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Automated infection risks assessments (AIRa) for decision-making using a blockchain-based alert system: A case study in a representative building

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ABSTRACT

Indoor air quality (IAQ) is an important parameter in protecting the occupants of an indoor environment. Previous studies have shown that an indoor environment with poor ventilation increases airborne virus transmission. Existing research has concluded that high ventilation rates can reduce the risk of individuals in indoor environments being infected. However, most existing ventilation systems are designed to be efficient under non-pandemic conditions. Ultimately, indoor environments will become hotspots for the transmission of airborne viruses. Current infection risk assessments can estimate virus transmission via airborne routes, but with limited information sharing among stakeholders. Our own research did not identify any systems that integrate risk assessments with smart sensors in order to support information sharing with experts in indoor environments in their decision-making process. To fill this gap, we designed a blockchain-based prototype (AIRa) that integrates CO_2 smart sensor data with infection risk assessments from a post-pandemic perspective. This system generates two types of alerts: (1) P-Alert and (2) R0-Alert for decision-making by building owners, such as increasing the ventilation rate or track and trace, as needed. AIRa shows various benefits over three existing infection-control alert systems. Our solution stores and shares information such as the timestamp and room number, instead of storing building user's personal information. Our approach does not require a QR code to be scanned or a mobile app to be downloaded in order to enable track and trace. However, AIRa is still an early prototype for evaluating the risks of airborne virus transmission in smart building environments. Multidisciplinary knowledge and technological research will be vital in formulating different alerts in the future.

1. Introduction

People spend 70–90% of their daily time in various buildings (Luthra and Dahiya, 2015), in which indoor air quality (IAQ) plays a vital role in the transmission of a wide range of infections. Occupants can easily introduce aerosolized infectious agents to the air within the building through actions such as coughing, sneezing and even normal exhaling (Noakes et al., 2006). Previous studies have shown that a populated indoor environment with poor ventilation increases the risk of infection and can easily become a hotspot for the airborne transmission of viruses such as COVID-19 (Megahed and Ghoneim, 2021/02). Moreover, poor IAQ can also cause health problems for the skin, the upper and lower respiratory tracts, the eyes and the nervous system. Due to the fact that people spend most of their time indoors for reasons of work, education and even exercise, IAQ is now recognized as an important parameter that needs to be controlled not only to provide thermal comfort, but also to protect occupants' health (Pitarma et al., 2017).

Since the COVID-19 virus is transmitted through the air, many countries have adopted some measures, like social distancing, to reduce the risk of indoor virus transmission (Morawska et al., 2020). This is because many buildings, particularly older ones, depend solely on natural ventilation by opening windows and doors, which may not be enough to reduce the risk of infection from airborne viruses. While newer office buildings and schools may have ventilation systems, their capacity is often not designed to cope with pandemics like COVID-19. For example, Mokhtari and Jahangir (2021) proposed intermittent

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occupancy as an option by changing occupants' patterns and schedules in university buildings, which, they claim, along with increased ventilation rates, can reduce the number of people infected by COVID-19 by up to 56%. Therefore, it is important to develop a system that can be used to collect data and monitor factors like IAQ to protect people from infection in indoor environments.

Some research has already been conducted focusing on risk assessments of virus transmission in indoor environments. For example, the Wells-Riley Model can be used to understand the transmission and evaluate the effectiveness of the control measure when virus air-emissions data for newly emerged viruses are not yet available (Buonanno et al., 2020). However, the information and assessment results are only shared among certain experts and are often not shared with all the stakeholders, such as building owners, operators, occupants and other users. Ultimately, this hinders the holistic decision-making process. Based on our search, we have not identified any systems integrating risk assessments with digital tools to support indoor environmental experts and epidemiologists in decision-making and the management of indoor air quality. One of the reasons for this could be the complex supply chain that links multiple stakeholders, posing a challenge to information sharing. At the same time, it is seen that many newer buildings are becoming smart with the emergence of widely available low-cost and low-power real-time sensors, which enable useful strategies in various building contexts to monitor various IAQ parameters (Parkinson et al., 2019). However, sensor data are often not managed by the building owners but are stored and managed by third-party service providers, which makes information sharing complex, time-consuming and often costly due to the service fees. To elicit knowledge and value from the collected data, it is necessary to build a secure infrastructure to facilitate information transfer and sharing between stakeholders.

Digitization has been suggested as an opportunity to improve occupants' health and comfort in the architecture, engineering and construction (AEC) sector (de Almeida et al. Rothballer). Blockchain technology has stimulated the interest of the AEC sector due to its decentralized structure and greater transparency, which can enable information sharing between different stakeholders (Wan et al., 2020a). For example, blockchain can be coupled with other advanced digital technologies, such as the Internet of Things (IoT)-enabled sensors and machine-learning (Casino et al., 2019/03). Combining these technologies can enable real-time risk assessments and distributed notification systems to inform multiple partners of real-time decision-making processes (Arumugam et al., 2018). This can have an impact on protecting building occupants from post-pandemic risks.

This paper proposes a decentralized alert system called *AIRa* to support early virus detection and decision-making for building management. It is one of the earliest works to integrate building IoT systems, assess the risk of airborne viruses, and generate alerts for short-term actions and long-term proactive control. This work employs blockchain technology for tracing and information sharing purposes, which allows building managers to review the history of population aggregation, provide tailored measures to safeguard occupants from virus infection, and adopt proactive strategies to counter virus propagation. The proposed prototype has been tested in a representative office of a building in Shanghai, China, which validated its advantages in virus infection control. For example, it can analyse sensor data to produce useful information that can provide guidance to reduce the risk of infectious airborne transmission without violating privacy. This is particularly useful for asymptomatic cases, which are based on environmental air quality, but for which there is no need to collect or process personal data.

This paper is organized as follows. Section 2 provides a summary of related work on risk assessments of infection of airborne viruses. Section 3 gives an overview of the proposed system and the sources and types of data collected. Section 4 explains the set-up of our use case. Sector 5 presents and validates our proposed system, outlining its benefits, potential expansion and expected alert fatigue. Lastly, Section 6 concludes the paper.

2. Related work

a. Infection risk assessment

Quantitative infection risk assessment is a tool used in epidemiological studies to understand the transmission dynamics of infectious diseases and predict the risks of disease to the public (Sze To and Chao, 2010). The Wells-Riley equation is widely used to estimate virus transmission through the air (Riley et al., 1978). The risk of the airborne transmission of an infectious agent indoors is expressed by the probability (P) between 0 and 1. If P is greater than 1, the individual may have already been infected. The equation is as follows:

$$P = \frac{D}{S} = 1 - exp\left(-\frac{Ipqt}{Q}\right)$$

where P is the probability of infection for susceptible population, D is the number of disease cases, S is the number of susceptible, I is the number of infectors, p is the breathing rate per person (m^3/s), q is the quantum generation rate by an infected person (quanta/s), t is the total exposure time (s), and Q is the ventilation rate (m^3/s).

Another concept in epidemic dynamics is the basic reproductive number, R0, which is derived from the Wells-Riley Equation (Buonanno et al., 2020; Liao et al., 2008). This is the average number of secondary cases generated when a single infectious case is introduced into a population where everyone is susceptible (Anderson and May 1991; Diekmann and Heesterbeek, 2000). If R0 is greater than 1, this implies that the airborne virus is spreading within the population and that the number of cases is increasing, while when R0 is less than 1, the disease is dying out (Liang et al., 2018). This can serve as a guideline for how intense the control policy should be to control the spread. Many researchers rely on both P and R0 to evaluate the effectiveness of infection control when information about a newly emerging virus is missing.

Table 1 provides a summary of the literature on infection risk assessments in different scenarios. A common conclusion is that a high ventilation rate can help reduce the risk of an individual or population being infected. Dai and Zhao (2020) estimated the infection probabilities (P)s of COVID-19 using different ventilation rates based on different confined spaces, including offices, classrooms, buses and aircraft cabins. They concluded that, in order to keep P below 1, the ventilation rate should be between 100 and 350 m^3/h and should be increased for a longer exposure time. Buonanno et al. (Buonanno et al., 2020) and Guo et al. (Guo et al., 2021) also pointed out the importance of maximizing the fresh air supply in HVAC systems, which is the most effective strategy for reducing infection risk during a pandemic.

Since CO_2 concentration is an indicator of indoor air quality, Liao, et al. (Liao et al., 2005) and Rudnick and Milton (2003) quantified the infection risk associated with CO_2 concentration levels and the inhalation of an indoor airborne infection using mathematical models. Thereby establishing the relationships between CO_2 concentrations and the basic reproductive number, R0. Except for industrial buildings, humans are the main source of CO_2 in an office (Kallio et al., 2021). A high CO_2 concentration in a confined space can increase the spread of airborne viruses indoors, as exhaled breath is another source of airborne infectious particles (Rudnick and Milton, 2003). Even if the confined space has a low concentration of CO_2 and with a poor ventilation system, when there is an infected person in the same confined space, there is still a lower risk of infecting other occupants. Today, CO_2 concentrations can easily be measured using smart sensors, which can use as an indicator to protect the occupants within a building.

The Droplet Lab in Singapore has developed a COVID-19 SG Dashboard using Wells-Riley which can calculate the probability of indoor transmission (P) in different scenarios based on time spent within different environments (e.g. trains, gyms, shopping malls, restaurants)

Table 1
Summary of related work on infection risk assessments.

Year/Author	Purpose	Model(s)	Scenario	Key Findings
2021 (Lab, 2021)	Estimate the risk of indoor transmission of COVID-19	Wells-Riley Model	Inside train, restaurant, indoor gym, and shopping mall	● Presented a dashboard with different variables to alter according to the scenario to calculate the risk. ● Assumptions of safe-distancing measures and proper hygiene practices (i.e. handwashing) are adhered to.
2020 (Dai and Zhao, 2020)	Estimated the association between the infection probability (P) and ventilation rate	Wells-Riley Model	Offices, classrooms, buses, and aircraft cabins	● High ventilation rate (100–350 m^3/h) is needed to ensure probability (P) is less than 1. ● With the mask on, the ventilation rate can be reduced to a quarter under the same condition.
2020 (Buonanno et al., 2020)	Estimated the viral load emitted by an infected individual based on different types of respiratory activities before and after the lockdown in Italy	Gammaitoni and Nucci model, Wells-Riley Model	Pharmacy, supermarket, restaurant, post office, and bank.	● Before lockdown, natural ventilation is insufficient to keep R0 below 1. With mechanical ventilation, R0 is close to 1 but not under, except in restaurant ● During the lockdown, natural ventilation is sufficient to keep R0 below 1 due to the limited number of customers present simultaneously ● Proper ventilation is a key factor to reduce transmission in indoor environments.
2008 (Liao et al., 2008)	Integrated scale model to predict whether simple control measures can contain epidemic growth of airborne infections in an early-stage outbreak.	Wells-Riley Model	Simulation: a real ventilation scenario	● R0 value can be reduced by enhancing the efficiencies of recirculation air filter capacity, air-exchange rate, and personal masks. ● Demonstrated that combination of interventions and engineering control measures have a high probability to contain the airborne infection.
2006 (Noakes et al., 2006)	Modelled the transmission of airborne infections in enclosed spaces	Wells-Riley Model incorporated with SIR epidemic model	Simulation of ventilated rooms	● High ventilation rates may remove the potential for an epidemic altogether; a moderate increase in the ventilation rate may make an outbreak more manageable in a real scenario. ● Much lower ventilation rates were necessary to prevent an outbreak by reducing the ward's occupancy density by only half the original number of occupants.
2005 (Liao et al., 2005)	Developed a CO_2-based risk equation derived R0. Estimated the R0 and its variability in a shared indoor space	Wells-Riley Model	Elementary schools for Influenza Hospital-SARS	● Reduced indoor CO_2 concentrations can be effective in limiting the spread. ● Room size, ventilation rate, breathing rate, and exposure should also be considered.
2003 (Rudnick and Milton, 2003)	Estimated the risk of indoor airborne transmission using CO_2 concentration.	Wells-Riley Model	Schools and office	● Derived an alternative model using CO_2 concentration from Wells-Riley Equation ● Increased outdoor air supply can prevent airborne transmission such as influenza

(Lab, 2021). However, currently there is no related interest in developing and implementing a system to send an alert to relevant stakeholders, such as a building manager, allowing that person to decide whether tracing is needed (Ferguson et al., 2003).

Given the use of smart sensors and extensive research on risk assessments, in this paper, we designed an alert system for decision-making based on existing models. This system can be a useful tool to study the costs, benefits and risks associated with specific strategies of disease control in an indoor environment such as an office floor (Liang et al., 2018).

b. Alert system.

During the COVID-19 pandemic, different ways have emerged of sending out an alert to curb the spread of the virus. One such method is contact tracing, where users are required to scan a QR code or download a contact tracing app on their cell phones. For example, in response to COVID-19 in countries such as Malaysia (2020) and Singapore (Agency, 2020), citizens are required to actively scan and check-in using a mobile app before entering premises for contact tracing purposes. If they are found to have been potentially exposed to COVID-19, they receive an alert to get tested and self-isolate. This temporary method requires the active participation of all building users in order to be useful. However, once the pandemic is over and everyone has been vaccinated, this strategy will no longer be necessary.

In the post-pandemic period, we shall need a more passive, non-contact approach to reduce indoor airborne transmissions, such as alert systems that can quickly identify high-risk areas on-site for investigation. For example, Valinejadshoubi, et al. (Valinejadshoubi et al., 2021) integrated a sensor-based alert system into BIM models to detect the level of thermal comfort or discomfort in the office at that time. The system generates an alert that is sent to facility managers in real-time to improve decision-making in maintaining occupant thermal comfort at a conducive level. However, we found no research effort on using the sensor-based alert system to guide building users to take actions or protect occupants from the indoor environment, especially where there was no automated functionality. Smart buildings equipped with sensors can maintain an optimum IAQ, such as CO_2 concentration levels, through smart controls.

There is evidence that improving IAQ quality, such as by increasing ventilation rates, can mitigate the transmission of viruses in an indoor environment (Brittain et al., 2020). However, most existing mechanical ventilation systems were designed to be energy-efficient under non-pandemic conditions and therefore exceeded the capacity during the pandemic (Melikov et al., 2020). Installation of more advanced purification and filtration techniques can also improve IAQ, but often at a great cost. Therefore, a more passive framework that allows decision-making using infection risk assessments which is cost-effective, as it does not require an advanced HVAC system. This can be an efficient way of preventing airborne virus transmission in indoor environments.

c. Blockchain

Blockchain technology is a distributed database that enables information sharing among multiple stakeholders with enhanced security and transparency. It provides a platform for real-time data sharing among a large number of members in a network with a higher level of trust in data (Glaser, 2017; Nærland et al., 2017). When using distributed ledgers, it is important to prevent false entries, whether intentional or accidental due to system misuse. Therefore, the validity of transactions is maintained by a consensus mechanism such as proof-of-work (PoW) or Practical Byzantine Fault Tolerance (PBFT) to prevent byzantine errors (false entries) (Castro and Liskov, 2002). The timestamp is another attribute of each block, which certifies that a certain transaction has taken place at the time and date specified (Majeed et al., 2021). Once the transaction has been validated, it is stored in the form of blocks and is chained with a cryptographic hash forming a blockchain that creates a tamper-evident environment (Drescher, 2017).

Smart contracts, a feature of some blockchain systems, offer programmable logic or rules, which are agreed and validated by consensus before implementation (Agrawal et al., 2021). They are also autonomously self-executing once the predefined rules have been met (Kim and Laskowski, 2017). Smart contracts can facilitate the exchange of information between two different actors in an accurate and verifiable manner without the intervention of a third party (Wan et al., 2020b). Zhu et al. (Zhu et al., 2021) developed a blockchain-based system to improve the tracing of disease information in the health reports of different hospitals and clinics. Judgments such as early warning logic, thresholds and early warning broadcasts are automatically executed by the smart contract under the supervision of the Centers for Disease Control and Prevention (CDC). In this way, smart contracts can reduce the complexity of service costs by increasing efficiency of, for example, information sharing within a complex chain of actors (Deebak and Al-Turjman, 2021).

In summary, experts and researchers agree on the potential for different blockchain applications, such as coupling blockchain and IoT, to enable information sharing and secure information storage, which enhances the momentum of smart cities (Majeed et al., 2021). Using this approach, we can harness the benefits offered by (1) blockchain in enabling secure information sharing, (2) IoT for sensing and communicating IAQ, and (3) infection risk analysis for assessment and visualization. This opens up a new decision-making process to protect the occupants inside a building and thus reduce the chances of them being infected by airborne viruses.

3. Methods

In this paper, the proposed blockchain-based alert system integrates infection risk assessment tools and IoT devices to enable early decision-making. This section will provide an overview of the proposed system and its approaches to risk assessment.

3.1. Overview

Fig. 1 presents an overview of the proposed system, which we call AIRa. In this system, multiple stakeholders are involved in requesting data, which is used to draw information from. The workflow of requesting building sensor data and information runs from a building user (the requestor) to the building owner and finally to a third-party service provider. Often, building owners need to engage a third party to store and manage sensor data, which will generate costs. Ultimately, this reduces the efficiency with which data can be obtained and makes collaborative work and analysis challenging.

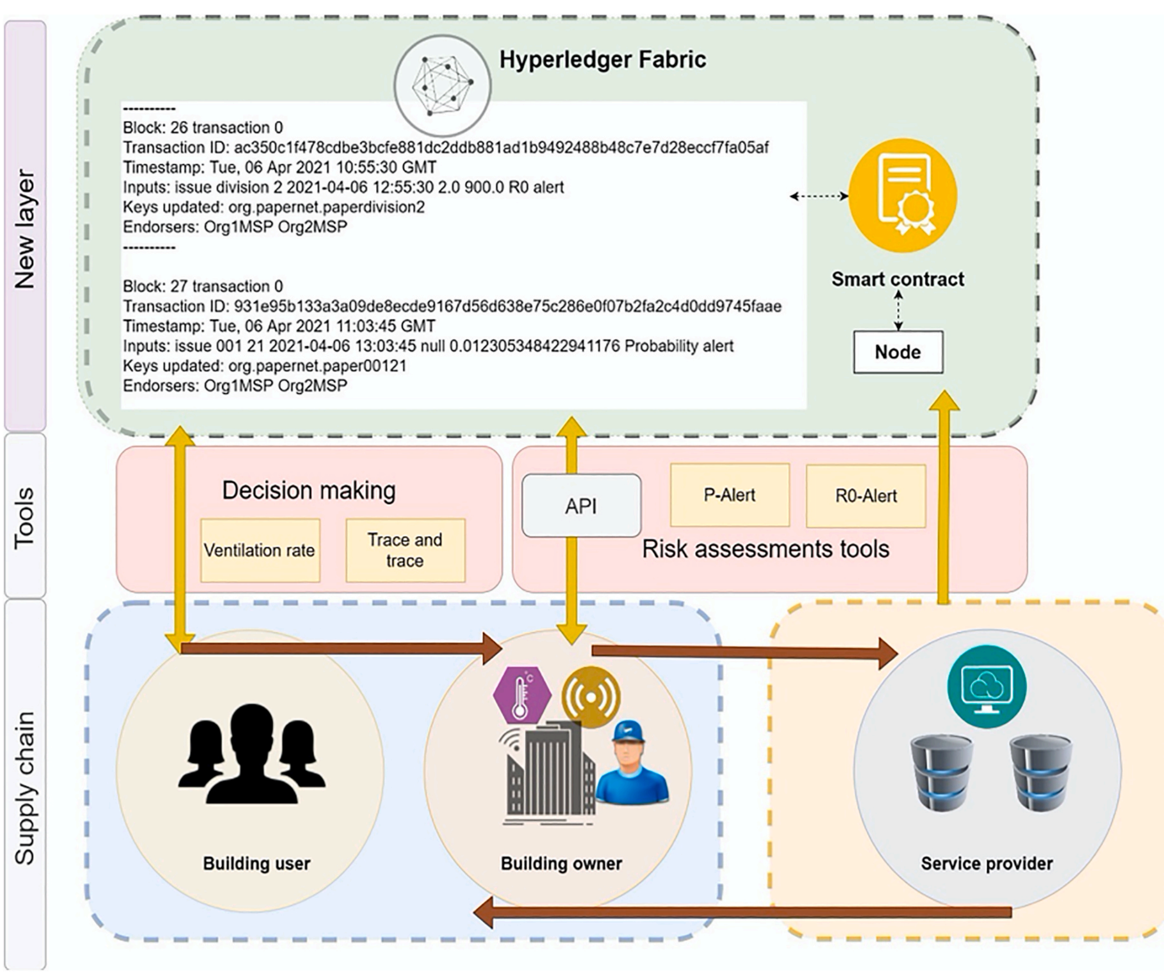

Fig. 1. Blockchain-based alert system framework (AIRa).

In this system, we use two types of infection risk assessment models: **(1)** the probability of infection (*P*); and **(2)** the basic reproductive number (*R0*). In estimating P, the probability of infection suspicion, we use the fundamental Wells-Riley Equation (Riley et al., 1978). As for R0, the degree of spreading, we adapt the work of (Liao et al., 2005; Rudnick and Milton, 2003), where *R0* can be estimated based on the indoor CO_2 concentration level. The CO_2 concentration level is detected using a CO_2 sensor and is then referenced to the corresponding *R0* value. The focus of this work is to assess the risks in the room and to trigger an alert to the building owner to take action to prevent the virus from spreading and infecting the building's occupants. This system can enhance the tracking of asymptomatic cases of influenza, which can still shed the virus and transmit disease when sharing the same confined space (Toner, 2006).

We select the Hyperledger Fabric, an open source private permissioned blockchain, to reduce openness, which is more suitable for the ecosystem. Blockchain plays a major role in this system in integrating the risk analysis and sensor data and thus enabling decision-making. When *P* and/or *R0* are greater than 0.5, it will trigger a smart contract to generate a real-time alert to the building owner enabling further action to be taken. This alert, once generated, will be stored on the blockchain. The building owner can also adjust the requirement of the alerts, such as increasing the alert limit, which depends on the condition of the room. This system is likely to be one of the earliest works in designing and validating blockchain-enabled alert systems that estimate infection probabilities in airborne infection transmission within an office building.

3.2. Process flow

In our system, we use two models in assessing the risks assessments, one a model-based approach, the other a hybrid approach. The model-based approach uses the Wells-Riley equation to estimate *P*, that is, the potential risks to an individual of virus infection. The hybrid approach is used to estimate *R0*, the potential for spreading based on the CO_2 concentration level in an indoor environment. In this work, we focus on viruses such as influenza because the relationship between infection rate and CO_2 concentration level in a confined space has been well analyzed compared to other viruses like COVID-19.

a. Model method: Probability of Infection, P

The Wells-Riley equation is as follows:

$$P = \frac{D}{S} = 1 - exp\left(-\frac{Ipqt}{Q}\right)$$

where *P* is the probability of infection risk, *D* is the number of cases of infection, and *S* is the number of susceptible. Table 2 lists the other parameters in the formula on the right-hand side. Besides the duration of the exposure and ventilation rates, the quantum generation rate of an infected person (q) is a critical parameter in estimating the infection risk. In this model, we assume that the value of q is 150 quanta/hr, as it is within the range of the quantum generation rate for influenza based on certain items in the literature (Rudnick and Milton, 2003; Sze To and Chao, 2010; Liang et al., 2018; Beggs et al., 2010). The value also corresponds to the value reported by Buonanno et al. (Buonanno et al., 2020), where the quanta emission of speaking is higher than 100 quanta/hr during light activities. Table 2 also lists the input values for initial risk assessments in the first 15 min. In this model, the ventilation rate can be adjusted because it has an impact on reducing the probability of infection (Dai and Zhao, 2020).

Fig. 2 shows the process flow for the input values in Table 2 fed into the infection risk assessment tool to estimate the probability of an individual being infected. If $P > 0.5$, this will trigger a smart contract to validate the transaction. Once it has been completed, the transaction will be stored in the blockchain, and a P-Alert will be generated for the building user. The building user can then take further action, for example, adjusting the ventilation rate to reassess the risk. A track and trace can easily be executed if anyone is infected and has developed symptoms of fever while in the indoor environment.

Table 2
Input values for initial risk assessments in the first 15 min.

Parameter, unit	Value	Assumptions/Comments	Reference
I	1	There is one infected person within a particular confined area.	(Dai and Zhao, 2020; Liao et al., 2005; Agency, 2020)
p (m^3/hr),	1.1	Only light activities such as speaking because this is a common level of activities in indoor environments	Zhu et al. (2021)
q (quanta/hr)	150	Speaking during light activities is higher and within the quanta generation of influenza	(Buonanno et al., 2020; Rudnick and Milton, 2003; Sze To and Chao, 2010; Liang et al., 2018; Beggs et al., 2010)
t (hr)	0.25	Since this is not a real-time assessment, we make an assessment every 15 min.	
Q (m^3/hr)	72	2ACH in a typical room with fans on and AC off; room size 12m^2 and 3 m height	Guo et al. (2008)

b. Hybrid method: basic reproduction number, *R0*

This model can enhance smart buildings by sending CO_2 readings using sensors for purposes of risk analysis to prevent the potential spreading of an airborne virus in a non-residential building (Liao et al., 2005). CO_2 concentrations are an indicator of indoor air quality (Kallio et al., 2021) and can be developed to estimate the potential risks in different conditions based on the CO_2 concentration levels in the room. In this model, we reproduce the graph of the CO_2 concentration levels and the corresponding *R0* of influenza for different hours of exposure within a confined space from (Liao et al., 2005), as shown in Fig. 4. In this model, we use the result of a 1-h exposure time in our system because we assume a regular meeting lasting at most 1 h. A CO_2 sensor is installed to provide real-time assessments. Other models such as a 2-h exposure time can also be selected by the building owner based on the office's requirements.

Fig. 3 shows the overall process of alert generation in AIRa. As shown, the CO_2 concentrations of a room or a floor of a building are measured continuously using sensors. The sensor data are fed into the risk assessment tools. According to Fig. 4, the threshold of CO_2 concentrations for a 1-h exposure is between 650 and 700 ppm before an alert is generated, since the threshold for this alert is set to be at $R0 = 0.5$. And when $R0 > 0.5$, it triggers a smart contract to validate the event and record it on the blockchain. An alert is also generated for the building owner to investigate the event and to take appropriate action if necessary. Although CO_2 concentration levels increase over time in confined spaces, the building owner can also choose to take no action, for example, if everyone is healthy and not showing any symptoms of influenza. If the estimated risk is less than 0.5, the sensor readings will be recorded in a centralized database.

4. Blockchain-based risk alert system: an example in use

The experiments are performed on the Aliyun cloud server with an Intel(R) Xeon(R) Platinum 8163 CPU @2.50 GHz processor, 2 GB memory and 40 GB disk, running on Ubuntu 20.04 (64 bit). We adopt Hyperledger Fabric v2.2 as the blockchain platform. The chain codes are written in Node. js v10.19.0, and the data-processing scripts are written in Python v3.9.2. The alert announcement billboard is powered by Flask v1.1.2 with Python v3.9.2, and the Infection information is powered by

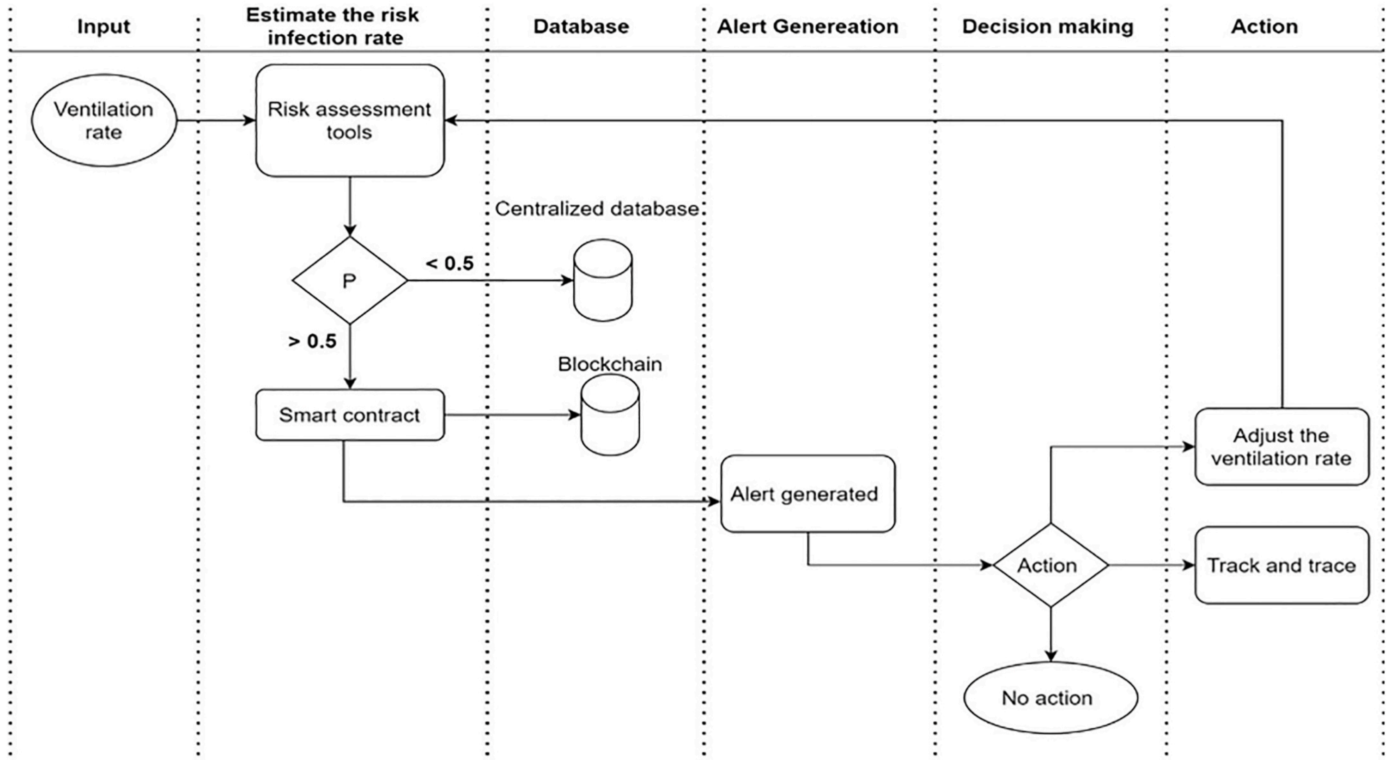

Fig. 2. Process flow of P-Alert Assessment.

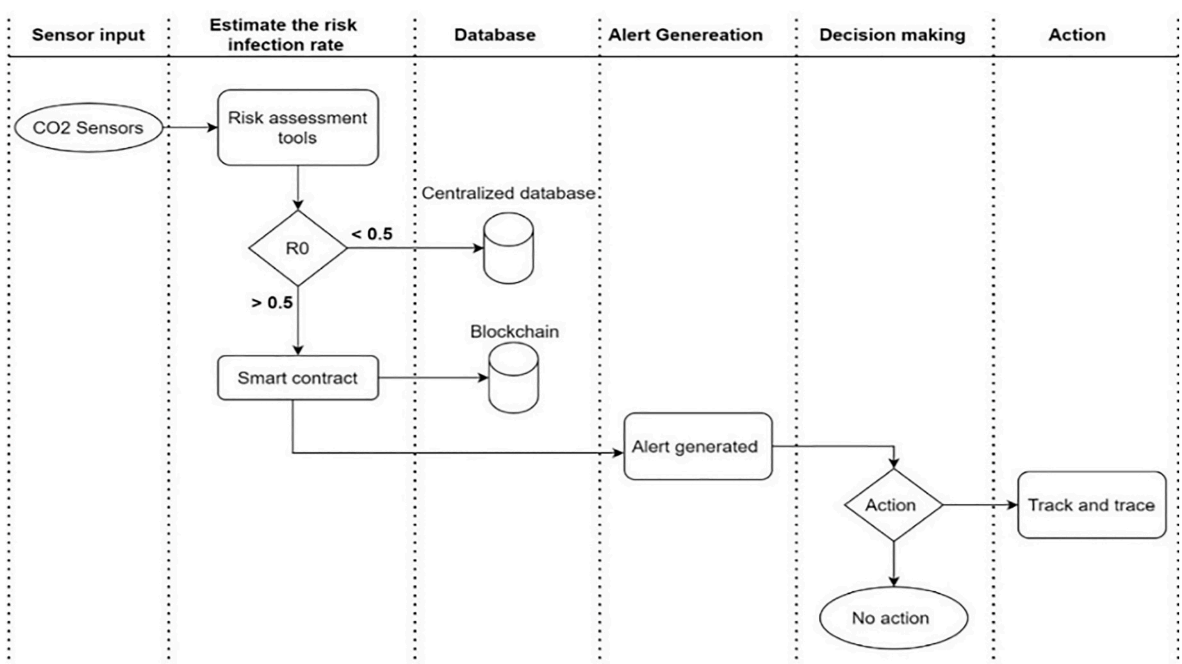

Fig. 3. Process flow of R0-Alert Assessment.

Streamlit v0.79.0. The source codes and online demo are available at https://github.com/NTNU-DT/AIRa.

4.1. Sensor and location

The experiments were conducted in an office on an office floor containing twelve meeting rooms with open doors and sitting desks, as shown in Fig. 5. No HVAC system has been installed on the office floor, whose occupants rely instead on natural ventilation. A digital gas sensor for monitoring indoor air quality in relation to, for example, CO_2, has been installed in the meeting room with a sensor directly measuring CO_2, as shown in Fig. 3. The area of the room is 12 m^2 by 3 m in height. The sensor model is CCS811, which has an output range of equivalent CO_2 (eCO_2) from 400 ppm to 29,206 ppm. The instrument is calibrated

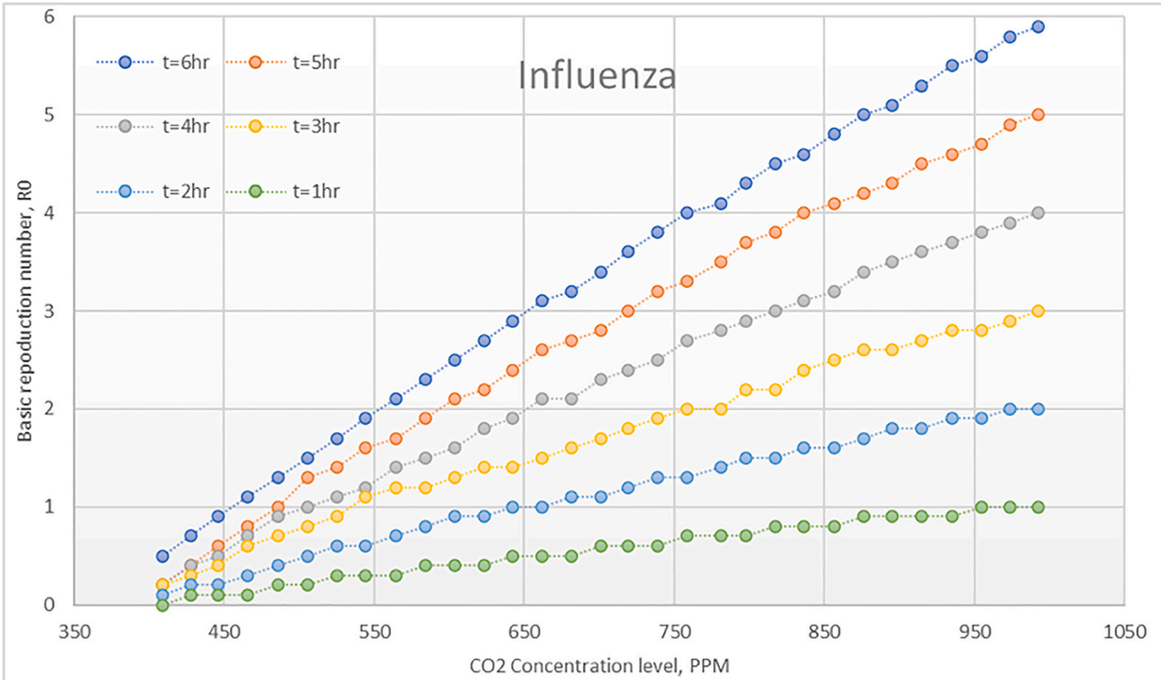

Fig. 4. R0 vs CO_2 level. This graph is reproduced from (Liao et al., 2005).

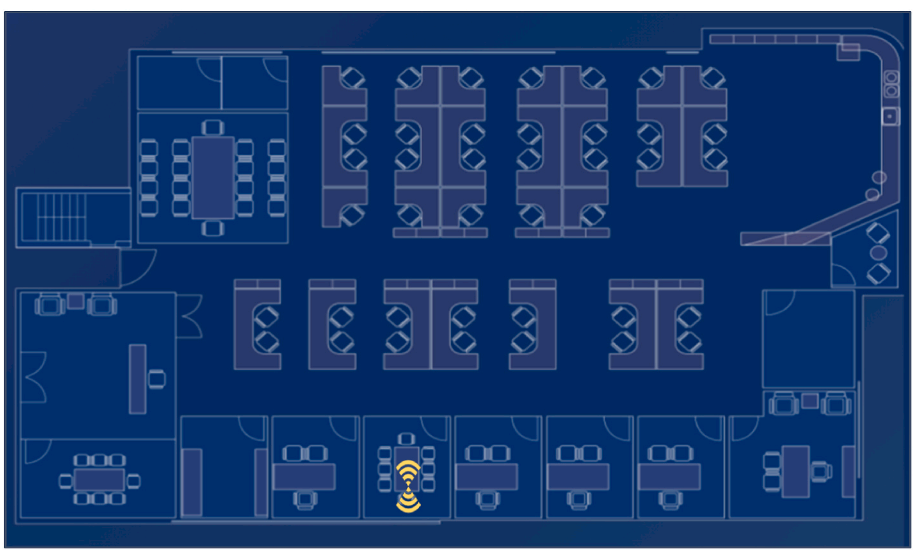

Fig. 5. The layout of the office under the study.

by the manufacturer before use. It has recorded a reading every 30 s since April 20, 2021. Since the data is not collected in an industrial building, we assume that the primary source of CO_2 is human respiration.

4.2. Process flow of verification and data-transmission mechanisms

We use Hyperledger Fabric, a private permissioned blockchain, to reduce the degree of openness, which is more suitable for the ecosystem. The blockchain is designed for one channel connecting a cluster of sensors in different rooms and sharing the details of the generated alerts. To identify the trusted data source with the blockchain system, we implement the following verification mechanism, as shown in Fig. 6.

Step 1 is to register the verification system connecting the building server to the blockchain network. In this step, the verification system submits its identity name and a secret key issued by the blockchain network administrator to the certificate authority server, which then issues, signs and stores a certificate encoding the public key in the blockchain. When the signing request has been met, the building owner receives a private key and a signed certificate in a wallet, concluding Step 2.

In Step 3 the identity of the trusted sensor is validated. The IP address and the port of the trusted sensor will be registered on the building server for validation. The verification system on the building server will send HTTP requests, with a token at step 4, to the trusted sensor with the registered IP address and port, which includes the sensor's username and password. In Step 5, each sensor immediately returns a unique token, which will be used to verify the identity of the building server.

In Step 6, the risk assessment system on the building server will automatically send HTTP requests to each sensor every 30 s to read the

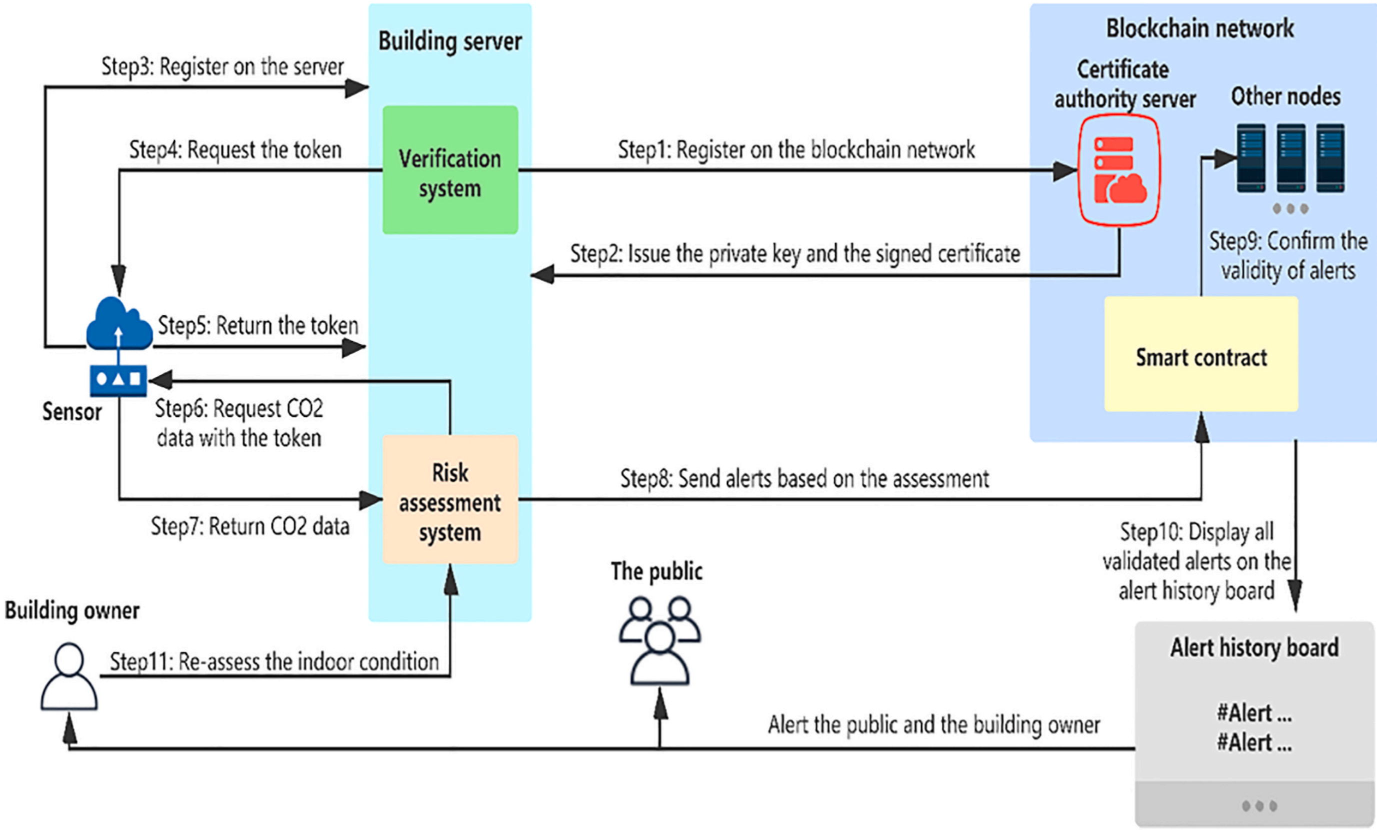

Fig. 6. Process flow of verification and data-transmission mechanisms.

real-time CO_2 data with the unique token of the sensor in the building. The sensor will then return the real-time indoor CO_2 concentration reading back to the building server after validating the corresponding token in Step 7.

In Step 8, the risk assessment system on the building server estimates the infection risk based on the collected CO_2 data and invokes the smart contract to send R0-Alerts based on the pre-set *R0* threshold by signing with the private key and certificate stored in the wallet. In Step 9, the alert is then processed by all nodes in the network to query and track the alert until its validity has been confirmed by a consensus mechanism in the blockchain. All validated alerts are then displayed on an alert history board, as shown in Step 10. The building owner can alter the parameters, such as the ventilation rate, that are entered into the risk assessment system to re-assess the indoor conditions and decide whether to issue a P-Alert based on the predicted probability of infection in Step 11.

5. Results and discussion

Fig. 7 illustrates the dashboard of this system, which generates alerts based on the room's condition to enable decision-making. The full alert history can also be found at https://github.com/NTNU-DT/AIRa. Two types of alerts are displayed, namely (1) P-Alert and (2) *R0* alert assessments, and they are stored chronologically at their exact time and date. Additional vital information such as the room number and CO_2 concentration levels are also displayed on the dashboard. In our system, we set the threshold for P- and R0-Alerts to 0.5 instead of 1 because the aim is to get the attention of the building owner to take action, if necessary, before the estimated risk of both *P* and *R0* becomes greater than 1.

When the CO_2 level in the room is above 650 ppm, as shown in the top right Fig. 7, the estimated *R0* is greater than 0.5 and this triggers an R0-Alert. The alert is then displayed in the alert history, as shown to the left of Fig. 7. Two similar R0-Alerts were also generated on April 21, 2021 because the concentration level of CO_2 in the room was increasing, which could increase the risk of spreading influenza if an infected person was in the same room. This alert is generated because a meeting was taking place in Room 001 at exactly that time. When this alert is generated, the building owner can take various actions, such as increasing ventilation by opening the windows to improve airflow and reduce the CO_2 concentration. The building owner can also choose to take no action if no one in the meeting room feels ill.

When a P-Alert is generated, as shown to the left of Fig. 7, this means that the risk of infecting other occupants in the same room is 0.5 and that the building owner should take action to prevent the risk from increasing. For example, the building owner can access to the Alert history to increase the ventilation rate by adjusting the sliding bar, as shown at the bottom right of Fig. 7, to reduce the CO_2 concentration in Room 001. We also included other parameters, such as the duration of the exposure, which the building owner can vary in order to reduce *P* to less than 0.5. However, if the P-Alert continues to be generated, the building owner should stop the meeting and re-evaluate the room's condition if necessary.

6. Discussion

6.1. Comparison of infection control alert systems

We compare our work (AIRa) with three existing solutions: blockchain-based disease information tracing (DIF) (Zhu et al., 2021), the TraceTogether (TT) Mobile App used in Singapore (Agency, 2020), and the COVID-19 SG Dashboard web app (Lab, 2021), as shown in Table 3.

DIF, TT and our own work all have an automated alert function to inform users for decision-making purposes. DIF sends alerts to health organizations when the number of COVID-19 cases in the hospital exceeds the predetermined threshold to facilitate tracing. As for TT, users

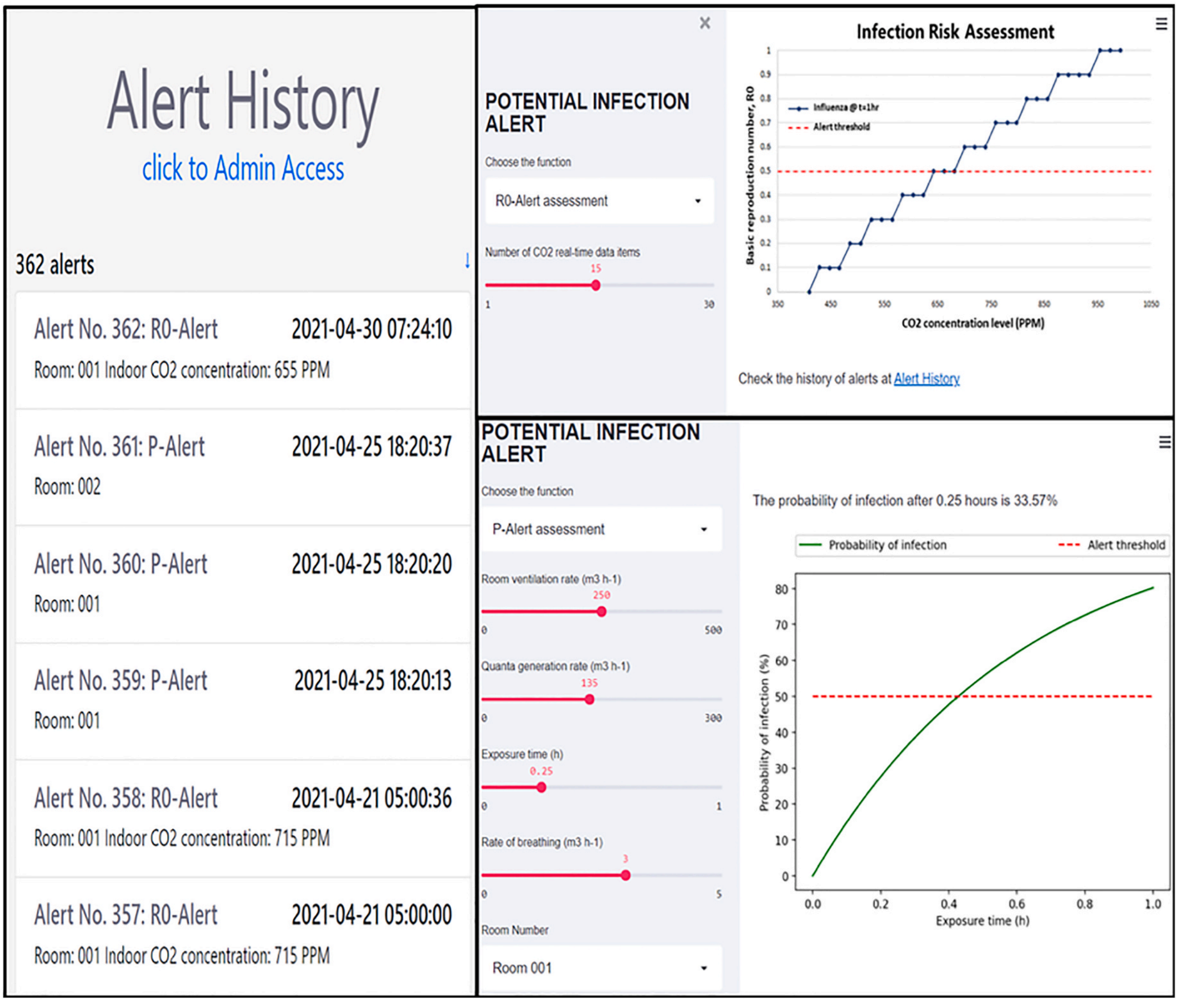

Fig. 7. Alert History (to the left), the user interface of R0-Alert assessment (top right) and the user interface of P-Alert assessment (bottom right).

Table 3
Comparison of infection control alert systems.

Solution	DIF	TT	Dashboard	AIRa
Justifications	Disease reports	Contact tracing	Estimation Wells Riley	Estimation Wells Riley
Alert function	Yes	Yes	No	Yes
Participation	Yes	Yes	No	No
Coverage	Nationwide	Nationwide	Confined space	Confined space
Types of tracing	Passive	Active	NA	Passive
Sensor	None	None	None	Yes
Approach	Long term	Short term	Long term	Long term
Privacy	Low	Low	NA	High

receive an alert when they are exposed to an infected person in the same premises at the same time. DIF and TT use early detection to reduce the risk of a large-scale pandemic and its future spread, but it may be too late, as the infection may have already occurred. Our solution, conversely, continuously monitors and estimates the potential risks and sends an alert for earlier detection when the conditions present a high risk to building users. The dashboard does not send any alert, but it has been selected for comparison because it provides users with information and assessments to measure the potential risk in a confined space.

Our proposed solution is passive and privacy-focused, allowing it to be used as a long-term approach to protecting occupants from virus infection in an indoor environment by sending an alert to building users, thus enabling infection risk analysis using sensors, unlike other alert solutions. Currently, scanning a QR code using a mobile app like TT to check-in before entering premises is used as a form of contact tracing to curb the spread of COVID-19. This approach has wider coverage compared to our work, but for TT to work well and be effective, all users must proactively remember to scan. Similarly, for DIF to be effective, many hospitals have to participate in the blockchain for nationwide tracing. Once the pandemic is over and everyone has been vaccinated, this strategy can undoubtedly be abandoned. Although our solution can only cover a confined space such as an office with sensors, it can still play an important role in making long-term assessments of the condition of indoor environments using sensors and infection risk assessment tools, as well as passive tracking without the need to check-in.

DIF can also enable long-term infection control assessments and passive tracking, but it raises privacy concerns because the solution stores sensitive information such as patients' names and test results on the blockchain. Due to its immutable nature, blockchain violates the General Data Protection Regulation (GDPR) of Art. 17, Right to erasure/right to be forgotten, especially in Europe, where patients should have the right to request deletion of all their health data (GDPR, 2020). For example, in one privacy breach in using TT (Agency, 2020), the police accessed data for criminal investigations that should be used solely to fight COVID-19 (IllmerBBC, 2021). Unlike TT and DIF, our solution only stores and shares information such as time, date, location, indoor air quality (e.g., CO_2 concentration level) and type of alert on the blockchain. If an alert fails to capture the attention of the building owner and track and trace is needed, the building owner can easily identify who booked and used a room based on the time, date and room number from their access control records, which are kept separate from the data on the blockchain. DIF did not mention and discuss the need for patient consent for data to be used, e.g., whether storage practices could violate the regulation itself.

DIF and our work are both implemented using Hyperledger Fabric, a private-permissioned blockchain. A private-permissioned blockchain is more suitable for the ecosystem because the information stored is only accessible to authorized members, thus reducing its visibility by the general public. Other advantages of using Hyperledger Fabric include its high throughput and low latency compared to other blockchain platforms, such as Bitcoin and Ethereum (Majeed et al., 2021). High throughput is essential to ensure that alerts are shared as quickly as possible so that the building owner can respond quickly. Blockchain also offers a distributed immutable data-management capability that can complement centralized databases, which are often vulnerable to attack (Tian, 2017). If the attack happens, the transaction on the framework can easily be used to reconstruct the events for retrospective investigation.

Blockchain is essentially a decentralized data-management platform. Unlike traditional centralized database management systems, blockchain can be scaled horizontally by adding more blocks to the chain, making it inherently suitable for storing time-series data such as indoor climate data. Depending on the block size, data with a certain time interval can be stored on the same block. This also means that low latency can be achieved for slicing operations on time series, e.g. querying the data in the same block. This allows for better efficiency than traditional centralized data-management systems. Therefore, the application of blockchain technology in the proposed system provides high query efficiency for scalable datasets. This is especially useful for alert systems for large groups of buildings, or hospitals monitoring indoor air quality for near real-time notification purposes.

6.2. Limitations and future work

The proposed system currently incorporates two types of models, one based on the fundamental Wells-Riley equation, the other on the reproduced graph of CO_2 vs R0 of influenza by Liao et al. (Liao et al., 2005). AIRa is relatively simple and mainly suitable for asymptomatic cases, but the platform can easily be extended, e.g., by adding other complex epidemic models, such as dose response models, to improve its risk assessment capability for indoor environments. For example, incorporating additional influencing factors such as ventilation-related interventions (e.g., particle filtration and air disinfection technology) (Morawska et al., 2020; Sze To and Chao, 2010) and the use of personal protection such as masks (Dai and Zhao, 2020) can provide more accurate infection assessments that are close to reality. In addition to infection risk assessments, health risk assessments can also be added to the platform to protect room occupants from harmful substances (Madureira et al., 2016) such as volatile organic compounds (VOCs), which can negatively impact respiratory health (WHO, 2010), as well as adopting a similar alert generation approach to support decision-making and early investigations.

Multidisciplinary knowledge and technology are critical to formulating infection control strategies (de Almeida et al. Rothballerr). Although the Wells-Riley model enables rapid risk assessments of infectivity, it comes with several assumptions, including the assumption that the air in a room is fully mixed and therefore has a uniform distribution of quanta throughout its space. However, the air in most rooms is not well mixed (Beggs et al., 2003). The probability of infection depends on indoor air characteristics, such as air distribution, quality and pattern. Technologies such as Computational Fluid Dynamics (CFD) can be integrated into our solution to visualize how air moves through space and show how airborne pathogens can move through buildings (Brittain et al., 2020; Cousins, 2020). With this integration, we can improve the risk analysis model to generate more useful alerts in the future that bridge the current knowledge gap on the risks of airborne viral transmissions in building environments.

The generated alerts will draw the building owner's or user's attention so that appropriate action can be taken. In future work to develop risk assessments using different models and influencing factors, the number of different alerts would increase. When the building owner constantly receives multiple alerts, this can easily lead to alerts being overridden without being read and ultimately to alert fatigue – a major concern, for example, in the healthcare sector (Wan et al., 2020b). It is common for system designers to limit their ability to change the alert setting in risk assessment systems to avoid the early detection of airborne viruses being missed. It is also common to request more alerts in risk assessment systems which could increase alert fatigue in the long run. Other alert optimization techniques, such as machine learning, would be essential in any future alert system.

7. Conclusion

Infectious diseases will continue to emerge and reemerge, presenting unpredictable challenges to public health. Early detection of high-risk areas and faster decision-making constitute a better preventive approach. AIRa is a blockchain-based risk assessment platform that integrates building sensors with risk assessment to generate alerts of potential airborne virus transmission for early decision-making by building owners.

The proposed platform, which has been designed and validated in research for this paper, can use a passive form of occupant tracking based on alert messages stored on the blockchain, including a timestamp of the event and the locations where it occurred. This immutable data can enhance digital forensics by tracking other anomalies that may have occurred at that time. Ultimately, this framework can be a potential solution for long-term proactive monitoring without affecting human behavior, such as scanning QR codes when entering a building.

AIRa can be useful in refining public and risk management strategies, allowing epidemiologists to reduce the risk of indoor infection at an early stage. Interdisciplinary knowledge of occupant behavior and virus epidemic dynamics will improve risk assessment systems to generate more accurate alerts to support decision-making in building environments. Although this framework is still in its infancy, it offers a good foundation for making smart buildings more efficient and protecting indoor occupants.

Credit author statement

Paul Kengfai Wan: Conceptualization, Methodology, validation, writing- original draft preparation, **Lizhen Huang**: Methodology, Main Supervision, Writing - Review & Editing, **Zhichen Lai**: Programming, **Xiufeng Liu**: Validation, discussing, Writing - Review & Editing, **Mariusz Nowostawski:** supervision, Writing - Review & Editing, **Halvor Holtskog:** supervision, Writing - Review & Editing, **Yongping Liu**: Discussing, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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