An inter-hospital digital twin for response to COVID-19 pandemic based on blockchain – A proof of concept

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Abstract

During the COVID-19 crisis, digital technologies have proved their capabilities in improving the efficiency of healthcare management. This study proposes a proof of concept study on configuring digital information to drive rapid response to the pandemic. Leveraging the rich data conveyed by dynamic digital twins and blockchain, patients and medical resources (e.g., doctors/nurses, PPE, beds and ventilators) can be better managed during the COVID-19 pandemic. Considering the needs of resources deployment/redeployment and fast response among UK hospitals, this paper develops a digital twin prototype for preparing healthcare systems ready for efficient operations in normal and pandemic situations through: (1) information integration of patient flow (privacy protected) and medical resource flow from hospital information systems; (2) predicting the demands of medical resources based on hospitals, regions and local pandemic levels and expected patients' trajectories. The main contents include developing and proofing the concepts for creating an inter-hospital predictable digital twin for pandemic response based on blockchain, which will set up innovative ways to support scientific decisions in the inter-hospital level to beat COVID-19 now and manage the crisis in the future.

Keywords: Digital twin; Blockchain; Inter-hospital; Information system

1. Introduction

Since the outbreak of COVID-19, the number of confirmed cases in the UK increased rapidly within a few weeks, reaching 271,222 by the end of May 2020 and 2488,780 by the end of December 2020 [1]. This unexpected increase put pressure on the National Health Service (NHS) system, which is exposed to unprecedented challenges of managing medical resources and patients. Especially at the beginning of the delay phase, the failure of early alert for the upcoming outbreak and the lack of effective management of such two flows (resource flow and patient flow) resulted in the shortage of resources and reduced full capacity of NHS to test, screen, quarantine and treat infected people in the UK and around the world. It also tragically resulted in a large number of infected and death cases from NHS staff. Over 300 NHS workers have perished in the line of duty and an extremely high mortality rate is observed in the UK (14.06% by 30 May 2020, 5th highest in the world) [1,2].

It is time to review our hospital management system and rethink how to manage the flows of resources and patients in and between hospitals to provide not only effective responses to deal with COVID-19 but early alert of the future pandemic at both local and regional levels. This study aims at creating such an inter-hospital predictable digital twin for pandemic response and alerts only if the interdependency is clarified and interoperability is achieved between different information sources/systems (e.g., patient booking system, record system, and beds management system) and different hospitals. However, current practices in hospitals need to be improved for constructing this resilient network due to (1) the loosely connected systems and hospitals, and (2) the lack of systems approach to processing information and making decisions. The great value could be released through integrating multiple information from

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two flows (patients and resources) and managing healthcare systems from both the same hospital and different hospitals as a whole using digital twins. Digital-enabled healthcare systems improved efficiencies and service performances for clinicians and patients during the pandemic [3,4]. For example, the newly released 'NHS Test and Trace' system is helping us approach the end of a nationwide lockdown. The digital twin is more than that, which is "a near-real-time digital image of a physical object or process that helps optimize performances of assets" [5]. A digital twin is a dynamic digital representation of an industrial asset that enables companies to better understand and predict the performance of their machines, find new revenue streams, and change the way their business operates [6]. The use of digital twins would support systems analyses in a digital-enabled way, which is not only able to integrate multiple information to provide a novel concept and a potential solution but can set up different levels of models from sub-systems, systems, to system-of-systems. This research would prove the concepts of creating an inter-hospital predictable digital twin for pandemic response to construct an information-sharing hospital network at a city level and provide contributions to information integration, modelling and analyses of resource flow using digital twins and blockchain technologies.

2. Literature review

As stated in Watts (2020) [7], "…*Even if we have neither effective COVID-19 drugs or vaccines to deploy, we do have other resources that bear on our capacity to respond to the disease: resources that include digital health-care technologies*…". Digital technologies play an important role in healthcare and also during the COVID-19 period. As shown in Table 1, various digital solutions have been proposed and developed for healthcare and the wider public. For instance, the World Health Organization (WHO) provided international and national dashboards, which track and visualise the real-time COVID-19 data and conditions according to each country and region. These dashboards would display related data in their maps and charts based on live geospatial updates and the real-time COVID-19 pandemic situations. Another successful digital technology system example is 'mHero', which is a mobile phone-based communication system created by IntraHealth International and the United Nations Children's Fund (UNICEF) in 2014 in Liberia for an Ebola outbreak [12]. During the COVID-19 period, this integrated system can provide 'real-time' and interactive bidirectional communication channels, and exchange information remotely (such as resources, management). These successful solutions highlighted that integrating existing digital health systems and expanding them using digital technologies are effective and critical to meet healthcare needs and manage such pandemics.

Creating rapid data integration and analytical platforms for clinical decision making and healthcare management can provide timely and on-demand solutions, especially when responding to the COVID-19 pandemic [8]. Based on such integrated systems/platforms of clinical decision support and healthcare management, interactive and up-to-date information and intelligent algorithms can also be used for rapid responses and execution. In Africa and Asia, the Zenysis [13] is developed to leverage the power of big data to strengthen health systems of different countries, establish Emergency Operation Centres for COVID-19, and restart health programs in a COVID-safe way. Shortly, Zenysis will also deploy new resources to help countries deliver COVID-19 vaccines efficiently and equitably.

In general, digital solutions can help synthesize fragmented data into comprehensive and integrated linked networks. Moreover, these embedded analytics can also be used to improve healthcare management in response to the global pandemic challenges, including epidemic surveillance, geospatial analysis and accurate therapeutic algorithms development [8].

Table 1. The summary of digital solutions during the COVID-19 period [8,9,10,11]

Digital solutions during the pandemic	Examples	Key characteristics
	Sri Lanka nCoV Surveillance system	

Systems for suspected patient tracking	TraceTogether developed by Singapore	1. To help accelerate detection, reporting, active surveillance and rapid response for COVID-19 cases; 2. To visualise cases by each country and region.
	WeChat/Alipay based tracker	
	Dashboards developed by WHO	
Telemedicine service systems	Creation of virtual chatbots and webbots for COVID-19 patients	1. To provide more services to patients; 2. To eliminate unnecessary patient contact; 3. To increase the penetration of virtual care.
	Development of robotic telemedicine carts	
	Tele or electronic intensive care units (e-ICU)	
	Non-invasive monitoring devices connected with a wireless network	
Diagnostics using Artificial intelligence (AI)	Integrated Health Information Systems (IHiS), Singapore	1. To obviate the need for manual temperature checks; 2. To improve the efficiency of analysis; 3. To provide home solutions to monitor and transmit individual parameters.
	Diagnostic and quantitative CT image analysis of COVID-19 cases, Shanghai, China	
	Wearable devices to track health conditions	
Administrative support to health care workers (HCWs)	mHero, a mobile phone-based communication system created by IntraHealth International and UNICEF	1. To provide two-way communication between HCW's, including information, resources etc.

Among all healthcare demands and services, healthcare resources are the foremost issue. Many healthcare facilities and resources were overwhelmed by the number of patients and the need for healthcare services provision [14], including sedative medications, personal protective equipment (PPE), and intensive care unit (ICU) staffing and beds, especially during the first months of the COVID-19 pandemic. These medical resources can be divided into two categories for allocation optimisation, namely renewable resources and consumable resources [14,15]. The renewable resources are available on a period-by-period basis, e.g., staffing, ventilators and beds, and the consumable resources are not constrained on a periodic basis but usually have limited availability in total. Many recommendations, guidelines and research have been conducted in these areas. In order to maximise the usages of ICU treatment and the number of patient lives saved, the triage committees were involved and can have access to enough information about individual patients to make effective decisions [16,17]. Many countries have experienced a shortage of ventilators during the COVID-19 period, some strategies of using ventilators have been proposed, such as allocating and withdrawing ventilators [18].

Moreover, many researchers also focused on predicting resources and allocating scarce resources. On a national and regional level, epidemiological models were used to predict the virus distributions. Some proposed models aimed at predicting the number of COVID-19 infections and hospital admissions, which can be linked with bed requirements and deaths of each hospital [19,20,21]. For instance, Prakash et al. (2020) propose a strategy for estimating the number of infections and the number of deaths. This approach can be used to provide a reliable prediction and plan the requirements for critical resources. Rachel et al. (2019) [23] developed an integrated disease outbreak and surge capacity model to evaluate the capacities of a region's healthcare system during the pandemic. However, this approach is simplistic and can not meet the requirements of resource scarcity. At the intra-hospital level, resources-based research mainly includes: a) patient flows or demand intensity, and b) priority of patient groups or triage of patients [24,25]. For instance, Melman et al. (2021) [24] proposed a discrete-event-simulation model to describe COVID-19, elective surgery, and emergency surgery patient flows in Addenbrooke’s hospital in the UK, which would directly link with resources needed. Currently, the majority of countries are planning their way back to a new normal. It is the right time to learn from COVID-19 lessons and create a comprehensive and predictable inter-hospital digital twin using digital methods with resource deployment capacities to face possible waves in the future.

Based on the literature reviews, it still lacks such a resilient solution that integrates existing digital healthcare systems and also can respond to emergency resource needs (such as the COVID-19) among different hospitals or at a city level. Hence, this study aims at developing and proofing the concepts for creating an inter-hospital digital twin for pandemic response based on blockchain. The concept was evaluated initially based on the Barts Health Trust in London.

3. Research methodology

This research consists of three stages (Fig.1). In the first stage, a comprehensive literature review has been conducted to identify and clarify critical interdependencies among different hospitals and confirm information coordination among healthcare information systems for patients and resources management leveraged at local (intra-hospital) and regional (inter-hospital) scales. The second stage is to develop a permissioned blockchain prototype for secure, decentralized and coordinated data exchange at the inter-hospital scale. This stage would authorize the hospitals a comprehensive, immutable log and transparent access to the shared data 'pool' with information identified in stage 1 across local dynamic digital twins within the communities, meanwhile strict accountable access control would be implemented to protect the sensitive healthcare information. Thus, the system architecture of inter-hospital digital twins based on blockchain would be designed for integrating existing information systems and further creating an inter-hospital digital twin. Finally, the proposed inter-hospital digital twin for pandemic response based on blockchain would be evaluated initially based on analysing COVID-19 actions of Barts Health Trust. Various hospitals of the same Trust would supply and query medical resources as a whole. Hence, the COVID-19 resources would be a main case, which aims at discussing information sharing and interdependency.

Moreover, this study would make three assumptions for modelling the supply-demand relationship: a) The demand for medical resources is only dependent on the number and health conditions of patients, and the relationships between is proportional; b) The capacities of renewable resources will be kept unchanged; c) The supply of consumable resources will be considered adaptable.

[Insert: Figure 1 Framework of the research methodology]

4. The development of an inter-hospital predictable digital twin for pandemic response based on blockchain

4.1 Overview of healthcare information and Healthcare Information Systems

4.1.1 Interdependencies identification for the inter hospital

Complex systems are characterised by having a large number of dimensions, nonlinear or non-existent models, strong interactions, unknown or inherently random plant parameters, time delays in the dynamical structure [26,27]. Healthcare systems are typically one kind of complex system, where large sets of components are brought together and interact with one another. As shown in Table 2, these healthcare systems can be divided into four levels, namely the system-of-systems, system, sub-system and asset levels [27,28,29,30].

Table 2. Decomposition of healthcare systems

Level	Sub-level	Definition	Example in healthcare systems	References
System-of-systems		Assembly of multiple, heterogeneous, distributed, occasionally independently	Healthcare systems at the regional scale, forming the inter-hospital	[27,31]

		operating systems embedded in networks at multiple levels		
System		Assembly of physical sub-systems for high-level functions	Hospital, testing centre or vaccine centre, and their served communities or areas	[27,28,29,30,32]
Sub-system		Geographically distinct entity created to meet specific high-level functions for the users of the system.	● Outpatient ● Emergency rooms ● Quarantine rooms ● ICUs etc.	[27,28,33]
Asset	Section	Physical entity created to meet specific functions for the system.	● Space ● MEP ● Furniture ● Equipment etc.	[29,30]
	Component	Physical entity with specific functions in each section.	● Beds ● Ventilators ● Pipes etc.	[28,29,30,34]

Many efforts have been made to investigate what kinds of interdependencies exist in complex systems (Table 3). For instance, Rinaldi et al. (2001) identified four types of system interdependencies between infrastructure systems, including physical, cyber, geographic and logical [32]. Mendonça and Wallace (2006) focused on service and space connections and also defined four categories of system interdependencies, namely input, shared, exclusive-or, and colocation [35]. Eusgeld et al. (2011) extended the aforementioned works and looked at different system interdependencies in more detail, where nine types of system interdependencies have been identified, including input, mutual, co-located, shared, exclusive-or, physical, cyber, geographic, and logical [27]. Saoud et al. (2017) further identified spatial and analytical interdependencies at the asset level [34].

Table 3. System interdependencies identified in previous works

Level	**Identified system interdependencies**	**References**
System	Four types of interdependencies, including physical, cyber, geographic, and logic.	[32]
	Two types of interdependencies, including functional and spatial.	[37]
	Four interdependent conditions defined, including input, shared, exclusive-or, and colocation.	[35]
	Five types of interdependencies, including physical, informational, geospatial, procedural and societal.	[38]
	Four types of interdependencies, including functional, physical, budgetary, and market and economic.	[31]
	Two categories of interdependencies, including location-specific (physical), and functional.	[39]
System & subsystem	Nine categories of interdependencies, including input, mutual, co-located, shared, exclusive-or, physical, cyber, geographic, and logical.	[27]
	Two kinds of interdependencies defined, including internal and external, where the external interdependencies were further represented by physical, cyber, geographic, and logical.	[33]
	Four types of interdependencies, including stochastic failure propagation, logic, asset utilisation, and resource input.	[40]
Asset	Two kinds of interdependencies defined, including spatial and analytical interdependencies.	[34]

In order to clarify where the interdependencies exist at the system and subsystem levels, the operation process of the inter hospital has been abstracted firstly (Fig.2). The operation management of complex systems has been very challenging due to complex system interdependencies among or within systems and with external environments [36]. These interdependencies are observed in the sequence of operation process in terms of location, service, medical resource and information, based on which it can be further clarified what these interdependencies are in the inter hospital. Moreover, these system interdependencies can be defined as bidirectional or unidirectional relationships at different levels where the output of one item is essential as the input of another one [32,37]. For example, the interdependency exists between two hospitals when transferring patients.

[Insert: Figure 2 Operation process of the inter hospital]

According to the operation process of inter hospital (Fig.2), this study would focus on the spatial, functional, physical, and cyber interdependencies at the system level (i.e., inter-hospital scale) (Table 4), where the spatial interdependency exists if a local event (e.g., COVID-19 pandemic) can create state changes in all systems; the functional interdependency exists when a function changes in one system will affect the services provided by the others; the physical interdependency exists if the state of one system is dependent on the material output(s) of the others; and the cyber interdependency exists if the state of one system depends on information transmitted between systems.

At the subsystem level (i.e., intra-hospital scale), two kinds of interdependencies will be considered in this research (Table 4). The functional interdependency can describe the relationship between services provided by subsystems, and the cyber interdependency can describe the information exchange between subsystems.

Essentially, the spatial, functional and physical interdependencies can be modelled and managed through the cyber dimension. Breaking the information barriers between diverse healthcare information systems contributes to a better coordinated healthcare system and facilitates better operation efficiency for healthcare organisations.

Table 4. System interdependencies in the inter hospital

Level	Types of interdependency	Definitions	Examples in the inter hospital	References
System	Spatial	A local event can create state changes in all systems	The outbreak of COVID-19 pandemic can affect the hospitals in related areas (e.g., location in Fig.1)	[32,37]
	Functional	A function changes in one system will affect the services provided by the others	Hospitals have been specified for cases in different health conditions, e.g., Royal London Hospital for high-risk cases while others for less high-risk cases (e.g., service in Fig.1).	[31,37,39]
	Physical	The state of one system is dependent on the material output(s) of the others	The medical resources can be requested by other hospitals if necessary and available (e.g., medical resources in Fig.1).	[31,32,38]
	Cyber	The state of one system depends on information transmitted between systems	The patient medical records will be transferred with patients to other hospitals (e.g., information in Fig.1)	[32]
Subsystem	Functional	The relationship between services provided by subsystems	Specific functions have been assigned to different units, from registration, testing, diagnosis, and treatment etc. (e.g., service in Fig.1).	[40]
	Cyber	The information exchange between subsystems	The patient medical records will be updated following the healthcare process (e.g., information in Fig.1).	[27,33]

4.1.2 Information coordination among Hospital Information Systems (HISs)

Considering the high interdependencies in the inter hospital, especially in terms of functions delivered jointly (functional) and information exchanged interactively (cyber), an appropriate coordination mechanism amongst different HISs is needed to secure the integrity of healthcare services provided to the patients. Fig.3 presents the hospital patient workflow and the corresponding supporting HISs, indicating that these HISs should work collaboratively to manage data generated during the treatment process of patients.

[Insert: Figure 3 The HIS main diagram - Hospital Patient Workflow]

The top three layers of Fig.3 are adapted from the Queen Mary Hospital's Minor Injuries Unit (MIU) patient workflow published by the NHS's Institute for Innovation and Improvement [41]. It is suggested that the patient's flow under their hospital journey has distinct stages that can be standardized to improve the quality of the hospital services further. The First Contact stage includes the patient's experience of symptoms, schedule the appointment, and arrive at the hospital. After the patient arrives at the hospital and the receptionist finishes filling in the casualty card, the patient is moved on to the next stage – The Patient Assessment stage. Under this stage, the patient is provided with assessment by nurses and physicians and the necessary first aid. After the patient goes to the waiting room, the hospital's internal stage of Patient Prioritization comes, where the priority of the treatment and assessment is decided. Then, the patient comes to the Treatment Stage and has an assessment like X-Ray and other necessary treatments. Finally, the patient comes to the Post Treatment stage, where the specialist is referred, and the appointment is made when necessary, with the completion of the rest of the documentation. In addition to the adaption of the original NHS's patient workflow diagram [41] over some detailed decision points and processes content to better fit the format of the swim-lane chart. This is because the swim lane process map can show both each step in a process and the key players [42]. Some patient workflow processes like in-patient ward arrangement are also included to make Figure 1 a more generalized hospital patient flow diagram that is not limited to MIU.

The bottom two layers of Fig.3 present the different HISs summarised in [43]. These systems, in practice, are inter-included for the case of commercial application. For instance, some commercial Clinical Information System (CIS) software systems included the embedded Nursing Information System (NIS) and Laboratory Information System (LIS) functions. In addition, Fig.3 also shows how these systems are connected by the transferring of different kinds of data. The details of each individual HIS is given as follows:

[Insert: Figure 4 Clinical Information System (CIS)]

One of the UK-based CIS intensive care unit projects indicates that the CIS provides the opportunity to obtain the most individualized data, timely feedback, streamlined data storage and management that requires less patient burden [44]. Fig.4 shows the CIS's capability of capturing, analysing, documenting, storing, and reporting the huge patient-related data (e.g., Clinical Notes, Computerised Physician Order Entry, etc.) generated inside a hospital. Input data for CIS may either be input manual or automated. Manual data input could be performed by the physician and include the numerical data (e.g., vital signs), free text data (e.g., progress notes) or structured text (e.g., admission diagnosis and prescribing) [45]. Automated input data may potentially include patient care equipment records (e.g., from ventilators and monitors) or other computer systems (e.g., pathology and radiology systems) [45]. While for output, data can be directly output for clinician's direct use, or to other computer systems (e.g., electronic medical records) and other external users (e.g., researchers), or 'pulled' as required by other system's user requests [45].

Also, a typical CIS system can potentially create a complete Electronic Medical Record (HER) or Electronic Health Record (EHR) that arms healthcare professionals with accurate, timely information and the connection to the National Hospital Information Network.

[Insert: Figure 5 Financial Information System (FIS)]

Fig.5 shows the architecture of a FIS. The hospital FIS includes information inputs and outputs like national insurance, non-clinical expenditure, and connections with other hospital information systems (e.g., PIS, LIS, and RIS, etc.). The connection of FIS with different procurement-related shareholders is based on the abolition of the Purchasing and Supply Agency in 2010. The purchasing and supply agency's responsibility for the national drugs contract was then transferred to the Department of Health Commercial Medicines Unit, while the telecoms and IT services were transferred to the Government Procurement Service [46]. In April 2019, the Supply Chain Coordination Ltd (SCCL) took over the administration of the NHS Supply Chain, which divided the responsibility for procurement into eleven different outsourced segments, known as "Category Towers", where each of them represents the procurement of different products (e.g., clinical consumables and non-medical products) [47]. For simplicity, in this paper, we encapsulate all these systems as a general FIS.

[Insert: Figure 6 Picture Archiving and Communication System (PACS) & Radiology Information System (RIS)]

Fig.6 shows the workflow integrated system schematic diagram that includes both PACS and RIS. It is suggested that for, in the UK, RIS and PACS, the aggregated multiple data are stored in a shared repository inside a virtual EPR or EMR inside the CIS [48]. Similarly, the orders from the clinician are normally passed through the CIS to the servers of RIS and PACS. RIS and PACS information output might include the data like medical images, diagnostic reports, pharmacy requests, and billing requests. Normally, when requests or (orders) made by the clinician are received, these requests are scheduled by the medical professional through the RIS server. In the meantime, the request for the medical appliances and the expenditure information is issued. Then, the radiologist will acquire images through various devices (e.g., MRI, X-Ray, CT, etc.). After the radiologist post-process images, the medical images and reports will be provided through the system connection network for clinical review and remote view.

[Insert: Figure 7 Nursing Information System (NIS)]

Fig.7 shows the NIS's workflow schematic diagram. There are two main systems that NIS mainly connects with: one is the CIS that allows the communicating and updating of various patient and medical information (especially the EMR); the other one is the FIS that allows the transferring of financial and other patient administration information. The main input/output data includes general nursing records, nursing history, drug search & blood test results, etc. The workflow for NIS can be separated into two parts; one is the related clinical tasks, the other is the non-clinical (administrative tasks). The clinical processes include the two main groups of tasks. The first group of tasks consist of drug checking, drug delivery, minor treatment, and drug information recording [49]. The second group of tasks comprises vital sign monitoring, physical assessment, and patient's status recording [49]. The non-clinical tasks related to the NIS include equipment checking using a barcode scanner, personal shifting and scheduling and completing patient documentation [50].

[Insert: Figure 8 Laboratory Information System (LIS)]

Fig.8 shows the LIS's workflow schematic diagram. Same as the case of NIS, CIS and FIS are the two main systems that LIS mainly connected with: one is the CIS that allows the communicating and updating of laboratory test information (especially the EMR), the other one is the FIS that allows the transferring of experiment specimen, appliance, and equipment receipts information. Similar to the arrangement of the pathology's classification into Anatomic Pathology (AP) and Clinical Pathology (CP), the LIS can provide the laboratory report according to these two flavours. A typical LIS enabled laboratory experiment starts with a phlebotomist using the LIS module to view orders to determine the specimens. After the patient's identification is verified, physicians and nurses collect the specimens from the patient and transfer them to the processing area. Finally, the phlebotomists conduct various laboratory tests accordingly (e.g., lipid panel test, basic metabolic panel test, etc.).

[Insert: Figure 9 Pharmacy Information System (PIS)]

Fig. 9 shows the PIS's workflow schematic diagram. Unlike NIS and LIS cases, FIS is the only system that PIS mainly connects with. The direct connection between the PIS and FIS allows the medicine and other medical equipment receipts can be quickly conveyed to the FIS. The input information of PIS mainly includes electronic prescriptions made by the physician, while the output information of PIS is composed of intelligent warnings, rejection notices, and other messages. The dose preparation process is closely connected to the PIS and involves several pharmacists' checks using equipment like the barcode equipment [51]. All this checking information recorded by the pharmacist will be input into PIS.

[Insert: Table 4 Information of each HISs in the intra- and inter-hospital levels**]**

Under the epidemic, COVID-19 patients are overwhelming the GPs and hospitals. To guarantee the medical resources supplied, CIS and FIS are federated to predict the upcoming demands for consumable resources and supports the decisions regarding the procurement, as an example that highlights information exchange between interdependent systems. The whole journey of admitted COVID-19 patients, including but not limited to their length of stay, levels of care and arrival/discharge scenarios from the CIS, indicates the demands of consumables in the upcoming days. The procurement data from FIS, which decides the inventories of these scarce resources, is adjusted in accordance with the predictable demands. Permissioned blockchain, designed to secure the information interactions among a group of authorised users, can be used here for enabling coordination between patient treatment (CIS) and medical expenditure of scarce consumable resources (FIS).

4.2 Development of the inter-hospital predictable digital twin for pandemic response based on blockchain

4.2.1 Permissioned blockchain prototyping for the inter- and intra-hospital information exchange

The demand for consumable medical resources, such as PPEs and medicines, basically depends on the estimated number of admitted patients as well as their desired levels of care. To ensure the supply of these critical medical resources procured through FIS, models that try to capture COVID-19 patients' journey/trajectory through evolving stages of care in the hospital are necessary, i.e., the daily count of patients in the general ward, in the intensive care unit (ICU), and in the ICU on a ventilator. Two major challenges come along. First, a validated probabilistic model is required that can simulate individual patient trajectories and produce the most likely aggregated counts [52]. Meanwhile, due to the privacy concerns, a secure data pipeline needs to be established to transfer the large volumes of patient data stored in CIS. The first challenge is tackled by adopting the Hidden Markov Model (HMM).

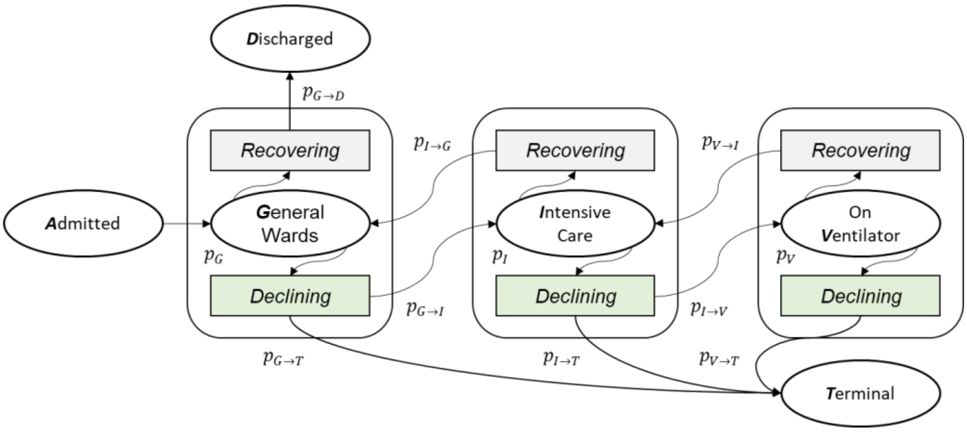


Figure 10 Diagram of the Hidden Markov Model for individual COVID-19 patient trajectory

As shown in Fig.10, 5 stages are defined to describe the health condition of COVID-19 patients, in which stage G indicates patients in the general ward, stage I represents patients in the ICU, stage V is patients on the ventilator (three intermediate states), and stage T stands for patients sadly dies, stage D stands for patients fully recovered and discharged (two absorbing states). To predict the patients' general trajectory, the HMM generates a sequence of segments via random process, in which the stage category indicator, the "declining" or "recovering" condition and the length of staying in specific stage are explicitly defined. Combining with the daily admissions counts, the upcoming consumable resources demand can be forecasted, and FIS can adjust according to the prediction, avoiding any resource shortage that might cause catastrophic consequences.

The transfer probabilities between different states are pretty much relying on the medical therapy used and treatment conditions in the specific hospital or Trust. Therefore, the HMM must be calibrated according to a certain volume of patient-level data collected through CIS. The information exchange process is supported by the permissioned blockchain prototype.

As the underlying technology behind Bitcoin, blockchain is known as a distributed public ledger built on "decentralized trust" [53]. Instead of using the conventional centralized client-server architecture, blockchain is identified as a peer-to-peer (P2P) network that publicly or privately distributes blocks and transactions within to all users, allowing any type of data to be stored in a reliable and verifiable way. As a responsible and transparent mechanism to store, distribute and exchange health-related data, blockchain technology provides a new way to tackle data privacy, security, and integrity issue in the healthcare sector [54]. Comprehensive reviews have been conducted to explore the potential of blockchain technology in massive healthcare applications [55,56,57,59,60] including but not limited to pharmaceutical supply chain, electronic medical record (EMR), remote patient monitoring (RPM), etc.

Since blockchain technology enables distributed, encrypted, and secure logging of digital transactions, it can be leveraged inter-hospital to transfer the patient's information in CIS between doctors and procurement managers, optimizing the medical resource supply chain amongst hospitals in a same Trust in a coordinated way [61]. Azaria et al. (2016) proposed the concept of Medrec, a decentralized record management system to handle electronic medical records using blockchain technology [62]. MedRec provides capabilities for managing authentication, confidentiality, accountability, and data sharing. The system provides easy access to patients' medical information through a blockchain network that consists of several medical stakeholders that are securing the network utilizing a Proof-of-Work consensus scheme. Dubovitskaya et al. (2017) used a permissioned blockchain for providing data sharing from the medical perspective [63]. In contrast to MedRec, the framework presented in [63] does not require any transaction fees and utilizes a centralized cloud-based storing service to ensure the availability of data. Alternatively, Hussein et al. (2018) focused on enhancing security considerations when sharing sensitive data with the deployment of a discrete wavelet transform and a genetic algorithm technique [64]. In this paper, the focus is concentrated on proposing a blockchain-based data-sharing framework to ensure a secure, anonymous approach for sharing and accessing COVID-19 treatment information amongst CIS and FIS while preserving patient privacy as much as possible.

Blockchain comes in many forms, public, private and consortium blockchains, depending on the participants [65]. The key requirement of a healthcare system that is working on COVID-19 patients' clinical record collections is to guarantee the information immutability, privacy, and consistency. The degrees of openness and decentralization of consortium blockchains are desired in this case [66]. A consortium blockchain includes multiple participants who do not trust each other. Each participant can specify one or more consensus nodes (CNs), and a transaction must be confirmed by most of the consensus nodes. Only the participant's consensus nodes have both read and write permissions, while other nodes have only incomplete permissions. By combining consortium blockchain with medical information systems, authorized users in hospitals across diverse local communities, can jointly maintain the information in the blockchain network via a consensus mechanism.

Leveraging the capability of consortium blockchain, a medical information-exchange platform and its business process are designed to create a shared ecology in which better coordination in consumable resource procurement can be achieved between different hospitals in the same Trust during the pandemic (shown as Fig.11). According to the information stored in diverse HISs, the platform enables the activities such as applying for authorization, uploading and requesting medical records, and generating consumable resources demand predictions, which are traceable in the blockchain. Regulatory authorities for medical records in each hospital and high-level procurement managers in the Trust are represented as CNs in the blockchain, which can regulate the legal members of the platform and monitor/manage the use of the patient-level medical records. Confidential sharing processes are enabled to record the information sharing transactions between these participants, which will be verified by the corresponding regulatory authorities [67]. Accordingly, the consortium blockchain architecture and the consensus mechanism among CNs ensure the accuracy, integrity, security, and efficiency of medical information shared amongst hospitals.

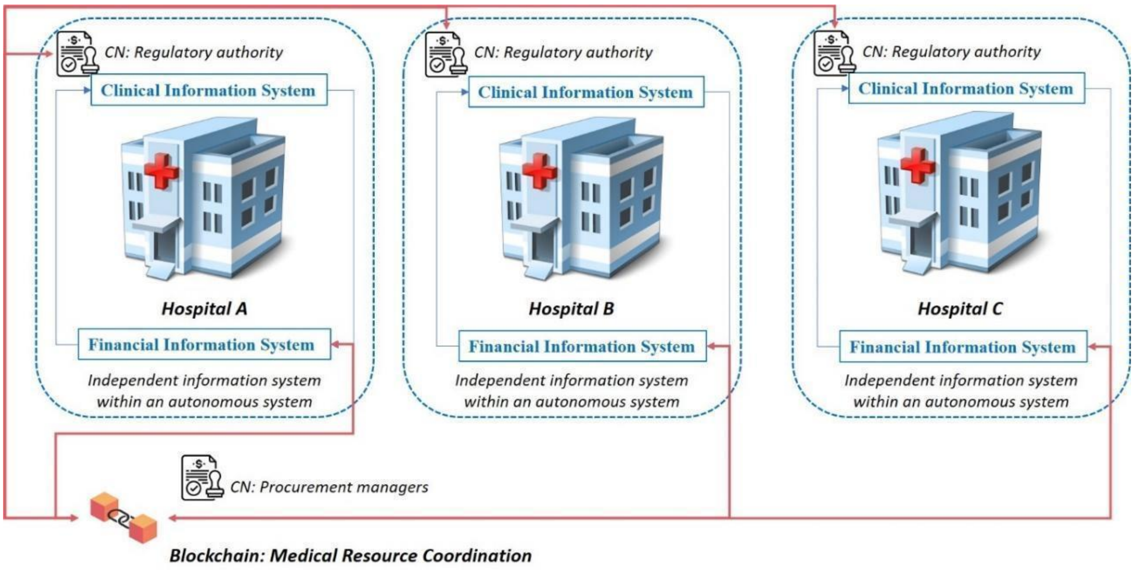


Figure 11 The proposed blockchain based data-exchange architecture

Specifically, an anonymous information sharing process is enabled between nodes connecting to each other through a P2P network, and it is in accordance with the permissioned blockchain's characteristics of the transmission value. Every node needs to be authenticated through a digital certificate mechanism before being admitted to the blockchain. The process is illustrated in Fig.12.

1st step: The procurement managers or any supply chain coordinators can send a request for an anonymous transaction to the regulatory authorities (RAs) running CIS in each hospital, asking for patient information that is stored in the data nodes under the regulation from specific RAs. At the end of the request command, the public keys of the requester and the relevant data nodes are embedded.

2nd step: When the RAs receive the request, they decide whether to authorise the request on the basis of the defined data utilization rules. If approved, the RA node generates a new symmetric key, encrypts the transaction using the generated key and establishes a mapping among the transaction, the key, and the relevant data nodes.

3rd step: The RA node sends back a reply message to the requester, containing the encrypted transaction using the generated key and RA’s private key and the encryption of the generated key using the data nodes’ public keys.

4th step: After getting the reply from the RAs, the requester informs the corresponding data nodes that the RAs have approved, and authorised the permission to process the transaction, proceeding with the data sharing for the approved piece of data from CIS.

5th step: When the data node receives the reply, it verifies the signature of RA to confirm the authorisation. If the signature is correct, it decrypts the generated symmetric key and uses this key to acquire the transaction data.

6th step: When the RA node receives the feedback from the data node, it verifies the signature of the nodes and aggregates the data shared possibly from multiple data providers, indicating the acceptance of the request result. And

7th step: The RA nodes broadcast the encrypted transaction. Every node within the network needs to verify the signature from this RA node and accept this transaction. Other nodes, other than the requester, do not have the permission to decrypt the embedded patient information, and only need to add the transaction and result to the block.

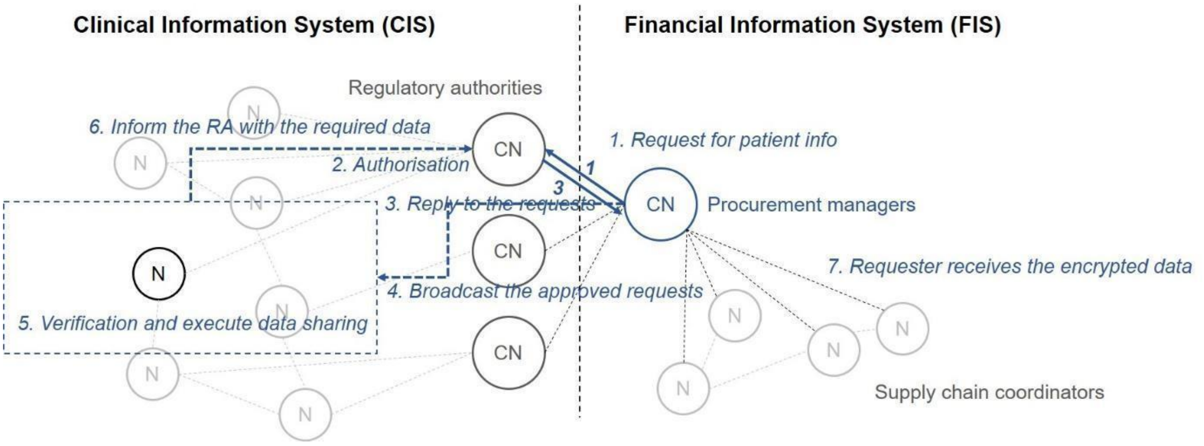


Figure 12 The anonymous information sharing process between CIS and FIS

In this sharing process, nodes that are not related to this request are unable to understand the messages transmitted through the network, but the transactions are jointly verified by all participants. This guarantees that different participants can transfer information seamlessly through this platform without being observed by any unrelated third parties. Besides, this design is compatible with the existing CIS or FIS running in hospitals and Trust, as long as an appropriate application program interface (API) is developed to execute data queries in the traditional database and respond to the request whenever needed.

4.2.2 Inter-hospital digital twin supported by blockchain-based information coordination

This work established the dynamic digital twin framework (shown as Fig.13) for the inter hospitals based on information interdependencies from section 4.1 and systems integration from section 4.2.1. The spatial, functional and physical interdependencies can be modelled and managed through the cyber dimension, which would break the information barriers between diverse healthcare information systems and contribute to a better coordinated healthcare system in the inter-hospital level. With this basis, sub-digital twins of each independent hospital can be integrated functionally to be an inter-hospital digital twin and information can be exchanged interactively. Completed geometrical digital twin models creation of three hospitals (i.e., the Whipps Cross hospital, Newham hospital and the Royal London hospital) and the area covering by the Barts Health Trust, including significant information of each hospital (i.e., architectures, locations, capacities and distances), shown as Fig.13.

This project proposed a hierarchical architecture at the inter-hospital levels. This architecture (as shown in Figure 12) consists of five layers: data acquisition layer, transmission layer, digital modelling layer, data/model integration layer and service layer. Data acquisition layer is the foundation of the inter hospital digital twin, which aims at collecting needed data using digital technologies and integrating each hospital digital twin (namely sub-digital twin). Transmission layer mainly aims at transforming collected data to the upper layers. Digital modelling layer presents the digital model (e.g., BIM in the hospital level and CIM in the city level). Data/model integration layer is the kernel in this architecture. Blockchain would be embedded in this layer and support medical resources deployment at different levels. The service layer is the top and implementation layer of the dynamic digital twin architecture that would provide information sharing and predictable functions in this study. More details of this system architecture can be found in authors' publications [74].

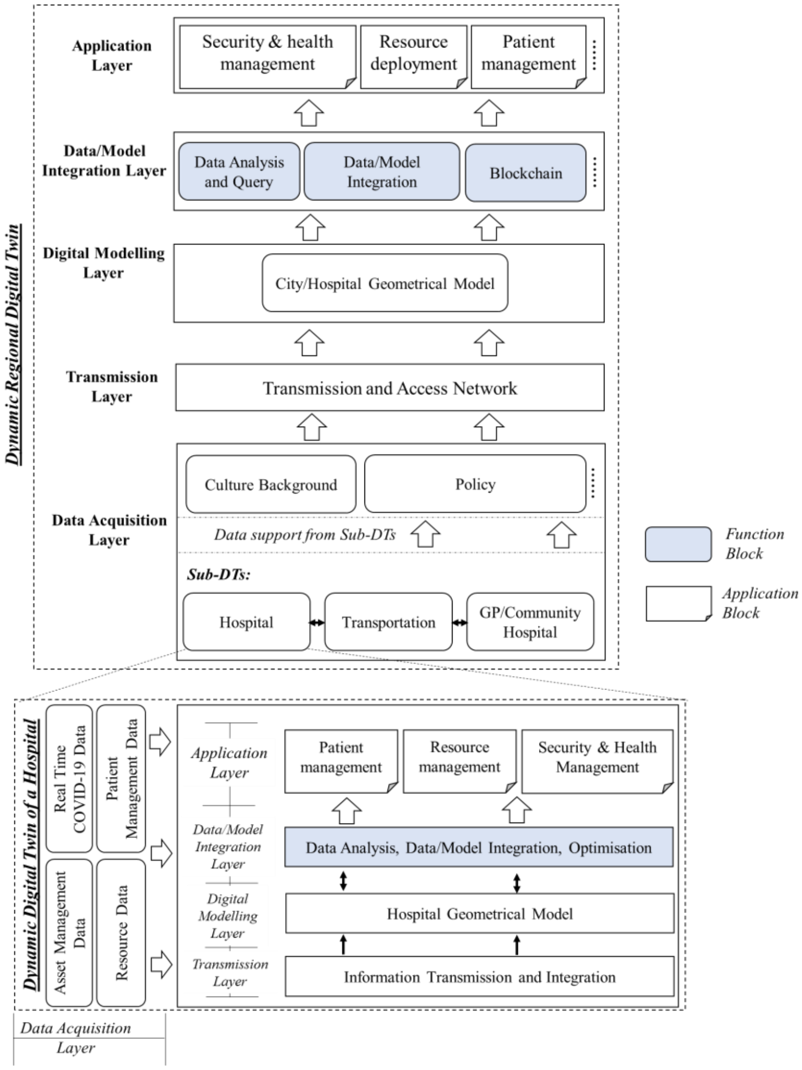


Figure 13 The proposed system architecture in the local (intra-hospital) scale and the regional (inter-hospital) scale based on permissioned blockchain prototyping (modified from [74])

5 Case study and prototype design for potential application

5.1 Basic Information on Barts Health

The proposed digital twin would be further detailed and core functional requirements would be populated. The detailed survey of Barts Health was conducted as follows. Barts Health NHS Trust, providing healthcare services for the people in east London, operates four major hospital sites and several community locations. This case study mainly focuses on the three major hospital sites, namely, the Royal London, Whipps Cross and Newham hospitals. The Royal London in Whitechapel is a major teaching hospital providing local and specialist services in state-of-the-art facilities. Whipps Cross in Leytonstone is a large general hospital with a range of local services. And Newham in Plaistow is a busy district hospital with innovative facilities such as its orthopaedic centre. Within the Barts Health Trust, the Royal London would be the main receiving centre for all of the most serious COVID-19 cases. Both Whipps Cross Hospital and Newham Hospital would focus on treating less complex or high-risk cases [68].

The case study proposed in this study used the Barts Health hospital digital twin that represented hospital resources deployment/redeployment at a deployable area (covering E and EC areas in London).

Furthermore, confirmed that the data resources used in this project would be from the public databases provided by Barts Health (daily collected by the research team) [69].

Barts Health has set a series of operating plans for the COVID-19 pandemic to provide safe and compassionate care to its patients during the hard time. Overall, policies created by Barts Health for the COVID-19 can be divided into the three parts. And detailed plans are listed in the following Table 6.

(1) reorganising clinical services to care for large numbers of patients affected by COVID-19

(2) making changes to elective, outpatient and other services to create capacity to care for patients with COVID-19

(3) supporting staff, and organising estates, informatics and procurement services, for making the necessary changes in clinical care.

Table 6 Creating capacity for patients affected by COVID-19 [70]

Increase the number of mechanically ventilated beds		
Scale up to 420 beds across Barts Health (>200 at St Bart's; >150 at Royal London; >35 at Whipps Cross; >26 at Newham)	Create up to 180 beds in unused areas of Royal London	operate the new Nightingale hospital at Excel in Newham
Increase the number of general beds to 2000		
Ensure up to 900 beds are available at the peak of the pandemic	Safely minimise admission and length of stay	Create additional capacity outside, like small local sites and private hospitals
Speed up the discharge arrangement to get patients home quickly when they have recovered		
Enhance clinical support services, transport services and new datasets services		

5.2 Required materials and personnel

This section summarises the required material and personnel for critical care in the UK. According to the guideline report released by the faculty of Intensive Care Medicine [71], the process of critical care services can be summarised as follows:

Table 7 Critical care service process [71]

N	**Steps**
1	Admission, Discharge and Handover
2	Capacity Management
3	Critical Care Outreach and Rapid Response Systems
4	Infection Control
5	Interaction with Other Services: Microbiology, Pathology, Liaison Psychiatry & Radiology
6	Rehabilitation
7	Intensive Care Follow Up
8	The Patient and Relative Perspective
9	Staff Support
10	Inter and Intra Hospital Transfer of Critically Ill Patients
11	Care at the End of Life
12	Organ Donation

Based on the processes, a wide variety of staff support or work in critical care units, including medical doctors, nurses and allied health professionals. These personnel includes: a). nurses; nurses are expected to have specialist skills including, for example, having knowledge of advanced assessments of patients' breathing and the advantages and disadvantages of non-invasive and invasive therapies to support breathing, such as mechanical ventilation; b). doctors; doctors are responsible to make key decisions immediately on the admission, care and discharge of patients as consultants; 3). allied health professionals; allied health professionals play essential roles in ensuring these patients receive the care they need during treatment and recovery. For example: physiotherapists, occupational therapists, pharmacists, dieticians, and speech and language therapists.

Medical equipment and consumables are needed as follows: a). equipment needed during COVID-19; In the most severe cases, COVID-19 can be complicated by acute respiratory disease syndrome (ARDS), sepsis, and septic shock, multiorgan failure, including acute kidney injury (AKI), and cardiac injury. These patients require a fully equipped ICU facilities with mechanical ventilation devices and accessories, monitoring systems, infusion pumps for nutrition and drugs/fluids delivery. A comprehensive list of medical devices for COVID-19 and related standards is available on the WHO disease commodity package (DCPs), which is summarised as Table 8. b). Personal Protective Equipment (PPE), which is equipment worn to minimize exposure to hazards that cause serious workplace injuries and illnesses. PPE may include items such as gloves, safety glasses and shoes, earplugs or muffs, hard hats, respirators, or coveralls, vests and full body suits.

Table 8 Medical Equipment needed for COVID-19 [72,73]

Situation	**Equipment**
Ordinary	pulse oximeters, nasal cannula, nasal prongs, simple face mask, mask with reservoir bag
Severe Case	mechanical ventilation devices, monitoring systems, infusion pumps

5.3 Proof the concepts of the proposed inter-hospital digital twin based on blockchain

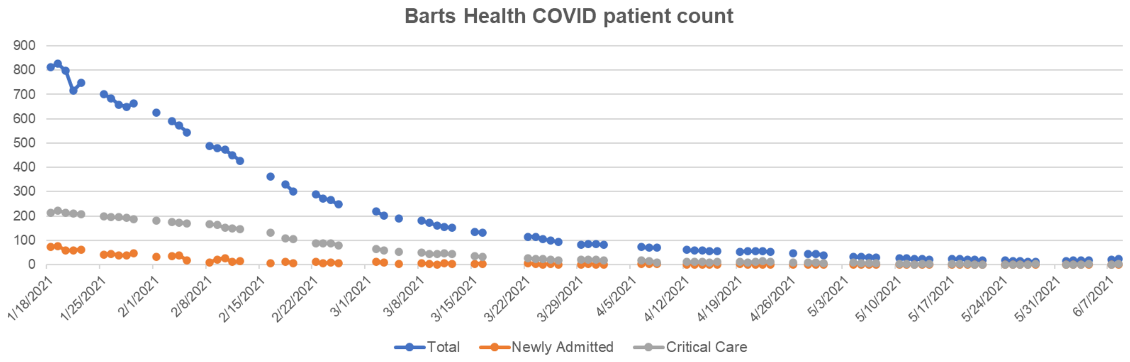


Figure 14 Number of COVID-19 patients in the Barts Health

Figure 14 gives the daily counts of COVID-19 patients in Barts Health between 1/18/2021 and 6/7/2021, more specifically, the total number of patients, daily admitted patients and the patients treated in critical care units respectively. Statistically, the ratio between total number of COVID-19 patients and that of patients under critical care remains within the range of 0.20 to 0.30 (~0.26) before the massive vaccination from May 2021. The medical records of these patients are used to estimate the Hidden Markov Model that simulates the patients' trajectories within Barts Health.

To enable the coordinated procurement for consumables (e.g., PPE), CIS and FIS need to be integrated, and the permissioned blockchain needs to be established as a secure network enabling the privacy-conserved data exchange. First, the COVID-19 patients are classified according to their condition, especially whether they are vaccinated or not, since their expected trajectories in hospitals could be very different considering that vaccine efficacy is believed to be greater than 95% against severe cases of COVID-19. The patients' data under the similar condition is used to calibrate the Hidden Markov Model, estimating the transfer probabilities (defined in Figure 10) between different states. The HMMs and the transition probabilities for vaccinated and unvaccinated patients respectively can be estimated to foresee the length of stay and their most likely trajectories in the hospital, which gives the corresponding consumable demands. The implicit assumption behind is that similar medical therapies and treatments are given to the patients in these four hospitals under the same Trust. This assumption needs to be testified to rule out any external factors that may influence the patient's trajectories during their stays in the hospital.

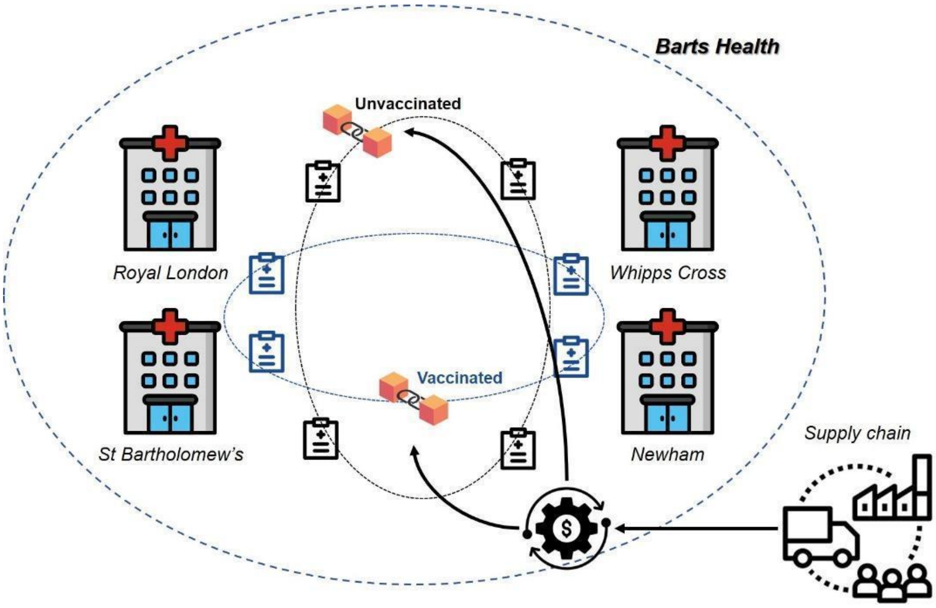
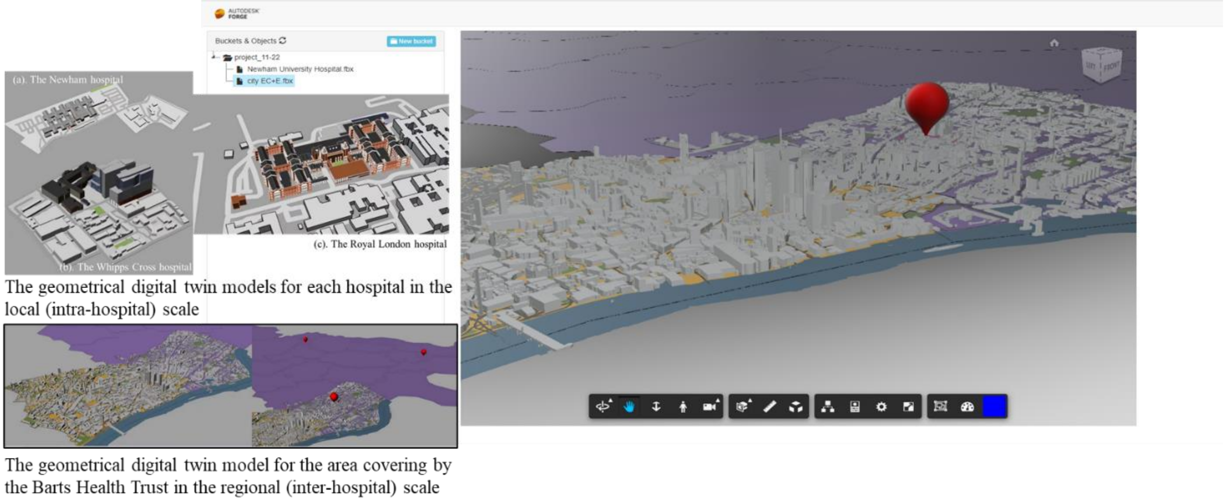


Figure 15 Blockchain based coordinated consumable procurement in Barts Health

Due to the ethical regulation from the hospitals, the medical records of patients are usually treated as sensitive data. To keep the integrity and security of medical information, a consortium blockchain architecture has been proposed in this project to enable a coordinated consumable procurement process. As shown in Fig.15, a P2P network is established between the CISs within the four major hospitals and the FIS for the Barts Health NHS Trust. At least one consensus node needs to be configured as the regulatory authority for each system, which is responsible for regulating the data flowing in and out each autonomous system. Adhering to the anonymous information sharing process defined in the section 4.2.1, the finance information system captures medical information from each individual CIS from the verified transactions embedded in the blockchain. According to the captured medical information, predictions can be made on the PPE requirements, guiding the procurement process interacting with the corresponding supply chain.

5.4 Web-based platform for visualising the proposed inter-hospital digital twin

The proposed inter-hospital digital twin based on blockchain and dynamic digital twins would be visualised through a web-based platform, shown as Fig.16. The geometrical digital twin models of three hospitals and the city-level model are object-oriented models and created using Sketchup. This web-based platform was developed based on Autodesk Forge and integrated the proposed blockchain functions and digital twins.



The geometrical digital twin models for each hospital in the local (intra-hospital) scale

The geometrical digital twin model for the area covering by the Barts Health Trust in the regional (inter-hospital) scale

Figure 16 Web-based platform

6. Conclusion

This paper presented the concepts of the inter-hospital digital twin framework. The main aim of this study is to articulate how blockchain can be used with systematic and digital approaches to improve the capacity and resilience of the NHS healthcare system, beating COVID-19 now and shielding the NHS in the future. To develop well-targeted outputs, this paper identified and clarified critical interdependencies among different hospitals and information systems for patients and resources flows management leveraged at local (intra-hospital) and regional (inter-hospital) scales. Then, we established a blockchain-based data exchange structure that can sufficiently address the access control challenge associated with sensitive healthcare data stored in dynamic inter-hospital digital twins, and a framework was also developed for the federated and interoperable regional dynamic digital twins via scalable, decentralized, and secure sharing of information and data. The proposed inter-hospital digital twin and the embedded blockchain were primarily evaluated by using data and strategies from Barts Health Trust. As shown in the case, through integrating Clinical Information System (CIS) and Financial Information System (FIS), the expected patients' trajectories can be predicted as the basis for determining the demands of PPE and other medical resoueces, which helps to realise efficient deployment of these medical resources in the Trust. In the future works, a detailed and practical case will be provided using information systems from the NHS Trusts. More digital technologies and innovative research will also be implemented in the healthcare areas.

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