016 by states

Although food safety regulations discussed in section 3.4 vary considerably within states, multistate outbreaks are higher than that of any single state. In addition, figure 4.3 shows that microbial contamination has been the primary reason for food recall in the US between 2007-2016. Genus type Norovirus Genogroup II, Salmonella enterica have contributed to 40.57% of the total recalls. Processing defects, physical and chemical contamination along the food chain also contribute to product recalls.

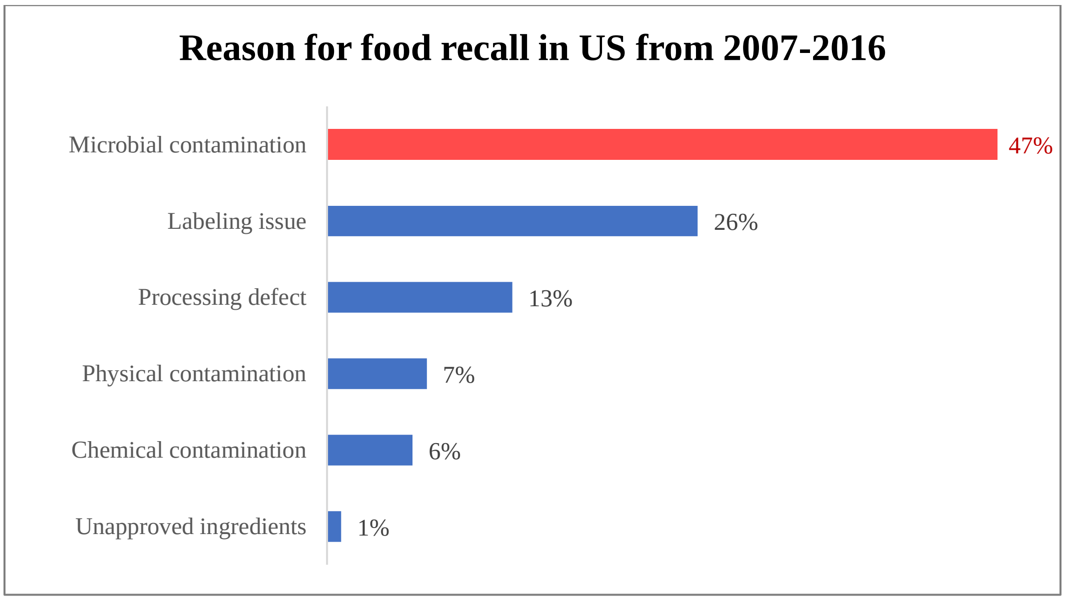

Figure 4-3. Reason for food recall in the US from 2007-2016

Figure 4.4 shows that meat and meat-based products from poultry, fish and cattle industry are prone to more food contamination than plant and plant-based products. Also, figure 4.5 indicates that 76% of these contaminations are recorded during the food processor stage which includes banquet facilities, child day care, fair, festival, other temp or mobile services, hospital, hotel/motel, long-term care/nursing home/assisted living facility, office/indoor workplace, prison/jail, religious facility, restaurant and school/college/university. The consumer stage of the food chain has recorded 21.82%, and the retailer stage has recorded only 1.92% events. A negligible 0.28% of these events have been reported from the food producer stage which includes cattle houses/farms and dairies.

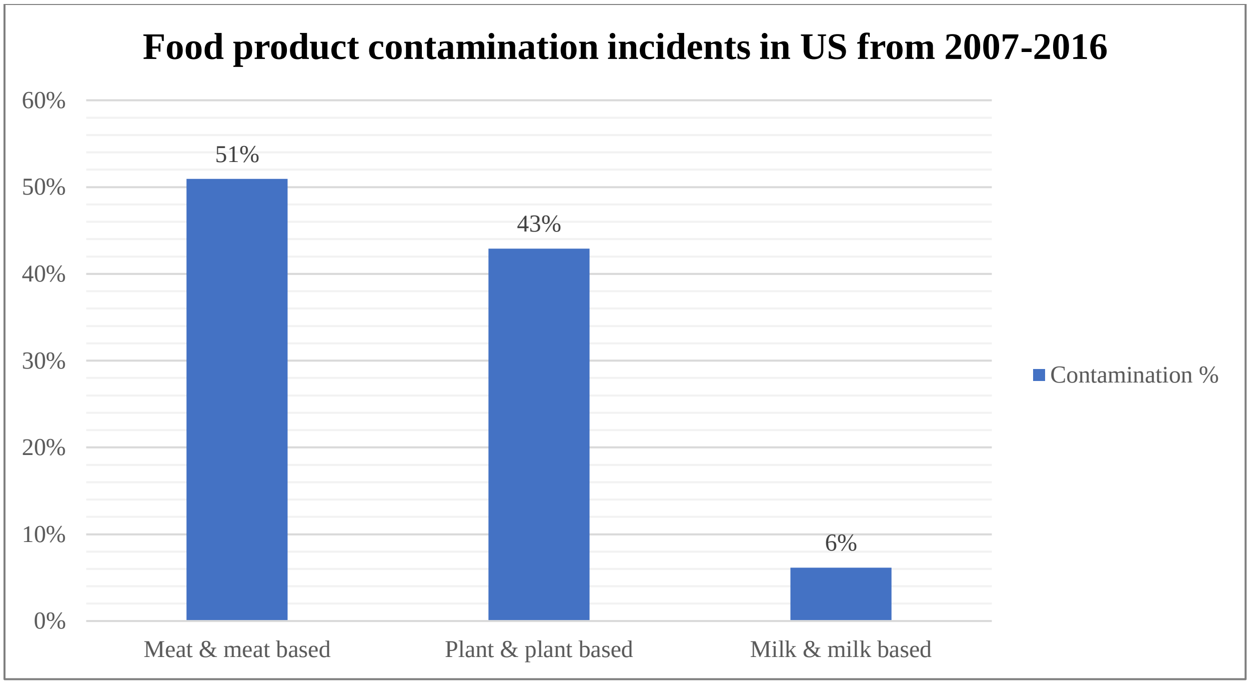

Figure 4-4. Outbreak incidents by food vehicle in the US from 2007-2016

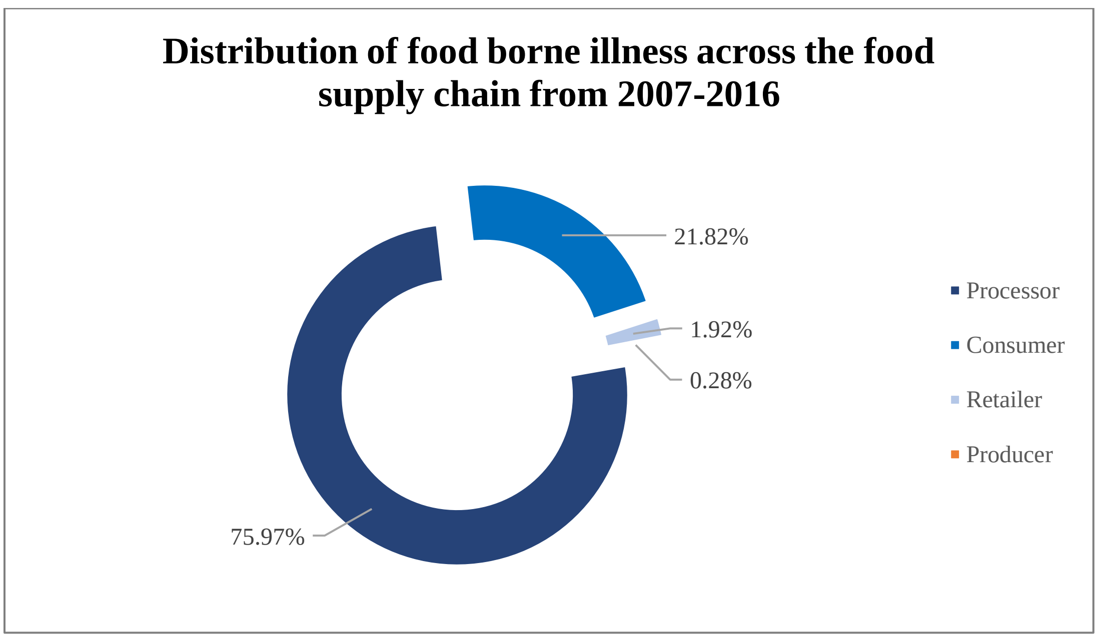

Figure 4-5. Outbreak incidents by stages in food supply chain in the US from 2007-2016

4.2 Current meat traceability systems in FSC

Before the first case of BSE (the mad cow disease) in Washington State, there was no policy to prevent or diminish the impact of animal health or food safety hazards using food traceability. Hence, the origin of the disease was only identified after few days to about 70 other imported cows from Alberta, Canada. A similar mad cow disease incident occurred in 2017, when USDA confirmed the fifth case in Alabama. Food safety guidelines are developed by USDA after the first incident, but the final regulations have been not issued until 2004. Also, a new Country of Origin Labeling (COOL) methodology was proposed to track country of origin and equipping retailers to label the meat products. This COOL system however, would not provide traceability that could link an animal or a meat product through the supply chain to its farm or producer as shown in figure 4.6. Though several meat traceability systems exist in the US (Golan et al. 2004), they have been mainly private, and market-driven, especially in vertically integrated retail supply chains like Walmart, where end to end supply chain traceability is an initiative to be pursued by the companies, especially with imported meat products.

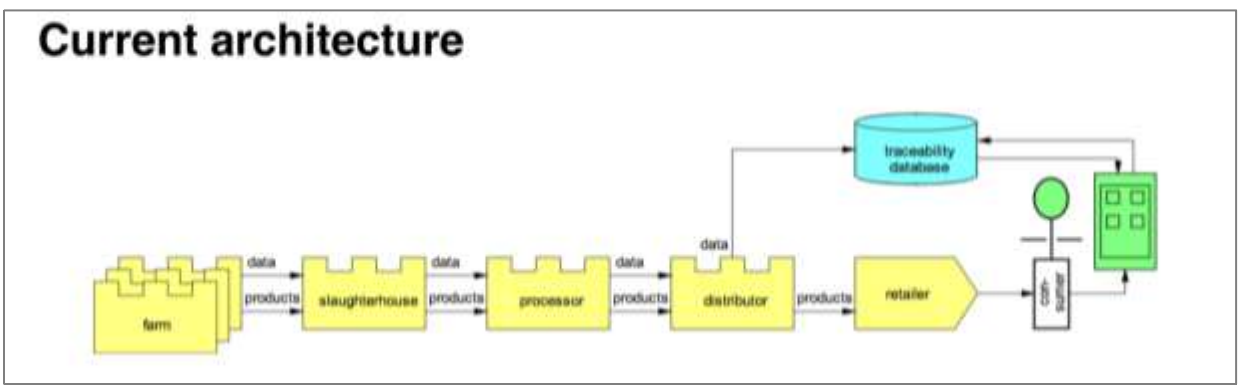

Figure 4-6. Current data traceability architecture of meat supply chains (Scholten et al. 2016)

From background literature on food safety regulations in section 3.4, it is evident that there are different approaches to establishing food traceability systems by states in the US. There lies a difference between food players in terms of companies that utilize mandatory systems, a combination of mandatory and voluntary systems, and voluntary systems. The EU and Japan have implemented compulsory traceability systems; all meat and met-based products produced domestically within EU and Japan must be able to fit for both forward tracking and backward tracking (i.e.) from the retail stage to farmhouse. Food traceability systems in Canada connects different stages from farmhouse and slaughterhouses to export hubs where meat products are exported. Even in Argentina a mandatory traceability system is available for exported cattle and related meat products; cattle and other meat products sold domestically are not traced if it is not produced in a geography with food disease outbreaks. Today food traceability is voluntary in the United States. There are also differences between systems in terms of their depth, breadth, and precision. There are no compulsory traceability systems in US, although several voluntary systems are operating, and new systems are being created according to the convenience of the private organizations.

4.3 A blockchain based approach

Based on foodborne illness statistics, food safety regulations in the US and current meat traceability tools discussed in previous sections, a blockchain based supply chain network has been designed for meat and meat-based products as shown in figure 4.7. It captures product traceability information using a range of IoT devices based on the type of the event to be recorded. A transaction could be a movement of animals or animal products, processing or testing of meat, value addition, packing, storage, and logistics. Due to many food outbreak incidents reported in the food processor stages, additional scan or checkpoints are added to the food processor or manufacturer stage (table 4.1). Multiple information recorded from an IoT checkpoint is converted into a transaction and pushed into the sawtooth network. Multiple transactions (or IoT scan information) are grouped into a transaction bundle, and transactions verified by transaction processors are published to the public ledger. In addition, the contract layer monitors every transaction bundle, to execute the smart contracts when a triggering event takes place (figure 4-1), and it ensures fair play between players in the supply chain according to terms of trade agreed upon joining the blockchain network. For example, a smart contract between a producer and a processor gathers IoT data from the first 3 scan points to evaluate the metrics across predefined cutoff values. Each smart contract needs to be digitally signed off by designated authorities from both the stages in the supply chain.

Each stage or stakeholder in the target FSC would act as a node communicating and transacting to multiple other nodes inside the FSC. A private blockchain model using Hyperledger Sawtooth platform is used for this research. It enables a clear line of communication between multiple players in the supply chain starting from the raw material supplier or farmer to the end customer. Since this research focuses on private blockchains, permission to read, write and validate transactions to the ledger are chosen by consensus. Hence any new player cannot be added to the network without the clearance from the primary network nodes. Also, access to the entire ledger is not uniform across all stages in the supply chain to avoid misuse of sensitive business information. However, the transacting nodes have access to the complete history of all their previous transactions and limited product location and quality information. This information is immutable and hence serve as a high starting point to establish fool-proof quality systems to identify and remove defects and food safety violations. This model provides an alternative approach to food product tracking by utilizing existing food quality systems and technology built into the supply chain stages.

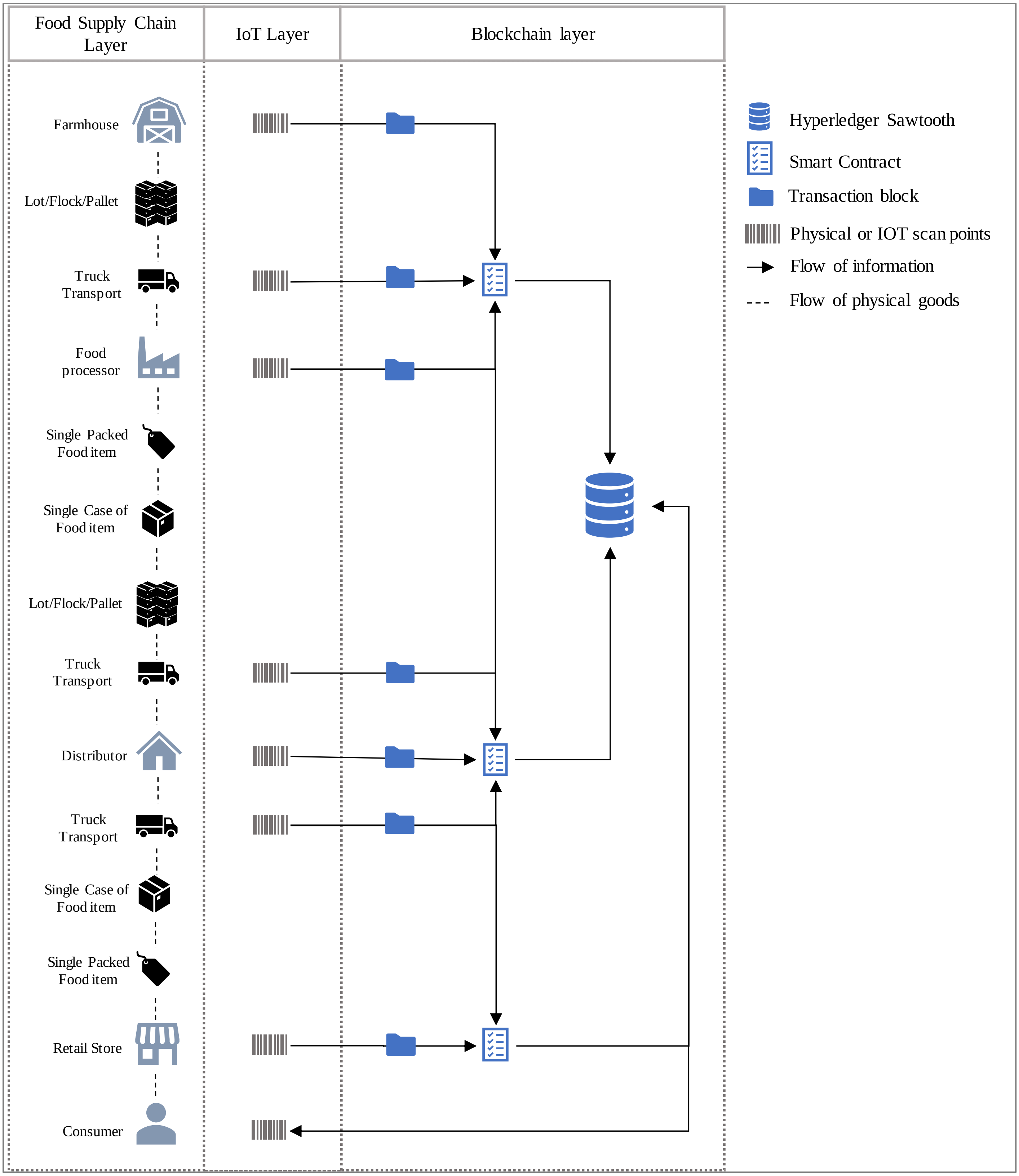

Figure 4-7. Blockchain-based food traceability system

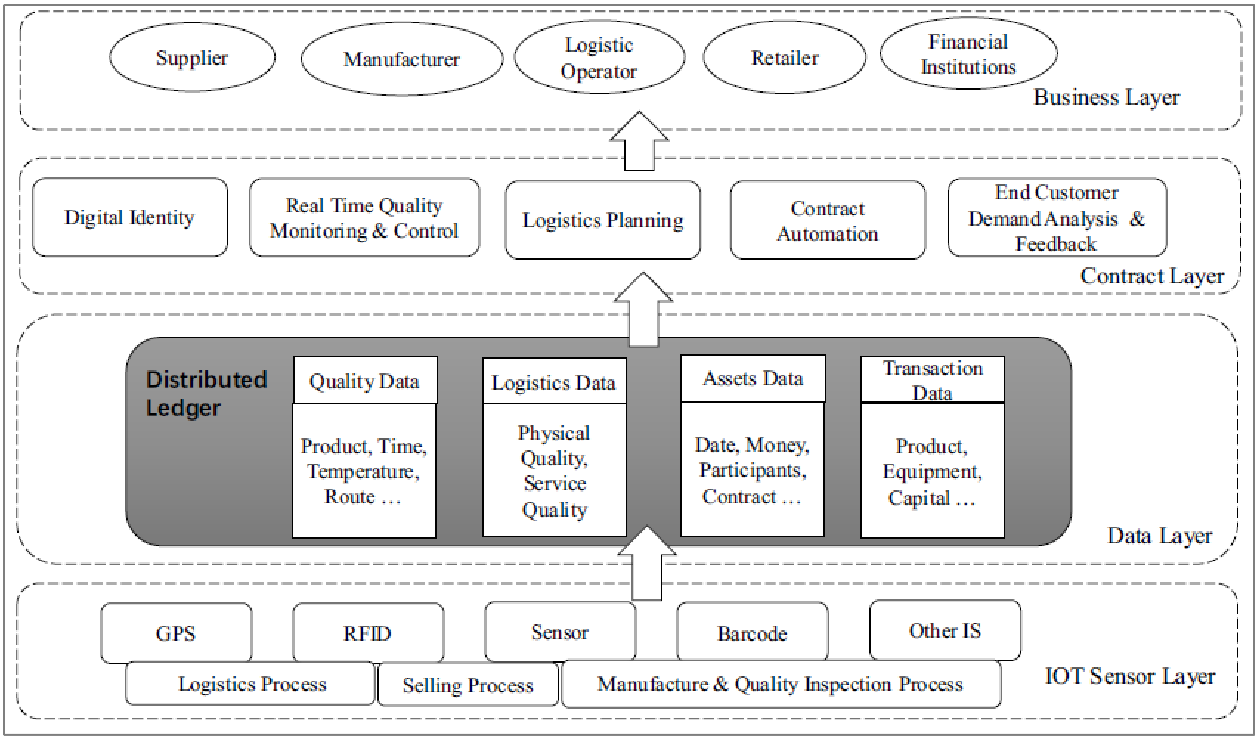

Figure 4-8. Software framework and interface of blockchain from Chen, Si et al. (2017)

4.3.1 IoT data capture

Mennecke and Townsend (2005) provide case studies where RFID tags on animals and RFID chip embedded bins to be used for individual tracking and recall purposes. This is the starting point for the traceability in next segment in the food chain. The manufacturers in the meat industry frequently use two types of cold chain management in delivering packed meat products to retailers or end consumers - frozen storage and cold storage (cooling, freezing, delivering and storage). Temperature is the primary postprocessing parameter in the determination of shelf-life in a cold chain of chilled and frozen food products. In addition, humidity levels are also monitored during transportation from food manufacturers to all downstream stages until the retailer.

Table 4.1 describes the list of IoT device enabled manual or automated scanning checkpoints that are situated along each significant supply chain stage – Producer, Processor/Manufacturer, Distributor, Retail, Logistics, and Customer. It also lists the type of event it would initiate within the blockchain – Object or aggregation or transaction event depending upon the stage it is in the FSC. In addition, the traceability information on the object or transaction and comments for the aggregation events are also tabulated. Procedures like meat inspection and acid decomposition are mandatory tests initiated at the food manufacturers by sampling a flock or lot of animals after pre-processing stages. This quality information (all Texture Profile Analysis) are not monitored in rest of the downstream supply chain stages. These tests are crucial to avoid food recall incidents as shown in figure 4.3 since food processor stages have recorded 76% of outbreak incidents in the last 10 years. Challenging the trust in the sampling methods or inspection methods are out of scope for this research. Since information like operator ID and a date-time stamp of the testing is captured in this method, it is relatively more straightforward to find the testing personal accountable for a lot or batch of food products in case a defect is detected in the later stages.

The scan checkpoints tabulated in table 4.1 correspond to the IoT or physical scan points under IoT layer in figure 4.7. In addition to the checkpoint name, the asset status name and possible traceable information is also represented. For example, the first checkpoint “Transfer to slaughterhouse” represents the movement of the animal product from the farm to the slaughterhouse. This transaction is denoted as IN_TRANSIT_TO_PROCESSOR in the script file and model file. The asset information that are tracked are breed type, total feed consumed, total weight of the lot, last vaccination date. In addition to asset level information, transaction level information like Order ID, Processor ID, Source ID are also tracked. It is vital to note that at the segmentation checkpoint, an animal lot with a unique Source ID is segmented into multiple food products. All these food products carry a unique product ID but share a common source ID.

Scan checkpoints	Asset Status	Traceability information/Comments
Transfer to slaughterhouse	IN_TRANSIT_TO_PROCESSOR	Breed, feed consumed, weight, last vaccination date
Meat Inspection (Sampling)	PROCESSOR_QCHECK	Operator, Texture Profile Analysis metrics, Hazardous materials, Temperature, Meat grade
Segmentation	SOURCE_SEGMENTED	The transition from animal carcass to sliced meat (track source ID)
Packaging	IN_PACKAGE	The transition from sliced meat to packed meat products (track weight, type of meat, temperature, meat grade, date of packing)
Transport to warehouse	IN_TRANSIT_TO_DC	Weight, temperature, relative humidity, mode of transport, current location
Distribution warehousing	IN_STORAGE_DC	Storage location, temperature, humidity, weight, operator ID, date & time
Distribution delivery	IN_TRANSIT_TO_RETAIL	Weight, temperature, relative humidity, mode of transport, current location
Retail storage	IN_STORAGE_RETAIL	Storage location, temperature, humidity, weight, operator ID, date & time
Retail sale	SOLD_RETAIL	Location, customer ID, price, weight, cashier

Table 4-1. Scan checkpoints, asset status, traceable asset information in a meat supply chain

4.3.2 Model implementation

Building a blockchain application requires initializing three essential aspects of the ledger. 1) Defining assets that will reside in the distributed ledger, 2) Defining the participants who transact the assets between them and 3) Transactions that will act on these assets to perform the state transition. Figure 4.9, clearly differentiates the read-only participants from other read and write participants. In addition, color codes are used to match an asset with its possible transactions and relevant participants. Packaged meat product is the only asset transacted from processor stage.

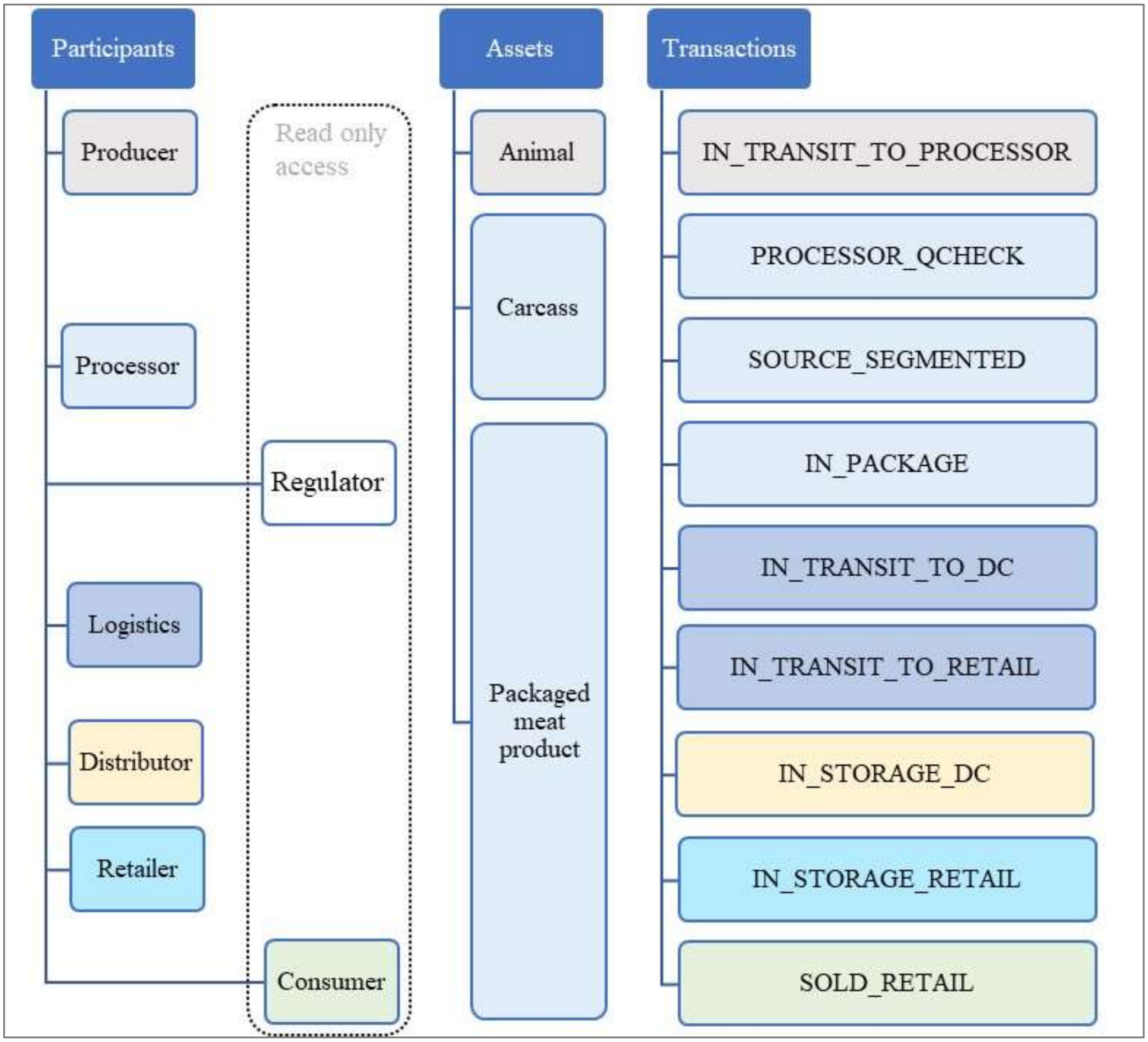

Figure 4-9. Blockchain business network components

Create a participant:

Participants are public/private key pairs stored in "localStorage," and all the application logic is contained within the "handlers.js" file inside the processor folder. The function shown in table 4.2 creates a random 256-bit private key represented as a 64-char hex string on the client side. The private key grants exclusive access to the blockchain network to a participant and hence cannot be shared with other participants. The function in table 4.3 returns a public key derived from the 256-bit private key created in table 4.2, which is safe to share to perform the transactions. It takes in the 256-

bit private key and returns the public key as a hex string. The actual code for initialization all the participants shown in figure 4.9 are available in Appendix.

```
makePrivateKey: () => {
        let privateKey
        do privateKey = randomBytes(32)
        while (!secp256k1.privateKeyVerify(privateKey))
        return privateKey.toString('hex')}
```

Table 4-2. Creating a random private key

```
getPublicKey: privateKey => {
        const privateBuffer = _decodeHex(privateKey)
        const publicKey = secp256k1.publicKeyCreate(privateBuffer)
        return publicKey.toString('hex')}
```

Table 4-3. Creating a public key

Create an asset:

The “createAsset” function adds a new asset to the state by taking in an asset name, the owner as the public key, and state. Once an asset address for a specific animal product is created with the sha512 hash, the state is set to state.set({ [address]: encode({name: asset, owner: owner}) }), as shown in table 4.4. Within the user interface, the owner of the asset can be selected from the Holder and provide a unique source ID for the animal product (for example, chicken in this case) to create an asset to be used by the producer participants.

```
const createAsset = (asset, owner, state) => {
        const address = getAssetAddress(asset)
        return state.get([address])
                .then(entries => {
                        const entry = entries[address]
                        if (entry && entry.length > 0) {
                                throw new InvalidTransaction('Asset name in use')}
                        return state.set({
                        [address]: encode({name: asset, owner})
                        })
                })
}
const getAddress = (key, length = 64) => {
        return createHash('sha512').update(key).digest('hex').slice(0, length)
}
const getAssetAddress = name => PREFIX + '00' + getAddress(name, 62)
```

Table 4-4. Code for creating an asset

Create a transaction:

The “transferAsset” function shown in table 4.5 proposes a transfer of ownership for an asset to the state by taking in the asset name, owner to transfer to, signer (current owner) and state. If all the verifications from the validators pass, the state is updated with the proposed transfer [address]: encode({asset, owner}). Any animal product assigned to a participant can be transferred to another participant (public key) when the receiving participant accepts or approves the transfer of ownership. The “acceptTransfer” function shown in Table 4.6 allows a user to accept a transfer of an asset and change the asset ownership. The “rejectTransfer” function in table 4.7 allows a user to reject a transfer of an asset, and the asset owner will remain with the original user.

All these codes for transactions are stored in the transaction processor and are created by the developer, along with an application SDK which provides a user interface. Buttons like transfer, create, reject or accept can, in turn, run these transaction processes in a production environment. However, the implementation of this research focuses only on developing the transaction processor and initializing the model parameters.

```
const transferAsset = (asset, owner, signer, state) => {
	const address = getTransferAddress(asset)
	const assetAddress = getAssetAddress(asset)
	return state.get([assetAddress])
		.then(entries => {
			const entry = entries[assetAddress]
			if (!entry || entry.length === 0) {
				throw new InvalidTransaction]('Asset does not exist')}
			if (signer !== decode(entry).owner) {
				throw new InvalidTransaction('Only an Asset\'s owner maytransfer it')}
			return state.set({
				[address]: encode({name: asset, owner: owner})
			})
		})
}
```

Table 4-5. Code for transferring an asset

```
const acceptTransfer = (asset, signer, state) => {
	const address = getTransferAddress(asset)
	return state.get([address])
		.then(entries => {
			const entry = entries[address]
			if (!entry || entry.length === 0) {
				throw new InvalidTransaction('Asset is not being transfered')}
			if (signer !== decode(entry).owner) {
				throw new InvalidTransaction(
				'Transfers can only be accepted by the new owner')}
			return state.set({
				[address]: Buffer(0),
				[getAssetAddress(asset)]: encode({name: asset, owner: signer})
			})
		})
}
```

Table 4-6. Code for accepting an asset transfer

```
const rejectTransfer = (asset, signer, state) => {
        const address = getTransferAddress(asset)
        return state.get([address])
                .then(entries => {
                        const entry = entries[address]
                        if (!entry || entry.length === 0) {
                                throw new InvalidTransaction('Asset is not being transfered')}
                        if (signer !== decode(entry).owner) {
                                throw new InvalidTransaction(
                                        'Transfers can only be rejected by the potential new owner')}
                        return state.set({
                                [address]: Buffer(0) })
                })
}
```

Table 4-7. Code for rejecting an asset transfer

All assets and the transaction process values are saved in the global state as a key/value pair, while the transaction processor allows the producer's application to create a transaction on the ledger, after being verified by the validator as shown in figure 4.10.

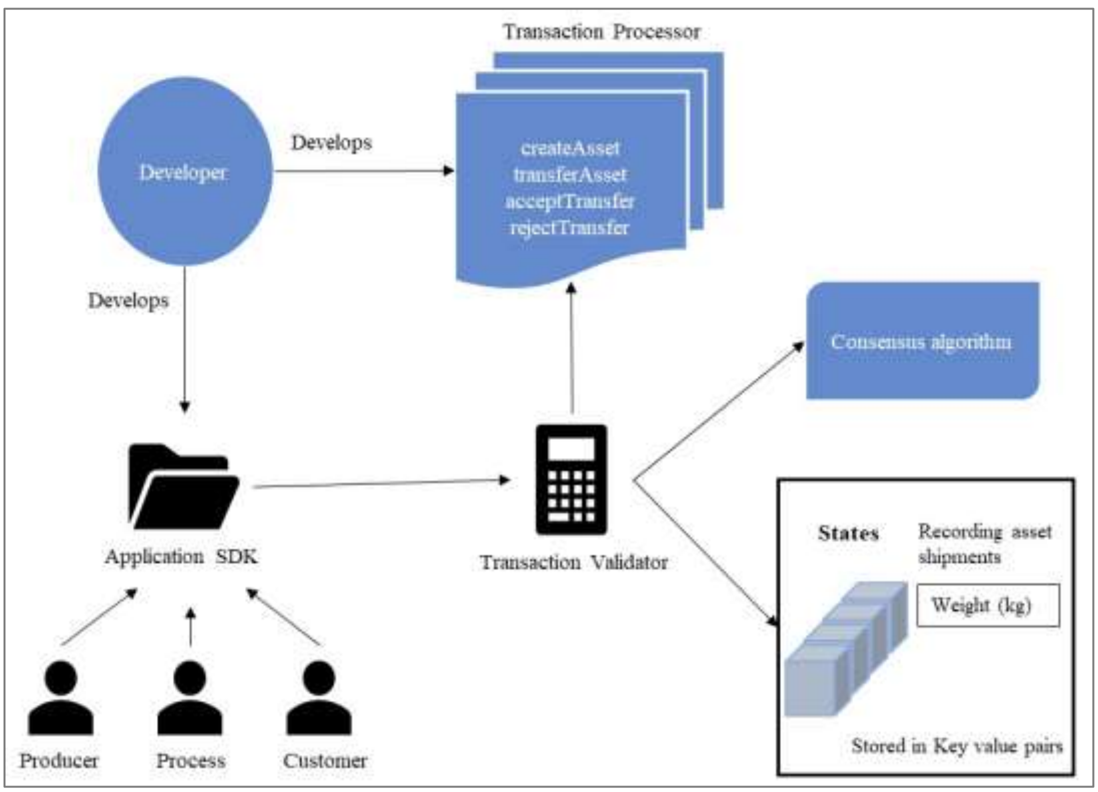

Figure 4-10. Hyperledger Sawtooth Blockchain Network

Creating a transaction logic

All participants, assets, and transactions initialized in the blockchain network are stored in a model file. A transaction logic document, also called as the script file, contains the logic to execute the transactions that are initiated in the model file. Based on the transaction logic, an asset undergoes a state transition from food producer to a food processor. Refer to Appendix for all transaction logic codes written with respect to the food tracking exercise undertaken in this research. Table 4.6 shows a function used to verify if a shipment has been received by the target node. The function "payOut" verifies three critical metrics of a shipment before issuing payment for receiving the asset. 1) Verify the incoming shipment time for delays 2) Check the maximum and minimum temperatures for violation of predefined temperature bounds and 3) apply penalties for violation of the contract terms and issue payment to the sender. Smart contracts are predominantly incorporated into the transaction logic, which verifies every transaction bundle before getting it published to the global state.

Adding access control

All networks must have an access control file named as "permissions.acl". Whenever any transaction process is invoked in a deployed blockchain network, the access control list is checked to ensure that the participant can invoke the operation. This file has been written to provide the major participants – processor, producer, logistics, distributor, and retailer, read and write access for transactions that are either initiated by the participants or transitioned from other states. Customers and retailers are provided read-only access to the public ledger and hence cannot write to the global state. This document also outlines the PoET consensus algorithm by randomly allocating waiting times to the validator nodes and choose the node with the least waiting time to execute the transaction validation function.

```
function payOut(shipmentReceived) {
   var contract = shipmentReceived.shipment.contract;
   var shipment = shipmentReceived.shipment;
   var payOut = contract.unitPrice * shipment.unitCount;
   console.log('Received at: ' + shipmentReceived.timestamp);
   console.log('Contract arrivalDateTime: ' + contract.arrivalDateTime);

   // set the status of the shipment
   shipment.status = 'ARRIVED';

   // if the shipment did not arrive on time the payout is zero
   if (shipmentReceived.timestamp > contract.arrivalDateTime) {
      payOut = 0;
      console.log('Late shipment');} else {
      // find the lowest temperature reading
      if (shipment.temperatureReadings) {
         // sort the temperatureReadings by centigrade
         shipment.temperatureReadings.sort(function (a, b) {
            return (a.centigrade - b.centigrade);
         });
         var lowestReading = shipment.temperatureReadings[0];
         var highestReading = shipment.temperatureReadings[shipment.temperatureReadings.length - 1];
         var penalty = 0;
         console.log('Lowest temp reading: ' + lowestReading.centigrade);
         console.log('Highest temp reading: ' + highestReading.centigrade);

         // does the lowest temperature violate the contract?
         if (lowestReading.centigrade < contract.minTemperature) {
            penalty += (contract.minTemperature - lowestReading.centigrade) *
contract.minPenaltyFactor;
            console.log('Min temp penalty: ' + penalty);
         }

         // does the highest temperature violate the contract?
         if (highestReading.centigrade > contract.maxTemperature) {
            penalty += (highestReading.centigrade - contract.maxTemperature) *
contract.maxPenaltyFactor;
            console.log('Max temp penalty: ' + penalty); }

         // apply any penalities
         payOut -= (penalty * shipment.unitCount);

         if (payOut < 0) {payOut = 0;
         }
      }
   }
```

Table 4-8. Transaction Logic for issuing payout after verifying shipment

An application SDK is not developed as a part of this implementation, and hence all results shown henceforth are backend data retrieved from the Amazon Web Services (AWS) Ubuntu server using sawtooth application for supply chain asset tracking. All IoT transaction information created for this exercise are available in Appendix. The command “$ sawtooth block list” shows all the blocks that have been created as a part of the Merkle Tree as shown in table 4.7. The table also illustrates the block ID (a 128bit character string), number of transactions inside a block, one of the signees and the corresponding asset transaction for which these blockchain transactions are created.

NUM	BLOCK_ID	BATS	TXNS	SIGNER	Corresponding asset transaction
9	fa1fcbed401de1b7eff62958032d66de130d4a6f241c 28b7b8c8ba2cb81bb7674203910b2dd76742110c0c a009907df5a3401370b0248af96f5f216ca25bb876	1	1	026v6y..	SOLD_RETAIL
8	b24cb16a61f1fcd40f0d7e802f7b71162a464d0f99a7 b3fc4a840b12db3473080c3bb2713cf8dfdb6131cd7 b3a46ec080dcacc53f2293e4649631d58476ca2f3	11	2	055c3c..	IN_STORAGE_RETAIL
7	fa1fcbed401de1b7eff62958032d66de130d4a6f241c 28b7b8c8ba2cb81bb7674203910b2dd76742110c0c a009907df5a3401370b0248af96f5f216ca25bb876	1	2	097b6o..	IN_TRANSIT_TO_RETAIL
6	2e54f0af7f8170437514aa2a7a953a53f5244b6c4f80 bf77f618a02dd6c5aa6b63600cae10c184ab1bcf4124 c5564c34e8e6170c516b1d2e668dc574332da996	1	2	036r4w..	IN_STORAGE_DC
5	f85e3af6ebdbc2d8611a99748da78cc19f19e93a8876 bbd14851a9938c4c6edf126e431a4a6627b37a8fbf5e e2ec64cbc97d69249e2fe98718923a1cced75bf1	1	2	058f0i..	IN_TRANSIT_TO_DC
4	25bd5333ac0e8bdb11f0278ac034dec4cfce1920c83a 1a1959da923b3e451ec81881858821b1a711b562df1 b2b7ddeb03c3d289c8aaeea602277553d5dbc2c10	1	2	085z7r..	IN_PACKAGE
3	15fd4610448dcd1aadb24913bd2e0d6a58ac87d5280 4586c6a1cfdaf5f122b557914551332018ba86352768 47cc9aa387f7c5f9ed341e8f01eb8db845def884a	1	2	068c0p..	SOURCE_SEGMENTED
2	e6055d439d737a27617f0df4f89fc2baff25f929d6b20 72b77f90fc6a2d942981566ac23afe74b49f147735a4 321c521f1f71c2ea57d0a75c1db5892ec29b049	1	2	064f4j..	PROCESSOR_QCHECK
1	0d4ed024a9c2a05a8c52e22cc89957d908dd567c2b6 2aa5353a9126adcc6b8e071a0fa75faf2109cb68e8a4 94337e1dabbf1249335a4e12a99d63995dbd16f92	1	2	024y7k..	IN_STORAGE_PROCESSOR
0	b93a002cd04530beb40a7588c4ad348adbea99e03e 15f3eb6020cf31b06465bf6e957a69b28de642e40ed 5036c3cd46878e03969cbfa72858bc9254389dbd1c0	1	1	045f8d..	IN_TRANSIT_TO_PROCESS OR

Table 4-9. All blocks created in the Merkle Tree

To make the information stored in the blockchain more accessible to the end customer, an excel VBA tool is built, that purges downloadable blockchain transaction data and uses an "UserForm" to display tracking dashboard shown in figure 4.11. This information is pulled based on the unique product ID that belongs to a unique source ID. Necessary information regarding the product, details of the food producer, processor and all the subsequent stages of transportation, distribution, and retail storage information are displayed for the end user. The tool currently doesn't flag any quality violations, but with more information on the state or country-specific meat quality standards, this can be implemented within this tool.

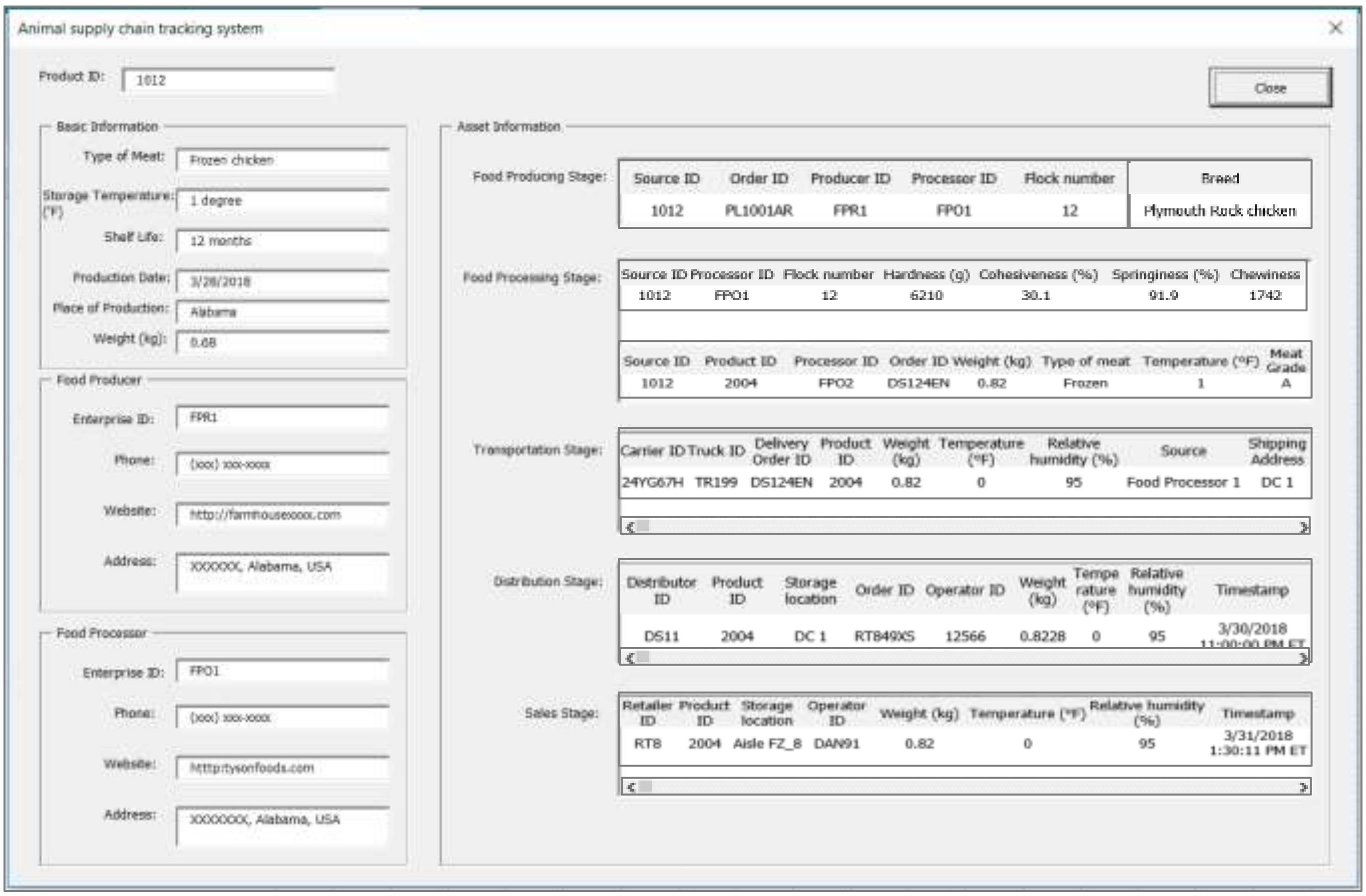

Figure 4-11. A meat tracking system for the food supply chain

A MicroStrategy or tableau application can also be developed leveraging this dataset to create a mobile app that scans a QR code in addition to the barcode affixed to every retail product sold as shown in figure 4.12.

Figure 4-12. Blockchain detectable label for a beef product

4.3.3 Model evaluation and discussion

A blockchain enabled tracking system can be compared against the conventional tracking systems discussed in section 4.2, against 3 parameters. 1) Food traceability efficiency, 2) Cost of implementation and operations and 3) Other Supply chain efficiencies – waste management, supplier management, benefits for different stages within the supply chain (supplier, manufacturer, distributor, etc.).

The primary advantage with a blockchain traceability system is the time advantage in controlling food illness outbreaks by investigating the chain of transactions regarding every target product ever sold and consumed. All asset transaction information can be pulled instantly using the unique product ID. However, this functionality is proportional to the effectiveness of data captured in IoT layer. Assigning stage-specific supervisors to review and digitally sign the IoT data captured is critical to maintaining the integrity of the entire system. Though a conventional IT tracking system can do a similar tracking function with comparable accuracy; blockchains stand out in three crucial factors. Firstly, its distributed nature connects the otherwise independent database silos in traditional IT architecture, especially in a horizontally integrated food supply chain. Secondly, all business partners can connect their internal production or ERP systems to the blockchain network, due to the standard topology, predefined terminology and sequence of operations, which is highly tedious in traditional systems that are already operational. Finally, access to business transactions is available for every new participant joining the network without the need to connect their enterprise systems to corresponding downstream and upstream systems.

Low capital cost for building, connecting and maintaining the blockchain infrastructure is an added benefit compared to a conventional tracking system. With the use of Proof of Elapsed Time (PoET), high energy consumption is not required, thereby removing the major setback in scaling a blockchain for all products in the supply chain. Blockchain provides other intangible benefits when introduced into a supply chain network. Transparency throughout the supply chain creates trust, balances the information asymmetry between suppliers and incentivizes good practices among vendors. Hence consumers are getting guaranteed value for the price they are paying. Liability to food outbreak ownership has been one of the primary roadblocks to food traceability. Meat manufacturers/ producers are concerned with the repercussions for their businesses if they are proved to be associated with animal illness outbreak or food safety hazard. In this context, there is little importance given for assuring quality for customers through food traceability. Incorporating the state and global quality regulations into a blockchain model can not only help trace the hazard but also prevent from happening in the first place. Efficient use of smart contracts inside the blockchain can alter the perceptions of food producers regarding the riskiness of traceability over time. Government regulators can also monitor the smart contracts written between food producers and processors to prevent unethical business practices like food processors having a gladiator or tournament pricing system between chicken farmers to depreciate the price of the chicken produce below the cost of its production. The recent BSE case in 2017, Alabama highlights the disadvantages in terms of slow reaction times of not having any type of national animal identification system in the US. Further analysis will be needed to compare the benefits and costs of a voluntary tracking scheme currently in the US versus adopting a system closer to that of Canada or Australia where there is a mandatory identification of animals, but most of traceability details are left to the industry.

Limitations of using, deploying and maintaining a blockchain system play a huge role in determining the adoption rate among in industry. As discussed in section 2.2.5, adoption of blockchain in food supply chain is a nascent concept, and it presents many challenges than solutions before adoption. More research is required to address the gap in requirements for software platforms and tools that can be used to develop large-scale blockchains, handling millions of participants in the FSC today. Extensive blockchain talent development is also a fundamental problem to be addressed.

Chapter 5

Conclusion and Future Work

Food provenance is one of the most challenging question that FSC companies are trying to solve today and this thesis is a small contribution towards answering that question. The primary objective of this research is to create a blockchain model that can be implemented in a food supply chain and provide its benefits and limitations over traditional tracking systems in terms of food provenance and asset traceability. From this research effort, it is evident that blockchains can be more efficient in tracking food provenance, preventing substantial scale contamination of food products, identify and remove the source of foodborne illness within seconds while the contemporary systems could take as much as weeks. It also would provide greater customer confidence which reflects in sales and customer satisfaction.

Future research efforts can be focused on identifying the different incentive schemes to be used within the blockchain network to facilitate uniform distribution of power regarding how the transactional data can be used within the FSC. A substantial operational change like adopting blockchains is possible only when it is pushed by the player with more significant influence over the business in other supply chain stages. Hence it would be interesting to find out how the balance of power between retailers and food processors would change the suggested blockchain model. One other potential research question to address is the scalability of a blockchain system. For example, when a single food processing unit is supplying to multiple retailers, there is a need to maintain multiple private blockchain networks, one for each retailer. If traversing a layer deeper, how a superstore like Walmart would maintain its blockchain network for hundred thousand SKUs it holds in a single retail location.

Appendix

Blockchain Sawtooth Codes

This chapter contains all the Hyperledger Sawtooth codes for creating an asset, creating a participant, creating a transaction procedure, creating a access control file and writing the transaction logic to control transaction processing by the validator.

Create ledger parameters

```
makePrivateKey: () => {
	let privateKey
	do privateKey = randomBytes(32)
	while (!secp256k1.privateKeyVerify(privateKey))
	return privateKey.toString('hex')}

getPublicKey: privateKey => {
	const privateBuffer = _decodeHex(privateKey)
	const publicKey = secp256k1.publicKeyCreate(privateBuffer)
	return publicKey.toString('hex')}

const createAsset = (asset, owner, state) => {
	const address = getAssetAddress(asset)
	return state.get([address])
		.then(entries => {
			const entry = entries[address]
			if (entry && entry.length > 0) {
				throw new InvalidTransaction('Asset name in use')}
			return state.set({
			[address]: encode({name: asset, owner})
			})
		})
}
const getAddress = (key, length = 64) => {
	return createHash('sha512').update(key).digest('hex').slice(0, length)
}
const getAssetAddress = name => PREFIX + '00' + getAddress(name, 62)


/** Transferring asset*/
const transferAsset = (asset, owner, signer, state) => {
	const address = getTransferAddress(asset)
	const assetAddress = getAssetAddress(asset)
	return state.get([assetAddress])
		.then(entries => {
			const entry = entries[assetAddress]
			if (!entry || entry.length === 0) {
```

```
                    throw new InvalidTransaction]('Asset does not exist')}
            if (signer !== decode(entry).owner) {
                    throw new InvalidTransaction('Only an Asset\'s owner maytransfer
            it')}
            return state.set({
                    [address]: encode({name: asset, owner: owner})
            })
    })
}
```

Model File

```
namespace com.biz

enum AnimalType {

  o CHICKEN

  o CATTLE

  o PIG

  o FISH}

enum Breed {

  o BROILER

  o PLYMOUTH_ROCK_CHICKEN}

enum MovementStatus {

  o IN_TRANSIT_TO_PROCESSOR

  o IN_STORAGE_PROCESSOR

  o PROCESSOR_QCHECK

  o SOURCE_SEGMENTED

  o IN_PACKAGE

  o IN_TRANSIT_TO_DC

  o IN_STORAGE_DC

  o IN_TRANSIT_TO_RETAIL

  o IN_STORAGE_RETAIL

  o SOLD_RETAIL}

enum ProductionType {

  o FROZEN_MEAT
```

```
  o FRESH_MEAT
  o ORGANIC_MEAT
  o OTHER}
abstract participant User identified by producerID {
  o String producerID
  o String Name
  o String address
  o String phoneNumber
  o String email}
participant Farmer extends User {
    o String address1
    o String address2
    o String county
    o String postcode
    --> Business business optional}
asset Field identified by cph {
  o String cph
  o String name
  --> Business business}
asset Animal identified by sourceId {
    o String sourceId
    o Breed species
    o MovementStatus movementStatus
    o ProductionType productionType}
asset Business identified by sbi {
     o String sbi
     o String address1
     o String address2
     o String county
```

```
    o String postcode
    --> Farmer owner
    --> Animal[] incomingAnimals optional}
abstract transaction AnimalMovement {
  o String[] logs optional
   --> Animal animal
   --> Business from
   --> Business to}
transaction AnimalMovementDeparture extends AnimalMovement {
  --> Field fromField}
transaction AnimalMovementArrival extends AnimalMovement {
  --> Field arrivalField}
transaction SetupDemo  {}
```

Script File

```
/*eslint-disable no-unused-vars*/
/*eslint-disable no-undef*/
function onAnimalMovementDeparture(movementDeparture) {
    console.log('onAnimalMovementDeparture');
    if (movementDeparture.animal.movementStatus !== 'IN_FIELD') {
        throw new Error('Animal is already IN_TRANSIT');
    }
    movementDeparture.animal.movementStatus = 'IN_TRANSIT';
    return getAssetRegistry('com.biz.Animal')
  .then(function(ar) {
      return ar.update(movementDeparture.animal);
  })
  .then(function() {
      if (movementDeparture.to.incomingAnimals) {
```

```
        movementDeparture.to.incomingAnimals.push(movementDeparture.animal);
      } else {
        movementDeparture.to.incomingAnimals = [movementDeparture.animal];
      }
      return getAssetRegistry('com.biz.Business');
  })
  .then(function(br) {
      return br.update(movementDeparture.to);
  });
}

function onAnimalMovementArrival(movementArrival) {
    console.log('onAnimalMovementArrival');
    if (movementArrival.animal.movementStatus !== 'IN_TRANSIT') {
        throw new Error('Animal is not IN_TRANSIT');}
    movementArrival.animal.movementStatus = 'IN_FIELD';
    movementArrival.animal.owner = movementArrival.to.owner;
    movementArrival.animal.location = movementArrival.arrivalField;
    return getAssetRegistry('com.biz.Animal')
  .then(function(ar) {
      return ar.update(movementArrival.animal);
  })
  .then(function() {
      if (!movementArrival.to.incomingAnimals) {
        throw new Error('Incoming business should have incomingAnimals on
AnimalMovementArrival.');}
      movementArrival.to.incomingAnimals = movementArrival.to.incomingAnimals
    .filter(function(animal) {
        return animal.animalId !== movementArrival.animal.animalId;
    });
```

```
      return getAssetRegistry('com.biz.Business');
  })
  .then(function(br) {
      return br.update(movementArrival.to);});
}
function setupDemo(setupDemo) {
    var factory = getFactory();
    var NS = 'com.biz';
    var producers = [
        factory.newResource(NS, 'Producer', 'PRODUCER_1'),
        factory.newResource(NS, 'Producer', 'PRODUCER_2')];
    var businesses = [
        factory.newResource(NS, 'Business', 'BUSINESS_1'),
        factory.newResource(NS, 'Business', 'BUSINESS_2')];
    var fields = [
        factory.newResource(NS, 'Field','FIELD_1'),
        factory.newResource(NS, 'Field','FIELD_2'),
        factory.newResource(NS, 'Field','FIELD_3'),
        factory.newResource(NS, 'Field','FIELD_4')];
    var transaction = [
        factory.newResource(NS, Asset, ' SOLD_RETAIL '),
        factory.newResource(NS, 'Asset ', ' IN_STORAGE_RETAIL '),
        factory.newResource(NS, 'Asset ', ' IN_TRANSIT_TO_RETAIL '),
        factory.newResource(NS, 'Asset ', ' IN_STORAGE_DC '),
        factory.newResource(NS, 'Asset ', ' IN_TRANSIT_TO_DC '),
        factory.newResource(NS, 'Asset, ' IN_PACKAGE '),
        factory.newResource(NS, 'Asset, 'IN_STORAGE_PROCESSOR'),
        factory.newResource(NS, 'Asset, 'IN_TRANSIT_TO_PROCESSOR')];
```

```
  return getParticipantRegistry(NS + '.Regulator')
.then(function(regulatorRegistry) {
    var regulator = factory.newResource(NS, 'Regulator', 'REGULATOR');
    regulator.email = 'REGULATOR';
    regulator.firstName = 'Ronnie';
    regulator.lastName = 'Regulator';
    return regulatorRegistry.addAll([regulator]);
})
.then(function() {
    return getParticipantRegistry(NS + '.Producer');
})
.then(function(producerRegistry) {
    producers.forEach(function(producer) {
        var sbi = 'BUSINESS_' + producer.getIdentifier().split('_')[1];
        producer.firstName = producer.getIdentifier();
        producer.lastName = '';
        producer.address1 = 'Address1';
        producer.address2 = 'Address2';
        producer.county = 'County';
        producer.postcode = 'PO57C0D3';
        producer.business = factory.newResource(NS, 'Business', sbi);
    });
    return producerRegistry.addAll(producers);
})
.then(function() {
    return getAssetRegistry(NS + '.Business');
})
.then(function(businessRegistry) {
    businesses.forEach(function(business, index) {
```

```
        var cph = 'FIELD_' + (index + 1);
        var producer = 'PRODUCER_' + (index + 1);
        business.address1 = 'Address1';
        business.address2 = 'Address2';
        business.county = 'County';
        business.postcode = 'PO57C0D3';
        business.owner = factory.newRelationship(NS, 'Producer', producer);
    });

    return businessRegistry.addAll(businesses);
})
.then(function() {
    return getAssetRegistry(NS + '.Field');
})
.then(function(fieldRegistry) {
    fields.forEach(function(field, index) {
        var business = 'BUSINESS_' + ((index % 2) + 1);
        field.name = 'FIELD_' + (index + 1);
        field.business = factory.newRelationship(NS, 'Business', business);
    });
    return fieldRegistry.addAll(fields);
})
.then(function() {
    return getAssetRegistry(NS + '.Animal');
})
.then(function(animalRegistry) {
    animals.forEach(function(animal, index) {
        var field = 'FIELD_' + ((index % 2) + 1);
        var producer = 'PRODUCER_' + ((index % 2) + 1);
```

```
        animal.movementStatus = 'IN_FIELD';
        animal.productionType = 'MEAT';
        animal.location = factory.newRelationship(NS, 'Field', field);
        animal.owner = factory.newRelationship(NS, 'Producer', producer);
      });
      return animalRegistry.addAll(animals);
  });
}
```

Access Control File

```
/**
 * Access control list.
 */
rule Default {
    description: "Allow all participants access to all resources"
    participant: "com.biz.User"
    operation: ALL
    resource: "com.biz.*"
    action: ALLOW
}
rule SystemACL {
  description:  "System ACL to permit all access"
  participant: "org.hyperledger.composer.system.Participant"
  operation: ALL
  resource: "org.hyperledger.composer.system.**"
  action: ALLOW
}
```

```
rule NetworkAdminUser {
    description: "Grant business network administrators full access to user resources"
    participant: "org.hyperledger.composer.system.NetworkAdmin"
    operation: ALL
    resource: "**"
    action: ALLOW
}
rule NetworkAdminSystem {
    description: "Grant business network administrators full access to system resources"
    participant: "org.hyperledger.composer.system.NetworkAdmin"
    operation: ALL
    resource: "org.hyperledger.composer.system.**"
    action: ALLOW
}
```

Merkle Tree in AWS Sawtooth

ubuntu@ip-172-31-35-247: ~

```
*** System restart required ***
Last login: Tue Apr  3 11:30:07 2018 from 71.58.102.164
ubuntu@ip-172-31-35-247:~$ sawtooth block list
NUM  BLOCK_ID
                                                              BATS  TXNS  SIGNER
8    b24cb16a61f1fcd40f0d7e802f7b71162a464d0f99a7b3fc4a840b12db3473080c3bb2713cf
8dfdb6131cd7b3a46ec080dcacc53f2293e4649631d58476ca2f3  11    66    036f3f...
7    fa1fcbed401de1b7eff62958032d66de130d4a6f241c28b7b8c8ba2cb81bb7674203910b2dd
76742110c0ca009907df5a3401370b0248af96f5f216ca25bb876  1     1     036f3f...
6    2e54f0af7f8170437514aa2a7a953a53f5244b6c4f80bf77f618a02dd6c5aa6b63600cae10c
184ab1bcf4124c5564c34e8e6170c516b1d2e668dc574332da996  1     1     036f3f...
5    f85e3af6ebdbc2d8611a99748da78cc19f19e93a8876bbd14851a9938c4c6edf126e431a4a6
627b37a8fbf5ee2ec64cbc97d69249e2fe98718923a1cced75bf1  1     1     036f3f...
4    25bd5333ac0e8bdb11f0278ac034dec4cfce1920c83a1a1959da923b3e451ec81881858821b
1a711b562df1b2b7ddeb03c3d289c8aaeea602277553d5dbc2c10  1     1     036f3f...
3    15fd4610448dcd1aadb24913bd2e0d6a58ac87d52804586c6a1cfdaf5f122b5579145513320
18ba8635276847cc9aa387f7c5f9ed341e8f01eb8db845def884a  1     3     036f3f...
2    e6055d439d737a27617f0df4f89fc2baff25f929d6b2072b77f90fc6a2d942981566ac23afe
74b49f147735a4321c521f1f71c2ea57d0a75c1db5892ec29b049  1     3     036f3f...
1    0d4ed024a9c2a05a8c52e22cc89957d908dd567c2b62aa5353a9126adcc6b8e071a0fa75faf
2109cb68e8a494337e1dabbf1249335a4e12a99d63995dbd16f92  1     2     036f3f...
0    b93a002cd04530beb40a7588c4ad348adbea99e03e15f3eb6020cf31b06465bf6e957a69b28
de642e40ed5036c3cd46878e03969cbfa72858bc9254389dbd1c0  1     1     036f3f...
ubuntu@ip-172-31-35-247:~$
```

Global State in Hyperledger Sawtooth after executing all asset transactions

Block	Asset Transaction	Nonce	Hash	Holder	Customer	Recipients	Status	Timestamp
9	SOLD_RETAIL	72608	0000e2ff1fb	970004	-	1	Processing	3/31/2018 11:19:00
8	IN_STORAGE_RETAIL	3001	00009a8e0d	Walmart, N	-	1	Completed	3/31/2018 1:30:11
7	IN_TRANSIT_TO_RETAIL	35363	00009c2d43d	Walmart DC	Walmart, N	1	Completed	3/31/2018 1:00:00
6	IN_STORAGE_DC	45473	00000130d4	Walmart DC	-	1	Completed	3/30/2018 11:00:00
5	IN_TRANSIT_TO_DC	50368	0000c07ccdd	Tyson Foods,	Walmart	1	Completed	3/29/2018 9:53:21
4	IN_PACKAGE	58965	00005946aac	Tyson Foods,	-	1	Completed	3/29/2018 1:00:00
3	SOURCE_SEGMENTED	14926	0000a94fef8	Tyson Foods,	-	2	Completed	3/28/2018 2:00:00
2	PROCESSOR_QCHECK	4783	000059afead	Tyson Foods,	-	1	Completed	3/28/2018 10:50:00
1	IN_STORAGE_PROCESSOR	73907	0000b6e265	Tyson Foods,	-	1	Completed	3/28/2018 10:30:00
0	IN_TRANSIT_TO_PROCESSOR	43108	0000826673	Farmhouse	Tyson	1	Completed	3/26/2018 9:53:21

Bibliography

Manos, Basil, and Ioannis Manikas. "Traceability in the Greek fresh produce sector: drivers and constraints." British food journal 112.6 (2010): 640-652.

Nakamoto, Satoshi. "Bitcoin: A peer-to-peer electronic cash system." (2008): 28.

Eyal, Ittay, et al. "Bitcoin-NG: A Scalable Blockchain Protocol." NSDI. 2016.

Dabbene, F., Gay, P., and Tortia, C. 2014. "Traceability issues in FSC management: A review,"

Armstrong, S. 2016. "Eight things you need to know about the future of retail," Wired UK,

Greenspan, G. 2016. "Four Genuine Blockchain Use Cases - CoinDesk," CoinDesk

Regattieri, A., Gamberi, M., and Manzini, R. 2007. "Traceability of food products: General framework and experimental evidence," Journal of Food Engineering (81:2), pp. 347–356.

Tapscott, D., and Tapscott, A. 2016. Blockchain Revolution: How the Technology Behind Bitcoin Is Changing Money, Business, And The World, Toronto, Canada: Penguin Canada.

Kim, Henry M., and Marek Laskowski. "Towards an ontology-driven blockchain design for supply chain provenance." (2016).

Abeyratne, Saveen A., and Radmehr P. Monfared. "Blockchain, ready manufacturing supply chain, using a distributed ledger." (2016)

Tian, Feng. "An agriculture-FSC traceability system for China based on RFID & blockchain technology." Service Systems and Service Management (ICSSSM), 2016 13th International Conference on. IEEE, 2016.

Provenance (2015), "From shore to plate: Tracking tuna on the blockchain."

Provenance (2015), "Blockchain: the solution for transparency in product supply chains."

BBC, June 2017, "United States suspends all Brazilian meat imports."

Forbes, 2014, "The 2008 milk scandal."

The New Indian Express 2017, "The great Indian toxic food fraud."

Kelepouris, T., Pramatari, K. and Doukidis, G., 2007. RFID-enabled traceability in the food supply chain. Industrial Management & data systems, 107(2), pp.183-200.

Elena Mesropyan, MEDICI. Retrieved Dec 10, 2017 from https://gomedici.com/22-companies-leveraging-blockchain-for-identity-management-and-authentication/

Bosona, Techane, and Girma Gebresenbet. "Food traceability as an integral part of logistics management in food and agricultural supply chain." Food Control 33.1 (2013): 32-48.

Yam, Kit L., Paul T. Takhistov, and Joseph Miltz. "Intelligent packaging: concepts and applications." Journal of food science 70.1 (2005).

Liao, Pei-An, Hung-Hao Chang, and Chun-Yen Chang. "Why is the food traceability system unsuccessful in Taiwan? Empirical evidence from a national survey of fruit and vegetable farmers." Food Policy 36.5 (2011): 686-693.

Schroeder, Ted C., and Glynn T. Tonsor. "International cattle ID and traceability: Competitive implications for the US." Food Policy 37.1 (2012): 31-40.

Engelseth, Per. "Food product traceability and supply network integration." Journal of Business & Industrial Marketing 24.5/6 (2009): 421-430.

Salampasis, Michail, Dimitrios Tektonidis, and Eleni P. Kalogianni. "TraceALL: a semantic web framework for food traceability systems." Journal of Systems and Information Technology 14.4 (2012): 302-317.

Azuara, Guillermo, Jose Luis Tornos, and Jose Luis Salazar. "Improving RFID traceability systems with verifiable quality." Industrial Management & Data Systems 112.3 (2012): 340-359.
Karlsen, Kine Mari, et al. "Literature review: Does a common theoretical framework to implement food traceability exist?" Food Control 32.2 (2013): 409-417.

Tian, Feng. "An agriculture food supply chain traceability system for China based on RFID & blockchain technology." Service Systems and Service Management (ICSSSM), 2016 13th International Conference on. IEEE, 2016.

Countries/Products Eligible for Export to the United States. Retrieved September 21, 2017 from https://www.fsis.usda.gov/wps/wcm/connect/4872809d-90c6-4fa6-a2a8-baa77f48e9af/Countries_Products_Eligible_for_Export.pdf?MOD=AJPERES

Polim, Rico, Qianyu Hu, and Soundar Kumara. "Blockchain in Megacity Logistics." IIE Annual Conference. Proceedings. Institute of Industrial and Systems Engineers (IISE), 2017.

Scharff, Robert L. "Economic burden from health losses due to foodborne illness in the United States." Journal of food protection 75.1 (2012): 123-131.

Daskalos, Chris G. Heinz College: School of Information Systems and Management. Diss. Carnegie Mellon University, 2015.

Provenance "From shore to the plate: Tracking tuna on the blockchain," 2016.

Markman, Gideon D., and Daniel Krause. "Theory building surrounding sustainable supply chain management: Assessing what we know, exploring where to go." Journal of supply chain management 52.2 (2016): 3-10.

Kim, Henry M., and Marek Laskowski. "Towards an ontology-driven blockchain design for supply chain provenance." (2016).

Francisco, Kristoffer, and David Swanson. "The Supply Chain Has No Clothes: Technology Adoption of Blockchain for Supply Chain Transparency." Logistics 2.1 (2018): 2.

Chen, Si, et al. "A blockchain-based supply chain quality management framework." e-Business Engineering (ICEBE), 2017 IEEE 14th International Conference on. IEEE, 2017.

Cost estimates of foodborne illness. Retrieved April 3, 2018 from https://www.ers.usda.gov/data-products/cost-estimates-of-foodborne-illnesses.aspx.

Starbird, S. Andrew. "Designing food safety regulations: The effect of inspection policy and penalties for noncompliance on food processor behavior." Journal of Agricultural and Resource Economics (2000): 616-635.

Wu, Haoyan, et al. "A Distributed Ledger for Supply Chain Physical Distribution Visibility." Information 8.4 (2017): 137.

Food & Drink Research Report 2016 - Lloyds Banking Group. Retrieved April 3, 2018, from http://www.lloydsbankinggroup.com/globalassets/documents/media/press-releases/lloyds-bank/2016/lb-food-and-drink-report-2016.pdf

Bulut, Harun, and John D. Lawrence. "Meat slaughter and processing plants' traceability levels: evidence from Iowa." (2008).

Marucheck, Ann, et al. "Product safety and security in the global supply chain: Issues, challenges and research opportunities." Journal of Operations Management 29.7-8 (2011): 707-720.

Parfitt, Julian, Mark Barthel, and Sarah Macnaughton. "Food waste within food supply chains: quantification and potential for change to 2050." Philosophical Transactions of the Royal Society B: Biological Sciences 365.1554 (2010): 3065-3081.

Maloni, Michael J., and Michael E. Brown. "Corporate social responsibility in the supply chain: an application in the food industry." Journal of business ethics 68.1 (2006): 35-52.

Van Der Vorst, Jack GAJ, Seth-Oscar Tromp, and Durk-Jouke van der Zee. "Simulation modelling for food supply chain redesign; integrated decision making on product quality, sustainability and logistics." International Journal of Production Research 47.23 (2009): 6611-6631.

Matopoulos, Aristides, et al. "A conceptual framework for supply chain collaboration: empirical evidence from the agri-food industry." Supply Chain Management: an international journal 12.3 (2007): 177-186.

Marsden, Terry, Jo Banks, and Gillian Bristow. "Food supply chain approaches: exploring their role in rural development." Sociologia ruralis 40.4 (2000): 424-438.

Golan, Elise H., et al. Food safety innovation in the United States: evidence from the meat industry. No. 34083. United States Department of Agriculture, Economic Research Service, 2004.

Scharff, Robert L. "Economic burden from health losses due to foodborne illness in the United States." Journal of food protection 75.1 (2012): 123-131.

Starbird, S. Andrew. "Supply chain contracts and food safety." Choices 20.2 (2005): 123-128.

Starbird, S. Andrew. "Designing food safety regulations: The effect of inspection policy and penalties for noncompliance on food processor behavior." Journal of Agricultural and Resource Economics (2000): 616-635.

Verhoosel, Jack, Michael van Bekkum, and Tim Verwaart. "HortiCube: a platform for transparent, trusted data sharing in the food supply chain." Proceedings in Food System Dynamics (2016): 384-388.

Kummu, Matti, et al. "Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use." Science of the total environment 438 (2012): 477-489.

Buhr, Brian L. "Traceability and information technology in the meat supply chain: implications for firm organization and market structure." Journal of Food Distribution Research 34.3 (2003): 13-26.

Meuwissen, Miranda PM, et al. "Traceability and certification in meat supply chains." Journal of Agribusiness 21.2 (2003): 167-182.

Liang, Wanjie, et al. "Modeling and implementation of cattle/beef supply chain traceability using a distributed RFID-based framework in China." PloS one 10.10 (2015): e0139558.

Dani, Samir. Food supply chain management and logistics: From farm to fork. Kogan Page Publishers, 2015.