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Medical-Waste Chain: A Medical Waste Collection, Classification and Treatment Management by Blockchain Technology

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Abstract: To prevent the spread of the COVID-19 pandemic, 2019 has seen unprecedented demand for medical equipment and supplies. However, the problem of waste treatment has not yet been given due attention, i.e., the traditional waste treatment process is done independently, and it is not easy to share the necessary information. Especially during the COVID-19 pandemic, the interaction between parties is minimized to limit infections. To evaluate the current system at medical centers, we also refer to the traditional waste treatment processes of four hospitals in Can Tho and Ho Chi Minh cities (Vietnam). Almost all hospitals are handled independently, lacking any interaction between the stakeholders. In this article, we propose a decentralized blockchain-based system for automating waste treatment processes for medical equipment and supplies after usage among the relevant parties, named Medical-Waste Chain. It consists of four components: medical equipment and supplies, waste centers, recycling plants, and sorting factories. Medical-Waste Chain integrates blockchain-based Hyperledger Fabric technology with decentralized storage of medical equipment and supply information, and securely shares related data with stakeholders. We present the system design, along with the interactions among the stakeholders, to ensure the minimization of medical waste generation. We evaluate the performance of the proposed solution using system-wide timing and latency analysis based on the Hyperledger Caliper engine. Our system is developed based on the hybrid-blockchain system, so it is fully scalable for both on-chain and off-chain-based extensions. Moreover, the participants do not need to pay any fees to use and upgrade the system. To encourage future use of Medical-Waste Chain, we also share a proof-of-concept on our Github repository.

Keywords: medical waste management; blockchain; smart contract; COVID-19; Hyperledger Fabric; Hyperledger Caliper; information visibility

1. Introduction

The problem of waste collection, classification, and treatment is becoming more serious. It is estimated that the world produced about 1.3 billion tons before 2019, and this is expected to increase to 2.2 billion tons of solid waste per year in 2025. On average, each person emits about 0.11–4.54 kg of stable waste per day [1]. These solid wastes can come from technological products in daily life (e.g., phones, computers, cameras) or medical care activities (e.g., masks, syringes). One of the reasons that the growth of waste has almost doubled since 2019 is the impact of the COVID-19 pandemic. Indeed, the amount of household and medical waste has increased dramatically since the outbreak of the disease in the city of Isfahan, Iran [2].

Since the last months of 2019, the COVID-19 pandemic has highly affected our lives. The peak of the pandemic in 2020 and 2021 caused an all-time-high demand for COVID-19 medical equipment and supplies. To meet this urgent need, most systems, methods, and technologies today leverage the supply chain of medical equipment and supplies for COVID-19 prevention. However, the waste of these products post-usage is not efficiently managed. Klemevs et al. [3] recognized the harmful effects of vaccine production as an attempt to prevent the spread of the pandemic: their production damages the environment, causing a shortage of energy sources for the world. Remarkably, the cold chain is estimated to account for 69.8% of the energy consumed during the vaccination life cycle, in which around 26–99% is dependent on the transport distance. Furthermore, building equipment to meet storage and distribution needs is costly, especially in developing countries. Hence, a system for managing and classifying waste as well as medical supplies during the pandemic is extremely urgent [4]. A sustainable supply chain model that responds to an emergency agreement should be emphasized while also considering equity to reduce environmental harm [5].

In the current collection, classification, and treatment model, many medical supplies and waste management systems are constructed based on (i) centralized data processing, or (ii) leveraging cloud-based centralized resources to process waste-related data [6]. For the centralized processing model, all processing and classification activities are handled independently, lacking cohesion, and are challenging to share with partners [7,8]. For the cloud-based decentralized processing model, the centralized storage and processing of data from multiple sources often leads to data inconsistencies among the involved parties, thereby creating limited cooperation opportunities for stakeholders [9,10]. In addition, this model is flawed in providing traceability, reliability, operational transparency, security, and reliability features in processing [11,12]. On the other hand, a significant factor in the current epidemic problem is the ability to encourage non-face-to-face interaction (i.e., limit face-to-face meetings) to avoid transmission, which has presented a complicated issue for the community, the management of equipment, supplies, and medical waste. As a result, a blockchain-enabled waste management strategy helps make better decisions, improves productivity, is cost-effective, and ensures compliance with [1] waste regulations.

Blockchain-based systems developed for waste management mainly focus on solid waste such as electronics, household waste, and agricultural waste. Implemented systems for the treatment and segregation of waste in the medical environment are few and need to be developed in detail. Current blockchain-based projects developed for waste management have implemented several types of services rather than sorting and disposing of waste, e.g., waste collection process management [13], vehicle-based shipment monitoring [14,15], waste classification [1], and auditability of waste handler actions [16]. A detailed analysis of the approaches and results achieved by start-of-the-art methods is given in the Related Work section. Most of the existing studies are designed on the Ethereum platform to provide a reward-and-punishment mechanism for the stakeholders involved in managing, classifying, and treating waste. The system ensures compliance with user actions via a series of waste management rules defined in the smart contract. However, a technique developed based on Ethereum will be greatly limited in funding and transactions per second (TPS) [17–19]. To solve this problem, we built a new waste treatment system based on Hyperledger Fabric dedicated to classifying, collecting, and reusing medical equipment and supplies between stakeholders in the healthcare environment. We introduce the Medical-Waste Chain (a medical waste classification and treatment management scheme using a blockchain-based system) to classify and manage medical waste using blockchain technology. The main contributions of this paper are as follows:

- We look at the critical opportunities that blockchain technology offers for the handling and classifying of medical equipment and supplies to improve operational transparency, traceability, security, and accountability in waste management processes. It will be clarified in the section Medical-Waste Chain Architecture.
- We present a case-study implementation (i.e., proof-of-concept) based on Hyperledger Fabric. To advance extensive research into waste collection, segregation, and treatment systems, we share our implementation of Medical-Waste Chain at https://github.com/Masquerade0127/medical-blockchain accessed on 12 June 2022, which will be analyzed in the Implementation section.
- We measure and evaluate Medical-Waste Chain based on many different scenarios. The evaluation results are outlined in detail in the Evaluation section.

This paper is organized as follows. Section 2 presents the background of the research. Section 3 offers a literature review of relevant issues. The Medical-Waste Chain overall architecture and implementation are shown in two following Sections 4 and 5. Section 6 describes the framework and benefits of the proposed system via evaluation. Finally, Section 7 describes the conclusions and future research opportunities.

2. Background

2.1. Blockchain Technology

Blockchain is well known for the success of Bitcoin [20] and is commonly characterized as a transparent, reliable, and decentralized ledger on a peer-to-peer network that manages transaction data on several computers at the same time. As a result, blockchain is seen as a trust circle that allows parties to be autonomous without relying on a single third-party confirmation [21].

The public, private, and consortium blockchains are three universally acknowledged forms. Bitcoin and Ethereum are examples of public blockchains. Any anonymous users may join the network, view the blockchain's content, execute a new transaction, or check the integrity of the blocks. Meanwhile, GemOS, MultiChain, and Eris are typical examples of a private blockchain in which only permitted users can join the network and write or send transactions to the blockchain [22]. A consortium blockchain is semiprivate, on the border between public and private blockchains. It is typically connected with the use of enterprise to better business. Hyperledger Fabric [23] is a business consortium blockchain framework. Ethereum [24] also allows for the creation of consortium blockchains (Golang).

Numerous features and components make blockchain technology useful and advantageous to the participated stakeholders. The smallest data unit on the blockchain that includes records, contracts, and information is called a transaction [25]. Any entity connecting to the blockchain is referred to as a node [25], and transactions are confirmed by particular nodes (known as miners) by examining the sender as well as the transaction's content. The nodes combine the complete transactions into blocks [25,26] and are in charge of determining if the transactions are valid, and if they should be stored on the blockchain.

- Ledger [27,28] is a data storage on a blockchain that uses a consensus algorithm to store immutable, sequential entries in blocks. For each channel, each node keeps a copy of the ledger. For efficient processing, the shared ledger encapsulates the whole transaction history for each channel and adds query capabilities.
- Cryptography [28] is one of the essential components of blockchain, which allows relevant access, and stores data in immutable blocks with a fixed sequential order, and establishes identity and authenticity.
- Consensus [28] is another crucial component of blockchain that is connected to how data submissions are accepted onto the distributed ledger. Consensus algorithms [29] are used in blockchain technology to maintain a single history of blocks by synchronizing the data inside the chain of blocks to ensure that no contradicted or invalid transactions exist. There are many existing types of consensus rules, such as Proof of Work (PoW), Proof of Stake (PoS), Proof of Authority (PoA), and Proof of Elapsed Time

(PoET). According to these algorithms, all participating nodes must prove something for someone to be granted permission to add a block to the current blockchain.

2.2. Smart Contract

2.2.1. Ethereum

Ethereum [30] is a decentralized platform to run smart contracts with the support of Turing-complete programming languages. Ethereum is executed by the Ethereum Virtual Machine (EVM) and written in high-end programming languages such as Solidity, Serpent, Low-level Lisp-like Language (LLL), and Mutan. Withdrawal limitations, loops, financial contracts, and gambling markets are possible on the Ethereum platform. Ethereum is now the most popular platform for smart contract development.

2.2.2. Hyperledger Fabric

Hyperledger Fabric [23] is an open-source enterprise-grade permission-distributed ledger technology (DLT) platform designed for large-scale commercial use. It has a few essential features that set it apart from other DLT or blockchain systems. Similar to Ethereum, Hyperledger Fabric is also Turing complete. However, unlike Ethereum, which executes smart contracts on virtual machines, Hyperledger code is executed in Docker containers, allowing smart contract applications to run with minimal overhead while sacrificing isolation (i.e., applications in one container are running on top of one operating system). Fabric succeeds in supporting traditional high-end programming languages such as Java and Go (also known as Golang) rather than building Ethereum's smart contract languages.

The support of multiple programming languages facilitates the development and maintenance of the Fabric platform. Additionally, Fabric assists in mitigating operating costs, including storing and querying information inside the blockchain, and quickly setting requirements for security features and user authorization.

In this article, we engage the Hyperledger Fabric platform in building a process that consists of a smart contract to manage the blockchain's stored data flows and back-end APIs to process input and output data. Then, all these components will be deployed on a container independently run on the peer-to-peer network system inside the Docker-compose platform.

2.3. Hyperledger Caliper

Hyperledger Caliper [31] is a standard blockchain apparatus; a Hyperledger project facilitated by the Linux Foundation. It is utilized to gauge the productivity of the particular blockchain execution with a predefined set of usage cases. The performance reports, transaction latency, and resource usage are produced by the Hyperledger Caliper so that the other projects of Hyperledger might leverage these resources. Hyperledger Caliper is an open-source project contributed by Huawei, Hyperchain, Oracle, Bitwise, IBM, and Budapest University of Technology and Economics.

3. Related Work

As explained in the introduction section, medical device management or reverse logistics activities (RLA) play an essential role in adequately managing devices in a medical environment. These operations preserve equipment at the end of its useful life and anticipate the necessary replenishment of missing equipment. However, refurbishing medical devices and anticipating their necessary replenishment is not a straightforward process, as there are many challenges associated with their appropriate repositioning into the medical market. This paper uses blockchain-based technology as a possible solution to establish connections with recycling facilities for medical devices and recycling medical waste while considering regulatory-security- and transparency-related compliance. Moreover, in the COVID 19 pandemic, the requirements for handling medical equipment and waste are highly urgent. The essential requirements in this phase are how to provide enough medical supplies, and to limit direct contact between stages. This section summarizes the management systems in three sub-sections: blockchain-based management systems, blockchain-based medical systems, and blockchain-based waste management systems.

3.1. Blockchain-Based Management Systems

Blockchain is a state-sharing and consensus-building technique that fulfills transaction record retention and synchronization of distributed network participant systems [32]. The main benefits of a blockchain-based system are the following: (i) there is no centralized server; (ii) all the executed transactions are logged; (iii) information is shared on the distributed ledger for the parties' assessment; (iv) information is organized into blocks when a new transaction is generated. Within a blockchain structure, we can classify three main types: public, private, and consortium (also known as hybrid). According to the developer's requirements, they can define the corresponding structure and platform; for instance, Bitcoin Core, Ethereum, Hyperledger Fabric [33].

Supply chain management integrates core business processes and information. The process goes through many steps, including customers and retailers, wholesalers, manufacturers, and suppliers, which add value to customers and other stakeholders [34]. The system incorporates a highly complex process that requires synchronization of various activities, resulting in randomness and supply chain risk [35,36].

Moreover, Casino has synthesized systems that apply blockchain technology in measurements, including supply chain management, as well as medical supplies [25]. There are very few articles that offer blockchain-based approaches to device management. One of them, by Douladiris et al. [37], introduced a medical device management model based on blockchain technology. In [38], based on structured interviews, the authors assessed the benefits and risks of incorporating the blockchain model in equipment management practices. Farouk et al. [39] have developed a theoretical framework that uses blockchain to enhance transparency and information sharing in electronic supply chain management activities for general device management procedures. In the same year, Dasaklis presented a blockchain-enabled architecture and a proof-of-concept implementation of mobile operations [16]. In addition, Le et al. [40,41] also exploit the advantages of blockchain technology to apply the cash-on-delivery model. Furthermore, in the process of delivery and receipt of goods between shippers, Ha Xuan Son et al. developed a transport model based on a blockchain-based decentralized mechanism [42].

Hyperledger Fabric is an open-source distributed ledger platform designed for developing permission applications at an enterprise grade. Fabric provides a platform to build fast, efficient, and secure enterprise blockchain applications. It is characterized as being suitable for business-to-business (B2B) transaction services, and its membership services limit the entry of unauthorized participants [43]. Due to having a node for verifying the transactions during transaction processing, it is possible to remove uncertain transactions early and quickly. Due to these benefits, and some advantages in the Background section, we intend to design a Hyperledger Fabric architecture-based system for blockchain-based management.

3.2. Blockchain-Based Medical Systems

Healthcare is one of the prominent fields where Blockchain is supposed to make a substantial impact. It generates a wide range of opportunities and possibilities in current healthcare systems. Specifically, in 2018, Kumar et al. [44] exploited the potential applications of blockchain technology in current healthcare systems to address the trustless and ambiguous aspects of such systems positively. A year later, Marcela et al. [45] introduced a blockchain-based peer-to-peer medical platform to manage electronic medical records (EMRs). Their proposal kept the encrypted data in the blockchain and allowed the patients to share the decryption key only with healthcare professionals they trust. Similarly, Wilber et al. [46] also surveyed the blockchain-based medical system to highlight the most important requirements in meeting the need for sensitive data protection. Moreover, some papers applied the blockchain architecture to define a healthcare system for specific diseases such as diabetes [47] and COVID-19 [48].

On the other hand, research on blood supply-chain management has been conducted by several approaches. Blockchain application in the healthcare supply chain is not as common as in other areas; they are considered "vital." Blockchain solutions are more suitable for healthcare supply chains; however, there are as yet no blockchain solutions in use for healthcare. Although research investigating the application of blockchain in this sector is increasing, it is mainly used for data sharing and recording data, while using it for supply-chain management is rare [49]. Some companies, like Imperial Logistics and FarmaTrust, use blockchain to manage pharmaceutical supply chains [50]. Other experimental projects such as OrganTree and Dhonor Blockchain also use this technology to connect organ donors, recipients, and practitioners by using incentives such as paying for funeral costs [51]. Several articles have investigated blood donation tracking. BloodChain and SmartBag focus on preventing contamination in the supply chain and reducing the spread of HIV in developing countries [52]. Another project, called BLOODCHAIN, focuses on motivating blood donors by giving monetary compensation. Wust and Gervais (2018) have proposed a flow chart to emphasize the importance of blockchain applications in tracking the origins of donated blood [53]. The model is presented and discussed in the paper to see whether blockchain can solve the problem; however, the situation has not been solved well. Nga et al. [54] applied blockchain to store and deliver the volunteer blood donations.

Several blockchain-based systems are introduced to define authorized users (i.e., parties) who can process the patient's privacy data for healthcare emergencies. For instance, Son et al. [55] developed a blockchain-based technology for dealing with crises in patient-centered systems, where the patient is allowed to define the privacy policy for all data collection requests in an emergency. In other words, these data could not allow access in a normal situation without permission from the owner. Moreover, Trieu et al. [17] extended this model to give more management power to patients. We define the access control model, in this paper, as more fine-grained in the privacy policy. Specifically, the users can explain the procedure depending on the time or place rather than the fixed policy.

Some approaches use a blockchain-based system to share the collected data among the healthcare centers, and to support the users in controlling their medical data. It means the patients could choose what kind of information related to their health history will be shared with the clinics, including sensitive information [56]. Moreover, Nghia et al. [57] introduced the SmartCare system to combine the history of medical resources from the other centers in the diagnosis phase to improve the treatment process.

3.3. Blockchain-Based Waste Management System

The removal or segregation of wastes, especially medical waste, continues to contaminate our ecosystem [58]. As an obvious example, 99% of items (including medical equipment and supplies) become trash within the first six months of first use [59]. This problem can be viewed as a catastrophic failure in material recovery. In particular, the circular economy (CE) aims at the elimination of both waste and misuse of resources. This system focuses on reusing, repairing, and recycling in a secure method. Thereby, we can ultimately reduce input materials and prolong the time of usage (instead of only six months on average) of equipment and supplies, minimizing pollution and the intorduction of other wastes into the environment. Morseletto et al. [60] have defined a circular economy as "an economic model directed at the efficient use of resources through waste minimization, long-term value retention, and resource minimization primary and closed-loop of products, product parts, and materials within the boundaries of environmental protection and socio-economic benefits." According to the above definition, a CE-based production and consumption system focuses on maintaining the utility and the value of products and materials.

To this end, the Ellen MacArthur Foundation [61] has introduced a series of principles (e.g., reuse, repair, refurbish, remanufacture, recover, recycle, and regenerate from waste streams). The primary purpose of the CE system is to achieve a world without waste.

Moreover, CE is considered a model of the future toward a green economy. For example, to reduce waste and increase recycling, Amazon has created CE loops based on partnerships and offers options for customers to reuse, repair, and recycle their products [62]. However, to be able to apply CE in the natural environment is exceptionally challenging [63], especially in a medical setting. A typical example drawn from the COVID-19 pandemic is that the waste treatment process is performed asynchronously, leading to a considerable amount of waste (e.g., personal protective equipment [64] and COVID-19 vaccines [65]). This also contributed to many subsequent waves of infection [66].

The management and classification system of medical equipment and supplies acts as a decentralized trading environment in the current context. The system consists of participants who share and authenticate data, and are solely responsible for the shared data. These data can be inventory data, digital assets, types of equipment, supplies, or any other kind of information [67] used in a healthcare environment. Understanding the demand for medical equipment and supplies is extremely important; it contributes to reducing the spread of COVID-19 disease in the community [68]. Blockchain-based management systems were introduced to address this problem. The next section focuses on exploiting waste management systems and medical supplies developed based on Blockchain technology.

Gupta et al. [13] proposed an Ethereum-based system called Electronic Waste Management (EWM). Based on the constraints defined in the smart contract, EWM has ensured compliance with waste disposal guidelines for electrical and electronic equipment (EEE). In EWM, the author proposed three main stakeholders offered by the system: manufacturers, consumers, and retailers of electronic components. Smart contracts calculate, record, report, and provide incentives for consumers to send back EEE waste to retailers to address the post-use waste problem. Furthermore, in the context of retailers, smart contracts focus on verifying that waste is received for all sold EEEs. Specifically, the retailer ships the EEE waste to the producer and pays a portion of the original cost of the EEE to the consumer. Smart contracts have also imposed penalties on EEE manufacturers if waste is not collected from retailers within a predetermined period.

Poongodi et al. [14] have proposed a 5G enabled system that supports tracking electronic products throughout their life cycle, based on blockchain technology. The system is deployed on the Ethereum platform. The system was built around five actors: manufacturer, supplier, retailer, customer, and e-waste facility. In particular, e-waste facilities offered rewards and incentives to customers if they sorted waste for treatment before sending it to e-waste treatment facilities. To accomplish this, the authors built a smart contract-based computation suite. Specifically, it required all related parties to comply with the rules outlined in the treatment of waste by escrow. This action encouraged stakeholders to take responsibility for e-waste segregation practices. Finally, the escrow and incentives were returned to the stakeholders when the smart contract logic-based calculations were evaluated.

Laura et al. [15] introduced an Ethereum-based management system to assist users in monitoring solid material waste (e.g., computers and smartphones). What differentiates this system from previous approaches is that it allows the owner to monitor and track the waste in transit from the receiving location (i.e., user address) to the substance-storage waste plant. The proposed system was based on the interaction between four actors: the collection manager, storage manager, transaction manager, and processing manager. The collection manager generated and stored a QR code (i.e., a QR code referring to a package containing solid waste on the blockchain). The transportation manager recorded the solid-waste-transport vehicle's status, location, and route information. This information was updated to the distributed ledger. In addition, to temporarily store encrypted data related to solid waste without affecting the entire system's performance, the authors used an off-chain storage system. However, to balance security and throughput, the system can use multiple blockchain platforms. Thereby, the problem, in this case, is how to synchronize between different blockchains.

Schmelz et al. [69] also presented an Ethereum-based system that could track waste across borders in a secure, tamper-proof, and privacy-preserving manner. In particular, sensitive and non-disclosure information (e.g., assets and waste processes) were stored locally and not on-chain. The system kept a log of the processes executed during the processing of audit-critical data. Specifically, it assigned a signature to the data before the transaction by applying a one-way hash function. On the other hand, the authorities examined and verified the reason for the delay in transportation access between the exchanged locations, the volume transported, and the validity of the waste treatment methods based on the information stored in the smart contract. However, they did not impose any penalty for violations in the transportation and disposal of waste.

The lack of transparency in waste collection and treatment activities could cause frauds that affect the entire system. To address this issue, Ahmad et al. [1] proposed a framework for traceability of personal protective equipment (PPE) for healthcare workers against COVID-19. In particular, based on image analysis related to waste collection, the authors presented a system that used analytical techniques to identify fraud. They compared data before and after the collection/treatment processes to identify fraudulent practices, i.e., calculated similarity index between two captured images, estimated garbage weight, location position, and time difference of two captured images. After computing such data, it determined what behavior was (not) allowed in garbage collection. Correct actions would be encouraged; otherwise, violators would be fined. However, blockchain's contribution to the system is somewhat ambiguous. Specifically, the technique used blockchain technology to securely transfer crypto-currencies to users as an incentive to collect waste. Moreover, another study conducted by Dasaklis et al. [16] proposed a blockchain-based system to track all remanufacturing/refurbishing processes for smartphones. However, the authors did not pay much attention to the reproduction/refurbishment process in either of the above approaches.

3.4. Limitation of Existing Research

These studies suggest a blockchain-based solution that can assist stakeholders in tracking and evaluating medical equipment and supplies (e.g., swabs and swab-sample test tubes) to verify their removal in a secure, transparent, and trustworthy manner. On the other hand, based on the decentralized mechanism, the counterparties can check and evaluate the entire process, thereby making an appropriate decision. However, none of the above studies highlight the need to improve transparency, efficiency, and rational usage of medical devices for waste management in healthcare environments during the COVID-19 pandemic.

4. Materials and Methods

In this section, we will analyze the waste treatment process during the COVID-19 pandemic in Vietnam, thereby analyzing and evaluating the conversion of medical equipment and supplies into hazardous medical waste. This information is derived from documents compiled by centralized quarantine procedures (Decision 878), household quarantine (Decision 879), medical quarantine (Decision 1551) and regional quarantine custody areas (Decision 904). In addition, we use the National Steering Committee's documents in the prevention of the COVID-19 epidemic on the mandatory isolation period (5 May 2021; Official letter 600/CD-BCD). We then analyze the possible limitations of the medical waste treatment process in the prevention of the COVID-19 epidemic in Vietnam. Finally, a proposed solution and model section will be presented.

4.1. COVID-19 Waste Treatment Process in Vietnam

Figure 1 details the treatment process and location responsible for COVID-19 waste in Vietnam. In general, there are five sources of COVID-19 waste generation: isolated treatment places (e.g., hospitals), isolated places (e.g., military barracks or public facilities requisitioned for quarantine purposes), testing places, vaccination places, and personal places under quarantine (e.g., households). The COVID-19 waste treatment process includes five steps, from identification to incineration of hazardous waste. Furthermore, the waste originating from a personal place under quarantine is not recognized as COVID-19 waste (e.g., masks, tissues, and cloths removed by quarantined individuals). These types of waste are required to be temporarily stored indoors and then disposed of into municipal solid waste after seven days of quarantine. If a household member is confirmed to be infected, this waste is treated as COVID-19 waste. According to Decision 3455, all COVID-19 waste belonging to medical facilities must be managed in these medical facilities' existing waste treatment system. Waste in the remaining areas must be managed by the People's Committee of the province or city. This process involves both the waste transportation to the designated treatment facilities and the entities responsible for the respective waste disposal. Finally, companies and waste treatment plants must process (e.g., incineration) hazardous wastes from two sources (i.e., the municipality and medical facilities).

The waste from hospitals is classified as a waste group with a high potential to cause adverse effects on the environment [70]. Most medical equipment and supplies are disinfected and used in a sterile environment, especially equipment and supplies such as gloves, masks, protective gear, etc. This equipment frequently comes into contact with laboratory products, research labs, or medical centers, so it must be determined which are the devices that need to be discarded and which are reusable devices. The primary purpose of this classification process is to avoid waste and ensure safety for the environment.

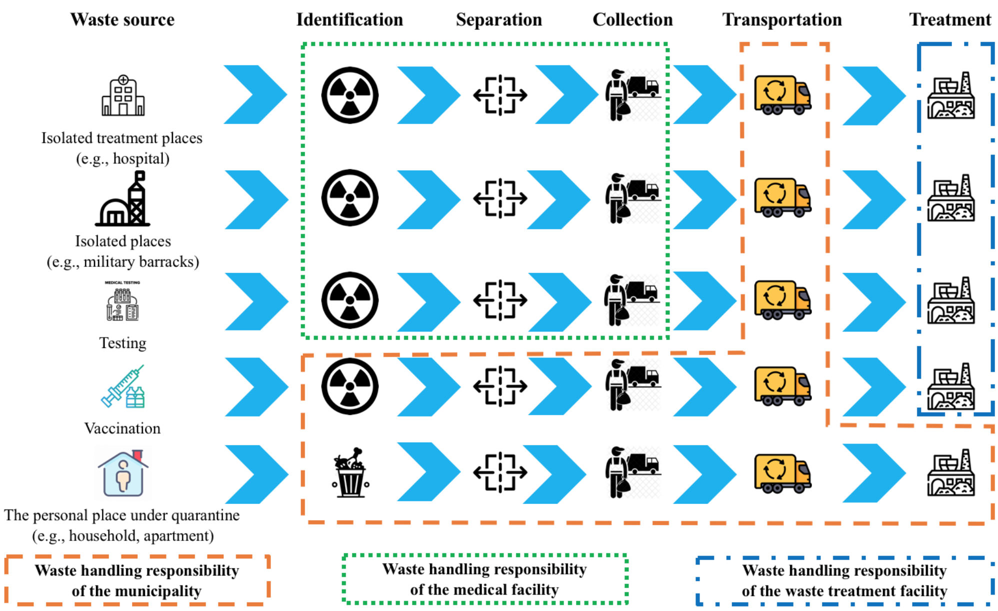

Figure 1. The current COVID-19 waste treatment process in Vietnam [71].

The disadvantage of the above model comes from the connection between the parties involved in the process of transportation to waste treatment, for example, from collection to transportation and from transportation to treatment. This transfer may introduce some mistakes in the transportation or waste treatment stage if the information transferred between the parties concerned is not strictly checked and monitored. All activities are carried out manually, and there is a lack of transparency in determining the origin and processing time of various types of waste.

Furthermore, the treatment process must also strictly adhere to time requirements (e.g., 7-day quarantine for a personal place under quarantine) and treatment level (e.g., destruction or recycling). The connection between stages can increase the risk of disease outbreaks on a large scale. Checking and identifying information is also extremely difficult because everything is processed manually, and the authenticity of the information is difficult to verify. Moreover, it is challenging to check the waste treatment process (e.g., that the steps are taken in the required time) of the Ministry of Health and the People's Committee of the province or the city level; these must be handled manually, and no system can support the verification process. Moreover, the centralized data storage can easily be attacked by malicious users or lose data when a problem occurs. Due to the above drawbacks, this paper proposes a COVID-19 waste management model based on blockchain technology.

4.2. Medical-Waste Chain Architecture

In the other cases, we also carried out monitoring and data collection in several hospitals in the south of Vietnam (i.e., Can Tho and Ho Chi Minh cities). We have carried out investigations of three hospitals in Ho Chi Minh City and two hospitals in Can Tho city during two months i.e., January and February 2022. In each hospital, we conducted a short interview by phone and messenger with the nurses and doctors who use the medical devices, as well as the cleaning staff of the medical facilities. For each facility, we also collected information regarding the usage time of medical supplies, the classification process after usage time, the methods of storing medical devices, and the stages of transferring medical devices between departments and hospitals. To ensure the reliability of the collected info, we contacted at least two people at each facility. The results show that hospitals and medical centers currently do not have a specific process to manage and reuse medical equipment and supplies effectively. It can be wasteful and inefficient in the use of equipment and supplies. Moreover, inefficient management can increase the amount of medical waste, adversely affecting the environment. Therefore, the medical device management model described in Figure 2 is proposed, with the aim of better managing medical equipment and supplies (called medical equipment), helping to classify, recycle, or effectively reuse these products. In addition, medical waste has the potential to affect the surrounding environment adversely. Good equipment management can help reduce the amount of waste released into the environment. Therefore, it is beneficial to minimize pressure and costs in the treatment and destruction of medical waste.

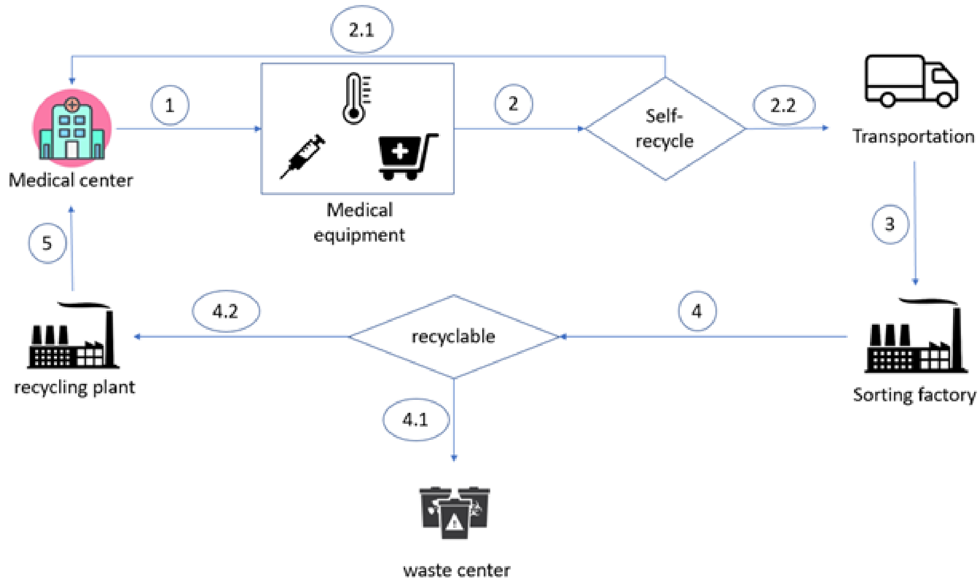

Figure 2. Our proposed medical-waste chain architecture.

With the risks listed above, this article offers a Medical-Waste Chain system to help manage and trace medical devices, making it easier to monitor and reuse them, based on blockchain technology. Thus, the users can save more on the purchase and sale of additional medical equipment and supplies, and limit the amount of medical waste to protect the environment. The Medical-Waste Chain system includes as its main objects:

medical centers, equipment and supplies, waste centers, recycling plants, sorting factories, and distributed ledgers deployed on the blockchain system.

First, when the device is transported to the hospital/medical center, the system initiates and stores data. Equipment and supplies are classified at the time of usage in the second step. Specifically, the sub-step (i.e., 2.1) presents the equipment and supplies that can be reused at the medical facility and stored, whereas one-time use equipment and supplies are collected and disposed of (i.e., 2.2). In the third step, the medical waste is transported to the factory for sorting. After that, the segmentation is carried out in step 4, wherein the recyclable equipment is transported to the disposal and recycling sites (4.2), and the remaining medical supplies are transported to the disposal area (4.1)

Figure 3 depicts the data initialization process for medical devices. When medical equipment is transported to the medical center, equipment data are extracted through existing services. After processing and extracting data, these services proceed to store data of the equipment at the data warehouse of the management system. Then, all data at the data warehouse transfers to the blockchain system for storage. In this step, the APIs of the smart contract receive the data and store them in the distributed ledger of the blockchain system in the form of transactions. In general, medical equipment data consist of the following fields:

```
equipment&suppliesDataObject = {
"equipment&suppliesID": equipment&suppliesID,
"name": name,
"quantily": quantily,
"unit": unit,
"packageID": packageID,
"state": 0,
"reUse": 0
};
```

Each piece of equipment or supplies will be stored with an identifier ID in the equipment&suppliesID field, which is used for querying and updating data of pieces of equipment and supplies in the future business. In addition, information such as name, quantity, unit, and package ID is also stored. Two necessary information fields, "state" and "reUse", will be initialized with a value of 0. The property "state" indicates the operating status of the respective equipment and supplies, with a value of 0 indicating that the equipment, supplies, or gadgets is stored and unused. Moreover, the "reUse" field indicates the number of reuses of such instruments during storage. A value of 0 means that their tools or accouterments have not been reused, and this value increases by 1 each time these inventory items are used in the medical center.

Figure 4 depicts the process of querying the data of equipment and supplies in a medical facility. The processing flow begins when the hospital or medical facility staff requests to query the data of any equipment or supply. The request is sent to the services of the management system, where the system determines the ID of the requested accouterments, then sends this ID to the APIs of the smart contract. The smart contract APIs send a request to the distributed ledger to query the item's data with the corresponding ID, then check the existence of the data to determine if the data are valid and complete. Smart contract query APIs send data to the query service, and the information is then returned to the user. In case the data in the smart contract are invalid or incomplete, the smart contract APIs return a "data broken" error message for the query service. This error message is sent to the user at the end of the flow. Furthermore, the smart contract also signals that the data do not exist if the data corresponding to the ID cannot be found in the distributed ledger.

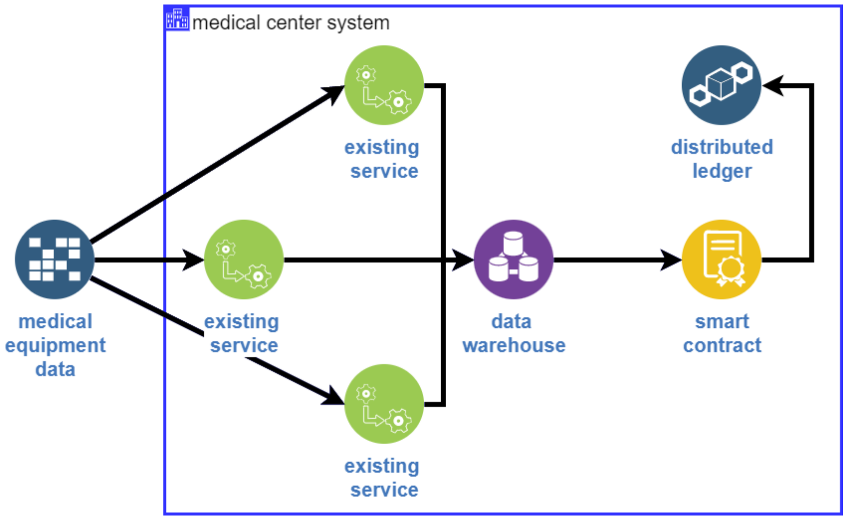

Figure 3. The data initialization process.

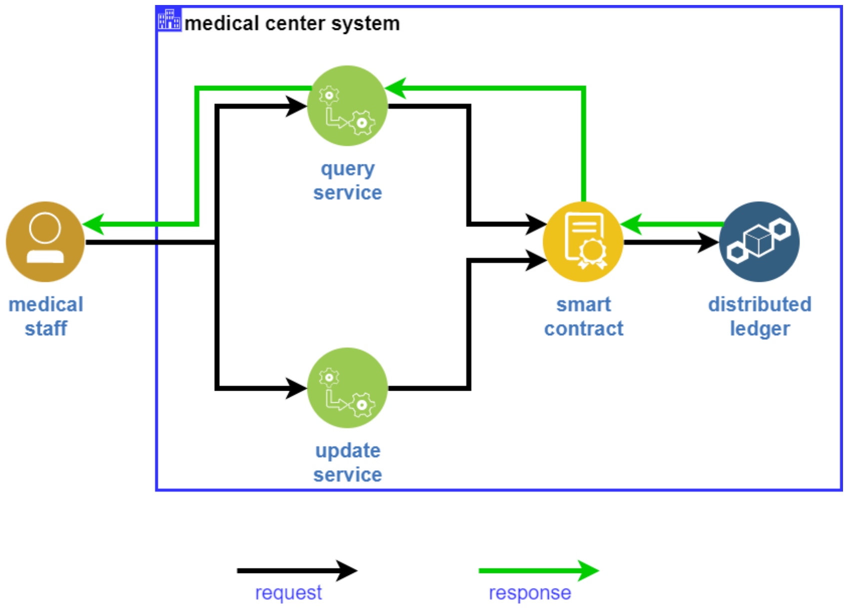

Figure 4. The data query process.

The data update procedure is depicted in Figure 5, which is used to change the status or usage times of medical instruments. Each piece of equipment or supplies was queried and checked for information to prepare for operations at the medical center/hospital. The item was updated with a "state" value of 1. Specifically, the medical staff sends a request containing the ID of the item to the query services of the management system at the medical facility. These services receive the corresponding identifier ID and send it further to the query APIs of the smart contract of the blockchain system. The smart contract proceeds to send a data query request with the corresponding ID of the instruments to the distributed ledger inside the blockchain system. If no corresponding data are found, the smart contract returns a message that the information does not exist in the system, which is sent back to the user as described earlier. If the data exist in the system, the smart contract converts the data format from bytes to JSON and sends the data back to the user. At the next step, the staff changed the value of "state" to 1 to determine the equipment, supplies, or gadget being used. For medical equipment and supplies that cannot be reused, the field "state" updates to 2, and the destruction process will proceed. The medical waste disposal process begins when equipment and supplies that cannot be reused at the medical facility is transported to the sorting plants. At this step, the "state" of the device is updated to the value 3. After sorting is completed, the recyclable equipment and supplies are transported to the treatment and recycling plants, and the “state” updates to 4. For equipment and supplies type "non-recyclable equipment&supplies" the items are transported to treatment plants and destroyed. At the disposal site, medical waste is sorted to determine which types of waste can be recycled and which must be disposed of and destroyed.

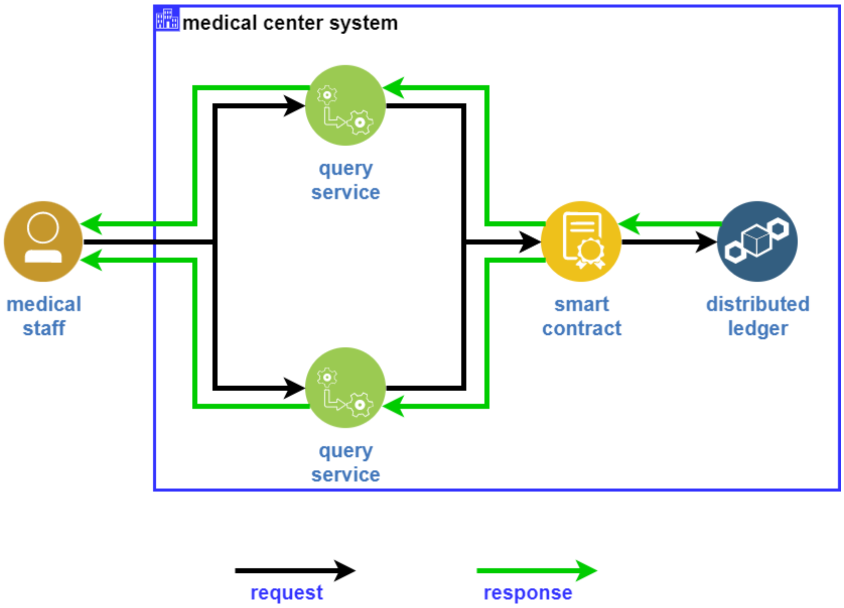

Figure 5. The data update process.

5. Implementation

5.1. Data Creation

The data initialization step is described in Algorithm 1. For each package or supply imported into a medical facility or healthcare center, the information corresponding to each device was generated and declared in the management system of the medical facility. Then, the information corresponding to the devices was stored in the distributed ledger through the smart contract APIs in the blockchain system. The data stored include information about the devices and their use status and the number of recycling times after use for devices that can be reused many times, specifically described as follows:

```
equipment&suppliesDataObject = {
"equipment&suppliesID": equipment001,
"name": equipment&supplies_name001,
"quantily": equipment&supplies_quantily001,
"unit": equipment&supplies_unit001,
"packageID": equipment&supplies_packageID001,
"state": 0,
"reUse": 0
};
```

The data include the overview information of the device and the status state. With a value of “0”, the device is described as being stored at the medical center and unused. A value of “1” indicates that the device has been used, and “2” means the device has been removed. In addition, the “reUse” field increases by 1 each time the device is used; this data field indicates the number of times the device is reused at the medical center.

Algorithm 1 Create data

```
Input: equipment&suppliesID, name, quantily, unit, packageID, state, reUse
Output: response success/failed
for Each package which contains medical equipment&supplies do
  create data of package
  create new data corresponding equipment&supplies
  store data of package and equipment&supplies to ledger
end for
```

5.2. Query Data

The information query function of the system is described through Algorithm 2. For each device stored at the medical center, the system checks the device's status. If the device can be used or operated normally, the "state" is updated to "1". If the device is damaged or unusable the "state" is updated to "2".

Algorithm 2 Query data

```
Input: equipment&suppliesID
Output: JSON object corresponding to equipment&suppliesID
for each equipment&supplies store in medical center do
  storing ID of equipment&supplies unit with correspondence ID of delivery unit
  if equipment&supplies working normally then
    query data of equipment&supplies corresponding id
    update "state" = 1 equipment&supplies not working normally
    update state broken of equipment&supplies
    update "state" = 2
  end if
end for
```

5.3. Modify Data

The smart contract's device information update function is described in Algorithm 3. Each used medical device is updated to a "state" of 1. After the end of the use process, if the device can be reused, the "state" information is updated to 0. Otherwise, the "reUse" information is increased by 1. The new information is updated and stored in the distributed ledger again for subsequent usage.

Algorithm 3 Query data

```
Input: equipment&suppliesID, newName, newQuantily, newUnit, newState, newReUse
Output: response success/failed
for each equipment&supplies in medical center do
  if equipment&supplies working normally then
    update "state" = 1
    if equipment&supplies end of uses then
      if equipment&supplies can be reusable then
        update "reUse" = "reUse" + 1
        update state data of equipment&supplies
        store at medical center equipment&supplies cannot reuse
        update "state" = 2
      end if
    end if
  end if
end for
```

6. Evaluation Scenarios

6.1. Environment Setting

Our paradigm is deployed on the Hyperledger Fabric network maintained inside Docker containers. In this section, the article measures the performance of smart contracts through 3 scenarios: initializing data of medical apparatus, querying information, and updating the corresponding data of these pieces of equipment and supplies. Measurements are done on an Ubuntu 20.01 configuration, core i5 2.7 Ghz, 8 GB RAM.

To prove the effectiveness of our model, we also perform several experiments by exploiting the Hyperledger Caliper that is used to design the test scenarios, and collect all the information regarding the performance.

6.2. First Scenario

In this scenario, the study measures the performance of the data initialization function performed through smart contracts, and the number of requests sent simultaneously from 3 users.

Figure 6 shows the execution result of the apparatus information initialization function. The data initialization script is conducted with three users simultaneously making 1000–6000 requests to the system. Based on the execution results in the image above, one can see that the number of successful and failed requests is kept at a stable level. In the create-package function, the number of failed requests ranges from 5554 to 10,059, while the number of successful requests is maintained at a much higher rate, from 41,080 to 44,563 requests.

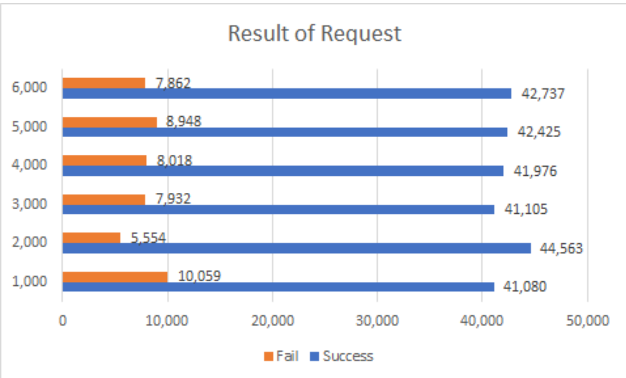

Figure 6. The result of processing requests to create equipment and supplies.

The latency graph in Figure 7 is also maintained at a stable level. Specifically, with the create equipment and supplies function, at 6000 simultaneous requests by three users, the largest latency was 1810.5 s, and the smallest delay was only 7.22 s. The average latency was maintained at 1046.1 s. We can see that the smart contract's processing capacity is kept at a stable level.

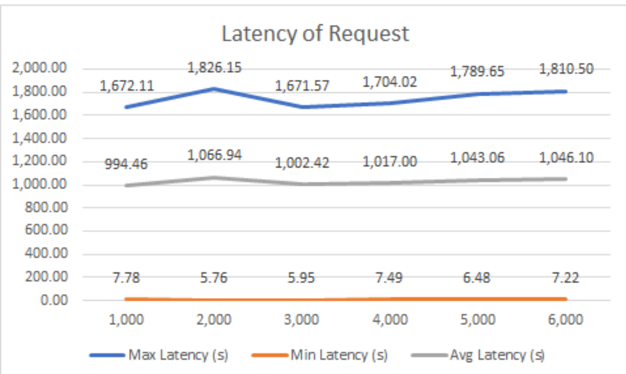

Figure 7. The latency of requests to create equipment and supplies.

6.3. Second Scenario

In this scenario, the article measures the function of querying data information of stored equipment and supplies after initializing or updating data.

Figure 8 shows the execution results of query data of equipment and supplies requests made by ten users, with the number of requests increasing from 1000 to 10,000. The number of failed requests ranges from 22,307 to 27,044. It can be seen that the percentage of failed requests is very small compared to successful requests that are consistently over 90,000 requests.

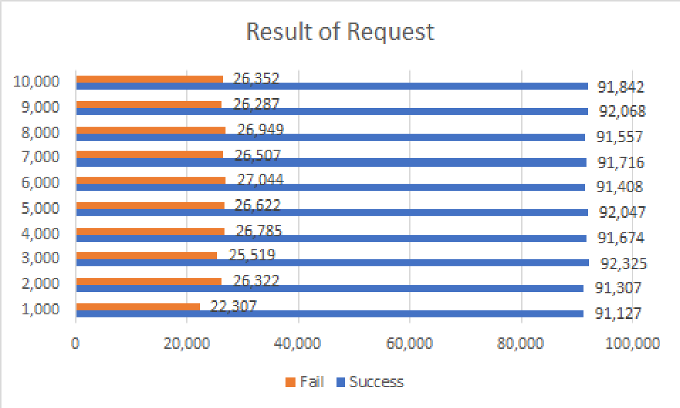

Figure 8. The result of querying for equipment and supplies.

Figure 9 depicts the latency of the data query function. The latency is low, specifically with 10,000 requests. The maximum latency is only 9.64 s, and the minimum is 0.02 s. The average latency is 6.37 s. Compared with the data initialization function, the latency of data query requests is lower because these requests do not create and store data, so the system responds faster.

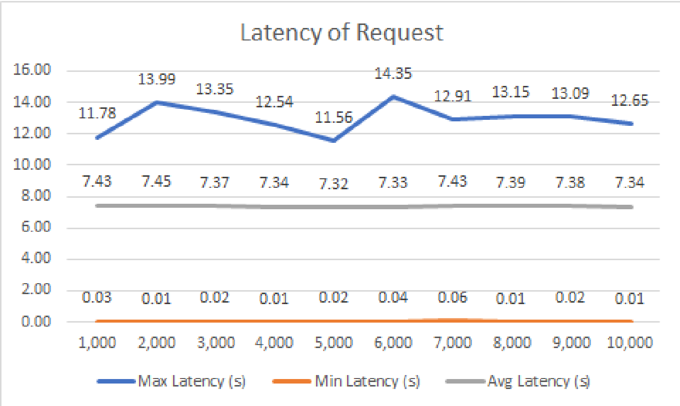

Figure 9. The latency of quering for equipment and supplies.

6.4. Third Scenario

The article presents the result of measuring update data of equipment and supply features. The number of users has been brought back to one user to track and compare the results with cases with more users.

Figure 10 details the measurement results of the information update function of medical devices. It can be seen that, although the number of users has been reduced, the high number of requests over a long period can affect the processing ability of the smart contract. Specifically, when bandwidth problems occur, the request traffic passing through the smart contract may be congested and not handled promptly, affecting the ability to handle requests from clients and reducing the number of successful requests.

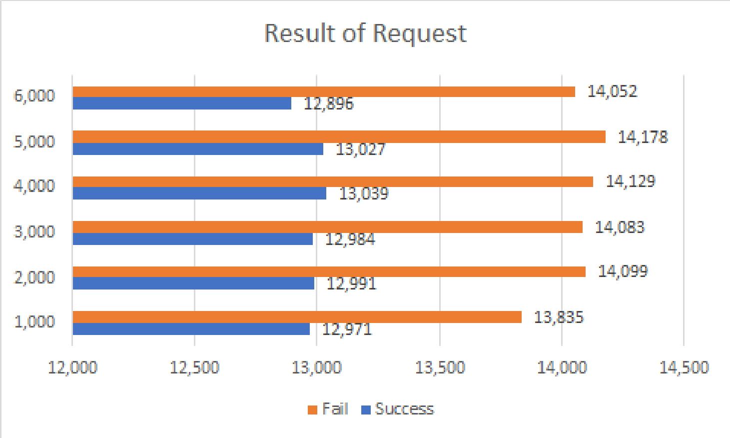

Figure 10. The latency of querying for equipment and supplies.

Figure 11 shows the latency of data update requests. In general, the latency is kept stable in 6 cases even when the bandwidth congestion occurs. It can be seen that the received request traffic and the resulting request execution do not reduce the processing capacity of smart contract data processing.

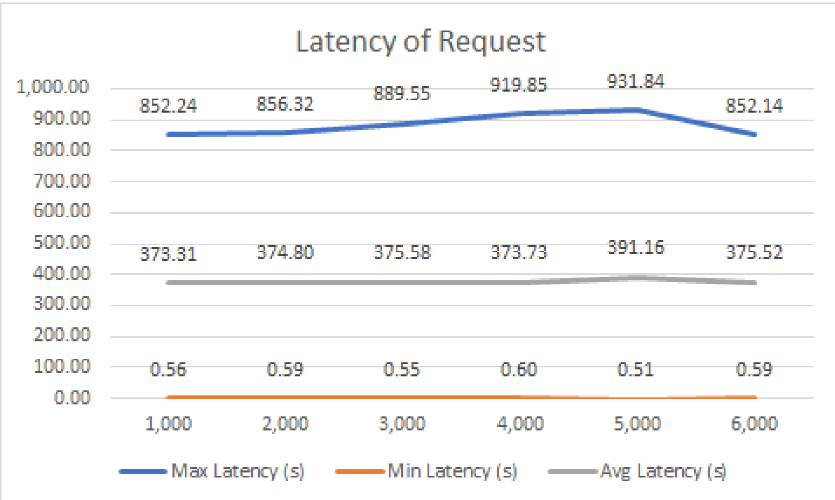

Figure 11. The latency of updating equipment and supplies.

6.5. Security and Privacy Discussion

For the authorization aspect, we will exploit attribute-based access control (ABAC) [72,73] to manage the access control process. The main benefit of this model is that only authorized users can access the release data. This not available in this version of the proof-of-concept. We will extend this service in the future work. Moreover, the query rewriting can apply to a complex context where the released data are shared with multiple users [74,75]. Finally, some approaches split the original policy into sub-policies [76,77] (i.e., public and private policy) to ensure the data are only accessed via permission even between parties in the same transaction.

Finally, compared to the prior work, this is the first approach providing a proof-of-concept to target medical waste management from the medical centers to the waste center. In the state of the art, some papers consider the general issues in waste management systems rather than focus on the specific case, i.e., classification, collection, and treatment. This paper highlights the blockchain technology to exploit the benefits of this system. We also present the results of our proposed model based on several experiments.

7. Conclusions

This article designed, developed, and evaluated the Medical-Waste Chain system, which manages (i.e., collection, classification, and treatment) the waste from medical equipment and supplies based on hybrid-blockchain technology. Thanks to real-time recording and sharing of waste treatment systems, medical equipment and supplies after usage are classified and consumed; distributed ledgers enable efficient management. The stakeholders' information is transparent to the other parties in the same transaction. This protocol helps participants track the related information of the source easily via the corresponding metadata, which is queried from the ledger. Additionally, Medical-Waste Chain prevents forgery and information tampering, making the medical waste management operation more transparent by solving problems in traditional medical institutions, such as missing entry inputs, exit, and band errors. Moreover, the Medical-Waste Chain system supports the waste transactions between the medical center and waste center, recycling plant, and the sorting factory, and can easily manage and query the related data. This function benefits both medical institutions and waste centers/factories: (i) reusing medical equipment and supplies from another facility, prolonging the life of the equipment and supplies, and (ii) preparing the materials for the recycling process, and scheduling the time to send and receive the medical waste. In addition to the actors directly benefiting from our proposed model, other advantages also profoundly affect other sectors of society, including (a) environmental facilities reducing pressure on the treatment of hazardous waste (i.e., the relevant information is easy to access and verify); (b) transport companies can trace the source and type of waste (i.e., improve productivity and safety during transportation); or (c) society benefits from a reduced risk of the spread of infectious diseases (e.g., COVID-19). A thorough evaluation of the Medical-Waste Chain is performed to prove the effectiveness of the proposed scheme. We also share the proof-of-concept on our Github repository to encourage future developments.

However, this work still has some issues to consider for future improvement. The first limitation of this paper is that this is only the first attempt at replacing the traditional waste treatment process based on blockchain technology. Aiming for a practical application process, where hospitals can use the proposed model for waste treatment and medical devices, is necessary. A pilot implementation in a medical facility is needed to assess the system's feasibility for future applications. On the other hand, the current mechanism does not provide a solution for validating the data transferred onto the on-chain, so a new oracle approach is absolutely necessary for off-chain processing based evaluations at each medical facility. Finally, we will have more complicated methods of building authentication and authorization services for our proposed model.

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