CREATING AN INTER-HOSPITAL RESILIENT NETWORK FOR PANDEMIC RESPONSE BASED ON BLOCKCHAIN AND DYNAMIC DIGITAL TWINS

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ABSTRACT

Developing and using the rich data implied by dynamic digital twins and blockchain is relevant to manage both patients and medical resources (e.g., doctors/nurses, ventilators etc.) at the COVID-19 and post COVID period. This paper aims at exploring the blockchain solutions for preparing healthcare systems ready for both efficient operation daily and in pandemic through (1) information integration of patient and medical resource flow from healthcare and medical records; (2) optimizing the deployment of such resources based on hospitals, regions and local pandemic levels switching from normal to the outbreak. The main idea is to develop the concepts of the novel framework for creating an inter-hospital resilient network for pandemic response based on blockchain and dynamic digital twin, which will set up innovative ways to best care for patients, protect NHS staff, and support government scientific decisions to beat COVID-19 now and manage the crisis in the future.

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 (UK Government, 2020). This unexpected increase place pressured the National Health Service (NHS) system to be exposed to unprecedented challenges to 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 (but also 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 (UK's Independent Fact Checking Charity, 2020) and an extremely high mortality rate in patients in the UK (14.06% by 30 May 2020, 5th highest in the world (UK Government, 2020)).

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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. We can create such an intra- and inter-hospitals resilient network 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 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 (Manthorpe, 2020; Solovjova, 2020). 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" (Parrott and Warshaw, 2017). 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 (GE Digital 2017). 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 total solution but can set up different levels of models from sub-systems, systems, to system-of-systems. This research would develop the novel framework for creating an inter-hospital resilient network for pandemic response to construct a resilient NHS network and provide a practical contribution to information integration, modelling and analyses of patient and resource flow using digital twins and blockchain technology.

2 RESEARCH ASSUMPTIONS

During the first months of the COVID-19 pandemic, many healthcare facilities and resources were overwhelmed by the number of patients and the need for healthcare services provision (Supady et al., 2021), including sedative medications, personal protective equipment (PPE), and intensive care unit (ICU) staffing and beds. These medical resources can be divided into two categories for allocation optimization, namely renewable resources and consumable resources. 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. It thus will be reasonable to propose three assumption for modelling the supply-demand relationship.

A1: The demand of medical resources is only dependent on the number and health conditions for patients.
A2: The capacities of renewable resources will be kept unchanged in a short period.
A3: The supply of consumable resources will be considered as constant.

3 THE FRAMEWORK OF RESILIENT HOSPITAL NETWORK DEVELOPMENT

The research process would include the following three steps: 1). identifying information requirements and quantifying interdependencies, including used systems approach for integration and decomposition of healthcare systems, confirmed operation processes of hospital network during COVID-19 and identified Interdependencies for the hospital network; 2). developing a permissioned blockchain prototype for secure, decentralized and coordinated data exchange at intra- and inter-hospital scale; and 3). designing the framework in the local (intra-hospital) scale and the regional (inter-hospital) scale based on dynamic digital twin and blockchain techniques for further network development. These steps would be discussed as follows.

3.1 Identifying information requirements and quantifying interdependencies

Complex systems are characterized 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 (Jamshidi, 1996; Eusgeld et al., 2011). 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 1, these healthcare systems can be divided into four levels, namely the system-of-systems, system, sub-system and asset levels (Pimmler and Eppinger, 1994; Senthilkumar and Varghese, 2009; Chou and Tseng, 2010; Eusgeld et al., 2011).

Table 1: Decomposition of healthcare systems.

Level	**Sub-level**	**Definition**	**Example in healthcare systems**	**References**
System-of-systems		Assembly of multiple, heterogeneous, distributed, occasionally independently operating systems embedded in networks at multiple levels	Healthcare systems at the regional scale, forming the inter-hospital network	(Zhang and Peeta 2011; Eusgeld et al. 2011)
System		Assembly of physical sub-systems for high-level functions	Hospital, testing centre or vaccine centre, and their served communities or areas	(Pimmler and Eppinger 1994; Rinaldi et al. 2001; Senthilkumar and Varghese 2009; Chou and Tseng 2010; Eusgeld et al. 2011)
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.	(Pimmler and Eppinger 1994; Eusgeld et al. 2011; Heracleous et al. 2017)
Asset	Section	Physical entity created to meet specific functions for the system.	• Space • MEP • Furniture • Equipment etc.	(Senthilkumar and Varghese 2009; Chou and Tseng 2010)
	Component	Physical entity with specific functions in each section.	• Beds • Ventilators • Pipes etc.	(Pimmler and Eppinger 1994; Senthilkumar and Varghese 2009; Chou and Tseng 2010; Saoud et al. 2017)

The operation management of complex systems has been very challenging due to complex system interdependencies among or within systems and with external environments (Li, 2018). 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 (Rinaldi et al., 2001; Zimmerman, 2001). For example, the interdependency exists between two hospitals when transferring patients.

In order to clarify where the interdependencies exist at the system and subsystem levels, the operation process of the hospital network has been abstracted (Fig.1). 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 and confirmed these interdependencies should be used in the hospital network.

Many efforts have been made to investigate what kinds of interdependencies are existed in complex systems (Table 2). For instance, Rinaldi et al. (2001) identified four types of system interdependencies between infrastructure systems, including physical, cyber, geographic and logical. 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. 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. Saoud et al. (2017) further identified spatial and analytical interdependencies at the asset level.

According to the operation process of hospital network (Fig.1), this research would focus on the spatial, functional, physical, and cyber interdependencies at the system level (i.e., inter-hospital scale) (Table 3), 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 3). The functional interdependency can describe the relationship between services provided by subsystems, and the cyber interdependency can describe the information exchange between subsystems.

Table 2: System interdependencies identified in previous works.

Level	Identified system interdependencies	References
System	Four types of interdependencies, including physical, cyber, geographic, and logic.	(Rinaldi et al. 2001)
	Two types of interdependencies, including functional and spatial.	(Zimmerman 2001)
	Four interdependent conditions defined, including input, shared, exclusive-or, and colocation.	(Mendonça and Wallace 2006)
	Five types of interdependencies, including physical, informational, geospatial, procedural and societal.	(Dudenhoeffer et al. 2007)
	Four types of interdependencies, including functional, physical, budgetary, and market and economic.	(Zhang and Peeta 2011)
	Two categories of interdependencies, including location-specific (physical), and functional.	(Utne et al. 2011)
System & subsystem	Nine categories of interdependencies, including input, mutual, co-located, shared, exclusive-or, physical, cyber, geographic, and logical.	(Eusgeld et al. 2011)
	Two kinds of interdependencies defined, including internal and external, where the external interdependencies were further represented by physical, cyber, geographic, and logical.	(Heracleous et al. 2017)
	Four types of interdependencies, including stochastic failure propagation, logic, asset organizatio, and resource input.	(Goldbeck et al. 2019)
Asset	Two kinds of interdependencies defined, including spatial and analytical interdependencies.	(Saoud et al. 2017)

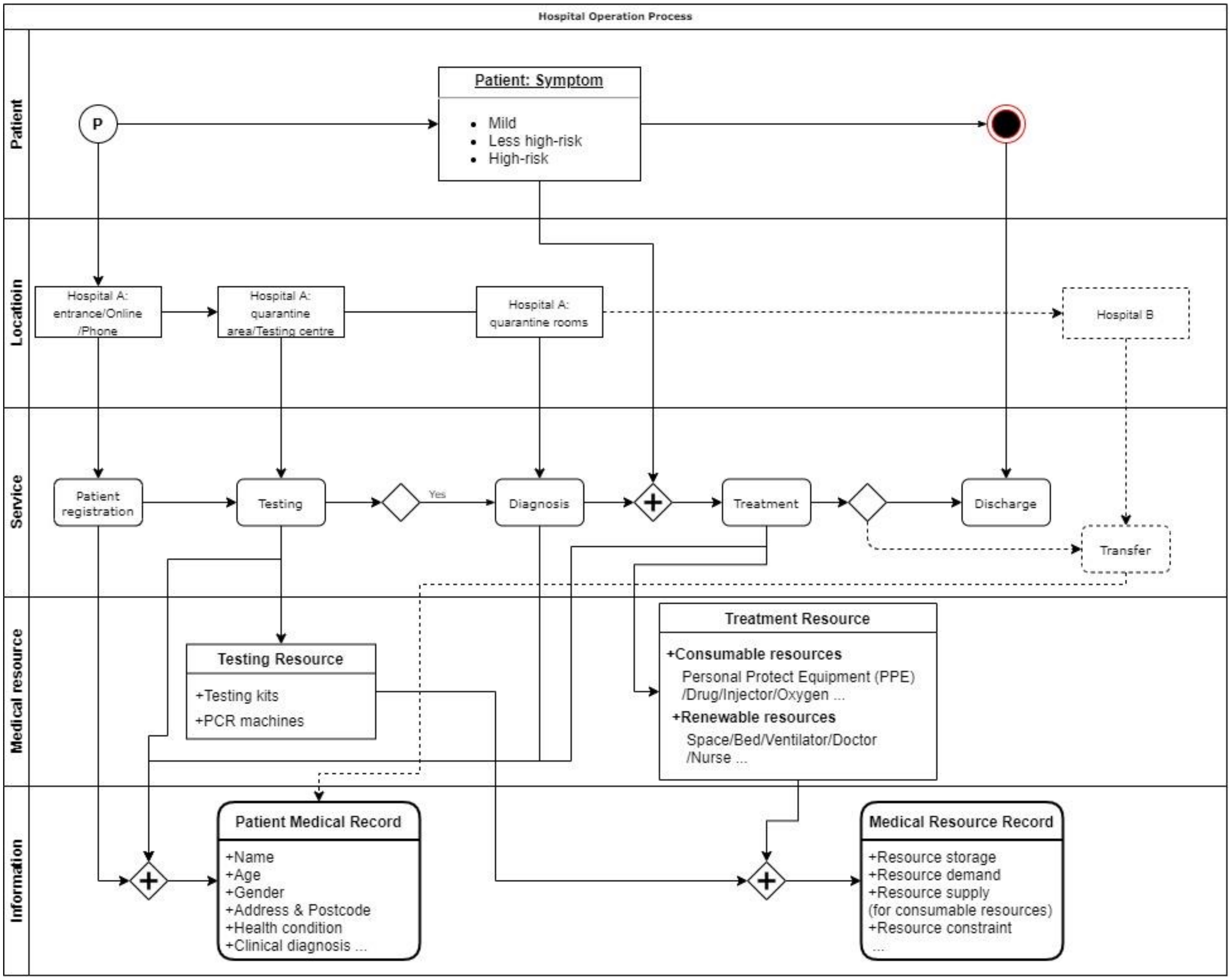

Figure 1: Operation process of the hospital network.

Table 3: System interdependencies in the hospital network.

Level	Types of interdependency	Definitions	Examples in the hospital network	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)	(Rinaldi et al. 2001; Zimmerman 2001)
	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).	(Zimmerman 2001; Zhang and Peeta 2011; Utne et al. 2011)

	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 resource in Fig.1).	(Rinaldi et al. 2001; Dudenhoeffer et al. 2007; Zhang and Peeta 2011)
	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)	(Rinaldi et al. 2001)
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).	(Goldbeck et al. 2019)
	Cyber	The information exchange between subsystems	The patient medical records will be updated following the healthcare process (e.g., information in Fig.1).	(Eusgeld et al. 2011; Heracleous et al. 2017)

3.2 A permissioned blockchain prototype development

As the underlying technology behind Bitcoin, blockchain is known as a distributed public ledger built on "decentralized trust" (Yli-Huumo et al. 2016). A blockchain can be seen as a distributed ledger that shares data among a network of peers (Hölbl et al. 2017). 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 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 (Khezr et al. 2019). Comprehensive reviews have been conducted to explore the potential of blockchain technology in massive healthcare applications (Hölbl et al. 2018; Kuo et al. 2017; Mettler et al. 2016; McGhin et al. 2019; Radanović and Likić 2018; Siyal et al. 2019), such as pharmaceutical supply chain, electronic medical record (EMR), remote patient monitoring (RPM), etc.

Under the current scenario, COVID-19 patients are overwhelming the GPs and hospitals. Since blockchain technology enables distributed, encrypted, and secure logging of digital transactions, it can be leveraged nationally to transfer the treatment-related information between patients, doctors, and healthcare providers, meanwhile optimize the medical procedures amongst hospitals in a coordinated way (Chang et al. 2020). Particularly, due to the imbalance distributions between COVID-infected patients and hospital capacities/medical resources, patients need to be flexibly allocated or even transferred between hospitals to reduce strain. It adds extra pressure to existing health information systems forcing medical providers to ensure that electronic health records are shared effectively and securely among remote care locations. Azaria et al. (2016) proposed the concept of Medrec, a decentralized record management system to handle electronic medical records using blockchain technology. 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. In contrast to MedRec, the framework presented in Dubovitskaya et al. (2017) 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. In this project, the focus is concentrated on proposing a blockchain-based data-sharing framework to ensure a secure, user-centric approach for sharing and accessing COVID-19 patient information amongst hospitals while preserving patient privacy as much as possible.

Using blockchain, Covid-19 patient's clinical records could be disseminated easily with peers (doctors or hospitals) in the healthcare system. Blockchain comes in many forms, public, private and consortium blockchains, depending on the participants (Zheng et al. 2017). The key requirement of a healthcare system that is working on Covid-19 patients' clinical record collections is to guarantee diverse features such as immutability (tempered-proof), privacy, and consistency. The degrees of openness and decentralization of consortium blockchains are desired in this case (Du et al. 2020). A consortium blockchain includes multiple participants who do not trust each other. Each participant can specify one or more consensus nodes, and a transaction must be confirmed by most of the consensus nodes. Only the participant's consensus nodes have read and write permissions; other external nodes have only incomplete permissions. By combining consortium blockchain with medical information systems, authorized users, mainly hospitals across diverse local communities, can jointly maintain the information in the blockchain network via a consensus mechanism.

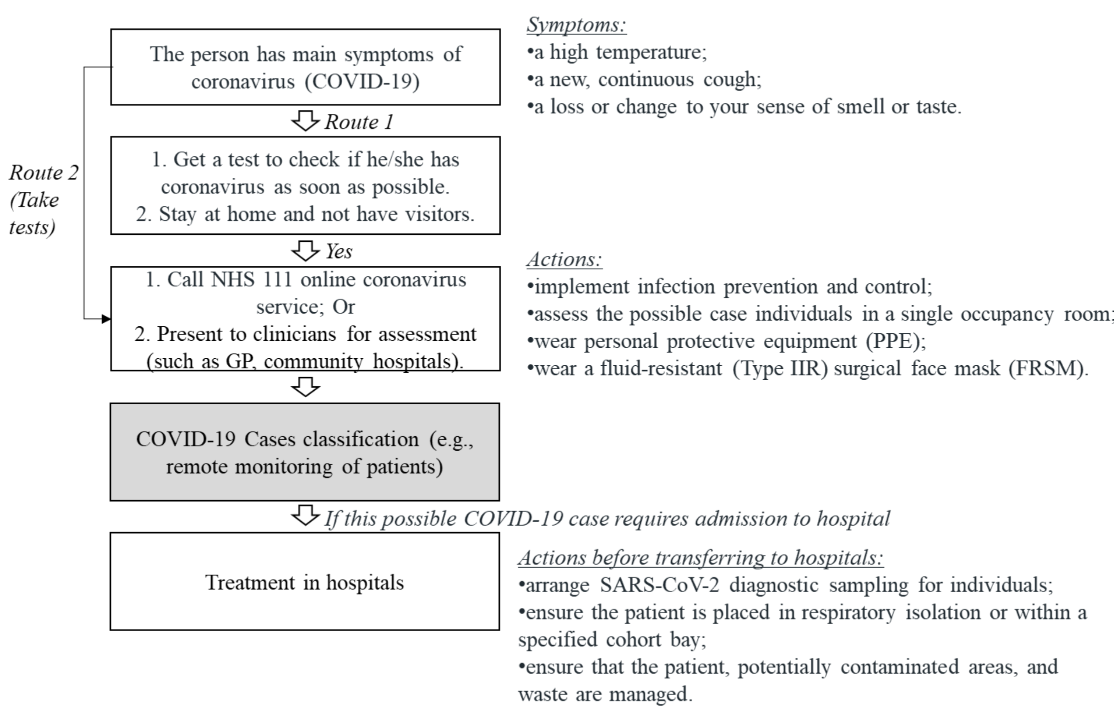

Figure 2: The COVID-19 patients admission strategies in the UK.

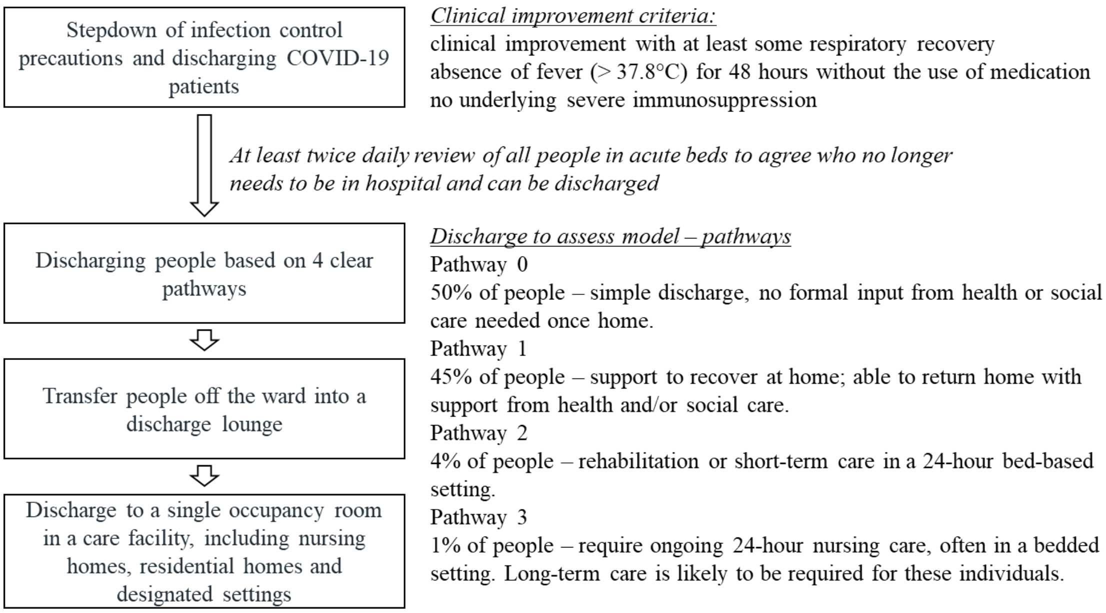

Figure 3: The COVID-19 patients discharge strategies in the UK.

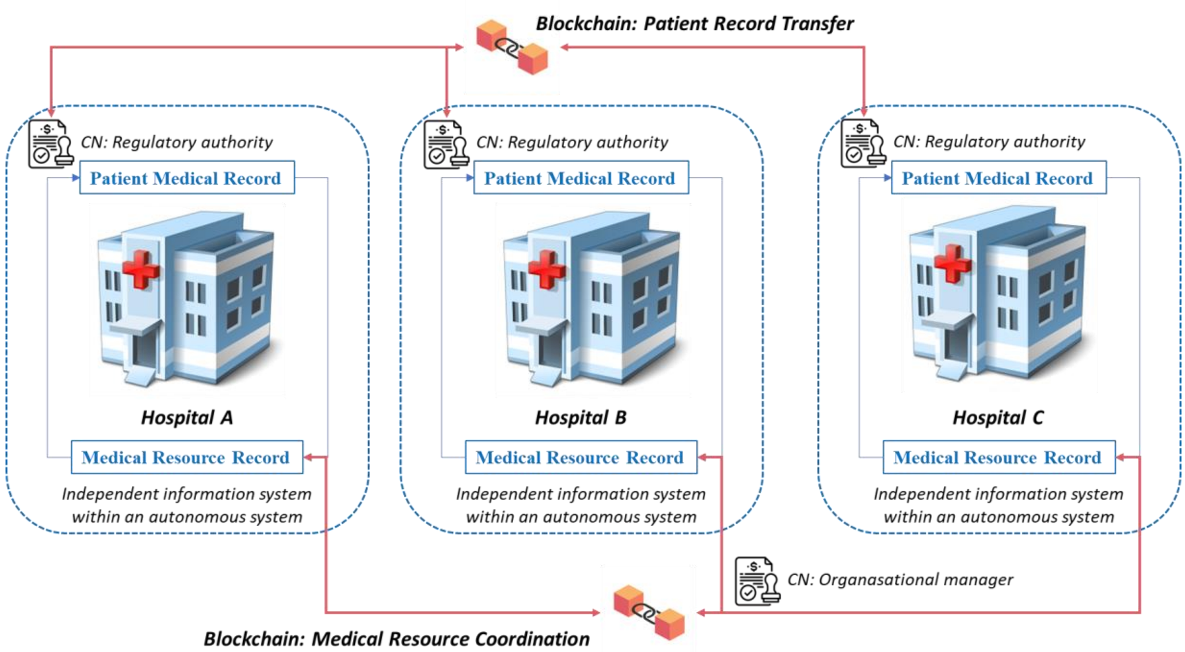

Figure 4: The proposed blockchain-based data-exchange architecture.

Hence, based on comprehensive reviews, the COVID-19 patients' admission strategies and discharge strategies in the UK were confirmed and summarized, as shown in Fig.2 and 3. Based on these admission and discharge strategies, the blockchain-based data-exchange architecture is established that realized the formulated information exchange paradigm. The consortium blockchains and corresponding consensus nodes (CNs) were designed, which guaranteed secure data transfer for both patients and medical resources information at the inter-hospital level. Leveraging the capability of consortium blockchain, a medical information-sharing platform is going to be established to create a shared ecology in which better coordination can be achieved between different hospitals during the pandemic (shown as Fig.4). Based on the analysis from section 2.1, business processes were defined to categorize information exchange paradigms beyond the autonomous hospital system between COVID-19 patients, hospitals, regulatory authorities (e.g., medical management departments/organizational resource managers). The paradigms include patient record transfer when the patient is transferred from hospital A to hospital B, and medical resource requests to support resource deployment/redeployment. Confidential sharing processes are enabled to record the information sharing transactions between these users, which will be verified by individual regulatory authorities in the next stage (Kleinaki et al. 2018). Accordingly, the consortium blockchain architecture and the consensus mechanism employed were designed to ensure the accuracy, integrity, security, and efficiency of medical information shared amongst hospitals.

3.3 This proposed hierarchical framework at the hospital and regional levels.

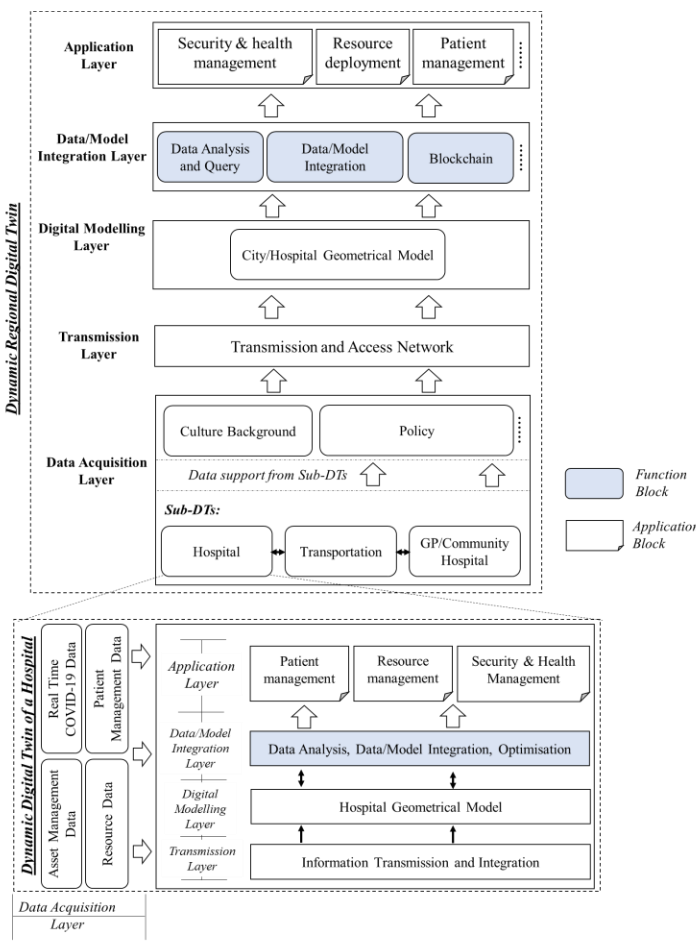

Figure 5: The proposed framework in the local (intra-hospital) scale and the regional (inter-hospital) scale based on blockchain.

This framework (as shown in Fig.5) is comprised of five layers: data acquisition layer, transmission layer, digital modelling layer, data/model integration layer and service layer. More detailed explanations of this framework are provided in the publications (Lu et al., 2020). Blockchain techniques proposed as the core function in the section 2.2 would be embedded in the data/model integration layer and support medical resources deployment at different levels. This framework would integrate different data resources and assets, and further create an inter-hospital resilient network for pandemic response based on blockchain, which would set up innovative ways to best care for patients, protect NHS staff, and support government scientific decisions to beat COVID-19 now and manage the crisis in the future. This framework will be evaluated in the future works.

4 DISCUSSION AND CONCLUSION

The main aim of this study is to articulate how blockchain can be used with systems and digital approaches to improve the capacity and resilience of the NHS healthcare system, beating COVID-19 now and shielding NHS in the future. To do this, and 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 each individual local dynamic digital twins, and a framework was also developed for the federated and interoperable regional dynamic digital twins via scalable, decentralized, and secure sharing of data. This paper discussed and presented the concepts of the proposed framework. This framework will be tested by real cases in the future and its evaluation will also be performed using hospital data sets.

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