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Facilitating information sharing within a supply chain: the blockchain framework

Thesis for the degree of Philosophiae Doctor

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Abstract

Firms focus on their core functions and engage in collaborative cooperation as a strategy to remain competitive. In recent decades, service industries such as providing medical check-ups and electric utilities have played a vital role in complex supply chains. A service chain is purely an intangible service that does not directly involve physical products.

Information sharing is a key aspect of establishing cooperation, as well as being the main element in opening new services. Firms invest in monitoring mechanisms, such as engaging an intermediate third party, to reduce information asymmetry, but often this comes at a cost and is often linked to opportunistic behaviour. Although third-party services can reduce information asymmetry, the reliability of the shared information remains a challenge.

Blockchain is a digital distributed computing network in which no member of the network can falsify or control the information it contains. The data-storage structure of blockchain makes tampering evident along with the consensus mechanism that maintains the integrity of the data. The smart contract is another feature of blockchain that has caught the attention of researchers, as it can facilitate information sharing without human intervention, thereby reducing human error and cost. This has also sparked an interest in how blockchain can play a role in horizontal and vertical information sharing in different industries.

To acquire deeper insights into these issues, this thesis starts with a systematic literature review in order to assess the current state of the art in information sharing using blockchain. Three case studies: health care, and the smart city and energy sectors, all different in nature, are examined. Blockchain-based frameworks are designed in accordance with their boundary conditions and requirements respectively. The present case study shows that blockchain with a smart contract can enable a new form of data-information sharing, a vertical level between service provider and building owner. This can open up new services and increase efficiency within a complex chain of stakeholders. Another outcome of this research on horizontal information sharing is that the latter gives patients in the healthcare sector certain benefits, such as reducing preventable medication error through collaborative care decisions and clinician burn-out. Blockchain can also reduce the dependence on third parties and complement the centralized database.

Although blockchain technology can facilitate information sharing within a supply chain, it is not a copy-and-paste approach. It is vital to study the nature of the domain, the technical requirements and boundary conditions like privacy in order to design a feasible solution using blockchain technology. Some future work, such as implementing these solutions in a real-world scenario to generate actual performances, are needed to gain support from top leaders in incorporating this technology for information sharing purposes.

Acknowledgements

Nearly three years ago, I joined the Trust and Transparency Project as a Ph.D. candidate. It is hard to believe it is already time to write my acknowledgements.

First and foremost, I would like to thank Associate Professor Lizhen Huang for her patience in guiding me in becoming an independent researcher, starting while I was still working on my master's degree and continuing up to the present day. I also would like to thank Professor Halvor Holtskog for all the interesting discussions we shared; they have widened my perspective in unexpected ways. I thank Associate Professor Mariusz Nowostawski for sharing his vast technical knowledge with me, including on the latest trends in technology. Special thanks also go to Professor Xiufeng Liu of the Technical University of Denmark (DTU) for efficient and effective remote collaboration despite the COVID-19 pandemic. Without the guidance and support all of those mentioned have provided, I would not have made it this far.

I would also like to thank all the members of my family, who have always supported me and encouraged me to move forward with my work. Special thanks go to both my parents, Wan Yet Fong and Wong Sai Ling, for constantly believing in me. My father deserves special thanks for his many heart-warming morning messages. I also would like to thank my brother, Daniel Wan, for his support whenever I needed it, and my sister-in-law, Jiang Shengnan, for sending pictures of my cute baby niece, Alicia Wan.

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List of Publications

Paper A P.K. Wan, L. Huang and H. Holtskog, "Blockchain-Enabled Information Sharing Within a Supply Chain: A Systematic Literature Review," in *IEEE Access*, vol. 8, pp. 49645-49656, 2020, doi: 10.1109/ACCESS.2020.2980142.

Paper B Wan P.K., Satybaldy A., Huang L., Holtskog H., Nowostawski M. "Reducing Alert Fatigue by Sharing Low-Level Alerts With Patients and Enhancing Collaborative Decision Making Using Blockchain Technology: Scoping Review and Proposed Framework (MedAlert)", *J Med Internet Res* 2020;22(10):e22013 doi: 10.2196/22013

Paper C Wan, Paul, Lizhen Huang, Zhichen Lai, Xiufeng Liu, Mariusz Nowostawski, Halvor Holtskog, Guanghua Yu. "Development of Blockchain-Based Automated Infectious Risk Assessment Alert System: A Case Study in an Office Building". *Energy*
Status: under review.

Paper D Wan, K. Paul and Lizhen Huang, "Energy Tracing and Blockchain Technology: Current State-of-Art". *4th International Conference on Intelligent Technologies and Applications (INTAP 2021)*; Norway 2021
Status: Accepted.

Additional publication

Paper I Hasselgren, Anton, Paul Kengfai Wan, Margareth Horn, Katina Kralevska, Danilo Gligoroski, and Arild Faxvaag. "GDPR Compliance for Blockchain Applications in Healthcare." *Conference: International Conference on Big Data, IOT and Blockchain (BIBC 2020)* October 24-25, 2020; Dubai, UAE doi:10.5121/csit.2020.101303

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List of Abbreviations

CDS	Clinical decision support
DIKW	Data, information, knowledge, and wisdom
ERP	Enterprise resource planning
EV	Electric vehicles
GDPR	General data protection regulation
IAQ	Indoor air quality
IoT	Internet of things
IT	Information technology
PBFT	Practical byzantine fault tolerance
PoW	Proof of work
RES	Renewable energy source
RQ	Research question
SCM	Supply chain management

Table of Contents

Part I:
Overview

Chapter 1

Introduction

Service plays an important role in supply chains [1]. Unlike a typical supply chain, a service chain is a purely intangible service that is not directly involved in physical products [1]. Over the last decade, there has been a rapid expansion of the service industries because it is a huge driver of profits for a firm [2]. In order to stay competitive, firms gradually shift from tangible products to services. Information is the key to the operation of services chains. Based on Ackoff's DIKW pyramid (see section 2.2), information is defined as when data, the building block of information, are put into context in such a way that they are usable and meaningful [3].

Typically, a firm like a manufacturing plant possesses more information and is better informed about some aspects of the exchange compared with other participating parties [4, 5]. For example, an IT service provider that owns a centralized database has an advantage in controlling the volume, accuracy and types of information that are shared with other clients or consumers [6-8]. This is known as information asymmetry and is often involved in opportunistic and self-interested behaviour [9]. To minimize such behaviour, it is common for firms to invest in monitoring and control mechanisms, though these come at a cost [10]. Anderson and Jap [11] suggest that information asymmetry could trigger suspicion among business partners, thus making it difficult to develop trust and satisfaction in the relationship. One of the methods used to reduce information asymmetry is to share information.

Information sharing has been identified as one of the strongest elements in building trust in business to business exchange relations [12]. In addition to establishing cooperation, information sharing can help a firm make better informed decisions and enable quicker responses to market opportunities and changes [13]. In this research work, information sharing is categorised into two types, namely vertical and horizontal level information sharing, based on the DIKW model. Horizontal sharing is information-information sharing where Firm A shares a piece of information with Firm B, as shown in Figure 1. This type of horizontal information sharing shares the same element across two firms. Vertical sharing, conversely, is data-information sharing where Firm A shares data and

Firm B receives information as shown in Figure 1. This vertical information sharing is facilitated by a blockchain layer that transforms data into information.

There are different methods of facilitating information sharing, such as third-party intermediaries, proactive sharing based on contractual agreements and verbal communication [14]. With the rapid digitization of, for example, the internet of things (IoT) in collecting and storing data, the volume of information generated is increasing exponentially and is constantly being transformed throughout the supply chain [15]. To improve management of the high volume of information and be able to share information with multiple stakeholders, it is usual to engage a third-party IT service-provider. The level of the reliability of distributed information using the above-mentioned methods is often poor in quality and fragmented [16] because the information shared is not verified. Thus, there is a need for a better information sharing tool such blockchain that can increase the reliability of information and enhance the efficiency in of the service chain.

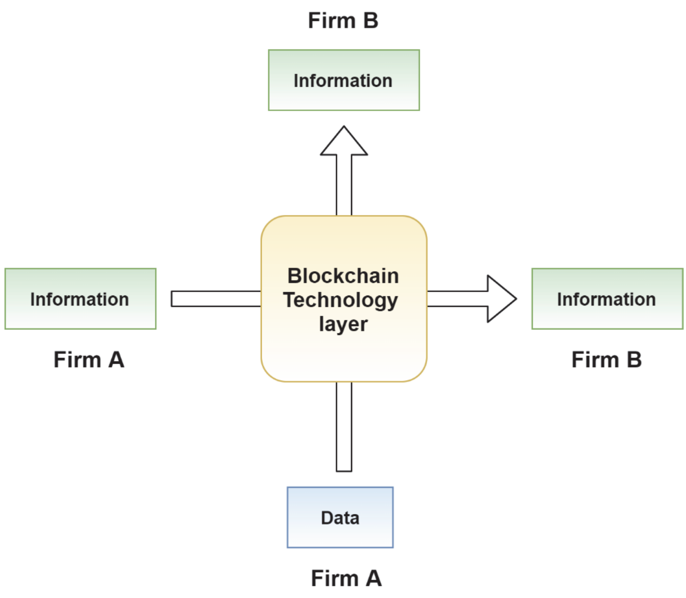

Figure 1. Vertical and horizontal information sharing

Blockchain is a digital distributed computing network in which no member of the network can falsify and control the information it contains. The blockchain data-storage structure makes tampering evident, and along with the consensus mechanism it maintains the integrity of the data. This technology was developed because central authorities have too much power and are vulnerable to abuses of power. Often, having to engage a third-party intermediary is not desirable because it introduces intermediary service costs for storing and managing information [17]. In addition, the firm must depend on and trust the services offered by the third party to facilitate information sharing. It is also not uncommon for the third-party intermediary to block access deliberately during disputes [18].

The main purpose of blockchain technology is to reduce some of the needs of the central authorities or to remove intermediaries and replace them with a distributed network in order to store, verify and safeguard the integrity of the transactions in multiple partnerships [19]. Unlike centralized authorities, which have full access and greater control of data ownership, blockchain technology ensures that all partners in the network have their own copies of the ledger [14] or can access it in the open cloud [19]. Having greater access and control of data ownership, blockchain can enhance transparency and enable firms to make decisions with greater confidence.

The smart contract is another feature of blockchain that that has caught the attention of researchers, as it can facilitate information sharing without human intervention, thus reducing human error and cost. Researchers now use smart contracts as an alternative way of governing and facilitating information exchange without the intervention of an intermediate third party [20, 21]. Similarly, this has sparked an interest in this research in how blockchain can play a role in information sharing both vertically and horizontally based on the DIKW model, as shown in Figure 1. In this way, the complexities of the service costs can be reduced by increasing efficiency, as with information sharing within a complex chain of actors [22].

The distributed nature of blockchain can also prevent single points of failure, a major weakness of a centralized system [23]. However, when it comes to applications in a business ecosystem apart from bitcoin and theory-driven frameworks, this is still at an early stage. There are many studies focusing on the benefits of blockchain technology that add value to information sharing. However, to the best of our knowledge, the only successful deployment of blockchain is still in relation to cryptocurrencies like bitcoin. Nonetheless, there is a growing interest in integrating blockchain as part of the digital transformation in various industries such as healthcare [24-26], smart cities [27-29] and the energy sector [30-32]. Therefore, in this research, I investigated how blockchain can improve information sharing in those three sectors as my case study.

1.1 Research aim

The usual understanding of information sharing sees in it more advantages than disadvantages. However, information asymmetry remains a challenge due to one firm having greater authority and control over information. Digital tools such as blockchain technology have attracted interest as a tool for information sharing because of their immutable and distributed nature. The goal of the project is to create knowledge regarding the extent to which blockchain can facilitate information sharing within a supply chain. To be more specific, this thesis analyses the vertical and horizon levels of information- sharing based on the DIKW model.

The aim of this thesis is to provide insights on information sharing using blockchain technology with enhanced vertical and horizonal levels sharing based on the DIKW model and using different case studies.

1.2 Research questions

To achieve the aim of the research, I have drawn up four research questions (RQs) to guide and structure my research.

RQ 1: What is the current state-of-the-art in information sharing using blockchain technology?

Paper A presents a systematic literature review of the academic literature across five different databases. The purpose of this paper is to identify and understand the impact of this technology for information sharing within a supply chain.

RQ 2: How can information sharing be enhanced by using blockchain on the horizontal level based on the DIKW model?

Paper B presents a case study of information sharing in the healthcare domain. The aim of this paper is to explore how blockchain can enable information to be shared with the patient for purposes of decision-making. This can enhance the overall quality of healthcare.

RQ 3: How can blockchain enable vertical (data-information) level information sharing based on DIWK model?

Paper C presents a case study of vertical level information sharing within a smart building domain. The aim of this paper is to examine how blockchain can enable a new type of data information sharing where a firm shares data and the data is processed into information for other another firm. This can enable better decision-making.

RQ 4: How can blockchain support both vertical and horizontal level information sharing?

Paper D describes the current state-of-art regarding electricity tracing in the energy sector. This paper aims to highlight the complexity of information sharing within the energy domain on both vertically and horizontally.

1.3 List of published papers

This research is presented in the form of four papers. Two have been published and available online; the other two are currently under review

List of included papers:

Paper A P.K. Wan, L. Huang and H. Holtskog, "Blockchain-Enabled Information Sharing Within a Supply Chain: A Systematic Literature Review," in *IEEE Access*, vol. 8, pp. 49645-49656, 2020, doi: 10.1109/ACCESS.2020.2980142.

Paper B Wan P.K., Satybaldy A., Huang L., Holtskog H., Nowostawski M. "Reducing Alert Fatigue by Sharing Low-Level Alerts With Patients and Enhancing Collaborative Decision Making Using Blockchain Technology: Scoping Review and Proposed Framework (MedAlert)", *J Med Internet Res* 2020;22(10):e22013 doi: 10.2196/22013

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Status: under review

Paper D Wan, K. Paul and Lizhen Huang, "Energy Tracing and Blockchain Technology: Current State-of-Art". *4th International Conference on Intelligent Technologies and Applications (INTAP 2021)*; Norway 2021
Status: Accepted.

1.3.1 Authors' roles and contributions

Paper A. Paul Kengfai Wan was responsible for conceptualizing and writing the manuscript and creating the figures. The systematic literature review was carried out and analysed by Paul Kengfai Wan. The manuscript was supervised and reviewed by Lizhen Huang and Halvor Holtskog prior to submission.

Paper B. Paul Kengfai Wan was responsible for conceptualizing and carrying out the research, creating the figures, and designing and validating the framework. The manuscript was written by Paul Kengfai Wan and Abylay Satybaldy. Mariusz Nowostawski supervised the technical aspects of the framework. The manuscript was supervised and reviewed by Lizhen Huang, Mariusz Nowostawski and Halvor Holtskog prior to submission.

Paper C. Paul Kengfai Wan was responsible for conceptualizing and carrying out the research, writing the manuscript, creating the figures, and designing and validating the framework. Zhichen Lai wrote the data-processing scripts in Python. The webpage was designed by Paul Kengfai Wan and Zhichen Lai. Guanghua Yu provided carbon dioxide concentration sensor data. The manuscript was supervised and reviewed by Lizhen Huang, Xiufeng Liu, Mariusz Nowostawski and Halvor Holtskog prior to submission.

Paper D. Paul Kengfai Wan was responsible for conceptualizing and writing the manuscript and creating the figures. The systematic literature review was carried out and analysed by Paul Kengfai Wan. The manuscript was supervised and reviewed by Lizhen Huang and Xiufeng Liu prior to submission.

1.4 Thesis organization

This thesis is organized in two parts: Part I and Part II. Part I consists of five chapters. Chapter 1 explains the motivations behind the research with reference to the four research questions, designed to achieve the aims of this research. Chapter 2 focuses on the background to the thesis. The scientific methodology with which this research was carried out is explained in Chapter 3. The four bibliographies are summarized in Chapter 4. The limitations of the research and possible future work are discussed in Chapter 5, which also contains conclusions regarding the research. Part II consists of all four full articles listed in the bibliography.

Chapter 2

Background

As this Ph.D. project is a cross-disciplinarity study, this chapter will give a clear overview of the relevant significant background.

2.1 Cooperation and coordination

A supply chain consists of multiple stakeholders such as suppliers, manufacturers, retailers, and customers [33]. The notion of the supply chain has become highly complicated and dynamic due to the rapid development of economic globalization and the intense competition pressure in the market [6, 34, 35]. This is mainly due to customers now being more demanding, expecting better customized products and services at an acceptable speed and cost. In order to adapt efficiently to the changes in the market and remain competitive, firms are focusing on their core function and are moving towards collective and collaborative work through outsourcing [35], the development of advanced value chains and open innovation [36]. The success of any firm is therefore no longer built around its capability and capacity, but rather on the capability and capacity of the entire supply chain [35, 37]. As a consequence, the number of members in a supply chain has increased rapidly, and members are often scattered globally. Proper management is therefore required to improve the management of complex supply chains.

Supply chain management (SCM) emerged in the 1980s as a new and integral way of managing the flow of raw materials from suppliers to the ultimate users [38]. SCM improves the visibility and controllability of the entire process, which helps firms to improve the management of supply chains [6]. The primary focus in a supply chain is on cost and efficiency. Firms with efficient SCM can reap a large amount of profit with only a small percentage reduction in the cost of materials. SCM has become a competitive weapon for many firms in their attempts to be successful in this uncertain market [35, 39]. Over the past decade, there has been a rapid expansion in service industries, which has enhanced the need for creative innovations and increased service productivity to accelerate economic growth [2]. Given the new business models, such as the sharing economy, the service chain is now playing an increasingly important role. Some experts predict that the world economy will eventually be ruled by services [40].

2.1.1 Service chain

The common understanding of a supply chain and most definitions of it see it as involving the flow of a product from its point of origin (upstream) into the hands of the customers (downstream) [41-43]. The term ***product*** may be a tangible physical product or a service [1]. In my research, I have defined the service chain in which the "product" consists purely of intangible services and not direct involvement with a physical product. Among well-established service-chain sectors are healthcare body-checking, electricity utility providers, financial consulting and even fortune-telling [1].

In order to stay competitive, firms move into a great number of services, as numerous projections predict that the world economy will eventually be ruled by services [40]. One growing sector is third-party logistics [44]. For example, logistic firms offer services such as sharing information on the location of the purchased item in near real-time with their customers. Customers can also decide where to pick the item up or drop it off. Firms now realize that providing not only quality products but also quality services are huge drivers of a firm's profits. Even though service supply chains now play a crucial role, particularly in the logistics sector due to the expansion of e-commerce, this has still not been well researched [44].

In product supply chains, sharing information (i.e. stocks of products, quantities or orders) among members is a practice to enhance the efficiency and adding value to the entire supply chain. However, as the members of the chain grow in number and become more complicated, the degree of information reliability among them is compromised. Similarly, in opening up new service chains, information is a core element and is needed for decision-making purposes. It is important to understand how information is derived from data and how it is related to data.

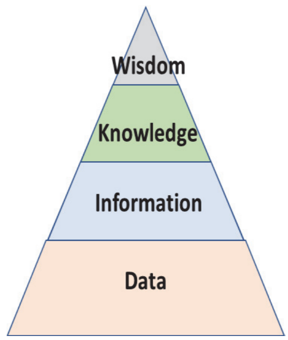
2.2 Data, information, knowledge, and wisdom (DIKW)

Information is identified as an important element in a service chain for decision-making purposes. It is also important to define the term *information*, as well as other terms like *data*, *knowledge* and *wisdom* (DIKW). DIKW has been discussed from the days of ancient Greek philosophers to more recent times, for example, by Ackoff (1989) or Bellinger (2004). The hierarchy that is referred to variously as the 'Knowledge Hierarchy', the 'Information Hierarchy' and the 'Knowledge Pyramid' is fundamental here [45].

There are differences in the perspectives and properties of DIKW as presented by Ackoff [3], Adler [46], Rowley [45] and Bellinger [47], but there are certain similar core elements of DIKW nonetheless. They can be summarized as in Table 1 (below). Ackoff's DIKW pyramid, as shown in Table 1, provides a graphic depiction of the hierarchy, from data in the bottom layer to wisdom, the topmost layer. Since in this thesis the core research is on information sharing, it is the information and data layers that are the focus of this work. Knowledge and wisdom are not discussed as lying outside my research area.

Table 1. Terms and core elements of Ackoff's DIKW pyramid

Term	Core elements
Wisdom	The capacity to place knowledge in a framework and apply it to different situations
Knowledge	Information that explains the know-how about something that provides insights
Information	Data that are put in context so as to be usable or meaningful
Data	Symbolic representation of objects, events and their environments



Ackoff [3]

2.2.2 DIKW and the IoT environment

Jennex [48] revised the DIKW Pyramid, as shown in Figure 2, which includes decision-support technologies such as Big Data or IoT-based sensors that reflect the current state of the real world. With digital advances in technology such as the Internet of Things (IoT) and the explosion of Big Data, there has been a shift from intuition-based decision-making to evidence-based decision-making [49-51].

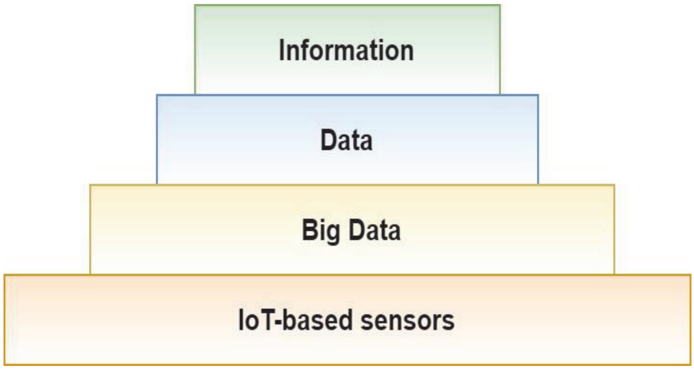


Figure 2. Revised DIKW Pyramid

This revised model shows that digital technologies can and must work together to improve the efficiency and effectiveness of decision-making. In both the revised and the traditional models, both information and data are needed to make decisions. In an earlier section, we saw that to establish cooperation between two firms, information sharing is key. Furthermore, pure data will not create the meaning for decision-making without the context.

2.3 Information silo

Information is important for firms faced with taking decisions. All information is usually stored and managed by information management systems, which are usually stand-alone systems also called "silos". Each box, as shown in Figure 3 below, can be viewed as a silo and can represent different departments within a firm. They are usually not connected with each other, which means that different departments often do not have access to the silo [52]. This can cause various operational problems, such as redundancy, inconsistency and integrity issues, frequently resulting in wrong decisions and planning mistakes [53]. Although currently information within firms is often still siloed and stored separately, personnel within the firm have easier access to it. For example, healthcare sectors often store and manage medical records and prescriptions in an electronic medical record (EMR) database to which clinicians within the same healthcare institution have easier access than people outside the organisation [54].

Figure 3. Information silo

As already mentioned in section 2.1, firms are moving towards collaboration in order to stay efficient and competitive by optimizing their core processes or services [55]. Information is important in coordinating efficiencies and effectiveness [56-59]. Having access to information can also assist in decision-making and enable quicker responses to market opportunities and changes [13]. Information is regarded one of the most valuable resources in remaining competitive in a supply chain and in building business-to-business exchange relations [8].

2.3.1. Information sharing

A key requirement for effective collaboration is that firms must be ready to disclose and share internal information with collaborative partners [55]. Information sharing represents the exchange of useful information between partners in a proactive and timely manner, as shown in Figure 4 [60, 61]. Product specification, the state of the product, ownership and even environmental impact are among the sorts of information that are widely being shared among related stakeholders for decision-making purposes [62], as well as to enhance collaborative work [14]. From a business cooperation perspective, information sharing has been identified as one of the most important preconditions for building trust in business-to-business exchange relations [12].

Due to digitalization, the volume of information sharing through interactions among members is increasing exponentially. This is due to the use of information technology such as the Internet of Things (IoT) and digitized and automated processes enabling firms to collect and process data and ultimately share information. However, large volumes of information confuse firms and buyers regarding which information to trust and what is relevant [6]. This is because information is constantly changing from the beginning to the end of the supply chain, thus producing several kinds of information on the service chain [15].

With a high volume of information, an information management system like enterprise resource planning (ERP) used in supply chain management is needed to store and facilitate information. Currently, there are different methods and tools for managing and sharing information. One of the most common methods, still widely used, is to engage a third-party service provider to facilitate and share information with multiple stakeholders. In Figure 4, Firm B is a third party managing information for Firm A. Often the service provider that owns the database system or the central authority has greater authority and control, and tends to have greater or fuller access to all the information than the data requester requiring certain pieces of information [8].

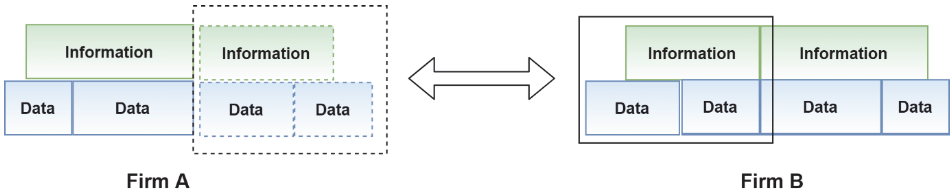


Figure 4. Information sharing

Typically suppliers possess more information about the product or services being supplied [8]. For example, product manufacturers have advantages in controlling the volume, accuracy and types of information they share with other members and consumers [6, 7]. Such information hierarchies result in information fragmentation leading to not all the members in a chain being able to obtain product information equally and indiscriminately [6]. This will create room for opportunistic behaviour.

2.3.2. Information asymmetry

Information asymmetry exists when a party or parties possess greater information and are better informed about some aspects of the exchange in a given situation relative to the other participating parties [4, 5]. Information asymmetry is often connected with opportunism [9] because buyers are not able to evaluate a service or product quality accurately before procurement [63]. In the case of the financial markets, the opportunity costs of lost transactions harms all parties that would benefit from greater amounts of economic activity within the given space [4].

It is common for firms (both buyers and suppliers) to invest in monitoring and control mechanisms to minimize this opportunistic and self-interested behaviour [10]. Information asymmetry is often the result of different information sharing practices, which was not intentional [4]. While some information may be deliberately withheld, as when suppliers possess more information, as shown by the different shapes in Figure 5, this creates room for dishonesty between partners. Anderson and Jap [11] suggest that information asymmetry could trigger suspicions among business partners, making it difficult to develop trust in and satisfaction with the relationship.

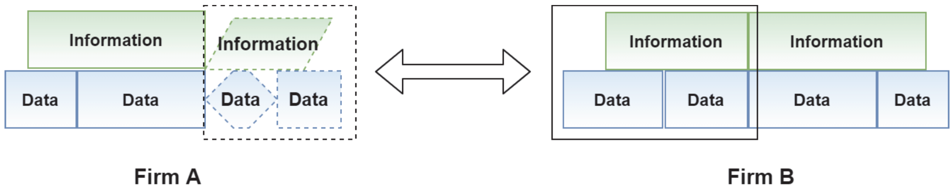


Figure 5. Information asmmetry

Tong and Crosno [8] demonstrated that information asymmetry is usually undesirable and that information sharing has more favourable impacts, particularly in consumer markets. Suppliers may share information to build relationships and reduce information asymmetry through various methods, as discussed in section 2.3.1. However, it is important to note that high levels of information sharing do not guarantee that information asymmetry will be eliminated [63] .

In this context, information trust refers to the reliability of information provided by one's commercial partners within a supply chain or central authority [64]. High levels of trust in respect of information are important for firms when it comes to decision-making over issues such as increasing profit margins and logistical planning. Overall, it acts as a catalyst to improve the efficiency of the supply chain. However, in reality many firms may be reluctant to share information with other members because of conflicting incentives [15]. This often leads to members lacking important information and possible compromises in the efficiency of the supply chain. In addition, volumes of such low-quality information are increasing. This thesis will not consider the willingness to share information or the incentives for information sharing within supply chains. It will focus instead on how an emerging technology such as blockchain technology can help reduce information asymmetry.

2.4 Blockchain technology

The term "blockchain" was first introduced with the launch of Bitcoin back in 2008 [65]. However, with the growing interest in blockchain outside the financial sector, the term has become more diluted in its definition [66]. The ISO/TC307 technical committee is currently working to standardize terms like *blockchain technologies* and *distributed ledger technologies* [67]. Since there is no standardized term for blockchain as yet, in this thesis blockchain technology is defined as a *distributed and decentralized tamper-evident digital ledger, in a chronological order, without any centralized authority,* as shown in Figure 6.

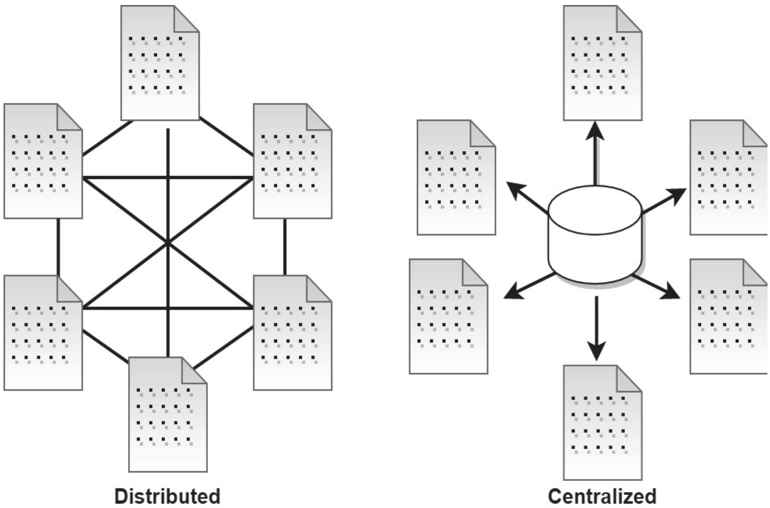


Figure 6. Distributed and centralized system

Blockchain technology runs on digital distributed computing networks [68]. No member of the network can control, tamper with or falsify important information in the network. Like data structure or a database, a ledger contains digital data records or transaction information [19]. It distributes validated, immutable transactions that are consistent between a large number of members in a network [21, 69]. Centralized databases do exhibit benefits such as larger storage and higher levels of efficiency, but they are also vulnerable to corrupted information and even the deliberate blocking of access during disputes by third-party service providers [18]. The data-storage structure and the consensus mechanism are among the important technical features of blockchain.

2.4.1 Data storage structure

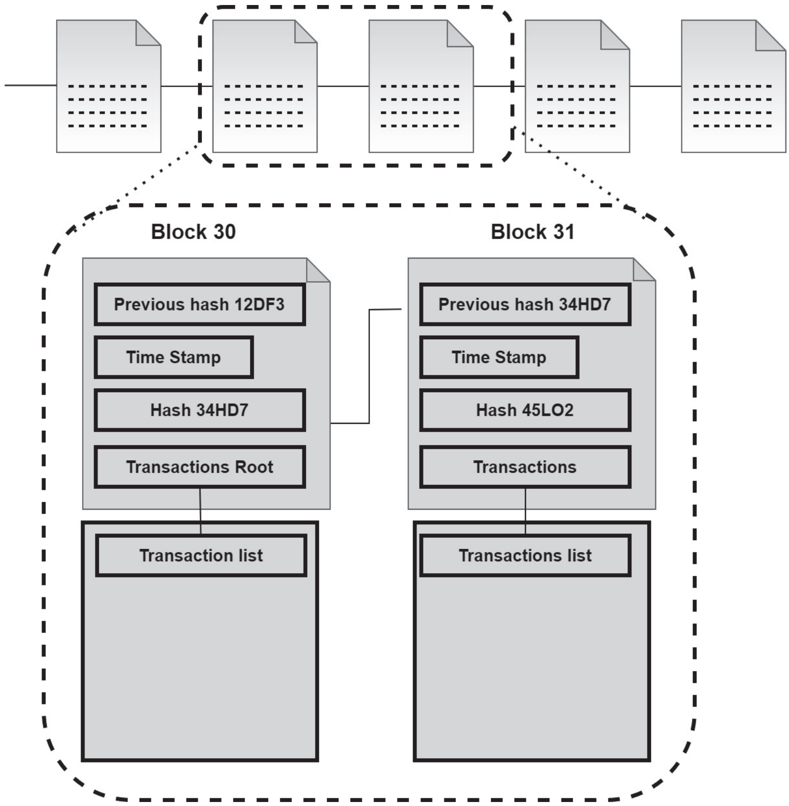


Figure 7. Simplified representation of blockchain

The data-storage structure offers a tamper-evident environment that prevents silent manipulation by making alterations obvious [70]. Data and information are aggregated into a block format, along with a time-stamp. Time-stamping is a way of keeping track of the time an event occurred. Each block is linked cryptographically (a form of encryption) to the previous block, forming a chain of records [71-73] that determines the sequencing order of events [19]: this is blockchain as shown in Figure 7. In blockchain, this link is used to provide tamper-evident storage.

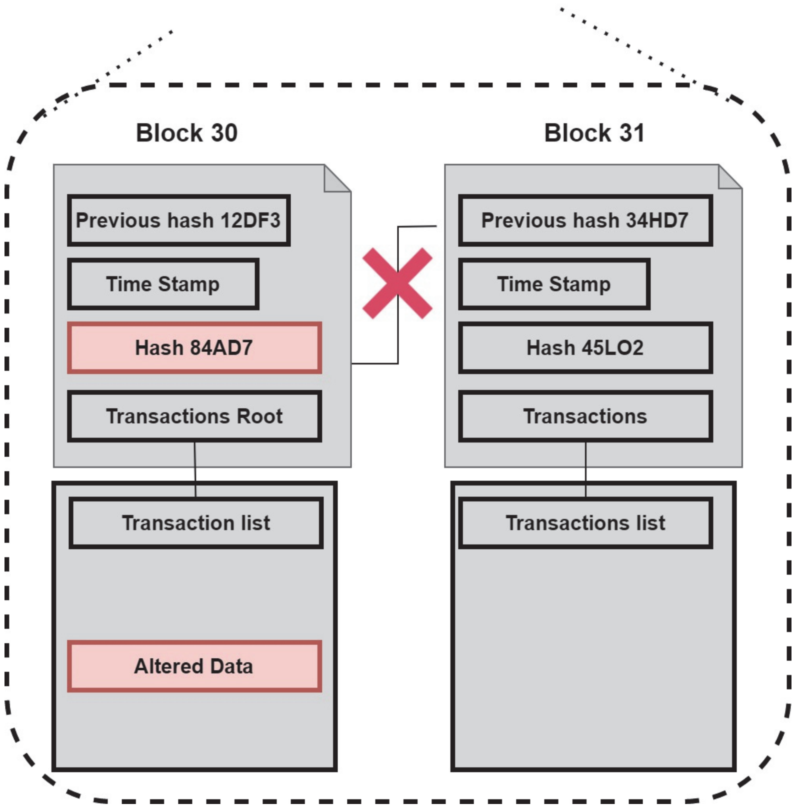


Figure 8. Altered data and hash breaking

Any attempt to alter stored information in blockchain, regardless the intention, breaks the cryptographic links, as shown in Figure 8. Thus, making the attempt and what has happened obvious maintains and ensures data integrity [70], a high level of which is needed when sharing information for decision-making purposes.

2.4.2 Consensus mechanism.

Another feature that plays a role in ensuring a high level of data integrity is the consensus mechanism, which verifies and adds information or data onto the blockchain. As any computer (node) in the network can generate or order a transaction [70], it is important to prevent false entries. As mentioned in section 2.4, blockchain technology runs on distributed computing networks, therefore it is important that most or all the computer (nodes) reach a consensus in order for a transaction to be accepted [74]. All computers in the network will communicate with each other with the goal of reaching a consensus [75]. Once the transaction has been accepted, it becomes part of the blockchain, and the new approved block is cryptographically linked to it. As more blocks are added, it becomes more difficult to change any information within the old blocks. Thus, the stored information becomes immutable.

Different types of consensus mechanism are being developed, the types of consensus to use depending largely on the types of services being implemented. For example, proof of work (PoW) is a consensus mechanism used in Bitcoin, while practical byzantine fault tolerance (PBFT) is widely preferred by private businesses. Each type of consensus mechanism determines aspects such as the transaction throughput, latency, scalability and security level of the blockchain [74]. For example, PBFT has high throughput and low energy consumption compared to PoW, while PoW has greater scalability compared to PBFT [68].

2.4.3 Smart contract

The smart contract is one of the most important features of blockchain [21]. A traditional solution is to use a third party as a trusted intermediary to monitor and execute the transaction as agreed. However, this solution is costly and prone to human error. Smart contracts enable a whole new type of regulation by transposing legal rules and contract agreements into technical and software rules [20, 76]. This relies on formal algorithms and mathematical code to regulate transactions as defined in the agreement, thus eliminating textual ambiguity [77]. In another words, it enables autonomous self-execution once a set of predefined rules has been met [77]. Less human interaction is needed, which saves the cost of negotiation and the time needed to communicate with members who may be scattered globally [21].

2.4.4 Public and private blockchain

There are two main categories of blockchain: private (e.g. Hyperledger) and public blockchain (e.g. Ethereum). They are slightly different in how the network is governed, and some blockchain features may be slightly different from those described in section 2.4. It is important to note that the variations in blockchain depend on where it is deployed. For example, a private blockchain may be more suitable than a public blockchain in the healthcare domain, as the former offers privacy and may be more compliant with data-protection regulations such as GDPR. Technical requirements such as throughput, which depends on the type of consensus mechanism, need to be considered when choosing a suitable blockchain [78]. Apart from technical requirements such as execution time and the latency of the network, boundary conditions [79] and solving key requirements [80] that fit the nature and type of the supply chain are important when choosing a suitable blockchain. In short, blockchain is not a one-size-fits-all technology [14].

Chapter 3

Summary of scientific methodology

3.1 Research design

Grounded theory is an analytical method for generating theories from inductive qualitative data using comparative analysis [81]. This approach is appropriate when little is known about a phenomenon [82] and when modifying existing theories or uncovering or expanding what is already known [83]. This thesis sets out to expand and uncover new knowledge from current theories. There are several distinct methodological genres of grounded theories, such as traditional and constructive theories, therefore classifying my work accurately in terms of theory is challenging. Nonetheless, in building and developing a new theory that is grounded in the data in order to answer my research question, the inductive approach is similar across all genres. In order to achieve this, the research for this thesis was designed as shown in Figure 9 below.

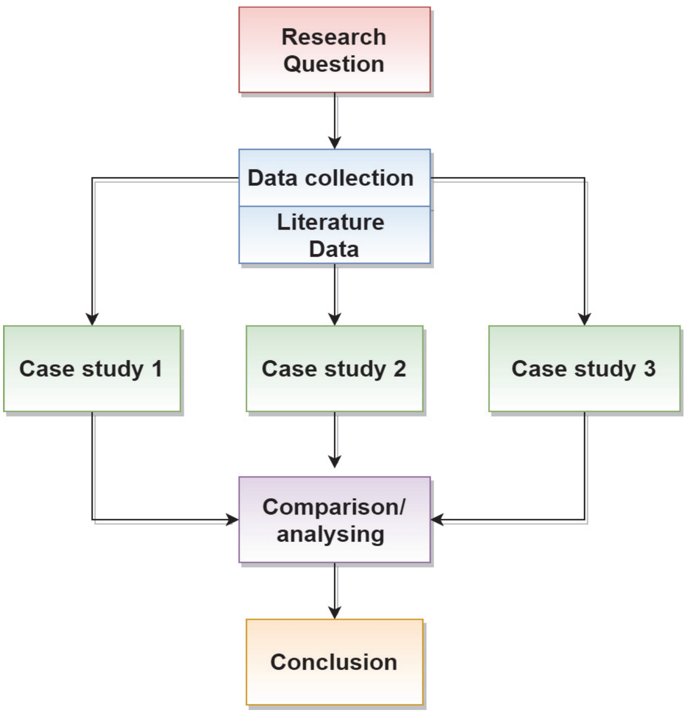


Figure 9. Research process flow

3.2 Research process flow

Research question

The first step is to identify the research question to be answered. A broad enquiry is conducted within the topic area, in this case ***blockchain technology*** and ***information sharing,*** with a view to understanding the problem. Relevant information regarding the topic area is collected to formulate a suitable research question. This step is important in navigating the right path for data collection.

Data collection

(a) Systematic literature review

A systematic literature review is deployed as part of the research design in order to collect various types of data, ranging from grey literature to extant data sources like published literature. The aim of this step is to understand the current state-of-the-art and to identify knowledge gaps within the chosen topics. In this research, the research question falls within the scope of information sharing and blockchain technology.

Case study

After identifying the current state of the art for blockchain technology and information sharing, I chose the case study as a method in three different domains: health care, smart cities and energy, as a basis for deeper research. In this step, the boundary conditions and key requirements of each domain are studied and identified. This is to ensure that the blockchain-based framework solution is feasible and fits the real-world scenario.

Comparison and Analysis

All case studies and the framework solution are compared and analysed to identify concepts and similarities. This step is intended to link the results of the collected literature review with the results from the case studies in order to draw conclusions from this research.

Chapter 4

Summary of included papers

4.1 Paper A: Blockchain-Enabled Information Sharing Within a Supply Chain: A Systematic Literature Review

P. K. Wan, L. Huang and H. Holtskog, "Blockchain-Enabled Information Sharing Within a Supply Chain: A Systematic Literature Review," in IEEE Access, vol. 8, pp. 49645-49656, 2020, doi: 10.1109/ACCESS.2020.2980142.

Purpose. Blockchain technology can solve the problem of fragmented information within complex chains of stakeholders. The purpose of this paper is to identify and understand the impact of this technology on information sharing within a supply chain.

Methods. A systematic literature review of the academic literature was conducted across five different databases to gather the widest possible samples. The collected materials, based on agreed criteria, are then exported for sorting and analysis. The process of the systematic literature review is shown in Figure 10.

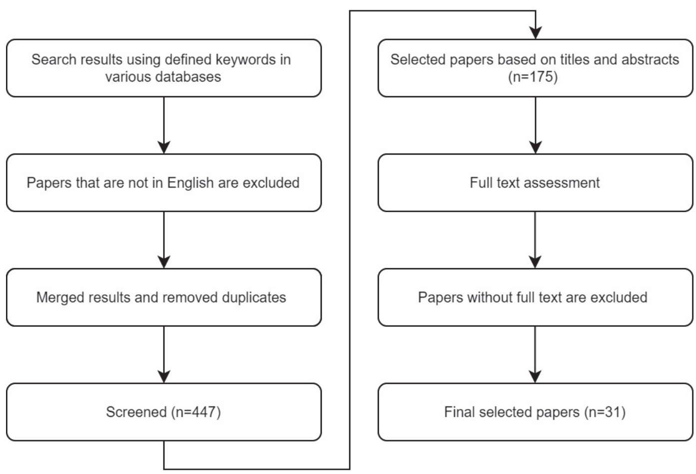


Figure 10. Systematic literature review process flow. From Paper A [14]

Findings. Thirty-one items of literature were collected and placed into the categories of "information sharing" and "information asymmetry", as shown in Figure 11. Twenty-four of these items (77%) focused on information sharing. Different types of supply chain, on, for example, health and medical, construction and smart cities, and even the military, focused on how blockchain-enabled information sharing with high levels of data trust that data in ways that can increase the efficiency of their respective supply chains. The remaining literature items focused on information asymmetry within a supply chain.

We then further categorized the literature items into "blockchain-based" and "other" solutions. Twenty-seven literature items (87%) used blockchain-based solutions to reduce information asymmetry or to facilitate information sharing. Four items of literature use other solutions in making decisions under conditions of information asymmetry. These were selected because they highlight knowledge gaps for which blockchain can be deployed not only in sharing information but also in hiding it.

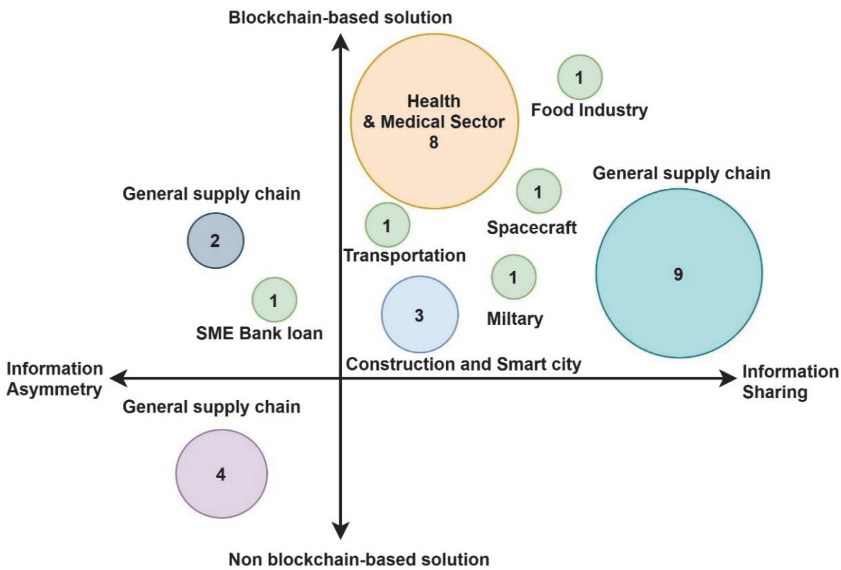


Figure 11. Literatures sorted based on types of information and solution. From paper A [14].

The removal of information silos offered by this technology has caught the attention of researchers from different types of services. For example, the role of blockchain in the healthcare service sector is to provide effective collaborative treatment and care decisions. Obtaining access to the correct information is often the main challenge faced by all sectors, particularly healthcare, which can involve issues of life or death. Current systems are not at the stage of secure, high-level information sharing among the relevant stakeholders like medical professionals (outside the medical institution), patients, researchers and even insurance firms, which creates difficulties for them. This raises the issue of the ownership of medical-record data and information.

Blockchain technology enables information sharing in a more transparent manner, which can improve collaboration and partnership. For example, construction firms can manage day-to-day work effectively if they can obtain trusted information from logistics partners about when materials will arrive. Another benefit offered by blockchain technology is the potential to remove additional auditing costs to ensure they receive goods and services as agreed. Ultimately, this can simplify procurement activities.

Blockchain-based information sharing offers operational benefits, but we found that in reality, the feasibility of a chain of firms agreeing to this may not be high. This is due to the high visibility of information not being ideal for any firms in a highly competitive market. In order not to obstruct progress with this technology, a suitable balance between information sharing and information hiding should be a parallel focus during the design phase.

Conclusion. We agree with all the published literature that this technology can enhance information sharing with higher levels of trust in data and reduce costs by eliminating regulatory compliance, but this is not a once-size-fits-all technology. To improve the bridging of blockchain with real-world contexts, the nature of the service chain, the boundary conditions and the level of information sharing must be studied and investigated.

4.2 Paper B: Reducing Alert Fatigue by Sharing Low-Level Alerts with Patients and Enhancing Collaborative Decision Making Using Blockchain Technology: Scoping Review and Proposed Framework (MedAlert)

Wan PK, Satybaldy A, Huang L, Holtskog H, Nowostawski M "Reducing Alert Fatigue by Sharing Low-Level Alerts With Patients and Enhancing Collaborative Decision Making Using Blockchain Technology: Scoping Review and Proposed Framework (MedAlert)", J Med Internet Res 2020;22(10):e22013 doi: 10.2196/22013

Purpose. Clinical decision support (CDS) is a tool that helps clinicians make decisions by generating clinical alerts to supplement their previous knowledge and experience. However, CDS generates a high volume of irrelevant alerts, resulting in alert fatigue among clinicians. This study aims to explore how a blockchain-based solution can reduce alert fatigue through collaborative alert sharing in the health sector, thus improving overall quality of health care for both patients and clinicians.

Methods. We designed a 4-step approach, as shown in Figure 12, to solve the problem of alert fatigue. First, we identified five potential challenges based on a scoping review of the published literature. Second, a framework is designed to reduce alert fatigue by addressing the challenges identified using different digital components. Third, an evaluation was made by comparing MedAlert with other proposed solutions. Finally, the limitations of the research and possible future work are also discussed.

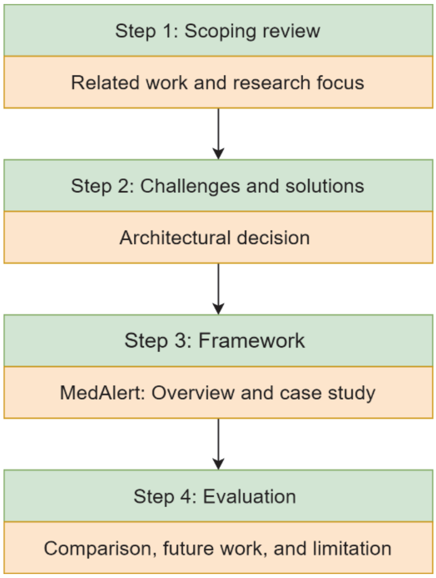


Figure 12. Research design process flow: 4-step approach. From Paper B [70].

Findings. 8 papers were selected and analysed out of 341 items of literature collected initially. We identified five main key challenges: (1) data integrity, (2) privacy issues, (3) patient identity, (4) lack of secure information sharing and (5) the extent of patient's knowledge in the medical field, as shown in Figure 13. These challenges must be taken into consideration in order to design and develop a feasible framework for reducing alert fatigue within the healthcare sector.

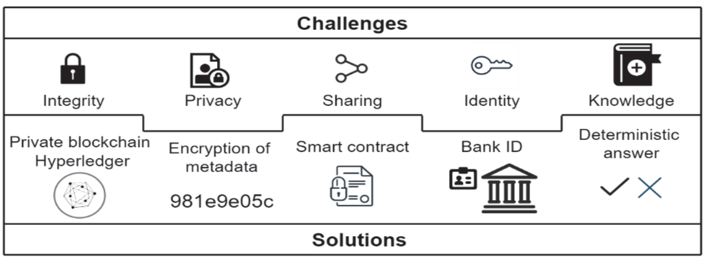


Figure 13. Architectural decisions in addressing the 5 key challenges. From Paper B [70].

We found that the best way of reducing alert fatigue is to task someone to attend to alerts, rather than reducing the total number of alerts. This is because the benefit of reducing certain alerts remains unclear. Currently, there is shift towards patient-centric data-sharing to enhance collaborative decision-making, but relevant work remains limited due to the five challenges set out above.

In our work, we open a new healthcare service by directing low-level alerts to patients when making decisions in order to reduce medical errors due alert fatigue. This approach is intended to improve communication between clinician and patients. There is a risk of significant medication error when the clinician does not query and validate certain health information. The risk can increase when generated alerts are overridden due to alert fatigue. Therefore, when patients receive an alert and they are uncertain, they can enter into direct communication in order to avoid preventable errors.

Conclusion. We agree that the way to reduce alert fatigue is to gain clinicians' attention while they are attending to patients. However, there is no perfect solution in which clinicians are able to address all the alerts generated, not even the removal of irrelevant alerts. Blockchain-based technology can provide a new layer by engaging patients in providing responses.

4.3 Paper C: Development of blockchain-based automated infectious risk assessment alert system: a case study in an office building

Wan, Paul, Lizhen Huang, Zhichen Lai, Xiufeng Liu, Mariusz Nowostawski, Halvor Holtskog, Guanghua Yu. “Development of blockchain-based automated infectious risk assessment alert system: a case study in an office building”. *Energy*

Status: under review

Purpose. Indoor air quality (IAQ) is an important parameter in protecting the occupants of an indoor environment. Indoor environments with poor ventilation have increased airborne virus transmission, and ultimately, they will become hotspots for such transmission. Infection risk assessments can estimate virus transmission via airborne routes. From our literature search, we did not identify any systems integrating risk assessments with smart sensors to support experts in indoor environments in their decision-making. One of the reasons for this is that the complex stakeholders involved make information sharing difficult.

Methods. CrowdTrac is a blockchain-based prototype which integrates CO_2 sensor data with infection risk assessments from a post-pandemic perspective. Our novel blockchain-based alert framework integrates infection risk assessment tools and IoT to enable early decision-making, as shown in Figure 14.

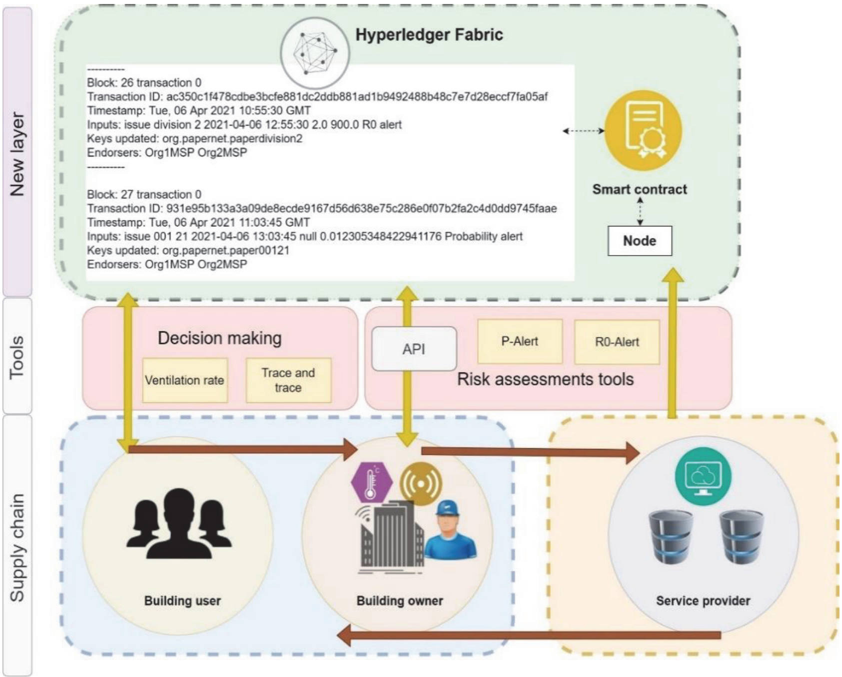


Figure 14. Blockchain-based alert system framework (CrowdTrac). From Paper C.

Multiple stakeholders are involved in requesting data to obtain information. The workflow of requesting building sensor data and information runs from a building user (requestor) to the building owner and finally to a third-party service provider, as shown in Figure 14. It is usual for the building owner to engage the third party to store and manage sensor data, which sometimes requires a service fee. Ultimately, this reduces the efficiency with which data can be obtained and makes collaborative work and analysis challenging.

In this framework, we used two infection risk assessment models: **(1)** the probability of infection (P), and **(2)** the basic reproductive number (R0). The experiments were conducted in an office on an office floor with twelve meeting rooms with doors and open desks with seating. No HVAC system is installed on the office floor, whose occupants mostly rely instead on natural ventilation. A digital gas sensor for monitoring indoor air quality such as CO_2 levels is installed in the meeting room with a sensor directly measuring CO_2, as shown. The area of the room is $12m^2$ with 3m height.

Findings. We found that, with information sharing, this solution can be used as a long-term approach in protecting occupants from viral infections in an indoor environment by sending an alert to building users, thus enabling infection risk analysis using sensors, unlike other alerting solutions. Although our framework can only cover a confined space like an office, it can play an important role and could be used long-term in assessing the condition of indoor environments using built-in sensors and infection risk assessment tools, as well as passive tracking without the need to check in.

We also found that blockchain can increase the transparency of vast amounts of data in a centralized database. With a timestamp alert that highlights anomalous events, transparency is enhanced by pinpointing the exact time at which to begin tracing and investigating the potential spreading by using datasets around the timepoint. This can increase the efficiency of digital forensics through deeper and more holistic analyses by using all the information on indoor air quality around that timepoint.

Conclusion. Our work opens up new services by integrating blockchain technology and building sensors with risk assessments to generate alerts of potential airborne virus transmission for early decision-making by the building owner. This immutable event can enhance digital forensics by tracking other anomalies that may have occurred at that timepoint. CrowdTrac can be useful in refining both public and risk management strategies, thus enabling epidemiologists to reduce the risk of indoor infection. However, it is still at an early stage, and a lot of work still needs to be done to realize this model as a new service in making smart buildings smarter.

4.4 Paper D: Energy tracing and blockchain technology: current state-of-art.

Wan, K Paul and Lizhen Huang "Energy tracing and blockchain technology: current state-of-art" 4th International Conference on Intelligent Technologies and Applications (INTAP 2021); Norway, 2021

Status: Accepted

Purpose. It is challenging to verify the provenance of the electricity because of the complex distribution networks involved. There is extensive research on using blockchain to track the provenance of food throughout the entire supply chain. However, the focus on the provenance of electricity remains small. The aim of this paper is to draw a clearer picture of the current state of the art of electricity tracing in the energy sector.

Background. Electricity can be generated from two types of sources: (1) renewable sources such as solar, wind and hydro; and (2) non-renewable sources like fossil fuels. For example, in a fossil-fuel plant, electricity is generated through the conversion of heat energy into electricity and is then transmitted through a series grid to the final consumer, as shown in Figure 15. Both energy sources generate electricity to support day-to-day living, but they have different impacts on the climate.

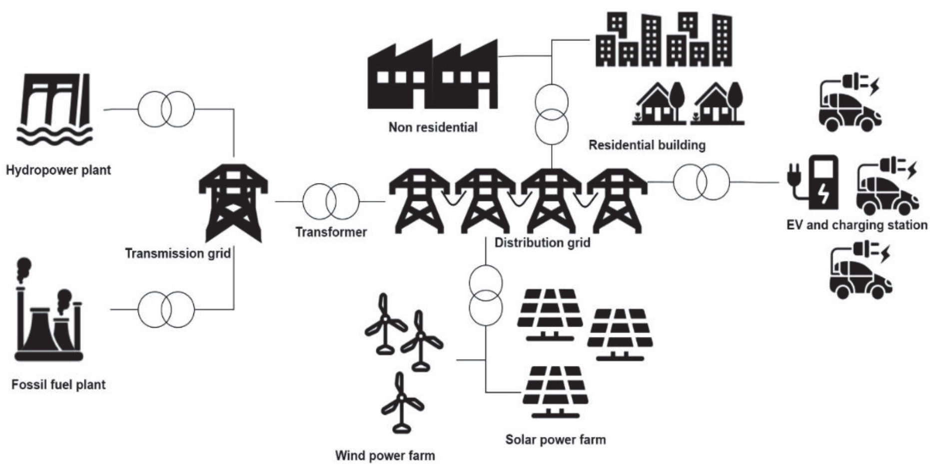


Figure 15. Layout of general electricity network. From Paper D.

Methods. To answer this question, a systematic literature review was conducting to address the two research tasks.

Findings. We initially collected a total of six papers. After a thorough screening based on our systematic literature search, only one paper fitted our criteria. Similarly, from our search in the commercial sphere, only one commercial project focused on energy tracing using blockchain technology.

We found that tracing electricity is challenging because of its non-physical properties. The concept of tracking the provenance of food is easier, as the current approach is to assign a unique identifier to the physical product, but that is not the case for electricity tracing. The fact that energy flows are highly dynamic makes electricity more challenging to trace from the source of the electricity to the final consumer.

We agree that renewable energy sources (RES) are a better alternative compared to fossil fuels when it comes to greenhouse emissions, but the volatile supply of energy that characterizes them only serves to amplify this complexity, which in turn makes the tracing of energy harder. Batteries may provide alternative storage for energy from RES during good weather conditions, but it faces issues such as reductions in power quality and increased energy losses during charging.

Conclusion. Current methods of trading green energy certificates may not accurately identify the energy source, since electricity is highly dynamic. Our work highlights the need to focus on energy tracing, although we did not find much relevant literature nor many commercial projects focusing on energy-tracing at this stage as yet. Nonetheless, it is vital to understand the entire end-to-end process from electricity generation to consumption in order to have a positive impact on climate change.

Chapter 5

Results and discussion

5.1 Discussion

From all the collected literatures in **Paper A**, they all agreed on that blockchain can reshape the element of information sharing by ensuring all members can obtain verified information within a supply chain. Information sharing not only helps establish partnerships in different types of supply chain like healthcare (**Paper B**), smart buildings (**Paper C**) and energy (**Paper D**); it can boost profits within supply chain particularly with reliable information [84]. From **Paper A**, a majority of collected literatures focused on healthcare sector where blockchain can provide an effective collaborative treatment and care decision which brings advancement in the sector [85].

Although the construction and smart-city sector is the slowest industry in digital transformation [86, 87], **Paper A** collected 3 out of 31 items of literature that focused on blockchain-enabled information this sector. Blockchain can solve the integrity of the information stored and recorded in building information modelling (BIM), a software which uses construction information to manage building design [88]. For example, when someone updates the BIM model, all information, such as the changes and who is responsible for the change, is recorded chronologically and shared with all participants that are working on the same model. This new layer can enhance information ownership and transparency, which can improve the efficiency of the collaboration.

Despite the extent of the literature collected emphasizing the advantages of information sharing with blockchain [89], **Paper A** highlighted that information sharing is never simple in real-world scenarios. **Paper A** identified various existing methods of storing and sharing information, such as using third parties, institutional trust (contractual agreements) and simple email. However, not all types information can be shared easily due to strict regulations [66]. For example, sharing medical information remains a huge challenge because medical information is highly sensitive and is usually owned by a healthcare institution. Different electronic health-record systems in each health institution can further complicate information sharing [90]. **Paper A** concluded that it is important to place a strong focus on understanding the nature of the supply chain, such as identifying the boundary conditions and the key requirements in developing an architecture for information sharing that fits the nature of supply chain sharing as a part of the future development of blockchain.

Paper B presented a case study to explore how blockchain-based solutions can enhance horizontal information sharing in the healthcare sector. In this case study, the main issue that was identified is that information does not flow beyond the health institution owing to strict regulations when it comes to sharing information with health institutions outside one's own institution. Currently, clinicians are filled with high amounts of low priority alerts and gradually become less responsive to them, which opens the door to preventable medication errors [91].

The blockchain-based framework (MedAlert) in **Paper B** opens up a channel for the horizontal flow of information alerts from clinicians to patients. When a low-priority alert is generated by the CDS system, this triggers the smart contract embedded in MedAlert and shares the alert with the patients. All the events are stored in blockchain, where the patients can also view them. MedAlert can act as common layer of information sharing to capture the attention of either patients or clinicians so they attend to the alert and thus prevent a potential medication alert. This novel solution can move towards collaborative decision-making between a clinicians and patients to avoid potential medication errors resulting from actions being overridden. Ultimately, this can improve the quality of the healthcare domain with respect to better patient outcomes and reduce physician burn-out.

Paper C explored the smart building sector by investigating the use of blockchain technology in vertical data-information sharing. Most buildings have sensors incorporated in them to monitor indoor air-quality (IAQ) parameters to protect indoor occupants. Most of the sensor data are stored and managed by third-party service-providers. Although data-sharing of IAQ is less restricted than health care because it does not intrude on personal privacy, it often comes with a service fee from the service provider. This reduces the overall efficiency to obtain data for analysis and improvement work.

In **Paper C**, a blockchain-based framework (CrowdTrac) aims to assess the potential viral infection based on CO_2 concentration levels in the room and sends an alert to building owners to take the necessary actions to protect the indoor occupants. The CO_2 concentration level in the room is continuously measured using a sensor and used as input the estimate risk. When the CO_2 concentration level exceeds the pre-set R0 risk threshold, it triggers the smart contract-embedded blockchain and sends an alert to the building owner, who can then take various actions, such as increasing the ventilation rate or taking no-action.

As mentioned in section 2.2, information is data placed in context: sharing pure data will not create any meaning or aid in decision-making. With respect to the vertical sharing explored in **Paper C**, a newer service can be created for decision-making by transforming IAQ data into a new parameter in a smart building to reduce the risk of indoor infections. Ultimately, this can aid in creating a smarter building.

Information sharing can not only establish new collaborations, but also open up new services. However, one key concern is data quality. Blockchain technology offers higher data quality, which can be a complementary tool in ensuring that shared information is not tampered with. This is very important in ensuring that good decisions can be developed from correct information in all sectors. **Papers B** and **C** are both examples where high levels of data quality are crucial when it comes to making decisions. For example, in the healthcare sector, making decisions based on low-quality information can have huge impacts on the patients.

The energy domain faces issues like the quality of the information sharing. **Paper D** highlighted the need to ensure claims when sharing information about "using only green energy sources" to supply electricity, with hybrid perspectives in both the horizontal and vertical contexts. Examples include smart-meter data-sharing horizontally and the impact of smart-meter data regarding occupant behavior on energy demand vertically with stakeholders. The push towards greener options is now a deciding factor and conforms with national regulations. Due to the complexity of how electricity is generated, transmitted and distributed, electricity-tracing is complex, making it difficult to justify the greenness of the different types of electricity.

5.2 Theoretical and practical contributions

In this research, I have identified the potential roles of blockchain in facilitating information sharing within a supply chain. The contribution of this research is accordingly summarized below:

- Blockchain enables new forms of vertical information (data-information sharing). It is more usual to share data or information on the horizonal level based on the DIWK model. Embedding smart contracts in blockchain enables autonomous self-execution once a set of predefined rules has been met. As a result, data can easily be placed in their meaningful context during the sharing process, as demonstrated in Paper C. This can lead to new ways of sharing data and information and ultimately increase the efficiency of a complex chain of stakeholders.

- Another outcome of this research on information sharing is that it shows the benefits of, for example, opening up new services with the help of digital tools like blockchain. Some papers argue that information sharing can often result in conflicts of interest. However, based on my research, information sharing in Paper B can be shown to have benefits, such as reducing preventable medication errors through collaborative care decisions and preventing clinicians from burning out. However, health-related information sharing is often difficult due to strict health regulations.
- In reality, the data and information layers based on Ackoffs's DIKW pyramid are fragmented and disjointed, making the transformation of data into meaningful information challenging. This may be a result of information silos and asymmetry, which may be due to unintentional information sharing practices. From this work, blockchain can play a role as a bridge in connecting and enabling the sharing of both data and information among stakeholders within a complex supply chain.
- Another outcome is that blockchain does not replace centralized databases because of certain downsides, such as single-point failures and being more prone to tampering due to different authority levels regarding access, as discussed in Paper A. However, in designing the framework of Papers B and C, blockchain represents an additional layer, rather than replacing centralized databases, despite their having similar functions in storing information. Conversely, blockchain can reduce the dependence on third parties in respect of the verification and control over the data, which could complement the centralized database.
- A copy-and-paste approach would not be practical when designing a blockchain-based framework. It is important to understand the nature of the domain, the technical requirements and boundary conditions like privacy, which must be studied and understood in designing a feasible solution using this technology.

5.3 Limitations, challenges and future work

These papers have brought new insights to information sharing with higher levels of trust in data using blockchain technology. There are some limitations in each of these works. Although a lot of the literature expects blockchain technology to gradually reduce reliance on third-party service-providers for information sharing purposes, which is costly and gives greater authority over the information, **Paper A** showed that many business leaders remain unsure what this technology means for their firms.

Information sharing can open up new services to enable more collaborative decision-making. Challenges such as ethical and privacy issues could be significant, as highlighted in **Paper B.** It is difficult to find the right balance of information sharing with new partners, despite the potential improvements in the effectiveness of decision-making. Although this technology can enable new services and improve effectiveness, future work on firms' perceptions and the acceptance of such newly enabled services are important to ensure smooth deployment.

In order to implement the findings of **Paper C** in a real-world scenario, future work is needed to address other key requirements and the nature of service supply chains to ensure the feasibility of this work. Furthermore, while a quantitative evaluation can complement the qualitative evaluation, it can also demonstrate the actual performance evaluation, which is currently lacking in the research domain. Without documented performance in real industrial situations, it is often difficult to persuade enterprises and gain support from the top management to incorporate this technology as part of the digital transformation.

Paper D only explored the current state of the art of energy tracing, due to the lack of access to data and information collection, such as smart-meter data within a neighbourhood. In future work, data collection in small neighbourhood will be needed for a meaningful analysis. Also, it will be important to identify the relevant stakeholder within the service chain of the electricity domain, as well as useful data and key requirements and boundaries. Other future work might seek to understand the applicable data regulations on storing data, since patterns of energy use can produce insights into the behaviour of a building's occupants.

Additional Paper I investigated General Data Protection Regulations (GDPR) and blockchain application in the healthcare sector. The role of GDPR is to regulate the collection, processing and securing of personal data to minimize the risks of privacy violation. However, GDPR could be violated due to the immutability nature offered by blockchain. Although in **Paper B,** the framework only stores metadata, not actual health data, to ensure a higher levels of privacy protection, researchers should work on, for example, Art. 17 (Right to erasure or to be forgotten) in cases when users want to have their data completely erased or deleted.

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Part II:
Original papers

Paper A

Blockchain-Enabled Information Sharing Within a Supply Chain: A Systematic Literature Review

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Blockchain-Enabled Information Sharing Within a Supply Chain: A Systematic Literature Review

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ABSTRACT A supply chain consists of many stakeholders such as suppliers, carriers and customers. It is often complex due to the rapid development of economic globalization and the intense competition pressure in the market which resulted in information sharing within a supply chain to be fragmented. Blockchain technology can solve this problem by having only a "one trusted ledger" that could reshape the element of data trust. The goal of this paper is to identify and understand the impact of blockchain technology for information sharing within a supply chain. The decentralized nature of blockchain technology offers a high level of transparency and has gained the attention from various sectors to deploy this technology. A systematic literature review in the academic literature was conducted using different databases. Blockchain-enabled information sharing can add value to enhance collaborative work in different types of supply chains such as health and medical, construction and smart city. From our findings, one potential impact of deploying blockchain-enabled information sharing within a supply chain is that it ensures all members in the chain can obtain verified information which enhances collaborative partnerships. Through this in-depth research, we highlighted potential barriers that could impede the development of blockchain technology in supply chain such as the lack of understanding of blockchain technology in businesses and conflict of interests. Future work such as information hiding, in parallel with information sharing, could close the gap in deploying this technology within a supply chain. Understanding the nature of different supply chain is also important to better prepare the deployment of blockchain. We acknowledge that our approach in selecting literatures in our systematic review may exclude certain literatures. Nonetheless, we tried to include as many relevant literatures as possible, to develop a roadmap on the current situation of blockchain-enabled information sharing within a supply chain.

INDEX TERMS Blockchain, smart contract, supply chain management, information sharing.

I. INTRODUCTION

A supply chain comprises many stakeholders such as suppliers, manufacturers, retailers, carriers and customers [1]. With the rapid development of economic globalization and the intense competition pressure in the market, supply chains have become highly complicated and dynamic [2]–[4]. This is mainly due to the fact that customers are now more demanding, expecting better customized products and better customer service that comes with an acceptable speed and cost. In order to adapt efficiently to the changes in the market and remain competitive, companies are now focusing on their core function, and are moving towards a collective and collaborative effort [4] such as outsourcing, development of advanced value chains, and open innovation [5]. Consequently, the numbers of members within a supply chain have increased rapidly. These members are often scattered globally, which result in information to be highly fragmented. Thus, to better manage and facilitate information sharing among the members within a complex supply chain, a higher co-ordination cost is needed in the form of e.g. quality systems, production standards, etc. However, information asymmetry still exists in the current supply chain.

Information asymmetry is often connected to opportunism in transaction cost economics [6], where information is not fully shared among collaborative partners, and creates room for dishonesty between partners. This interpretation is not what this paper deals with. Our understanding of information asymmetry is defined as hidden information [7], [8], which could be either intentional or unintentional. This happens

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when not all members within a supply chain obtain product information equally and indiscriminately [3]. Typically, product manufacturers have advantages in controlling and hiding the volume, accuracy and types of information to share with other members, and even to consumers [3], [9]. Conflict of interest is one of the main reasons for hiding information from other members [10]. This low transparency and highly controlled information flow reduce data trust among members and the efficiency of a supply chain. Data trust in this context refers to the reliability of information and data provided by trade partners within a supply chain or central authority [11]. Accurate data trust in information sharing can act as a catalyst to improve the efficiency in a supply chain.

To decrease the transaction cost, information sharing is identified as an important strategy. Information sharing is where members within a supply chain share information such as product specification, the state of product, ownership, location of data, and even the environmental impact [11]. Information sharing is important for firms which go beyond decision making processes such as increasing profit margin and logistics planning. It is also a key element to enhance collaborative work among members. However, information is constantly transforming from the beginning to the end of the supply chain [10] and the volume of information increases exponentially. With the large volume of information distributed, this could confuse firms and buyers on which data to trust [3], because there is no verification of the truthfulness of the information provided. Thus, there is a need for a better information sharing tool to combat fraud, pilferage, and enhance poorly performing supply chains [12].

Blockchain technology can solve this problem by having only a ''one trusted ledger'' that could reshape the element of trust. It is a type distributed ledger technology that can be a solution to a trustable information sharing, by providing a permanent digital footprint to all members in the network. This means every approved transaction occurred throughout the supply chain is recorded in a tamper-evidence environment. Any malicious attempt to alter the information will be obvious and evidential. Blockchain technology can also couple with the Internet of things (IoT) and smart devices to digitize and automate processes to collect and share information in real-time with other members, which improves the transparency and increases the efficiency of a supply chain. These potential impacts on supply chain has caught the attention of many researchers. However, the holistic contribution and barriers of blockchain-enabled information sharing within a supply chain remain unclear. Therefore, in this paper, we will investigate and understand how blockchain technology can change current information sharing within a supply chain.

A systematic review will provide a clearer picture on current exploration and research work on information sharing within a supply chain [13], [14]. This can give a deeper knowledge by identifying the potential benefits which are unclear, challenges that hinder the growth of blockchain technology, and knowledge gap in this domain. Our systematic literature review aims to answer the following research question (RQ):

- RQ1: How blockchain technology has an impact on information sharing in the supply chain

To answer our main research question, we have defined 3 research tasks (RT):

- RT1: To identify industries where blockchain technology can have a significant impact on information sharing within a supply chain
- RT2: To investigate the current potential challenges or barriers in the deployment of blockchain within a supply chain
- RT3: To identify future development of information sharing using blockchain technology within a supply chain

This paper begins with a summary of the various methods in managing information sharing among members within a supply chain in section II, and is followed by the introduction of blockchain technology and smart contract in section III. Section IV explains the research methodology in conducting the systematic literature review and material collection. Section V discusses the current state-of-the-art and the findings from our defined research questions. We conclude the paper in section VI.

II. VARIOUS METHODS IN FACILITATING AND MANAGING INFORMATION SHARING

Currently, there are many methods to facilitate information sharing (e.g. Quality assurance with third party intermediaries, direct integration, hub-and-spoke architecture and verbal communication). These methods exhibit many challenges that inhibit the efficiency of a supply chain. We understand that there are other means of managing information but in this paper, we focus methods such as third-party intermediaries, institutional trust and communication as summarized in Table 1.

These methods are still commonly used for information sharing. However, the level of trust-worthiness of the documented data and distributed information is of poor quality and often fragmented [15]. The lack of data trust is a huge barrier for the integration of business process across organizations [15], [16]. Thus, new technology such as blockchain technology could solve these challenges by enabling a new form of digital data trust.

III. WHAT IS BLOCKCHAIN TECHNOLOGY AND SMART CONTRACT

Blockchain technology offers a decentralized environment that is built on data trust using a digital approach [22]. Weber *et al.* [16] insisted that blockchain could be an emerging technology for decentralized and transactional data sharing across a network of untrusted participants. It distributes validated, immutable transactions that are consistent to a large number of members in a network [22], [23]. In this decentralized environment, there is no member in the network that can control, tamper with or falsify important information, because

TABLE 1. Summary of current methods in facilitating and managing information sharing.

Methods	Purpose	Challenges	Authors
Third party intermediaries (Centralized database System)	To store and manage information and data in a centralized database system **Example:** **Medical and health sector:** To store and secure various forms of sensitive medical records. **Manufacturing sector:** To store and share information such as quality, certifications, site documentation.	1. Vulnerable to abuse 2. Incur high cost 3. Strict legal regulation for sharing 4. Fragmented and scattered information 5. Paper-based documentation 6. Difficult to justify the accuracy of information 7. Vulnerable to hacking	[15] [17] [18] [15] [12]
Institutional trust (Textual contract and agreement)	To regulate and control behaviour of members in the network based on legal framework and agreement	1. Textual agreement is subjective and inherent with ambiguity 2. Legal action are lengthy and bureaucratic	[4, 19] [20]
Communication (phone, face-to-face, field visit)	To understanding the production process flow, existing quality certifications and to share common values	1. Time consuming 2. Incur high cost 3. Difficult to manage communication efficiently with all suppliers	[21] [3]

it is no longer a single-point storage within a centralized system.

Every single transaction is verified through consensus within the decentralized system and stored in a block format. Reaching a consensus agreement by all participants in the network, before recording it permanently, is the key feature of blockchain technology [24], [25]. The participants of the network then proceed to validate the information and create a block. Each block is linked with another block forming a chain [26], [27]. This provides traceable and transparent information to all members. Smart contract is one of the most salient features [22], and can be embedded in blockchain.

Smart contract removes the requirement for a centralized third-party to manage, verify and store information in real-time [24]. It enables a whole new type of regulation by transposing legal rules and contract agreements into technical and software rules [20], [28]. It relies on formal algorithms and mathematical code to execute transactions autonomously when all the requirements are fulfilled, as defined in the smart contract [29]. This resulted in lesser human interaction being needed, which saves cost of negotiation and time needed to

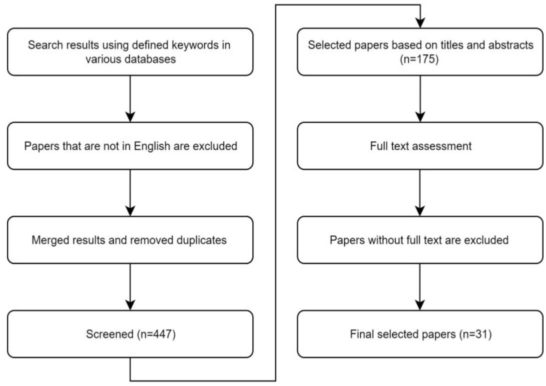

FIGURE 1. Systematic literature review process.

communicate with members that are scattered globally [22]. Although blockchain technology is still at its early stage when it comes to application in businesses apart from cryptocurrencies like bitcoin, there is a growing interest in transforming and building a more robust data trust in various industries.

In short, blockchain technology can enable a new form of data trust to mitigate those challenges as shown in Table 1. It has also been speculated to have a strong impact on supply chains on how information is shared among members in a secure manner, with no centralized third party to govern data and information. It also redefines the rules and regulation of information sharing using smart contract. Today, attention from the academic sphere on this emerging technology within a supply chain is increasing.

IV. RESEARCH METHODOLOGY

A. CONDUCTING SEARCH

This paper will perform a systematic literature review to investigate the topic of blockchain-enabled information sharing within a supply chain. This methodology provides a transparent and reproducible process of selection, analysis and reporting of previously conducted research of selection on a specific topic [30], [31]. The main purpose is to explore the current existing state-of-the-art of academic research on information sharing and blockchain. In order to have a widest coverage of all published literature, we carefully planned our systematic literature review process and is summarized as shown in the Fig 1 as shown below.

The review of material starts as early as in 2008, since the term blockchain was firstly introduced, until December 2019 prior to the submission of this paper. Material collection was carried out through various databases (Scopus, Web of Science, Emerald Insight, IEEE Xplorer digital library and Business Complete) to gather widest possible samples.

In order to capture blockchain technology across different industries, and to be as comprehensive as possible, generic keyword strings such as "blockchain technology", "information flow", "information sharing", "information asymmetry" and "supply chain" were employed as research

FIGURE 2. The number of literatures collected in each year.

criteria to collect literatures. And the keyword strings were structured and combined as shown below:

- "blockchain technology" AND "information flow", AND "supply chain"
- "blockchain technology" AND "information sharing" AND "supply chain"
- "blockchain technology" AND "information asymmetry" AND "supply chain"
- "blockchain technology" AND "supply chain"
- "information sharing" AND "supply chain"
- "information asymmetry" AND "supply chain"
- "information flow", AND "supply chain

B. MATERIAL COLLECTION

After a thorough screening according to our systematic literature review flow, we selected a total of 31 literatures. All these literatures which met the requirements are exported to EndNote and Microsoft Excel to generate tables and figures for analysis.

In addition to that, some literatures that did not meet all the requirements but consists of relevant information are also exported to Excel sheet under different tab. This is important for us to gain a more comprehensive knowledge in different types of supply chains.

C. MATERIAL ANALYSIS

From Fig 2, the earliest selected literature is published in the year 2017 (n =3) and with a visible growth in 2018 (n= 12). 16 literatures were collected in 2019. This increasing trend highlights the growing interest of researchers in the field of deploying blockchain-based solutions for information sharing within a supply chain. This is due the potential of blockchain in enhancing the traceability and transparency within a complex supply chain.

From Fig 3, in Asia, highlighted in green, has the highest total number of literatures of (n=21) from different countries such as Singapore (n=1) and Japan (n=2). In this region, China (n=16) has published the highest number of literatures within this field. In Europe, bars in orange, United Kingdom and the Netherlands (n=2) have the most literatures published compared to the rest of the European nations. USA has published 2 literatures in North America.

Among the collected literatures, the majority of the research work is within the health and medical sector domain (8/31 literatures) and general supply chain (15/31 literatures) as shown in the Fig 4. below.

In our analysis, we categorized the selected literatures into information sharing and information asymmetry. As shown

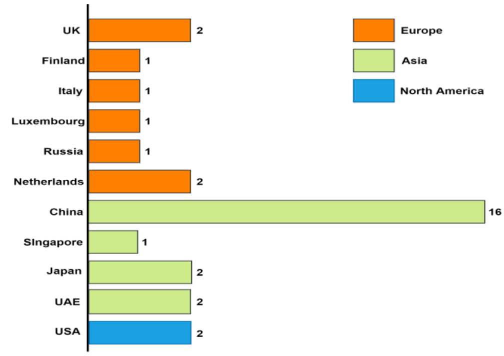

FIGURE 3. The number of literatures published based on countries.

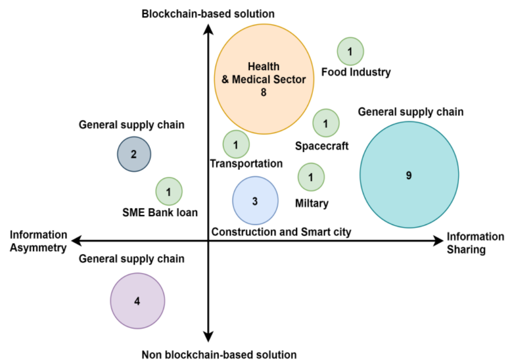

FIGURE 4. The number of literatures sorted based on the types of supply chain, information and solution.

in Fig 4, 24/31 (77%) literatures focused on information sharing. Different types of supply chains such as health and medical, transportation and even military focused on how blockchain-enabled information sharing with high data trust can increase the efficiency in their respective supply chain. While the remaining literatures focused on information asymmetry within a supply chain.

We then further categorized the literatures in the blockchain based and other solutions. From Fig 4, 27/31 literatures (87%) used blockchain-based solutions to reduce information asymmetry or to facilitate information sharing. There are 4 literatures which use other solutions in making decisions under information asymmetry. These 4 literatures are selected is because it highlights the knowledge gap where blockchain can be deployed not only for information sharing but information hiding as well. The total list of 31 selected literatures are summarized in Table 2.

V. FINDINGS AND DISCUSSIONS

A. CURRENT PERSPECTIVE ON INFORMATION SHARING USING BLOCKCHAIN TECHNOLOGY WITHIN A SUPPLY CHAIN

The number of academic publications in this topic is increasing, starting from 2017, which shows that researchers have started to recognize the potential impact of blockchain

TABLE 2. Summary of selected literatures.

Authors	Methodology	Key findings(s)
Information Sharing – Blockchain-based solution		
General supply chain (9 literatures)		
Al Barghuthi, et al. [32]	Case study	A blockchain-enabled technology in facilitating the exchange and sharing of information without the involvement of intermediaries acting as arbitrators. This removes the risks of centralization and enhance trade procedures in handling and processing of data throughout the trade supply chain
Teslya and Ryabchikov [33]	Architecture	An integration of IoT and a blockchain-based technology in solving issues such as durability and unchangeability of information. Smart contract can also be used to execute under certain condition.
Cui and Idota [3]	Case study and platform	Inconsistency of information will lead to decision-making mistakes or delay decision. A blockchain-based platform to transform the current information sharing and interaction in supply chain. Transactions are verified and confirmed without third-party intermediary.
Nakasumi [10]	Proposed solution	Supply Chain Management systems provide information sharing and analysis to companies and support their planning activities but are often asymmetric which lead to disturbance of the planning algorithm. A blockchain-based solution to solve the problem of asymmetric information between companies.
Wen, et al. [1]	System model	Information sharing among entities such as suppliers, manufacturer, carriers, retailers and customers has always been one of the major challenges in the field of supply chain management. The Industrial Internet of Things (IIoT) can help entities to get real-time data in the supply chain to share key information and reduce costs. However, it is still at the risk of a single point of failure and privacy issue. A blockchain-based solution by combining IIoT devices to blockchain to monitor, record and store real-time data in the network by smart contract.
Du, et al. [34].	Research	Using blockchain technology to achieve the goal to increase efficiency for information sharing and data fusion between different business information systems. The processes of data transmission and conversion can also be simplified.
Engelenburg, et al. [35]	Software Architecture	Businesses are obliged to share certain information. However, due to the highly competitive business environment, they are reluctant to share more information. A blockchain-based architecture is designed to store events and rules for information sharing that are controlled by businesses. This could solve the fear of sharing sensitive information.
Nizamuddin, et al. [36]	Framework	Blockchain-based solution and framework for document sharing and version control to facilitate multi-user collaboration and track changes. The solution could also be extended to shared digital assets and content which may include video, audio and photos.
Huang, et al. [37]	System models	Group data sharing enables information sharing among multiple parties for co-operative purposes but not all parties in the same organization want to share data. A blockchain-based data sharing scheme can achieve information sharing for multiple groups with anonymity and traceability.
Health and Medical Sector (8 literatures)		
Xiao, et al. [18]	Framework	EMRshare is a blockchain-based framework for medical record sharing with the goal to resolve trust issues, which is resulted from existing centralized database system, among different participants such as patients, clinicians, researchers and other relevant parties.
Shen, et al. [38]	Framework	A blockchain-based solution called MedChain which integrates blockchain technology to replace questionable third party. This could be a new service for healthcare information sharing and to achieve a higher efficiency in data sharing.
Chen, et al. [39]	Platform	Medical information is private and valuable for medical research. However, data might be manipulated improperly and privacy issue making information sharing challenging. Blockchain technology can solve this issue by recording and sharing verified information among parties without an intermediary.
Jiang, et al. [40]	Architecture	A blockchain-based model in solving how information sharing among members of different role (e.g. patients are mainly to authorized information sharing and doctors mainly are to submit requests). This model can also improve communication among medical institutions and effectiveness of medical resources.
Fan, et al. [17]	Framework	Current electronic medical records (EMRs) lack a standard data management and sharing policy. MedBlock, a blockchain-based framework, handles patients' information by allowing an efficient access to and retrieval sensitive medical information from EMRs. Patients can have an ownership of their personal data.
Alam Bhuiyan, et al. [41]	Framework	A blockchain-based solution that can eliminate healthcare breaches and better facilitate healthcare coordination through information sharing. Smart contract can be a solution where access to medical record is automated and regulated entirely.
Liang, et al. [42]	Application	A blockchain-based technology mobile healthcare system for personal health data collection, sharing and collaboration among individuals, healthcare providers, insurance companies and research purposes. Tree-based data processing and batching method to handle large sets of data collected.

TABLE 2. *(Continued.)* Summary of selected literatures.

Zhang, et al. [43]	Architecture	A blockchain-based architecture called FHIRchain can solve siloed clinical data which creates barriers to efficient information exchange and impedes effective treatment decision made for patient. This architecture fulfils the requirements and standard for shared clinical data.
Smart Construction and Smart City (3 literatures)		
Qian, et al. [44].	Framework	Platforms for information sharing for construction of smart cities is progressing but only between governmental agency and department. A blockchain-based approach enables an effective information sharing with non-trusted organizations and public during construction while preventing any illegal access and tampering of data.
Zheng, et al. [45]	Architecture	Smart construction relies on BIM for manipulating information flow, data flow, and management flow but little efforts focusing on information security. A blockchain-based architecture called "BcBIM" can guarantee the data integrity and provenance. BcBIM can keep track of the last record modification without tampering.
Li, et al. [46]	Review	Blockchain technology can address trust issues and information sharing in construction industry. One of the methods is by integrating blockchain technology with building Information modelling (BIM).
Food Industry (1 literature)		
Wu, et al. [47]	Framework and case study.	Supply chain management suffers from issues such as lack of information sharing, long delays for data retrieval, and unreliability in product tracing. A case study about the food supply chain with the development of a blockchain-based food tracing system is designed to tackle food safety issue.
Logistics and Transportation (1 literature)		
Imeri, et al. [48]	Conceptual solution	An efficient information sharing is crucial for a sustainable process of transportation. A blockchain-based model can be a solution for the current operations which have several drawbacks in terms of data security and trust among stakeholders.
Spacecraft (1 literature)		
Zheng, et al. [49].	System model	The spacecraft supply chain is full of high risks characterized by intensive knowledge and technology. In order to minimize enterprise risks and improve its overall profit, a blockchain-based solution is applied to decision-making problems in a spacecraft supply chain. The use of blockchain technology can reduce transaction costs among spacecraft supply chain stakeholders and fulfil information sharing, thus improving the overall profit.
Military sector (1 literature)		
Zaerens [50].	Framework	Open information sharing within military alliance (circle of trust) such as NATO gets complicated. Open information sharing might increase the risk of revealing too much information. A blockchain-based solution can enhance information sharing, trust and openness without compromising security issue.
Information Asymmetry – Blockchain-based solution		
Bank credits and finance (1 literature)		
Wang, et al. [51]	Theoretical model	A blockchain-based theoretical model that allows low-risk and high quality small and medium-sized enterprises (SMEs) to display their credibility and risks through information distribution.
General supply chain (2 literatures)		
Longo, et al. [52]	Model simulation	Conventional ICT has reduced information asymmetry and increased the degree of interorganizational collaboration, but trust issues still exist. A blockchain-based model can solve trust issue by establishing a single, immutable record that can be viewed by anyone with rights
van Engelenburg, et al. [53]	Architecture	Information is not shared could due to members in supply chain do not have direct contact and/or do not want to share competitive and sensitive information. Such information asymmetry contributes bullwhip effect. The feasibility of blockchain-based architecture for reducing information asymmetry and bullwhip effect is explored. Requirement such as only provide access to data to the appropriate parties is very crucial in supply chain management.
Information Asymmetry – Non blockchain-based solution		
General supply chain (4 literatures)		
Jinfa, et al. [54]	Case study	Information held by members of the supply chain often is asymmetric and many retailers prefer pursuing risk.
Lai, et al. [55]	Case study	Information asymmetry is beneficial to the reseller, but is inefficient to the manufacturer and the whole supply chain.
Wang, et al. [56]	Proposed solution	Information asymmetry does not always lead to inefficiency of the supply chain.
Yang, et al. [57]	Model	Information asymmetry affects the decisions of the involved partners' and reduces performance of a traditional retail supply chain. A model for dual-channel supply chain under asymmetry of revenue between manufacturer and retailers.

on information sharing within a supply chain. The growth is owing to the decentralized nature of blockchain, which eliminates the dependence on unreliable centralized third parties to govern sensitive information and decrease the transaction cost. With blockchain technology, every information is recorded permanently and distributed to every member in the network, which improves transparency and traceability in supply chain. This capability drives the momentum of deploying blockchain.

Blockchain-based solution improves traceability of the information of a product [58]. This solution can be adopted into various complicated supply chain to enable the fight against food fraud, counterfeit medicine and luxury jewellery like blood diamonds. Improving the information traceability throughout the entire collaborative processes within a supply chain can increase the level of data trust since each information flow is recorded permanently. In Perboli *et al.* [58] study, they suggested that information such as certification and authentication of its product units from all producers along the chain must register a batch ID and store it in blockchain. This can result in a higher visibility of all the processes which can guarantee the provenance of the product. This decentralized structure in blockchain improves transparency of information.

Transparency is compromised, due to many discrete activities that are not visible and difficult to track in a globalized and complicated supply chain. ElMessiry and ElMessiry [59] studied within the supply chain of textile industry, and they pointed that many discrete activities of the production are outsourced, where it contributes the most value to the product. Often these discrete outsourcing activities occurred in developing nations, where manufacturing rules and regulation on quality standards are less enforced. This could result in producing lower quality products. ElMessiry and ElMessiry [59] also proposed a blockchain-based framework solution that all transactions involved in the supply are recorded in blockchain to increase transparency. Smart devices with sensors can be integrated with blockchain to send real-time information.

Blockchain-enabled real-time information tracking has a huge potential in changing the way information is shared and distributed among multiple partners. For example, using of IoT sensors to send information regarding the storage and traffic condition of the road in real-time. The information is then recorded permanently in blockchain, and distributed to members such as logistics and transportation firms [3]. This allows firms to take appropriate emergency actions when unplanned activities occurred. The integration of smart contract embedded in blockchain can also be explored where tasks can be executed autonomously, and send notification to logistics firm in real-time information using IoT enabled sensors and devices [60]. This can increase real-time decision-making process of members in the chain and efficiencies.

Within a supply chain, document sharing and version control can benefit from blockchain technology [36]. Version control of documents, regardless of whether they are in paper or digital formats, has become one of the most important aspects when collaboration between different parties increases, primarily for sharing information. However, information asymmetry is one of the challenges in using digital information, and 83% of productivity is consumed by version management issues [61]. Existing documents version control systems are mostly centralized, where changes and updates to any documents without the knowledge of users is possible [36]. Nizamuddin *et al.* [36] proposed a blockchain-based solution for version control for digital documents embedded with smart contract, to facilitate multi-user collaboration. Any changes must be validated and tracked without a centralized third party. Blockchain technology ensures a secured and high level of trust of information sharing among different parties in a supply chain. Application of blockchain is still at a very early stage and thus, it is important to understand the significant impact of using this technology for information sharing in different industries within a supply chain.

B. RT1: TO IDENTIFY INDUSTRIES WHERE BLOCKCHAIN TECHNOLOGY CAN HAVE A SIGNIFICANT IMPACT ON THE INFORMATION SHARING WITHIN A SUPPLY CHAIN

1) MEDICAL AND HEALTH INDUSTRY

Blockchain technology can provide an effective collaborative treatment and care decision which brings advancement in medical and healthcare domain [43]. This technology can remove information silos which are impeding information sharing among patients and medical professionals. Medical data and information are continuously generated every time when someone visits a clinic or hospital [41]. And to this day, traditional paper-based are still utilized to record medical information. To better manage the high volume of information, it is common for hospital to engage a centralized databased system, with such electronic medical records (EMR) to store and manage highly sensitive data. This method, however, is vulnerable to leakage and alteration without leaving any traces.

Getting access to correct and verified information of the patients during emergency situation is a matter of life and death [41]. Medchain [38], EMRshare [18], MedBlock [17] and FHIRchain [43] are some blockchain-based solutions and frameworks to distribute trusted information in medical and health sector. Among those solutions, Medchain is a blockchain-based solution that facilitates information sharing among multiples roles like patient, requesters and healthcare providers which achieve higher efficiency and satisfy security requirements in information sharing [38].

Currently, data protection is not up to par, and is vulnerable to data breaching where the patient's information is stolen or lost [41], [62]–[64]. This results in a series of complicated procedures which is bounded by strict legal regulations, when it comes to medical data sharing outside an organization [18]. This bureaucratic procedures in obtaining information impedes medical professionals in performing a better treatment and diagnosis, when someone goes to a hospital that is not where he/ she is from. Blockchain can shift the ownership from a centralized third party to patients themselves.

Blockchain-based technology enables patients to have the ownership over their own medical record data and information. Smart contract enables patients to grant authorization and access his/her accurate medical records since medical information belongs to the patient. Academic researchers have come up with different blockchain-based solutions that enable sharing of information without compromising privacy, security and ethics [18]. Thus, improvement such as diagnostic accuracy, gathering information and confirmation, preventing inadequacies and errors in treatment plan and medication is expected with use of blockchain technology in this sector. [43], [65]–[68]

2) SMART CONSTRUCTION AND SMART CITY

The construction sector is perceived as one of the slow industries in the adoption of digital technology [69], [70]. For example, there is some evidence that building information modelling (BIM) is gradually being utilized in architecture, engineering and construction (AEC) industries. It uses construction information from various databases to manage the essential building design throughout its life cycle [45], [71]. However, the adoption of BIM in construction has been slow, mainly due to the fact that the updated information in BIM cannot be tracked, and often revision history is not retained. Even if revision histories are stored and available, the integrity of the historical data is not validated and thus making it very hard for users to fully trust it. Information sharing using blockchain-based solution can increase data trust.

Zheng *et al.* [45] suggested a blockchain-based framework called bcBIM that can solve integrity of the information shared and recorded in BIM. For example, information is stored chronologically and is falsification free guaranteed [45], [72]. When someone adds to and updates the BIM model, information will be stored in blockchain, and distributed to all participants that are working on the same model [46]. In addition to that, recorded information in BIM with blockchain-based solution is validated and verified. Users can now work on the BIM model, and be able to know who is responsible for those changes. This adds a new layer of trust to the information, by providing the ownership of the changes transparently. This can lead to a higher degree of collaboration work.

Collaboration within a partnership can increase in this industry when information is more transparent and shared more freely [46]. For example, the construction sector can trust information obtained from the logistics partner, to ensure materials are arriving as expected to reduce potential delay. This decentralized platform can also track and trace the provenance of the material purchased for construction. This can simplify the procurement activities, because the construction company does not need to incur additional cost to audit the materials and practices in a supply chain.

The development of smart city has progressed steadily mostly due to the increase of the availability of digitized information and data [44]. Government agencies are also actively encouraging business enterprises and research institutions to use government data to make innovative applications to move towards smart city [44]. However, the current information sharing only flows among governmental department or registered/trusted social agencies, while non-trusted institution such as private or SMEs are not granted access. This is due to various forms of potentially national security risks. The use of blockchain-based platforms increases information sharing among non-trusted institutions, which breaks the wall between trusted and non-trusted parties with smart contract embedded in the platform. For example, an organization would send a request to obtain certain piece of information, and a smart contract would only execute information sharing when the other party agreed and digitally signed. This can facilitate and secure information flow without putting the institution at risks.

3) OTHER INDUSTRY

a: BANK LOAN FOR SMES

Blockchain-based technology increases opportunities for low-risks and high potential small and medium-sized enterprises (SMEs) to obtain bank loans and other forms of financial aid. However, many of them are not able to display their credit quality effectively to obtain monetary help [73]. Information asymmetry between banks and SMEs, along with insufficient collateral are making it harder for them to obtain bank loans [51]. Wang *et al.* [51] proposed a blockchain-based solution to mitigate information asymmetry, by storing verified information such as financial statement and assets of SMEs. The process of verifying financial document enables low-risks and high-quality SMEs with non-tampered financial statement to be visible to banks which could potentially increase their opportunities of getting a loan. The use of blockchain technology can filter out high risk SMEs where they could not produce credible financial statements to banks. In the long run, this can also slowly eliminate the requirement of having enough collateral from SMEs as part of the assessment to get bank loans approved.

b: TEXTILE SUPPLY CHAIN

Information sharing has a significant positive effect in collaborative work in a complex global supply chain such as the textile industry [74]. However, information sharing among members throughout the chain on quality related issues is close to non-existent [59]. This is due to many discrete activities which are not visible and difficult to track, starting from raw material to final product, making necessary investigation of the root cause challenging. ElMessiry and ElMessiry [59] studied within the supply chain of textile industry, and pointed out that losses by discarding the final finished textile due to quality issues can reach up to 40%. To solve this issue, they [59] proposed a blockchain-based framework so that all information and transactions involved within the supply chain are recorded in blockchain to increase transparency of the provenance of the product. This may prevent unethical acts like child labour from entering the chain because every piece of information about the textile is recorded and validated. It is important to identify the potential barriers that impede the advancement of blockchain technology in the supply chain.

C. RT2: TO INVESTIGATE THE CURRENT POTENTIAL CHALLENGES OR BARRIER IN THE DEPLOYMENT OF BLOCKCHAIN WITHIN SUPPLY CHAIN

Unwillingness to share information among members within a supply chain due to conflict of interest is a challenge that slows down the momentum of deploying blockchain [52]. Blockchain-enabled solution which offers a high transparency, on the contrary, may not contribute to, but could further increase, the unwillingness of organization to use this solution to store and share information. This is due to having a high visibility of information and transaction to inappropriate members is not ideal for any company because of the highly competitive nature of supply chains. Such conflict of interest makes companies less inclined to deploy or even reject blockchain as a solution, despite the extent of the literature emphasizing the benefits of information sharing using blockchain [75], particularly in the context of a global supply chain operation where members are scattered globally or do not trust each other [76]. The lack of understanding of blockchain further retards the adaptation.

Normally, the main challenge of digital transformation is the lack of understanding of digitization in the industry. For example, there is a limitation in knowledge and understanding of BIM in the construction sector [77], resulting in organizations' misconception of what this digital technology can achieve [46]. This often ended up with abandonment and the inability to embrace the technology in this sector [78], [79]. Similarly, blockchain technology may face the similar challenge, despite having the capabilities to offer various benefits such as facilitating immutable information sharing among partners, increase transparency and traceability of a product.

The hype of blockchain being disruptive has gained interest beyond financial industries, but many business leaders remain unsure what that means for their companies, and what blockchain is. In a survey of 308 senior executives at large companies in the United States, 39% of the respondents had little or no knowledge about blockchain technology [80]. Till today, many SMEs claimed that they have little knowledge about blockchain [52], [81]. Investment of both time and money are needed to overcome the barrier of deployment of blockchain are inevitable at this infancy stage. More efforts in closing these knowledge gaps are needed to understand the potential of this technology in supply chain.

Many companies are not willing to risk making large investments in blockchain that may not create large value to their organization [82] is also one of the barriers. Information and data are constantly generated and flowing among different partners across the supply chain. A blockchain solution is ideal when crucial pieces of information are recorded and stored in blockchain after verification. However, this technology comes at a cost. Companies may not be willing to spend time and money to develop an architecture framework that integrates blockchain technology that supports and fits into their overall business strategy [82] due to fear of low returns. If a company plans to adopt blockchain in their organization, time and effort are required in sorting and identifying the suitable type of blockchain (permissioned or permissionless) to be employed, who has rights and who are restricted [83]. Without this step, a company may end up spending a large amount of money, with low value added to their firm. In addition, many companies feel that their current information sharing system are functioning fine. To deal with such challenges, a new business model for blockchain service with less cost and less risk should be developed.

D. RT3: TO IDENTIFY FUTURE DEVELOPMENT OF INFORMATION SHARING USING BLOCKCHAIN TECHNOLOGY WITHIN A SUPPLY CHAIN

Information hiding using smart contract embedded in blockchain should be focused in parallel with information sharing within a supply chain. Information sharing can provide operation benefits [52], but the feasibility, in reality, for any firms in global supply chains agreeing to this may be very low. For example, high level of information sharing in medical service such as medical diagnosis and prescriptions from medical professional like doctors may result in resistance towards the implementation of blockchain-based technology. This is because some doctors would perceive this as a threat to their autonomy or even as a form management control tool [84], [85]. With the use of smart contract, part of the information, such as the name of the doctors and hospitals, would be hidden, without compromising the integrity of the information, if a patient would like to obtain second opinions from other hospitals. Therefore, effort focusing on information hiding using smart contract to hide certain of information and granting access upon request should also be a part of the solution framework design.

Reported work lacks the sharing of performance evaluation of using blockchain technology [18]. Many researchers have attempted to address this issue by designing blockchain-based architecture and visual framework solutions. From the Table 2, 8/31 in the medical sector designed different blockchain-based solutions but only 3 published literatures provided performance evaluation analysis. Sharing of such evaluation and analysis on the performance remains very limited. ElMessiry and ElMessiry [59] is another example in the textile industry, where they attempted to use computer simulation on their framework, but they pointed out that the use of blockchain is very new, and is difficult to demonstrate the improvement on transparency. Without the documented performance in real industry, it is difficult to persuade enterprise and gain support from the top management [12] to deploy this new digital tool for information sharing. In short, effort in measuring and comparing the effective of using blockchain on information sharing can be the next step of the development of deploying blockchain in a supply chain.

Despite many literatures expect blockchain to achieve various strategic supply chain objectives, for example reducing cost through the elimination regulatory compliance cost and increasing the speed through digitization [86], it is not a one-size-fit-all technology. It is crucial to place a strong focus in understanding the nature of the supply chain as a part of future development of blockchain. For example, identifying the boundary conditions [87], and addressing the key requirements [53] in developing an architecture for information sharing which fits the nature of supply chain that supports information sharing. This is to better prepare the adoptation of blockchain technology in a real-world scenario.

VI. CONCLUSION

The high volume of information generated from members in a supply chain makes information sharing complicated and highly fragmented. To better facilitate information sharing, different methods, such as engaging a centralized third party, is still commonly used to facilitate information sharing among multiples parties within a supply chain. In addition to that, a legal contract is signed between two institutions or more to enhance collaboration work. However, malicious acts such as alteration to information in centralized database system, without leaving any traces, compromise data integrity and the level of transparency and traceability. Emerging technology such as blockchain technology may transform the current methods of storing information in a decentralization network where no single authority controls over information without compromising data integrity. This paper explored how blockchain-enabled information sharing can rebuild and fortify the element of information and data trust among members within a supply chain.

Blockchain technology has gained great interest within the supply chain due to the decentralized structured with high transparency and traceability. However, research focusing primarily on blockchain-enabled information sharing within a supply chain remains limited. In this systematic literature review, we contributed by identifying what are the significant impacts with the deployment of blockchain-enabled information sharing within a supply chain. The main finding is that this technology ensures members in the chain can obtain verified information which enhances collaborative partnerships. The use of blockchain-based platforms with embedded smart contracts can increase information sharing between trusted and non-trusted institutions with lower security risk. This can benefit any types of supply chain by removing information silos which often happen in reality.

Through this in-depth research, we also contributed by highlighting barriers in the development of blockchain technology in supply chains. One of the potential challenges is the unwillingness of firms to share information to other members, due to conflict of interests. The lack of understanding of this technology also impedes the deployment within a supply chain. Till today, many business leaders remain unsure what blockchain is, and how can it contribute to their businesses, while many SMEs claimed they have little knowledge on this. Hopefully these findings can draw a more comprehensive overview to researchers in developing relevant steps to overcome highlighted challenges.

In this paper, we also provided some potential future work for blockchain-enabled information sharing that is worth investigating by researchers, that could bring a positive impact on the expansion of this new technology. More effort in information hiding, in parallel with information sharing, could potentially close the gap in deploying this technology within a supply chain. Future work in understanding the nature of a supply chain is also important to better prepare the deployment of blockchain. Lastly, we acknowledge that our approach in selecting literatures in our systematic review may exclude certain literatures. Nonetheless, we tried to include as many relevant academic papers as possible, to develop a roadmap on the current situation of blockchain-enabled information sharing in supply chain.

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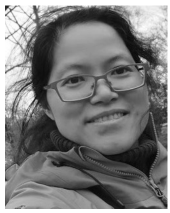

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Paper B

Reducing Alert Fatigue by Sharing Low-Level Alerts With Patients and Enhancing Collaborative Decision Making Using Blockchain Technology: Scoping Review and Proposed Framework (MedAlert)

Original Paper

Reducing Alert Fatigue by Sharing Low-Level Alerts With Patients and Enhancing Collaborative Decision Making Using Blockchain Technology: Scoping Review and Proposed Framework (MedAlert)

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Abstract

Background: Clinical decision support (CDS) is a tool that helps clinicians in decision making by generating clinical alerts to supplement their previous knowledge and experience. However, CDS generates a high volume of irrelevant alerts, resulting in alert fatigue among clinicians. Alert fatigue is the mental state of alerts consuming too much time and mental energy, which often results in relevant alerts being overridden unjustifiably, along with clinically irrelevant ones. Consequently, clinicians become less responsive to important alerts, which opens the door to medication errors.

Objective: This study aims to explore how a blockchain-based solution can reduce alert fatigue through collaborative alert sharing in the health sector, thus improving overall health care quality for both patients and clinicians.

Methods: We have designed a 4-step approach to answer this research question. First, we identified five potential challenges based on the published literature through a scoping review. Second, a framework is designed to reduce alert fatigue by addressing the identified challenges with different digital components. Third, an evaluation is made by comparing MedAlert with other proposed solutions. Finally, the limitations and future work are also discussed.

Results: Of the 341 academic papers collected, 8 were selected and analyzed. MedAlert securely distributes low-level (nonlife-threatening) clinical alerts to patients, enabling a collaborative clinical decision. Among the solutions in our framework, Hyperledger (private permissioned blockchain) and BankID (federated digital identity management) have been selected to overcome challenges such as data integrity, user identity, and privacy issues.

Conclusions: MedAlert can reduce alert fatigue by attracting the attention of patients and clinicians, instead of solely reducing the total number of alerts. MedAlert offers other advantages, such as ensuring a higher degree of patient privacy and faster transaction times compared with other frameworks. This framework may not be suitable for elderly patients who are not technology savvy or in-patients. Future work in validating this framework based on real health care scenarios is needed to provide the performance evaluations of MedAlert and thus gain support for the better development of this idea.

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KEYWORDS

blockchain; health care; alert fatigue; clinical decision support; smart contracts; information sharing

Introduction

Background

Clinical decision support (CDS) is a tool to facilitate medical decision making by generating clinical alerts [1], ranging from simple medication-specific alerts based on stored clinical rules and information to more complex patient-specific alerts by integrating CDS with electronic health records (EHRs) [2]. For example, CDS warns clinicians by generating an alert if a new prescription poses a threat to patients [3]. This real-time alert disrupts the workflow and draws clinicians' attention so they can evaluate and make appropriate decisions in a quick and efficient manner [4]. CDS has replaced previous situations in which clinicians make decisions solely on the basis of their knowledge and past experience [5]. CDS is now considered an essential health information technology that improves the overall quality of health care [6]. However, current CDS tools generate a high volume of irrelevant alerts, resulting in alert fatigue [7].

Alert fatigue or alert burden is defined as the mental state that results when alerts or reminders consume too much time and mental energy, which can cause clinicians to override or ignore both clinically irrelevant and relevant alerts unjustifiably [8]. Clinicians are now drowning with alerts and gradually becoming less responsive to and less respectful of them [9]. This is mainly because generated alerts are mostly irrelevant or low priority, and fortunately, they are not life threatening. In the long term, these *cry-wolf* alerts have desensitized clinicians, resulting in high overriding rates ranging between 77% and 90% [10-12], which opens the door to preventable medication errors.

Alert fatigue started becoming increasingly common in the health care sector decades ago and is now widely recognized as a national concern, often due to the lack of a corresponding action plan [13]. CDS failures and errors caused by individuals have resulted in direct costs of more than US $20 billion in the United States [14,15]. Alert fatigue is perceived as a major problem because it extends beyond the health care industry. Other sectors, such as off-shore oil drilling [16] and heating, ventilation, and air-conditioning systems in buildings [17], are also experiencing alert fatigue. For example, fault detection systems generate high volumes of alerts, leading to operator alert fatigue and resulting in energy wastage in buildings. Currently, there is a persistent upward trend and increasing requests for new alerts [13], which does not help alert fatigue. This only exacerbates the alert fatigue and makes it more widespread.

Overriding alerts is clinically appropriate if the alert generated is incorrect [7]. However, due to the low specificity and high volume of alerts generated by CDS, relevant alerts may also be dismissed, resulting in preventable prescription errors and adverse drug events. Deactivation [18] or running low-priority alerts in silence [19] are among the suggestions for reducing alert fatigue. However, these approaches in managing alerts effectively are difficult because of strict regulatory bodies and other external pressures. Many are in fact pushing for more rather than fewer alerts to reduce or avoid preventable medication errors [13].

In Norway, approximately 12% of patient harm is caused by the incorrect use of drugs [20]. One in three elderly people have been given the wrong medication, and an estimated one thousand deaths per year are thought to be due to medication errors, despite the use of e-prescriptions [21,22]. During a meeting at the Norwegian University of Science and Technology (NTNU), a health care representative from Innlandet Hospital presented in his presentation that approximately 8% of total health care spending went on correcting medication errors within the Innlandet region. [23]. We, therefore, agree with Wright et al [24] that the health care sector can only benefit from the potential value of CDS-generated alerts when they are well designed and properly implemented. Thus, there is a need to seek an alternative, innovative approach to improve the management of clinical alerts and reduce alert fatigue among clinicians.

Objectives

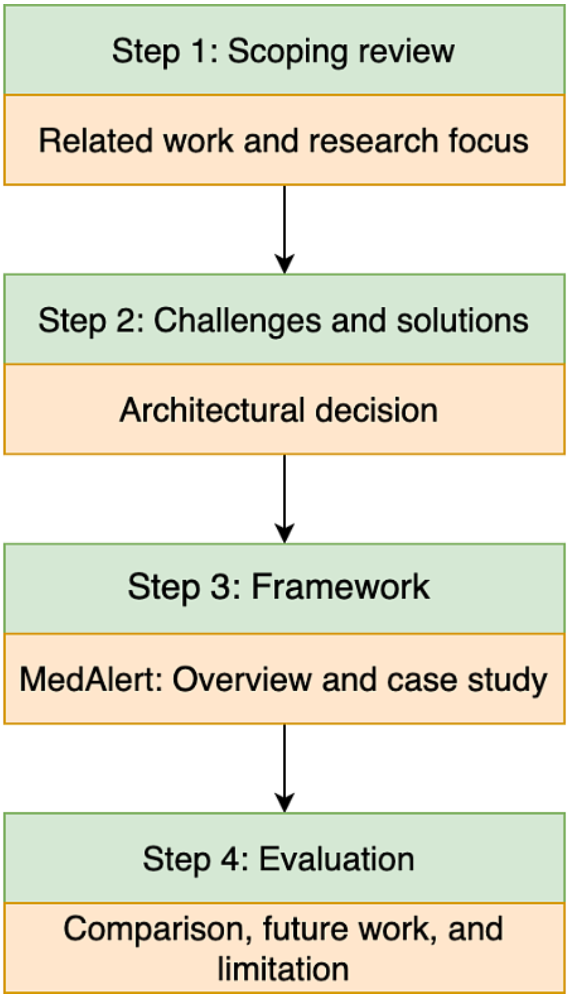
Blockchain technology has gained attention as a potential solution in the health care sector, mainly due to its potential in moving toward collaborative treatments and decision making [25-27]. A large range of literature has been published anticipating this technology with a view to improving the health sector with respect to the overall well-being of clinicians and the quality of patients' health care by sharing medical records and history [26]. However, studies focusing on clinical alerts using blockchain remain limited. This has led us to our main research question in this paper, which is to explore and understand how a blockchain-based solution can help to reduce alert fatigue in the health sector by sharing alerts and thus enhancing collaborative decision making. To answer this question, we designed a 4-step approach, which is explained in the *Methods* section.

Methods

Design Approach

The 4-step approach, shown in Figure 1, is designed to answer our research question and explain how the paper is organized. The first step is to conduct a scoping review to explore the current state of the art in this area. The literature we finally selected and the existing solutions we have chosen are then analyzed in step 1. Step 2 is designed to identify potential challenges and technical solutions for reducing alert fatigue. Architectural decisions are explained in this step. The framework is designed in step 3. An overview of MedAlert, together with a case study, is elaborated in this step. Finally, the framework is evaluated by comparing it with other proposed solutions. The comparison, future work, limitations, and benefits are also discussed in step 4.

Figure 1. Research design process flow: 4-step approach.

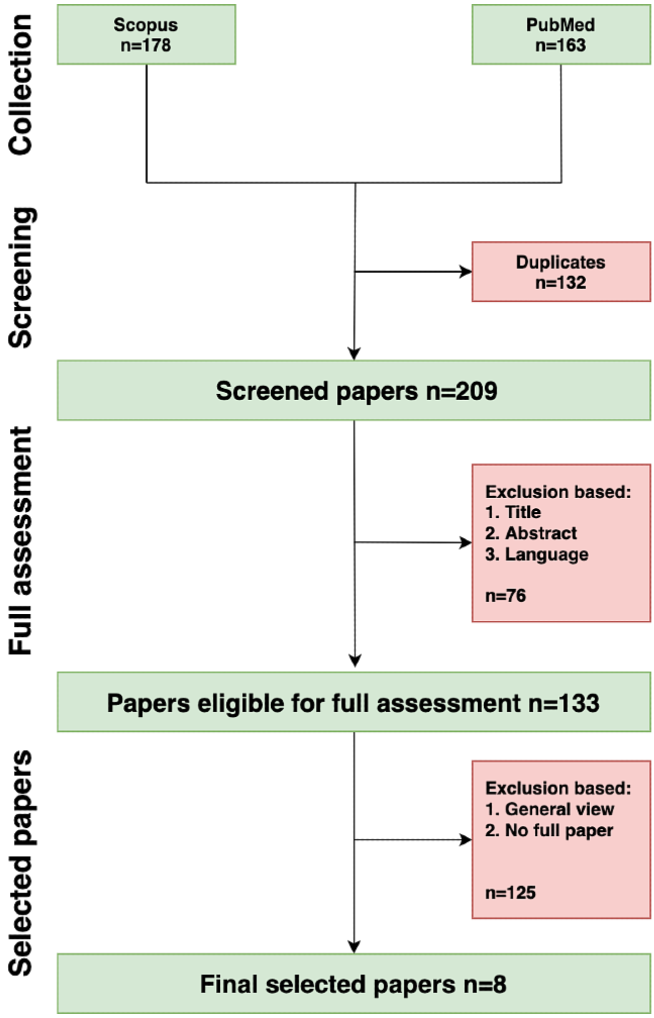


Scoping Review: Search Strategy

A scoping review was conducted with the aim of exploring the current state of the art in academic research with the widest possible coverage of all the published literature. The reporting of this scoping review was guided by PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-analysis extension for Scoping Reviews) [28]. We performed searches on 2 bibliographic databases, Scopus and PubMed. To be as comprehensive as possible, generic keyword strings such as *blockchain*, *clinical decision support*, *alert burden*, and *alert fatigue* were used as search criteria. Multimedia Appendix 1 details the structures of the keyword strings.

We acknowledge that industries are also working on blockchain-based solutions within the health care sector, but often, the details of the frameworks are not disclosed. Therefore, in our research, we focus primarily on the academic sphere because the architecture frameworks and solutions are described in published work. Peer-reviewed articles, conferences, reviews and proceedings, and dissertations are included to provide a broad overview of different aspects of alert fatigue resulting from CDS. Only English papers were included, with no restrictions on the year or country of publication. We excluded general views, no full paper, and conference abstracts. The selection process for the scoping review is summarized in Figure 2.

Figure 2. Process of scoping review.



Results

Related Work and Research Focus

Alert fatigue is a major problem faced by clinicians and is now a rising concern in the health care sector. The published literature on alert fatigue in the academic sphere started as early as 2007. We collected a total of 341 published items and finally selected a total of 8 [13,15,29-34] that fit our research criteria based on the scoping review in Figure 2. We then entered these items in Microsoft Word and Excel for deeper analysis. We summarize and sort these literatures according to their different key foci, methods, and benefits in Multimedia Appendix 2 [13,15,29-34].

Carli et al [35], Powers et al [36], and Hussain et al [37] pointed out that the high degree of alerts with low clinical relevance is one of the root causes of alert fatigue in their systematic literature reviews. This is because hospitals and other private health care institutions use or purchase commercial CDS tools to improve the overall quality of their health care systems. It is common for vendors and designers of commercial CDS tools to sharply restrict the ability to modify the setup for alert systems, resulting in a high volume of low-relevance alerts [2]. The strict, low-specificity settings imposed by vendors are due to their fear of being exposed to potential litigation if the removal of alerts fails to prevent a potential medication error.

One common attempt to address alert fatigue is to reduce the number of alerts of low clinical relevance by clustering alerts with similar clinical management options [32] or better specifications to generate useful alerts [31]. The machine learning algorithm–based CDS is another suggested method to generate more context-driven alerts [15] and patient-centric alerts [34]. Soundararajan et al [30] designed a blockchain architecture framework to leverage blockchain and smart contracts in support of clinical support tools that generate more patient context–appropriate alerts and thus generate fewer inappropriate alerts, which could reduce physician burnout. However, the actual benefits to patients and the extent of the positive impact on alert fatigue remain unclear.

All these efforts have managed to reduce the total number of alerts generated, but the fundamental issue of alert fatigue has still not been tackled. Bryant et al [38] pointed out that despite intensive efforts to reduce irrelevant alerts of commercial systems, overriding rates remain as high as reported over a decade ago. Medical experts suggested that improving alert fatigue should go beyond just reducing the total number of alerts [39].

Getting someone to attend the alerts is one way to reduce alert fatigue. Smithburger et al [5] suggested a potential strategy for directing alerts to medical professionals other than clinicians, for example, nurses. A study conducted in three academic medical centers in the Netherlands evaluated shifting time-dependent drug interaction alerts to medical staff such as nurses or pharmacists [40]. These results demonstrated the ability to improve the efficiency and effectiveness of such alerts and showed that incorrect administration times were reduced by 29% when they were directed at nurses. This can enable more collaborative treatment and decision care, whereas blockchain technology can be leveraged to enable alert sharing [25].

In our work, we have explored how blockchain can be leveraged to reduce alert fatigue by directing low-level alerts to patients in achieving high-quality collaborative clinical decisions. There has been a recent shift toward a more patient-centric data sharing for better collaborative decision making within the health care sector [41]. However, the relevant work remains limited. Thus, we contribute by designing an exploratory blockchain-based framework that enables low-level alert sharing with patients to enable more collaborative decision making while maintaining a high level of privacy and security. To design a sound framework, we need to understand and consider the challenges involved in facilitating the sharing of clinical alerts.

Data integrity and user privacy are two of the main concerns of the health care industry worldwide [42]. One of the reasons for this is that most of the current health care systems have weak and vulnerable centralized data storage procedures for preserving and managing sensitive medical data [43]. In 2019, the database of the Health Sciences Authority in Singapore was hacked for the third time in less than a year because of security loopholes, and more than 800,000 personal details were exposed [44]. Identity theft is another issue of concern in the health sector. According to Pandey et al [43], 10% of data breaches in the health industry in the last 10 years were categorized as identity theft.

There is a range of literature on blockchain-based frameworks that serves as an alternative to current vulnerable centralized database systems. EMRshare [45], Medchain [46], FHIRchain [25], and MedBlock [47] are examples of blockchain-based solutions that ensure high levels of data integrity and privacy for sharing medical records. In addition, smart contracts can enable a new service for health care to facilitate information sharing without a third party. For example, Medchain enables medical record access between multiple roles, such as patients, requesters, and health care providers, and helps them to achieve higher levels of efficiency and to satisfy security requirements [46]. This can improve collaborative decision making between different stakeholders, for example, clinicians and patients, in the health care sector.

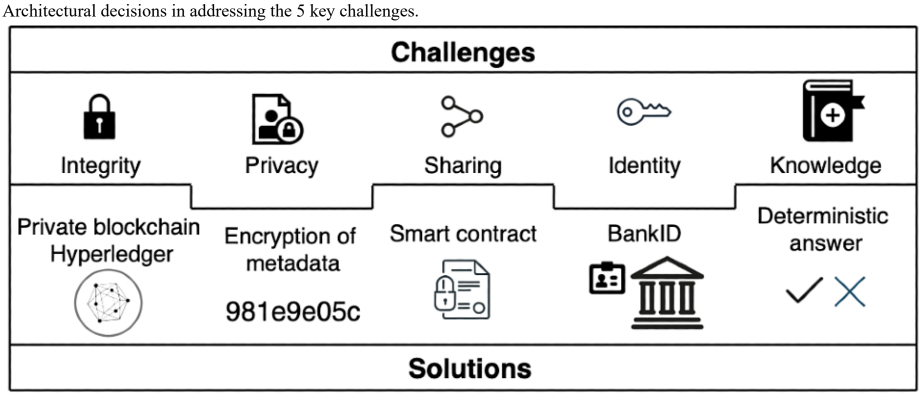
Five key challenges must be addressed to develop a secure and effective blockchain framework and thus reduce the alert burden within health care. These 5 key challenges are as follows:

1. Data integrity
2. Privacy issues
3. Verifying and authenticating participants' identities
4. Lack of secure information sharing
5. The extent of patients' knowledge in the medical field

Architectural Decisions to Address These Five Key Challenges

In this section, we address the challenges suggested in the previous section. The architectural decisions are summarized in Figure 3.

Figure 3. Architectural decisions in addressing the 5 key challenges.



Challenge 1: Data Integrity

Context

Health information is sensitive and must be highly secured, without the possibility of any data manipulation. Any alteration in a patient's medical history could result in severe medication errors and even death. Medical data are often stored in and managed by centralized trusted third-party databases. However, such a centralized database can be vulnerable to single-point failures, resulting in loss or corrupted medical data and blocking of access deliberately during disputes by service providers [48]. Some modern EHR systems can be configured to have a backup and data redundancy mechanism that improves data storage resilience, but it requires additional configuration and maintenance that might be error prone due to human factors. According to some security experts, current systems in protecting our health data do not achieve the desired modern security standards [49].

Solution

A solution that offers resiliency out of the box and a tamper-sensitive storing environment to prevent any *silent* manipulation by making alterations obvious to members in the network.

Technical Requirement

Blockchain technology is a distributed ledger that contains replicated and synchronized digital data. It provides a platform for real-time data sharing between a large number of members in a network with a higher level of data trust [50,51]. *Data trust* denotes the reliability of the information and data provided [52]. A high level of data trust is important for decision making.

The data storage structure is a salient feature of blockchain, which ensures that information and data are stored in a tamper-evident environment [53]. All valid transactions are recorded in a block format, and each block is linked with a time stamp and hash references forming a chain of blocks [54]. Any attempt to alter information, for example, in the off-chain database, regardless of the intention, breaks the hash reference and thus makes it obvious to the other members of the network. This way, a hash reference creates a tamper-evident environment that maintains and ensures data integrity. The transactions recorded on the blockchain remain immutable and tamper-proofed owing to the structure and writing rights of the blockchain itself, which can guarantee a high level of data integrity.

Challenge 2: Privacy Issues

Context

Medical information, including medical records, prescription histories, patients' personal information, and surgical records that are stored in digital formats, are classified as digital assets. This information requires high levels of privacy protection because it relates to the patient's current physical or mental health and can reveal information about his or her health status [55]. Ensuring that current or new health services are in compliance with standards, such as General Data Protection Regulation (GDPR) is crucial to avoid unlawful behavior. For example, encryption, pseudonymization, or anonymization of personal data, whenever possible, to prevent unlawful data processing [55].

Solution

A private permissioned blockchain is a better option when it comes to ensuring on-chain data privacy and compliance with privacy regulations because transactions are visible only to members. Certain members of the network are granted permissions to read and write on the blockchain. By storing only metadata instead of actual health data, we can avoid exposing actual sensitive personal data, such as full name, diagnoses, and prescribed drugs, which could violate a patient's privacy.

Technical Requirement

To increase the level of privacy protection, private blockchains such as Hyperledger are preferred over public blockchains, primarily because of the lower degree of visibility and level of *openness*. Information on private blockchains is only accessible to authorized members of the network and not just anyone with internet access. Only an authorized member, in our case clinician, has permission to write and store on the blockchain. This allows the framework to be more compliant with data protection regulations such as GDPR or HIPAA (Health Insurance Portability and Accountability Act) without compromising the privacy of patients [49].

Encrypting metadata in blockchain provides a higher level of security and protection for patients [25] because metadata are treated as sensitive data in health care. This prevents any unauthorized hacker from obtaining actual health information improperly. Encrypted metadata can act as a reference pointer to the patient's prescription profile in the health system. The reference pointer links transactional data from the blockchain to the actual data stored on an off-chain database. This acts as a form of protection because it isolates the patients' actual medical information from the reference itself. The pointer breaks and becomes invalidated when any alteration to the patient's data occurs in the off-chain database. Another benefit in storing encrypted metadata is the lightweight reference pointer, which is more suitable and efficient to store on blockchain, which currently has limited storage capability. This can be a scalable alternative [25].

Challenge 3: Verifying and Authenticating Participants' Identities

Context

It is important to ensure that the right patient receives the designated clinical alert from the clinicians. Clinicians working in hospitals can verify and authenticate themselves with the credentials offered by health care institutions through logging into the health care system. However, health care systems today lack a standard platform [56], particularly for patients, to verify and authenticate their digital identities.

Solution

Use a trusted digital identity management system to verify patients' digital identities. Digital identity denotes the digital representation of entity attributes such as birth or other registered name, national ID number, and registered mobile number to access systems and applications using an identity mediation process [57-59]. This allows patients to authenticate their identities accurately and thus either authorize or revoke access to certain requestors. This is a way of protecting patients' sensitive data, including managing their medical records, and it guarantees that security and privacy are compliant with local legislation and laws [60,61].

Technical Requirement

Federated digital identity management, registered once and trusted by many concepts, is widely used in consumer spaces such as Facebook and Google and is trusted by many applications [62]. Unlike traditional centralized identity management, users do not need to set up and register their digital identities with every service provider. In this system, mutual trust is established by receiving components of proof distributed by two or more centralized owners or by mutually recognizing each other's trust and proofing standards [62]. Consortiums of leading banks and mobile operators have created private federated identification procedures, such as BankID in Norway [63] and Smart-ID in Estonia [64], to facilitate the distribution of verified and authenticated identities, thus enabling their citizens or users to access various portals, services, and platforms directly.

Challenge 4: Lack of Secure Information Sharing

Context

Each medical institution has its own way of governing medical records and data. Often, moreover, they are not interaccessible, thus making information sharing difficult. Along with strict legal regulations and the lack of trust in medical institutions outside the organization, information exchange becomes more challenging [45].

Solution

Use a common layer to enable information sharing securely without altering the current health care IT infrastructure and to enhance collaborative decision making.

Technical Requirement

Smart contracts can govern and facilitate information exchange between two different actors accurately and verifiably without the intervention of an intermediate third party. It also enables autonomous self-execution, once a set of predefined rules is met [65]. For example, when an alert is generated from CDS, it triggers a smart contract to direct the alert to the identified patient. The integration of smart contracts can increase the efficiency of members' real-time decision making and overall information exchange. All events are recorded in the blockchain with a time stamp, and the blockchain structure can act as a common layer of information storage without changing the existing IT infrastructure. Smart contracts can track real-time performance and also query past events for the purposes of analysis.

Challenge 5: The Extent of Patients' Knowledge in the Medical Field

Context

When directing alerts to patients for a collaborative decision, the main problem is that they may not have sufficient knowledge to make the correct decision. Making a wrong decision can be fatal to patients.

Solution

Only low-level and nonlife-threatening alerts are directed to patients governed by smart contracts. Patients will receive clinical alerts and then provide information back to the clinician. The aim of directing alerts to patients is bring the alert to their attention, instead risking its rapid dismissal by clinicians due to the high volumes of alerts. This could reduce alert fatigue and the total number of alerts because clinicians can place the emphasis on higher-level alerts.

Technical Requirement

Smart contracts execute actions by sending notifications to patients when the CDS generates an alert. The alert is then directed to the patient in the form of a question with a deterministic answer, either *Yes* or *No*. Given a real-time response, the clinician is able to modify the prescription accordingly and eliminate medication prescription errors based on the responses provided by patients.

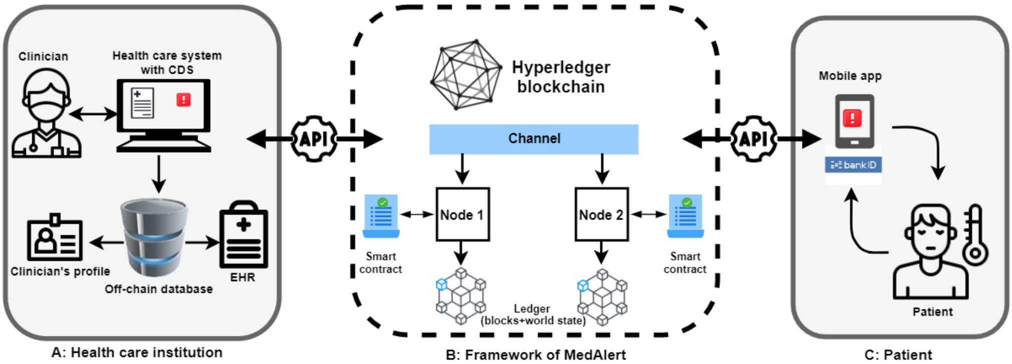
Principal Finding: MedAlert

Overview

This section provides an overview of MedAlert as a potential solution for reducing alert fatigue and enabling a more collaborative process of clinical decision making. This case study is developed as a two-step scenario: (1) *how a patient logs in with BankID to verify and authenticate his or her identity before revealing the alert* and (2) *how a patient is involved in the decision-making process.*

Figure 4 shows how MedAlert (B) enables the interaction between a clinician in a health care institution (A) and a patient (C). The MedAlert is hosted in a private blockchain framework such as Hyperledger. The clinician authorizes through logging into his or her profile with their credentials issued by the health care institution, whereas the patient can log in with BankID to verify and authenticate himself or herself. The blockchain nodes can be administered by a collection of health care organizations such as hospitals but not on a patient's mobile device due the high requirement of computational resources and a consistent network connectivity. These nodes host ledgers and smart contracts that can be queried and updated by peer-connected applications.

Figure 4. Overview of MedAlert. API: application programming interface; CDS: clinical decision support; EHR: electronic health record.



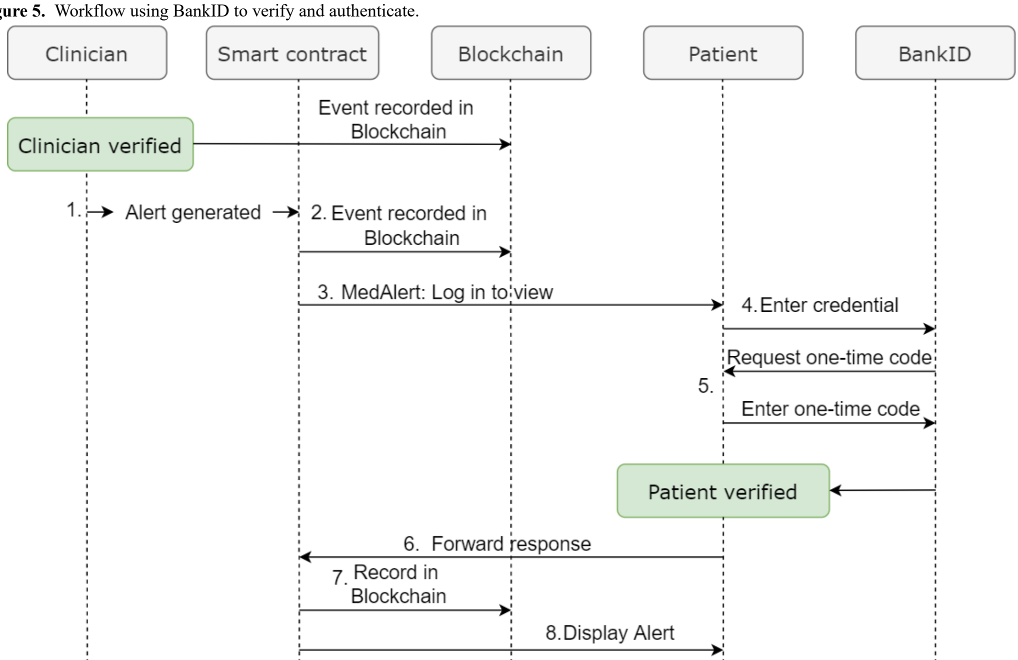
Application programming interfaces (APIs) can enable alert sharing with multiple health care systems. Representational state transfer (REST) APIs can establish communication between mobile client apps and the blockchain network. A client app sends a transaction proposal using organization-specific REST APIs that enable apps to connect to nodes; invoke smart contracts that generate transactions; submit transactions to the network that will be ordered, validated, and committed to the distributed ledger; and receive events when this process is complete.

The consensus protocol in the private blockchain enables transaction data integrity. For every transaction, each node will verify that the transaction has been endorsed by the required organizations according to the endorsement policy of the smart contract that generated the transaction. For example, some transactions may only need to be endorsed by a single organization, whereas others may require multiple endorsements before they are considered valid. This process of validation verifies that all relevant organizations have generated the same outcome or result.

How a Patient Logs In With BankID to Verify and Authenticate His or Her Identity Before Revealing the Alert

This section describes the step-by-step workflow, as shown in Figure 5. Before clinicians can access patients' EHRs or prescribe new drugs, they need to authenticate their identities by logging in their credentials into the health care system. This event is recorded in the blockchain. When the clinician prescribes a drug to a patient and assumes that it could pose a threat to the patient:

Figure 5. Workflow using BankID to verify and authenticate.



1. A clinical alert (red exclamation mark) is generated from the CDS system, as shown in Figure 4. This triggers the smart contract.
2. This event is then recorded in the blockchain.
3. The smart contract also sends the alert to the patient's registered mobile number.
4. The patient receives a message with a link to verify and authenticate his or her identity. Then he or she must log in to verify and authentic himself or herself by providing his or her registered user ID (eg, the 11 digits of a social security number) as sketched in Figure 6 (left).
5. The patient is then required to enter his or her one-time code for final authentication, as shown in Figure 6 (right).
6. When the authentication and verification is successful, the response is forwarded to the smart contract.
7. This event is also recorded in the blockchain.
8. The patient is then able to view the alert.

Figure 6. Personal credentials to verify identity (left) and request of one-time code to authenticate (right).

How a Patient Is Involved in the Decision-Making Process

After the patient has verified and authenticated his or her identity, the patient can access and read the information in the alert. The workflow is shown in Figure 7.

1. The first alert asks: "Do you have renal disease?" The answer to the question is either *Yes* or *No*, as shown in Figure 8 (left).
2. When the patient responds, the smart contract is then triggered, and the patient sends the response back to the clinician. The transaction is recorded in the blockchain.
3. The clinician updates the prescription according to the answer provided.
4. If another low-level alert pops up, the patient has to respond in real time before the prescription is finalized. The patient can view his or her history, as shown in Figure 8 (right).

Figure 7. Workflow for involving a patient in the decision-making process.

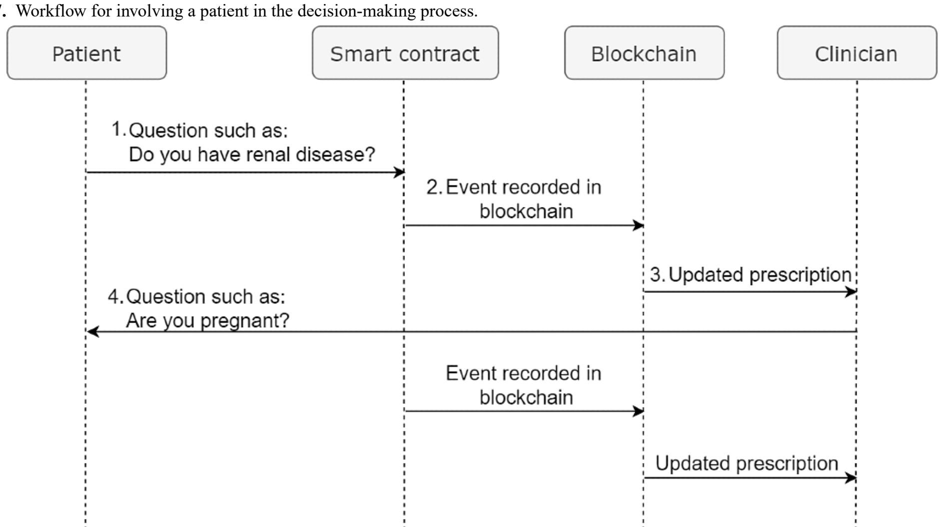
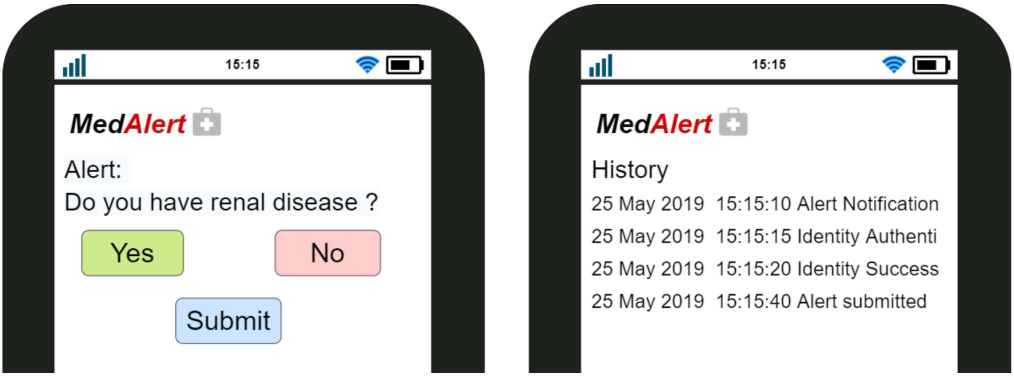


Figure 8. Question in alert (left) and history log of patients (right).



Discussion

Comparison With Prior Work

Three different frameworks (MedAlert, MedRec, and MedAware) are compared in Table 1. These solutions can reduce the total number of alerts generated but with fundamentally different technologies. Both MedRec and MedAware focus on reducing alert fatigue by filtering irrelevant alerts. MedRec utilizes a smart contract embedded in a blockchain platform, from which CDS retrieves medical records via MedRec to retrieve relevant patient information and generate alerts that are more context based. MedAware uses a machine learning algorithm to flag more relevant and accurate alerts in real time after analyzing patients' historical medical records. However, improving alert fatigue should go beyond just reducing the total number of alerts [39]. These two solutions only capture the clinician's attention.

Table 1. Comparison of different framework solutions.

Solution	MedAlert	MedRec	MedAware
Alert reduction	Yes	Yes	Yes
Alert capturing			
Clinician	Yes	Yes	Yes
Patient	Yes	No	No
Privacy			
Ownership	Clinician and patient	Clinician and patient	N/A[a]
Encryption	Yes	No	N/A
Blockchain			
Type	Private: Hyperledger	Public: Ethereum	No, machine learning
Smart contract	Yes	Yes	N/A
Miners	No	Yes, medical background	N/A

[a]N/A: not applicable.

Unlike MedRec and MedAware, MedAlert reduces alert fatigue by capturing the attention of both clinicians and patients. We believe that the way to reduce alert fatigue is to get the clinician's attention, but there is no *perfect* solution in which clinicians are able to pay attention to all alerts [15], not even after the removal of irrelevant alerts. Therefore, MedAlert directs low-level alerts to patients and induces them to pay attention to provide real-time responses. This is a novel initiative moving toward a clinician-patient collaborative decision-making process to avoid potential medication errors resulting from action being overridden. This can improve the quality of the health care domain with respect to better patient outcomes and reducing physician burnout.

MedAlert runs on the private Hyperledger blockchain, which ensures a higher privacy compared with MedRec, which runs on the public Ethereum blockchain. This is because private blockchain is better suited to a highly regulated industry such as health care due to the stricter requirements regarding patient privacy and data protection. To avoid information leakage, both MedAlert and MedRec record only metadata or reference pointers rather than patient's medical data on blockchain. To enhance patients' data privacy, all metadata is encrypted and stored on MedAlert blockchain, where only authenticated patients can view the transactions and authorized clinicians can read and write transactions. This makes MedAlert better compliant to standards such as GDPR (Art. 32. Security of processing) compared with MedRec.

Apart from ensuring a higher-level privacy environment, MedAlert, deployed in private Hyperledger, has a better performance than MedRec, deployed in Ethereum. The assessments from Pongnumkul et al [66] show that Hyperledger outperforms Ethereum in 3 evaluation metrics: execution time, latency, and throughput. For example, the average latency of Ethereum is about 2 times at a low number of transactions and can increase up to 14 times that of Hyperledger at a high number of transactions. This is important when fast information sharing is needed between a clinician and a patient during collaborative decision making.

MedAlert can improve the flow of communication between clinicians and patients. Clinicians may need to ask for and validate information with patients because without this step, there is a significant risk of error in ordering or prescribing medication [67]. This risk can increase when alerts generated by CDS are simply overridden. MedAlert can reduce this and prevent it from happening by sharing clinical alerts with patients. Patients can receive the alert and be asked to provide information. If they are uncertain, they can enter into direct communication with the clinician and deal with the alert that way.

Future Work

Validation work such as threat analysis is needed in future work to elucidate the effectiveness and the potential vulnerabilities of using MedAlert before deploying it in the eHealth sector [68]. This would provide a documented performance evaluation of MedAlert to persuade health care leaders of the benefits of this new digital tool and gain sufficient support from them for its deployment. Despite numerous published literature on how blockchain can record immutable transactions and enhance interoperability and thus improve health care, many leaders remain unsure about what blockchain has to do with health care. Proof of validation is an important step in scaling up this framework and making it applicable to the real world [69].

Second, sorting and tiering alerts based on severity, for example, sorting into 3 tiers: low, mid, and high, are needed as a part of future work to validate MedAlert. This is to determine which low-level alerts are suitable for patients because clinicians tend to accept high-severity alerts slightly more often than mid- or low-severity interaction alerts [11]. However, the process of tiering alerts is highly subjective when it comes to deciding which alerts are considered low level and time consuming for all medical experts before reaching a common consensus. Thus, this initial step in selecting which alerts are to be shared with patients can be challenging.

Decentralized identity management is an alternative way of verifying and authenticating users. It eliminates the limitations of centralized identity systems, helps achieve compliance with the most comprehensive national data protection laws, and returns ownership and control of identity data back to the individual. Various decentralized identity management systems exist that provide solutions using a distributed ledger technology. Evernym [70], uPort [71], and Sovrin [70] are some examples of identity projects that are working on decentralized identity platforms. However, these sophisticated solutions are still at a provisional stage, where more validation, discussion, and investigation are needed [60].

Limitations

MedAlert is suitable for a specific group of users. Collaborative decision making may be challenging for patients who are less technology savvy, particularly for elderly patients, who may not be able to use MedAlert effectively. For example, the steps where patients need to verify and authenticate themselves and thus gain access to alerts could be confusing for the elderly and may induce unnecessary stress on them. MedAlert is not suitable for in-patients either where they require constant monitoring. This is because they may not be able to provide a response when they are unwell in the hospital.

Directing low-level alerts to patients may create ethical issues where the responsibility is indirectly shifted on to them in cases when they provide incorrect responses. In a study conducted in medical centers in the Netherlands where alerts were directed to nurses, despite improvements in efficiency and effectiveness, the study concluded that such alerts should not be directed to nurses [40]. It is difficult to find the right balance of responsibilities between clinicians, nurses, and patients in a collaborative decision-making process.

Privacy concerns are covered by the GDPR. Storing digital assets, such as medical records on blockchain, could violate personal privacy. Although MedAlert only stores patients' metadata on blockchain, it is not entirely anonymous. Malicious acts include attempting to learn about and identify actual personal patients based on the pseudo-anonymous information on blockchain. In addition, the permanent storage of information, both data and metadata, belonging to a person could violate GDPR (Art. 17 Right to erasure or to be forgotten) in cases when users want to have their data completely erased or deleted.

Conclusions

CDS supports the decision-making process in preventing medication errors by generating alerts. Clinicians can now rely on these alerts along with their knowledge and past experience to avoid medication errors. Due to the low specificity and highly restricted modifications of the CDS setting, a high volume of irrelevant alerts has caused clinicians to experience alert fatigue. This results in a high overriding rate, which can cause medication errors.

From our scoping review, we found different methods of reducing the number of alerts, such as machine learning algorithms and blockchain technology, by filtering out irrelevant alerts. We developed a different solution that is similar to what medical experts pointed out, where improving alert fatigue should go beyond just reducing the total number of alerts.

In line with this idea, we designed MedAlert, a blockchain-based solution, by sharing low-level alerts with patients where clinicians typically have a greater tendency to override low-level alerts. The goal is to ensure that alerts catch the attention of both patients and clinicians, thus preventing medication errors, instead of being habitually overridden. In our own work, we introduced a second layer by engaging patients in providing a response and making them, at least, partially responsible for alert verification. This second layer reduces alert fatigue of clinicians and, at the same time, engages patients in the collaborative process, making it harder for medication errors to occur.

Other potential advantages of MedAlert over other frameworks include ensuring a greater degree of patient privacy and the ability to establish a new communication layer between patients and clinicians. Smart contracts and the use of BankID (federated identity management) are useful in authenticating patients and ensuring that the right person receives the alert.

Directing alerts to patients faces challenges such as finding a balance between patients and clinicians without raising ethical issues. This solution may not be suitable for elderly patients or in-patients where they require constant monitoring. Sorting and tiering the alerts based on levels of severity is also challenging because it is subjective and may vary between different panels of medical experts.

For the health care sector to benefit from the potential value of this innovative idea, future work, for example, on the validation of MedAlert based on real-world scenarios, such as the degree of compliance with GPDR, is needed. Providing documented evaluations of the performance of MedAlert is crucial to gain the support of health care leaders in nurturing this idea as a potential solution to reducing alert fatigue.

Acknowledgments

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Conflicts of Interest

None declared.

Multimedia Appendix 1

Search strings.
[DOC File , 59 KB-Multimedia Appendix 1]

Multimedia Appendix 2

Summary of selected literature.
[DOCX File , 25 KB-Multimedia Appendix 2]

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Abbreviations

API: application programming interface
CDS: clinical decision support
EHR: electronic health record
GDPR: General Data Protection Regulation
IT: information technology
NTNU: Norwegian University of Science and Technology
REST: representational state transfer

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Paper C

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Paper D

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