Developing resilient hospitals through agent-based modelling

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Abstract

Fully-functioning hospitals shall be the backbone of society. The present UK hospital design procedure over-emphasises empirical knowledge and experimental research, but a lack of abilities to address new infectious diseases and the increasing global connectedness. Approximate one fifth of UK confirmed cases and majority of infected healthcare workers in NHS hospitals are associated with nosocomial infections. This paper discusses a new perspective to develop more flexible hospital building layouts concerning clinical network efficiency to better control nosocomial infections through agent-based modelling for infectious disease epidemiology.

Keywords: Resilient hospital; Agent-based modelling; Infectious disease epidemiology; BIM; SARS-CoV-2

1. Introduction

When Big Ben chimed to mark the start of 2021, most of the UK's residents were told to stay at home to stop the spread of the coronavirus disease (COVID-19). COVID-19 has led to over 50,000 daily confirmed cases and an overall 2.5 million cases in the UK by the end of 2020 (Figure 1). The quick spread of the disease was also due to the new variant, known as B.1.1.7, which was more transmissible than non-variant SARS-CoV-2, i.e. the original virus that led to COVID-19 (Mahase, 2020). Alongside the increased number of confirmed COVID cases, the hospital admission of COVID patients also surged significantly and this has gone beyond the normal capacity of many NHS hospitals (Figure 2). In many UK cities, an immediate response to such a surged demand for hospital capacity was to convert a large building such as a conference centre into a Nightingale hospital or to construct a field makeshift hospital from scratch. More efforts have been made to stretch the existing hospital capacity by converting clinical spaces and normal patient rooms into intensive care units (ICU). But such conversion projects were not always successful: existing hospital infrastructures were found to be insufficient to carry the extra loads in many cases (WSP, 2020). Many conversions during the 'pandemic mode' have not sufficient separated infected patients from other patients, medical staffs and essential medical equipment, which has led to serious nosocomial infections. According to the inspection report by the UK Care Quality Commission (CQC) in December 2020, at least one half of UK hospitals have not got suitable designated pathways to allow patients with positive COVID test results to be safely discharged (CQC, 2020a). This agrees with the research by Nguyen *et al.* (2020) who assessed the nosocomial infection risk of COVID-19 among healthcare workers in the UK and the USA and found that frontline healthcare workers had increased risk in comparison to those working in the general communities. In the UK, one fifth of confirmed cases and 89% of infected healthcare workers in NHS hospitals were attributed to healthcare-associated infections (or nosocomial infections) (Evans *et al.*, 2020). The local NHS Hillingdon hospital has to be closed following severe COVID-19 infections among medical staffs in July 2020 (CQC, 2020b).

Healthcare Safety Investigation Branch (HSIB) attributed serious COVID-19 transmissions in the hospitals to the flow of patients and medical staffs which concerns hospital design (HSIB, 2020). The HSIB report also highlighted the importance to "*reconsider the design of ward work systems and equipment layout to mitigate the risk of nosocomial transmission*". Furthermore, an investigation following the incident of severe COVID-19 infections at NHS Hillingdon hospital raised following issues concerning hospital building design (CQC, 2020b):

1) Adequate social distancing cannot be maintained in the entrances and corridors of the hospital. This became worsen due to retail outlets which open directly to each other along a narrow corridor leading to the main entrance of the hospital.

2) There were no clear signs in the corridors and lifts referring to COVID-19 awareness. There were no signs in the lifts showing the maximum number of persons due to infection concerns; patients congregated outside some treatment room and waited for further assessment, with apparent social distancing violation concerns.

Fully-functioning hospitals shall be the backbone of society. Modern hospital design philosophy is predominantly based on the evidence based design (EBD) approach which is a scientific methodology that emphasises the use of data acquired in the past to inform the present design process and, in the meantime, collect further data via post-occupancy evaluation process to enrich the evidence database (Phiri and Chen, 2014, Hamilton and Watkins, 2009). There are growing concerns on this design approach before the pandemic, including an overemphasis on empirical knowledge gained by experimental research which excludes design knowledge generated outside healthcare and a lack of abilities to address new infectious diseases and the increasing global connectedness.

2. Current research and the research gap

The measures of infection control vary greatly according to the transmission characteristics of a disease. As an example, the risk of an infectious disease transmitted through droplets (>5μm) expelled from a respiratory tract is normally considered low over a 1-metre distance from the patient. A surgical (droplet) mask is considered sufficient to protect a healthcare worker from droplet transmission. With regards to an airborne disease, the small particles expelled from the respiratory tract is normally less than 5μm in size. Aerosols can also be developed during the medical procedures such as suctioning, sputum induction and endoscopy and they can remain active in air for a long period of time. As an example, SARS-CoV-2 virus can survive in air for at least 3 hours (van Doremalen *et al.*, 2020). A review of the literature shows the beneficiary effect of single-occupancy rooms on the control of infectious diseases (Van Enk, 2006). Rickman *et al.* (2020) however reported that 12% of COVID-19 patient-to-patient infections happened in the single-occupancy rooms. To prevent the transmission of an airborne disease, specially designed ventilation system (e.g. negative pressure ventilation) becomes essential (Camden and Islington NHS Foundation Trust, 2018).

There was a debate about the transmission mode of SARS-CoV-2. World Health Organization (WHO) stated that SARS-CoV-2 is primarily transmitted through respiratory droplets and direct contact in March 2020 (WHO, 2020). This is based on Ong *et al.* (2020) who reported that no airborne transmission was identified in over 75,000 COVID-19 cases in China. Most hospitals implemented a 2-metre social distancing rule which seems to be an effective precautious measure and this has been recommended by the NHS guidance (Public Health England, 2020). It should be noted that WHO (2020) stated in the same report that an airborne transmission of SARS-CoV-2 can take place during ordinary medical procedures including: "*endotracheal intubation, bronchoscopy, open suctioning, administration of nebulized treatment, manual ventilation before intubation, turning the patient to the prone position, disconnecting the patient from the ventilator, non-invasive positive-pressure ventilation, tracheostomy, and cardiopulmonary resuscitation*". A study at Addenbrooke's Hospital shows that the risk of frontline healthcare staffs to contract the disease in a COVID-19 ward was 47 times higher than that for community-related exposure (Ferris *et al.*, 2021). A significant drop in COVID-19 infections was only achieved after December 2020 when the staff face masks were upgraded to Filtering Face Piece 3 (FFP3) which has better protection against inhalation of droplets and aerosols. To conclude: SARS-CoV-2 can be transmitted through respiratory droplet and direct contact and the risk of airborne aerosol spread is very high. Due to the different transmission characteristics and the asymptomatic infectiousness of SARS-CoV-2, evidence obtained from the previous epidemics may not provide sufficient data for the assessment of the efficacy of public health interventions introduced this time (Maziarz and Zach, 2020).

The current UK general design guidance for healthcare facilities (Department of Health, 2014a) stresses the importance to prevent and control healthcare-associated infections (HCAIs) although the 'primary precautions' are to prevent pathogenic organism transmission through direct contact and respiratory droplets. This is based on the previous evidence that only "*a small proportion of patients requiring isolation will require special ventilated isolation facilities*" (Department of Health, 2014b). As a result of this, many NHS hospitals lack specially designed negative pressure rooms which is essential to control the spread of airborne diseases. Some hospital rooms were converted into isolation rooms with installed fans to create negative pressure during the pandemic. But it is still not clear about the efficacy of such improvised intervention approach. Most hospitals have the same pathways for arrival patients and convalescent patients to be discharged from hospitals. All these may lead to the serious nosocomial infection in the UK this time.

UK healthcare practitioners developed Nightingale hospitals in just a few weeks using modern construction approaches when many hospitals ran out of spaces during the first lockdown (Figure 1). Alongside the release of lockdown, community transmission may resurge and it is important to take more proactive actions to prevent nosocomial COVID-19 infections. Epidemiological modelling has been increasingly used to provide critical information on guiding COVID-19 interventions since the start of the pandemic (Giordano *et al.*, 2020, Dell'Anna, 2020, Nadler *et al.*, 2020). These studies have shown that crowding within a building environment can increase the risk of droplet and airborne disease transmissions. The modelling of a large number of individuals by considering their real behaviours affected by physical, social environmental factors can be very complex. Haghani and Sarvi (2018) developed discrete choice modelling (DCM) to simulate the pedestrian decisions. Antonini *et al.* (2006) developed agent-based modelling approach based on DCM to represent individuals' behaviour under an emergency evacuation circumstance. Rozo *et al.* (2019) conducted agent-based simulation to develop best building evacuation plans by considering individuals' various speed and obstacles inside a building. Agent-based modelling is a form of computational model for simulating the actions and interactions of individuals (agents). Agent-based modelling has also been used to examine the efficacy of non-pharmaceutical interventions including physical distancing and mask-wearing during the COVID-19 pandemic in France (Hoertel *et al.*, 2020). It should be noted that above modelling processes have not sufficiently considered the complex built environments and the effect on individual interactions within the field of public health. The research project conducted at Brunel University London have applied complex spatially-explicit stochastic simulations by considering the real hospital built environment systems (Tang, 2020). This work helps to assess the effectiveness of present infection control approaches, and to pave the way for the development of more resilient healthcare and residential care home facilities.

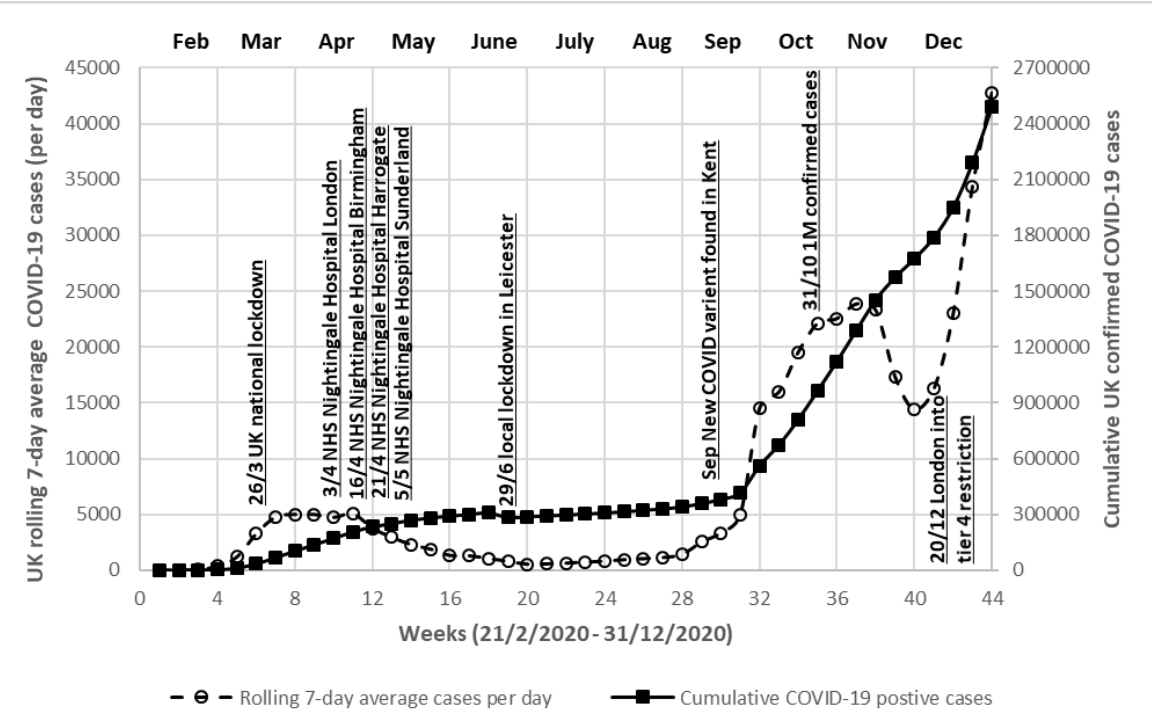


Figure 1: COVID-19 daily cases and cumulative cases in the UK (based on published data by (Public Health England, 2021a))

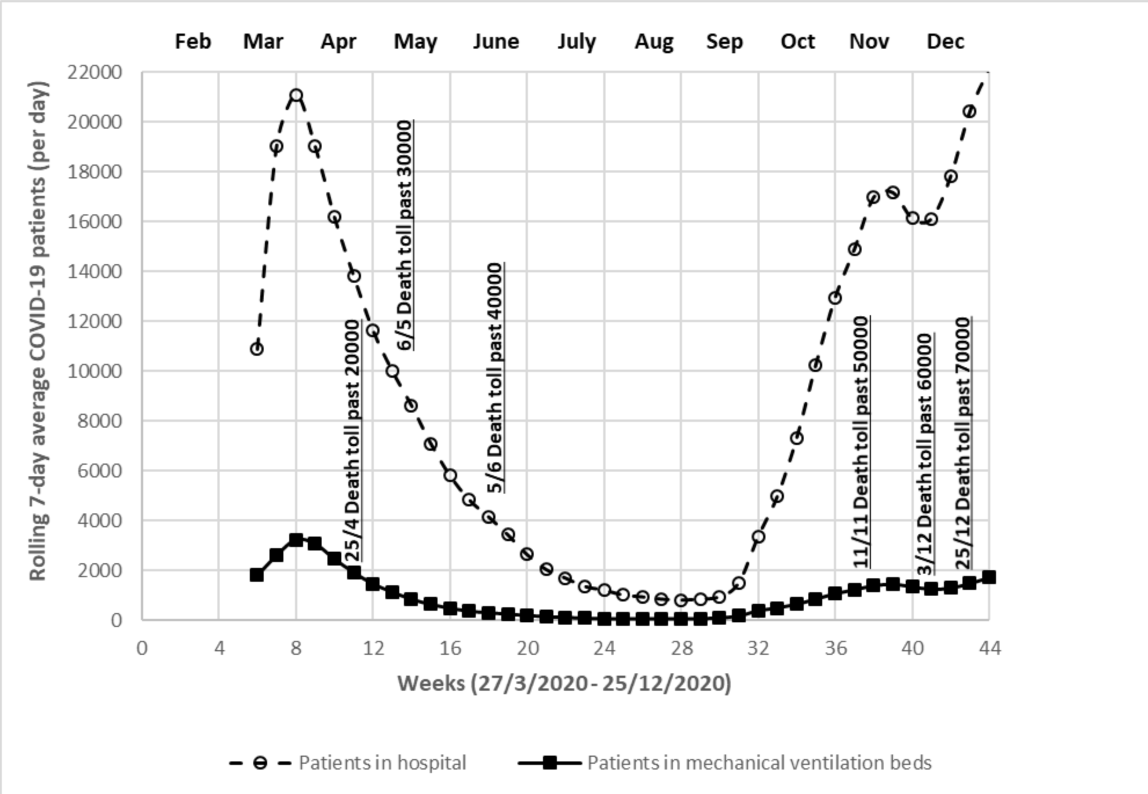


Figure 2: Hospital admitted COVID-19 cases in the UK (based on published data by (Public Health England, 2021b))

3. Research areas and questions

COVID-19 shines a spotlight on the existing hospital design procedures. Serious nosocomial infections during the outbreak of COVID-19 are implicated in the contaminated built environments. This indicates that the present hospital infection control and prevention measures cannot sufficiently control nosocomial infections. Particular attentions shall be paid to the following issues concerning the design of a hospital building:

1) There are growing concerns on the current NHS hospital design procedure which overemphasises on empirical knowledge gained via experimental research but a lack of abilities to address uncertainties such as a new infectious disease especially when its transmission characteristics is unclear.

2) Based on a review of the literature, effects such as human motions on the epidemic dynamics within a complex building layout has not been sufficiently addressed by the present epidemiologic modelling.

3) Modern hospitals lack the flexibility to accommodate a sudden surge of patients. A review of the literature shows the beneficiary effect of single-occupancy rooms on the control of infectious diseases. However, there are still uncertainties concerning the integration of additional single-occupancy rooms, especially when airborne isolation is considered essential to control the transmission of an airborne virus like SARS-CoV-2.

There will be many more new viruses and their transmission characteristics can be more complicated than SARS-CoV-2. It is important to design hospital buildings not only following the fear of infection, but for changes or the ability to cope better with future challenges. This project focuses on agent-based modelling for infectious disease epidemiology by considering the complex hospital built environments and the interactions between individuals. This will have substantial benefits for the UK hospital facilities, primary and community care services and pave the way for the development of more resilient hospital design guideline in a bid to better infection prevention and control.

4. Agent-based modelling for SARS-CoV-2 epidemiology

The main purpose of this work is to justify the needs for developing flexible building layouts, upon which a more effective clinical network and hospital building layout can be developed to control nosocomial infections. This was conducted through a case study investigation: a clinical infection unit (CIU) managed by the infectious disease team was created using Autodesk Revit (Figure 3 (a)). It has orthogonal column gridlines and the spacing between adjacent columns along both directions is 6 metres. The CIU provides clinical diagnosis of outpatient with suspected infectious diseases including respiratory diseases (e.g. SARS, TB with and without drug resistance) and gastrointestinal infections (e.g. viral, bacterial and parasitic infections). It also provides specialist inpatient services and routine surgeries. Figure 3 (a) shows the proposed directions for patients and medical staffs. Structural slabs, columns, walls, alongside important components that may affect the motions of patients including heavy X-ray and scanning machines, were created using building information modelling (BIM) software Revit (Autodesk, 2020). The Revit model was saved as an Industry Foundation Classes (IFC) file which is a standard format for exchanging BIM information across different software. The IFC file was then imported into agent-based simulation software MassMotion (Oasys, 2020) with geometrical information of all structural and non-structural elements. Walls, furniture and instruments were imported into MassMotion as obstacles (Figure 3 (b)). In MassMotion modelling, 200 visitors (or agents) were created to get medical help and they arrived at the CIU within 30 minutes. The clinical process is schematically shown in Figure 4: 40% of the total visitors were to seek medical help on possible gastrointestinal infections; the other 60% were to seek medical help in respiratory distress. No accompanying visitors for patients were considered in the computer simulation. Human factors such as crowd movement patterns on the epidemic dynamics were considered in MassMotion by simulating visualized patient movement pathways, upon which the potential risk of nosocomial infection was assessed. With a 95% confidence level, patients walk at an average speed of 1.35 m/Sec and a standard deviation of 0.25 m/Sec. The actual moving speed of each patient also depends on the density of patients in close proximity (Kinsey, 2015). These allow the MassMotion solution algorithm to randomise the walking speed of each person to better simulate the real-life conditions in a large population sample (Fruin and Strakosch, 1987). Other effects on agent walking speed including age, familiarity and level of panic will be considered in future investigations. Each patient chooses the path inside the hospital based on a minimum time cost model or Equation 1 (Kinsey, 2015):

$$Cost = W_D \times \left(\frac{D_G}{V}\right) + W_q \times Q + W_L \times L \qquad \text{Eq. 1}$$

Where:

Cost: Perceived total travel time alone the route (Sec)

W_D: Distance weight of each person

D_G: Total distance from the person’s present position to the destiny (m)

V: Velocity of each person (m/Sec)

W_q: Queue weight of each person

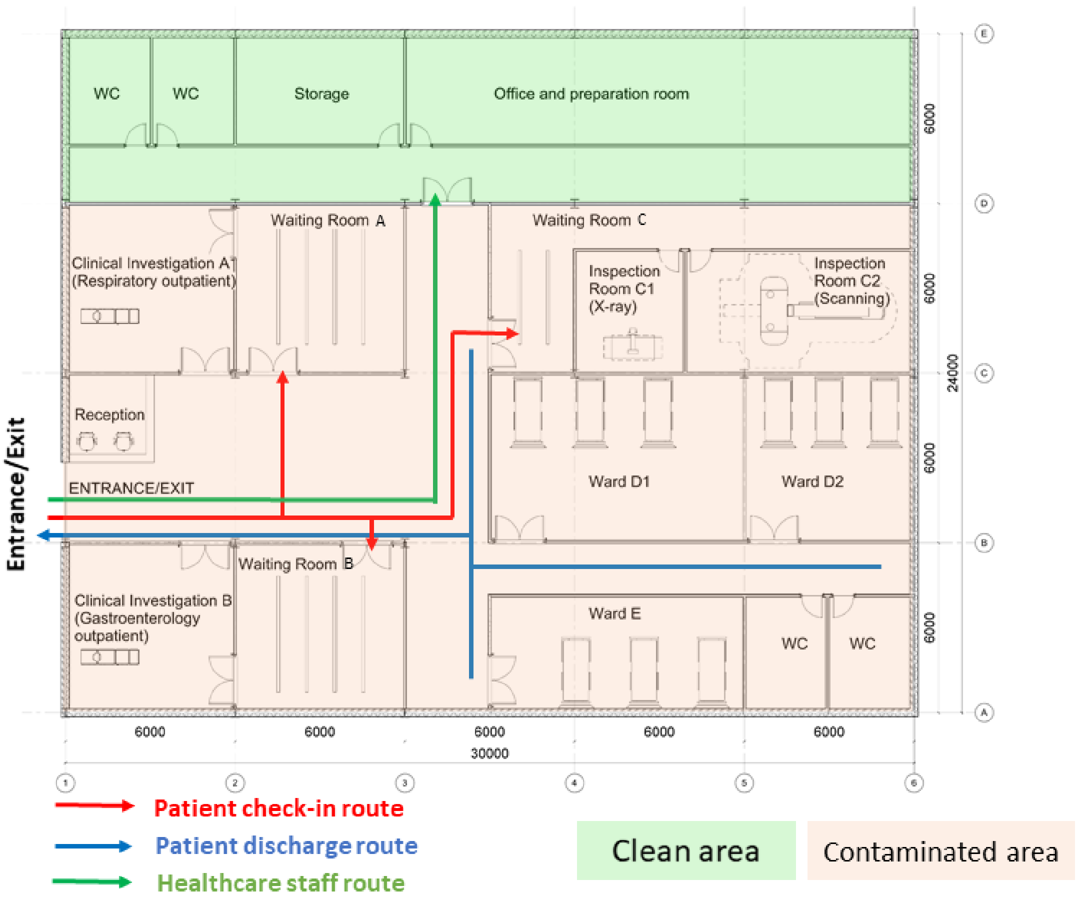
Q: Expected time in queue before reaching a particular point (Sec)

W_L: Geometric component traversal weight

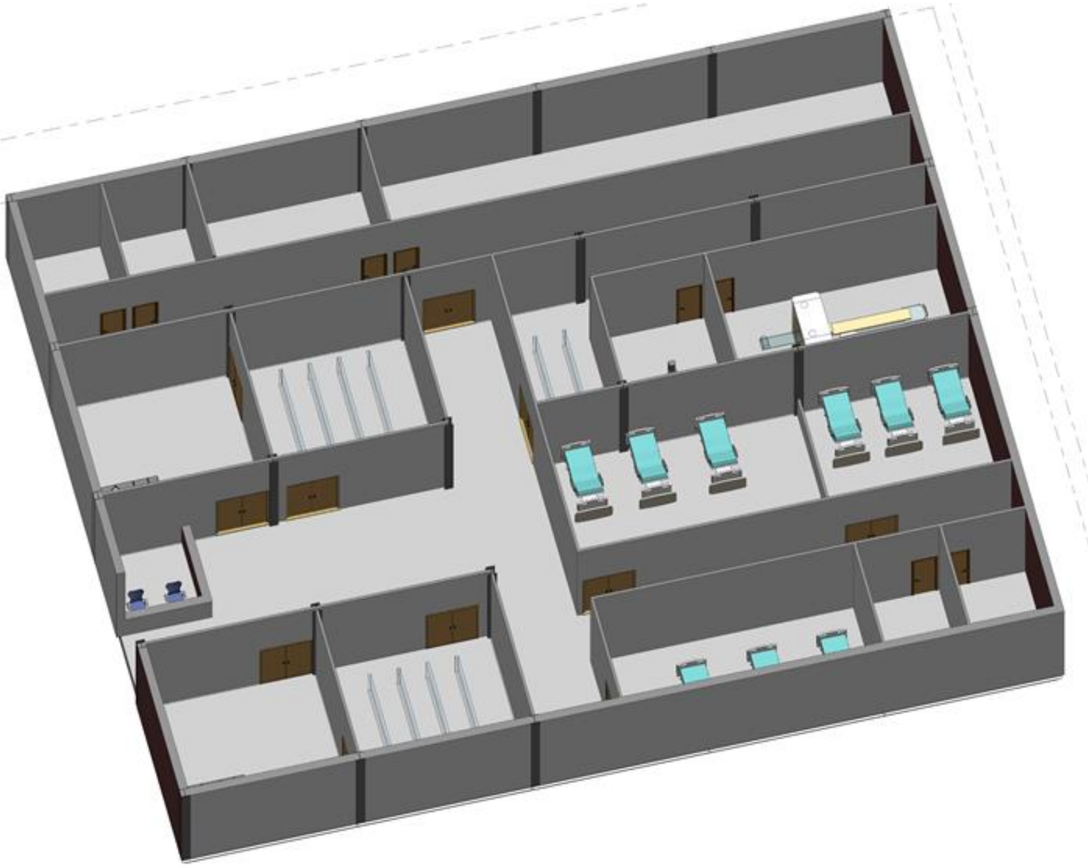
L: Geometric component type cost (Sec)

In the MassMotion model (Figure 5), 5 out of 200 patients were considered to have contracted COVID-19. All 5 COVID-19 patients were considered to be highly infectious. Out of the 5 patients, 3 patients seek clinical support for respiratory distress and 2 patients seek clinical support for possible gastrointestinal infections. The latter was according to a UK based research which indicates that COVID-19 patients, especially children, also show gastrointestinal infection symptoms: nearly half of children tested positive developed diarrhoea, vomiting and abdominal cramps (Mayor, 2020). Airborne transmissions of SARS-CoV-2 were considered in all three waiting rooms (i.e. waiting room A, B and C) based on a 10% probability of infection. This was achieved in MassMotion via a 'broadcast' function when any of the COVID patients entered the waiting rooms.

Other possible places such as the corridors where direct or airborne transmission may also occur, a pedestrian density (e.g. patients per meter squared) analysis was conducted and results are discussed in Section 5. Agent-based modelling under virtual hospital built environments provides useful information for the efficacy of non-pharmaceutical interventions such as social distancing and gives hospital practitioners a new perspective to develop resilient hospital building layout to cope better with future uncertainties such as other infectious diseases with various transmission dynamics.


WC
WC
Storage
Office and preparation room
Waiting Room A
Waiting Room C
Clinical Investigation A (Respiratory outpatient)
Inspection Room C1 (X-ray)
Inspection Room C2 (Scanning)
Reception
Entrance/Exit
ENTRANCE/EXIT
Ward D1
Ward D2
Waiting Room B
Clinical Investigation B (Gastroenterology outpatient)
Ward E
WC
WC
6000
24000
30000
Patient check-in route
Patient discharge route
Healthcare staff route
Clean area
Contaminated area

(a) Plan view



(b) Isometric view

Figure 3: Case study – medical centre Revit model

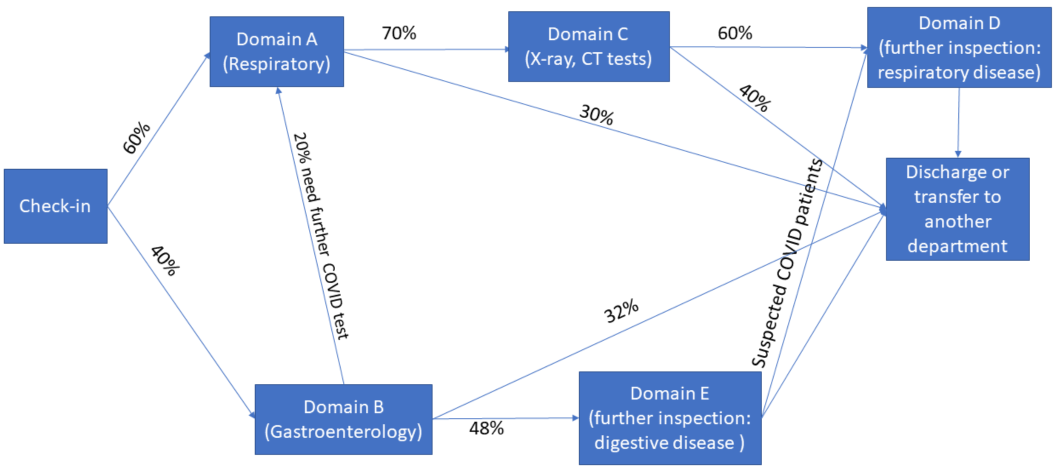


Figure 4: Simplified clinical network model

Figure 5: Agent-based modelling in the medical centre (Figure 3)

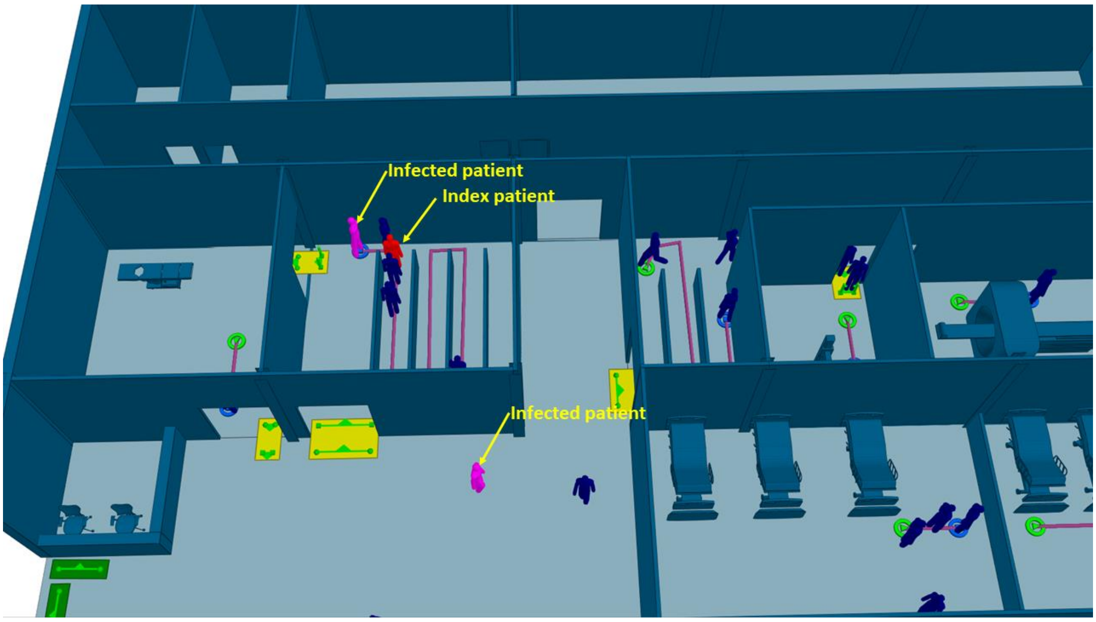
5. Results and discussion

MassMotion modelling results are shown in Figure 6. Figure 6 (a) shows the possible primary nosocomial infections due to the presence of the COVID patients. When the 5 COVID patients entered the building at time 6, 12, 18, 24 and 30 minutes, 7 other patients (out of 195) met the definition for hospital acquisition or nosocomial infections. These include 4 infected patients in waiting room A and 2 patients in waiting room C. When considering a higher infection rate of 20% (e.g. to consider the new variant such as B.1.1.7 which is more transmissible than original SARS-CoV-2), 16 patients (out of 195) were found to be infected, indicating an 8.2% infection rate. Among the 16 nosocomial cases concerning patient-to-patient infections, 7 cases occurred in the waiting room A, 5 cases in the waiting room B and 4 cases in the waiting room C.

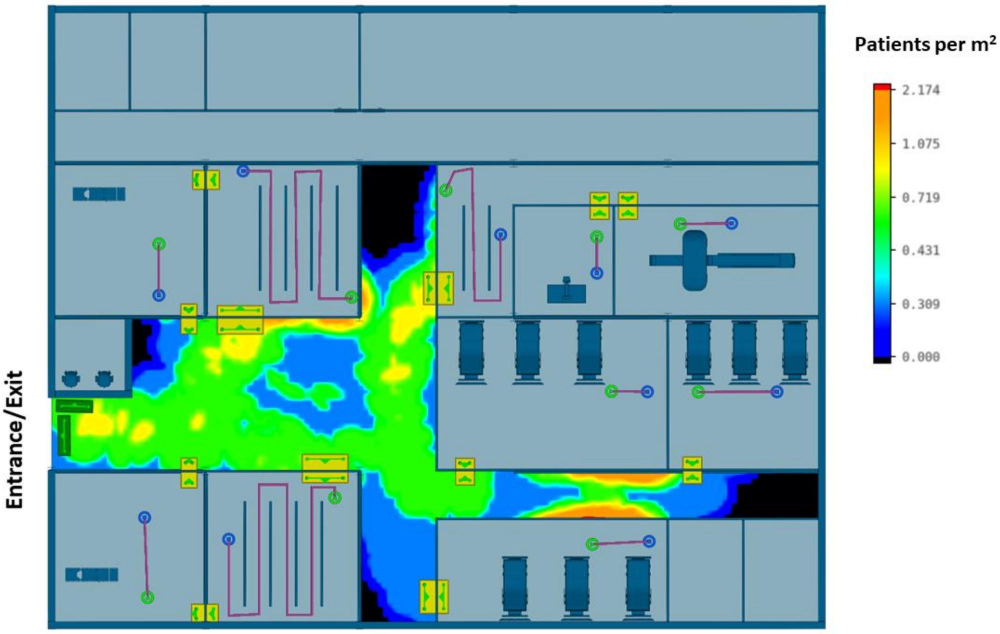
Figure 6 (b) shows severe pedestrian congestion in the concourse of the building which has been reported as a major reason causing social distancing violation (CQC, 2020b). In order to retrofit the current building facilities to be a suitable COVID-19 treatment centre, a new layout is proposed and shown in Figure 7 (a), with reconfiguration of room and concourse. The new building layout is based on the existing column gridline arrangements as shown in Figure 3 and it provides extra separation and compartmentalisation. Figure 7 (b) shows that having separate check-in routes effectively reduce overall congestion in the corridor (e.g. patients per meter squared). The new building layout (Figure 7 (a)) also offers a two-way system for medical staffs and patients which will greatly help to maintain adequate social distancing space for patients and medical staffs, in a bid to better nosocomial infection control.

It is essential to keep the flexibility of space, based on the installation of the decentralised ventilation system, as the technological change and future uncertainties will almost certainly outpace the development of a conventional hospital building during its whole lifecycle. Additional room and capacity shall be made for the infrastructure capacities such as redundant power and medical gas (e.g. oxygen gas) supplies. As an example, a target oxygen saturation of 94-98% is normally required for acutely ill patients (O'Driscoll *et al.*, 2008) while some NHS hospitals have to drop this baseline to 88-92% due to insufficient gas supplies as a result of a rising number of COVID-19 patients in January 2021 (BBC, 2021). There is however no clear evidence if this rationed medical care will affect the recovery of COVID-19 patients.

The outbreak of COVID-19 presents a significant challenge for the health and social care facility design in the UK and around the world. This is despite that the government and devolved administrations, including the health and social care system has planned extensively over the years for an event like this. As an example, the UK 'Annual flu programme' is regularly tested and updated to ensure the supply of flu vaccine would meet the annual demands. On the other hand, the present hospital design procedure has not been reviewed and updated in the same way to accommodate the demands of pandemic outbreaks or to reflect how the public respond to a new threat. After the pandemic, it will be helpful to convert the additional ICU spaces for other purposes, e.g. paediatric rooms to accommodate possible post-COVID baby boomers. The use of removable external walls and lightweight internal partitions can greatly facilitate this process including the installation of extra entrances and separations. This can be further enhanced with modular construction based on the use of lightweight materials. In 2020, George Eliot hospital expanded their ward bed units through modular construction. 33 modules made of lightweight steel were prefabricated and shipped to site which helped to reduce the entire construction programme from 20 to 14 weeks (Wernick group, 2021). There will be many more new infectious diseases and their transmission characteristics can be more complicated than SARS-CoV-2. It is important to learn from previous lessons to better prepare for the threats to hospital resiliency as the world is more connected, and climate change creates more favourable conditions for the transmission of the zoonotic diseases.

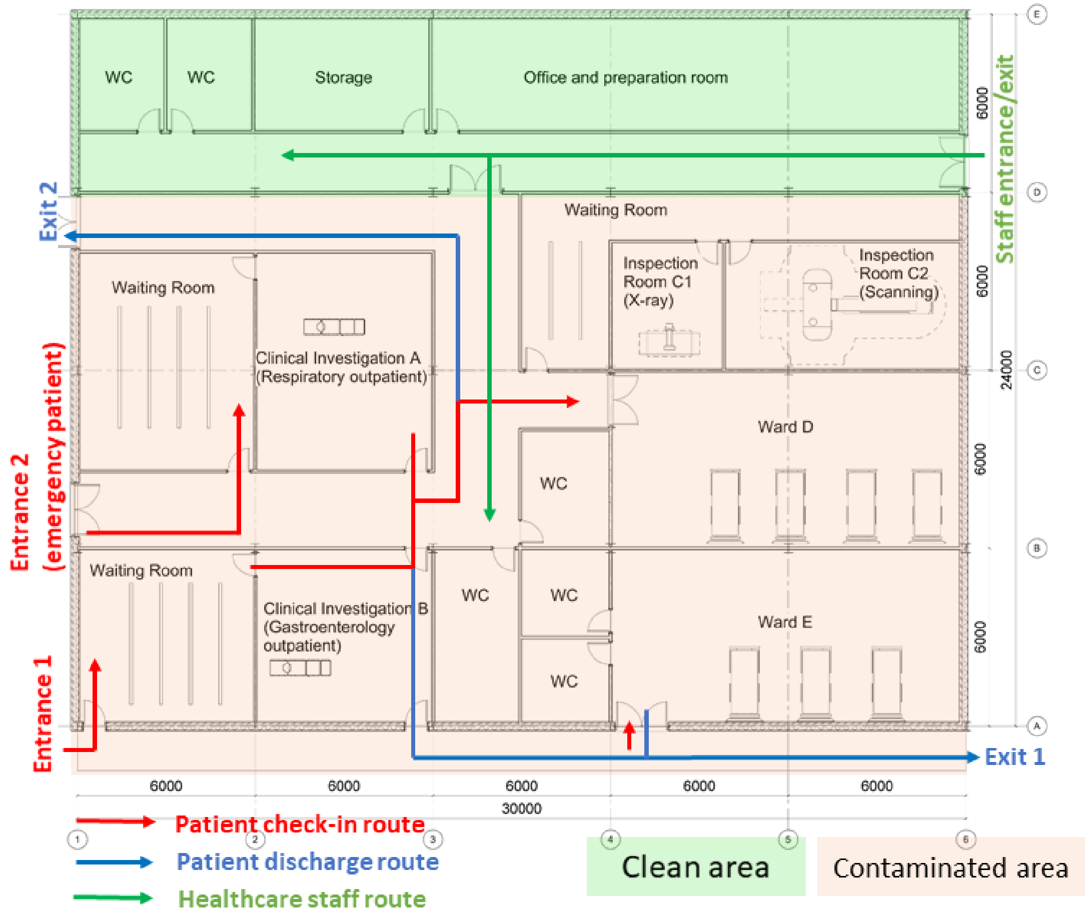


(a) Agent-based modelling for nosocomial infection

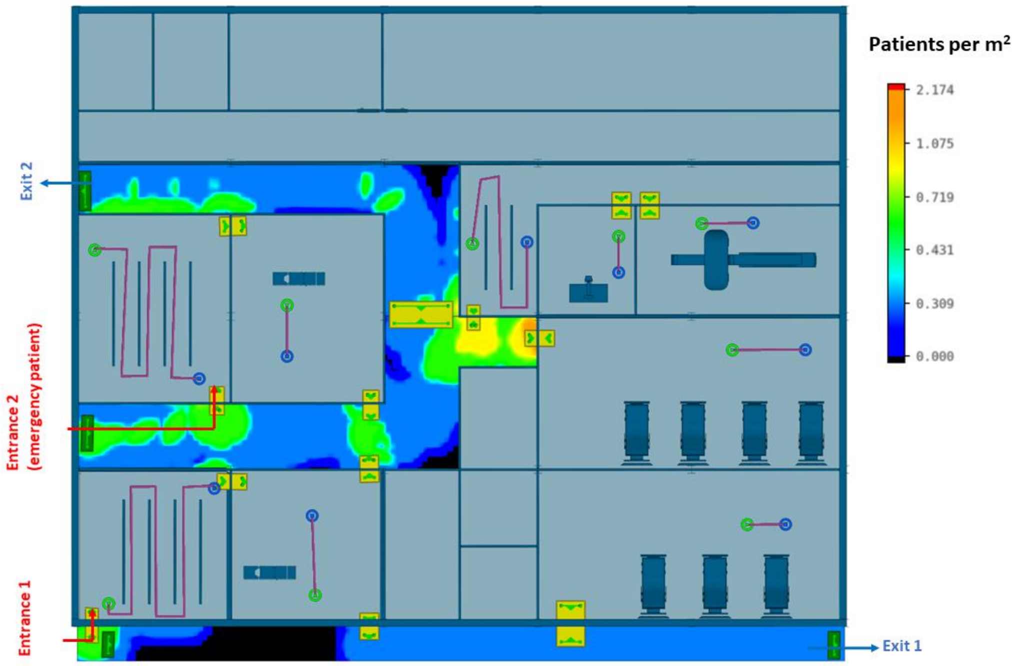


(b) Concourse congestion analysis (patients only)

Figure 6: MassMotion modelling result



(a) Building layout



(b) Concourse congestion analysis (patients only)

Figure 7: Development of COVID-19 treatment centre based on existing building (Figure 3)

6. Conclusions and future work

Serious nosocomial infections during the outbreak of COVID-19 are implicated in the contaminated built environments which requires further multidisciplinary studies. This paper presents a new perspective to develop flexible hospital building layouts concerning clinical network efficiency and nosocomial infections based on agent-based modelling for infectious disease epidemiology. Design for resilience can be achieved by keeping the flexibility of space for the future and this will be further enhanced with modular construction and prefabrication using lightweight steel. Future research will be orientated towards the calibration of the numerical modelling through experimental approaches. Different infectivity of asymptomatic and pre-symptomatic patients, and super-spreaders who can infect a large number of people will also be considered in future investigations.

Acknowledgements

The authors gratefully acknowledge the support of the ICE Research and Development Enabling Fund (2020), the Brunel University London RDF fund (LBG189) and the XJTLU Research Development Fund (RDF-15-01-19 & RDF-15-02-32). The authors also wish to thank the tremendous supports from their families.

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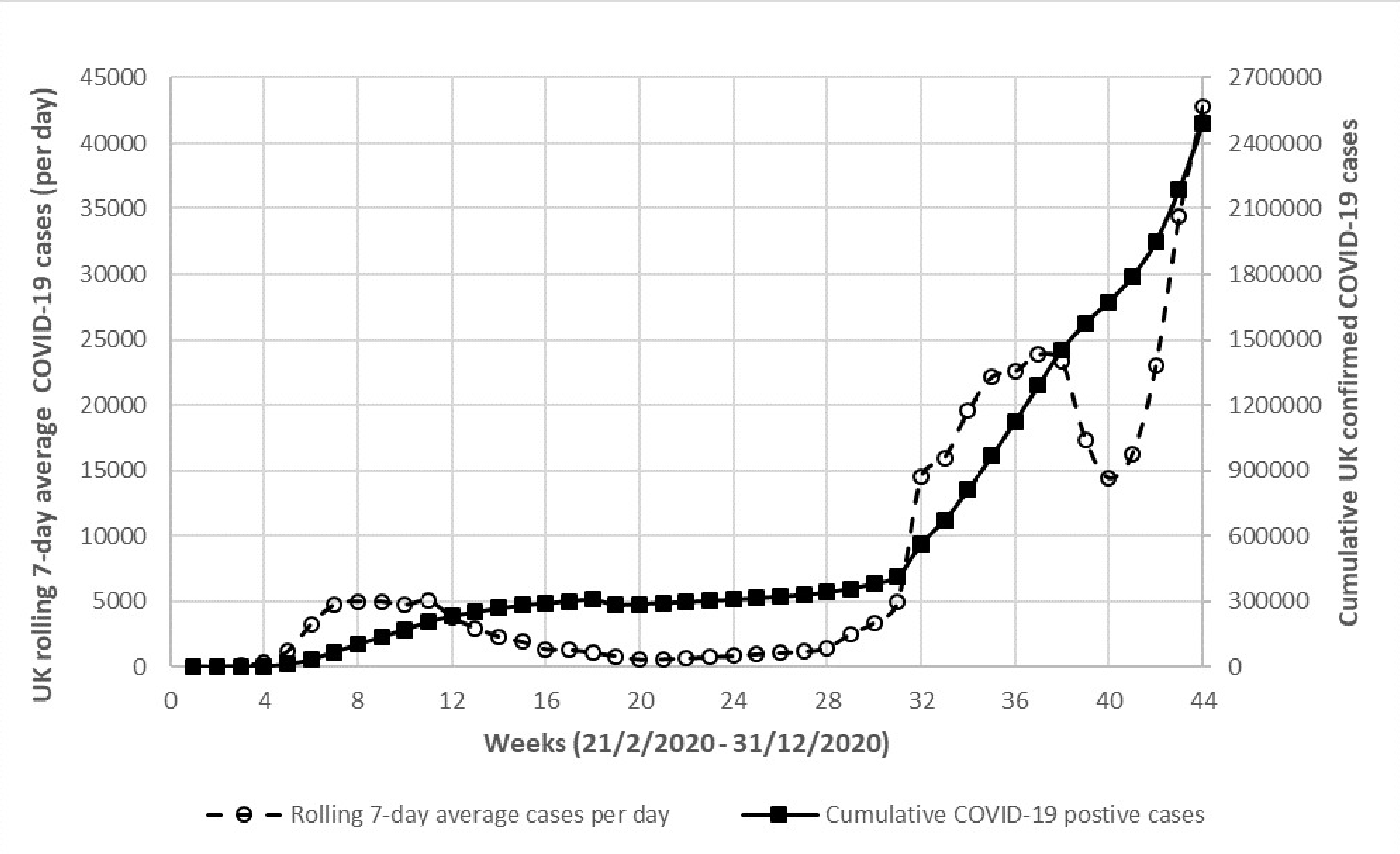
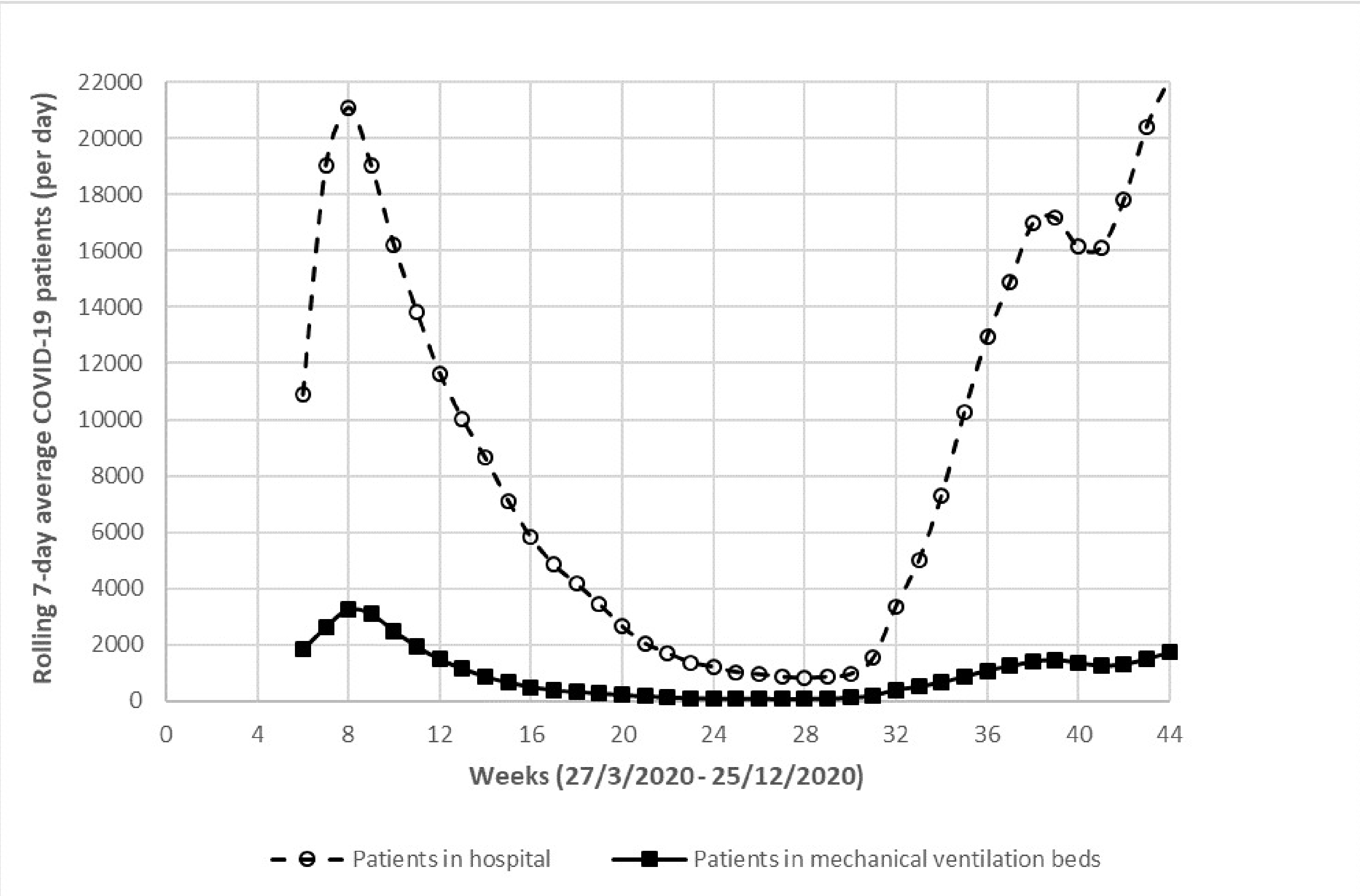
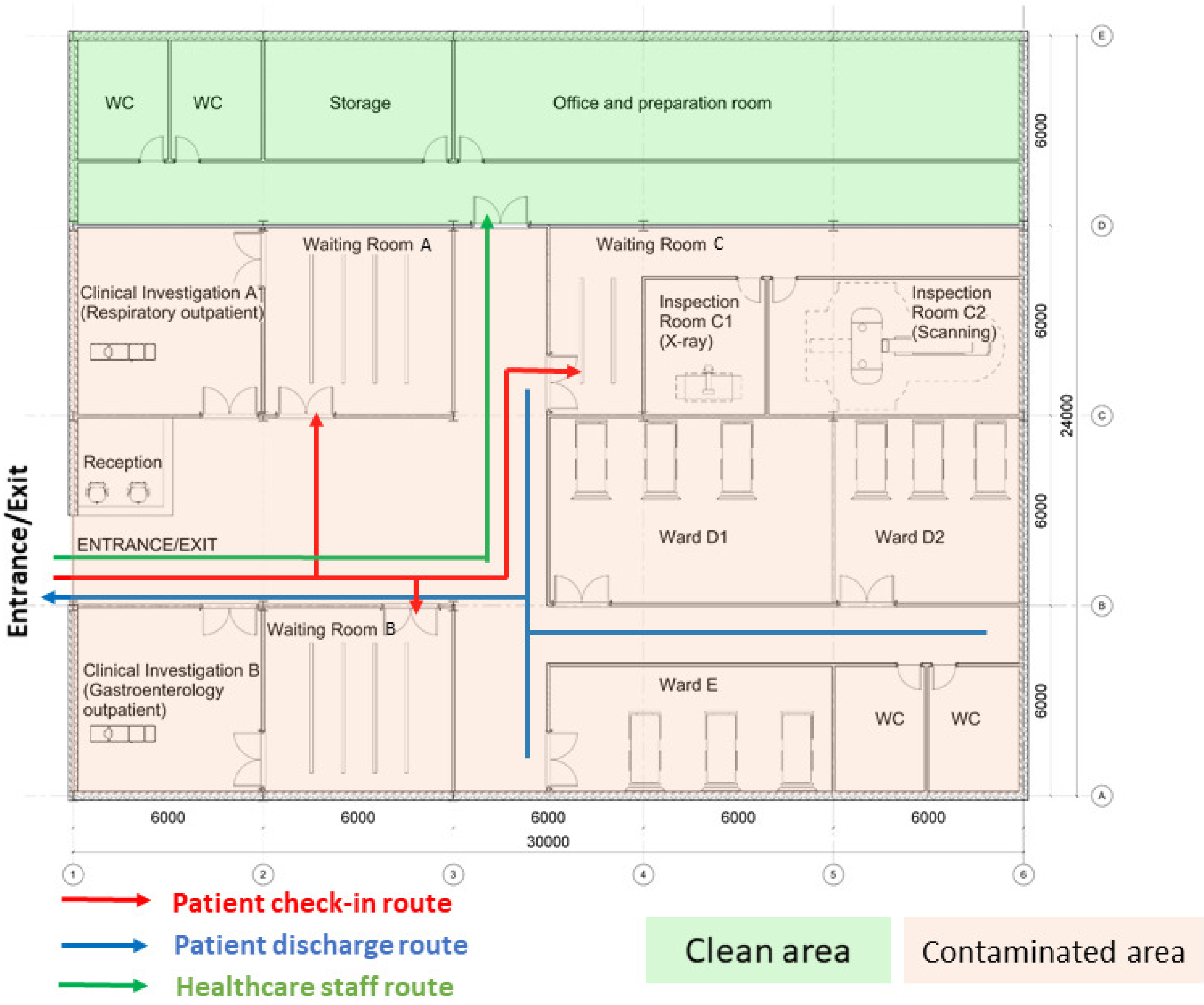
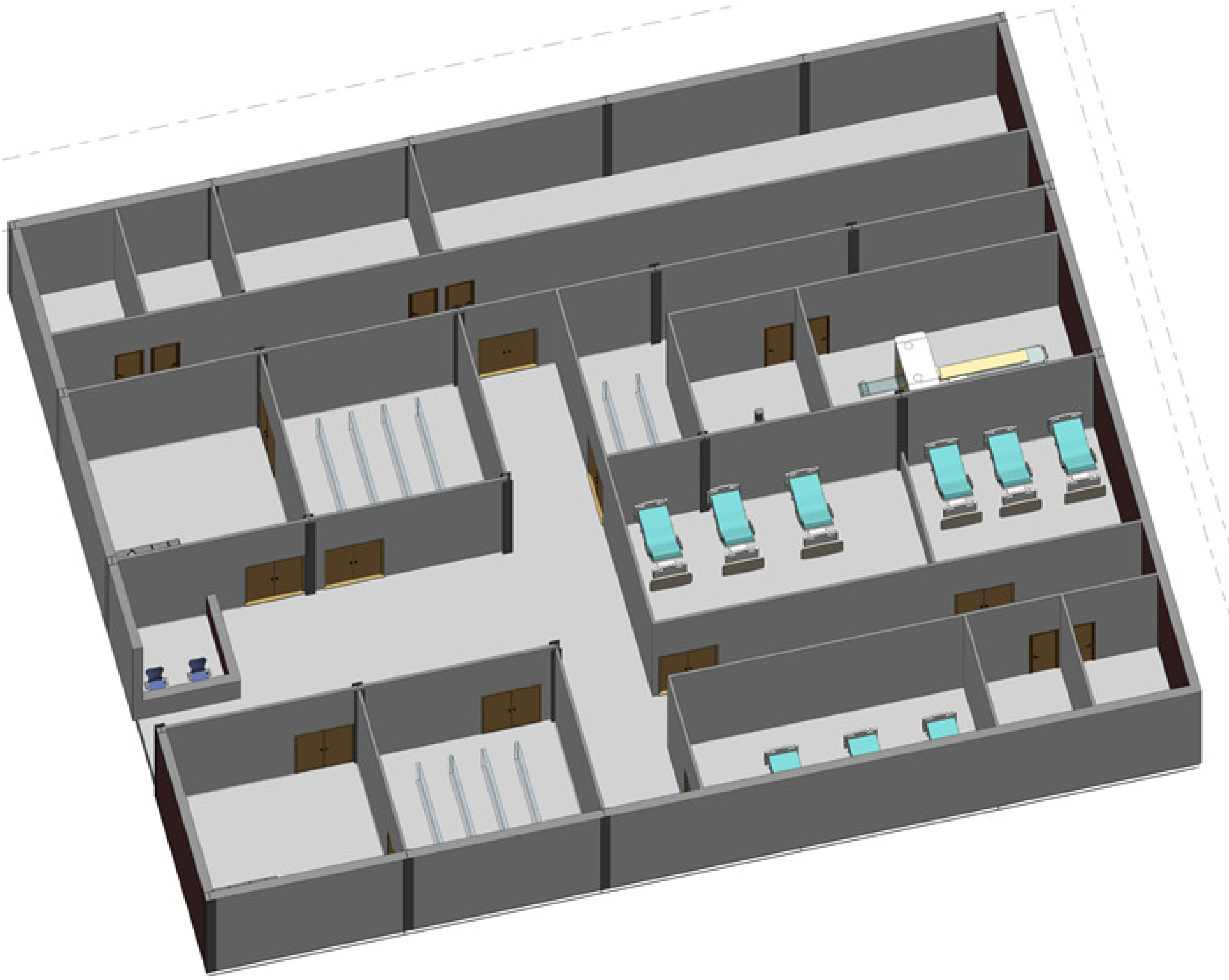

UK rolling 7-day average COVID-19 cases (per day)
Cumulative UK confirmed COVID-19 cases
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
2700000
2400000
2100000
1800000
1500000
1200000
900000
600000
300000
0
0 4 8 12 16 20 24 28 32 36 40 44
Weeks (21/2/2020 - 31/12/2020)
Rolling 7-day average cases per day
Cumulative COVID-19 postive cases


Rolling 7-day average COVID-19 patients (per day)
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
4
8
12
16
20
24
28
32
36
40
44
Weeks (27/3/2020 - 25/12/2020)
Patients in hospital
Patients in mechanical ventilation beds


WC
WC
Storage
Office and preparation room
Waiting Room A
Waiting Room C
Clinical Investigation A
(Respiratory outpatient)
Inspection Room C1 (X-ray)
Inspection Room C2 (Scanning)
Reception
Entrance/Exit
ENTRANCE/EXIT
Ward D1
Ward D2
Waiting Room B
Clinical Investigation B (Gastroenterology outpatient)
Ward E
WC
WC
6000
6000
6000
6000
6000
30000
6000
6000
6000
6000
24000
Patient check-in route
Patient discharge route
Healthcare staff route
Clean area
Contaminated area



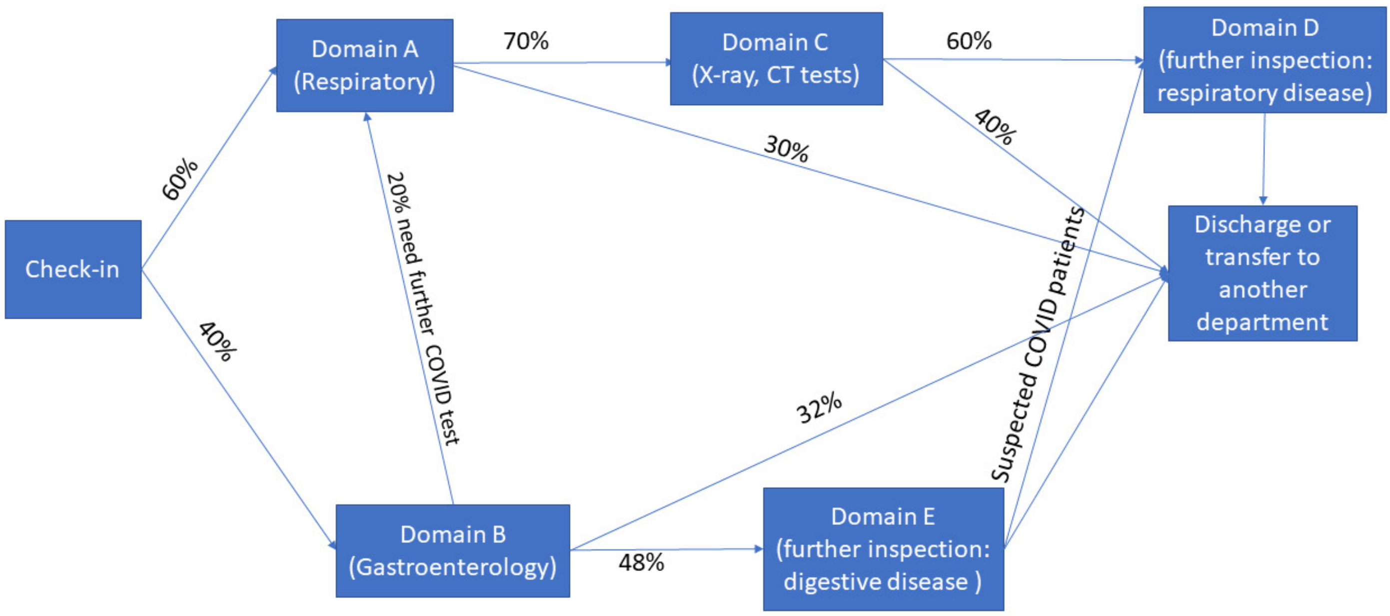

Check-in
60%
40%
Domain A
(Respiratory)
70%
Domain C
(X-ray, CT tests)
60%
Domain D
(further inspection:
respiratory disease)
40%
30%
20% need further COVID test
Discharge or
transfer to
another
department
Suspected COVID patients
32%
Domain B
(Gastroenterology)
48%
Domain E
(further inspection:
digestive disease)

Figure 5.tif Figure

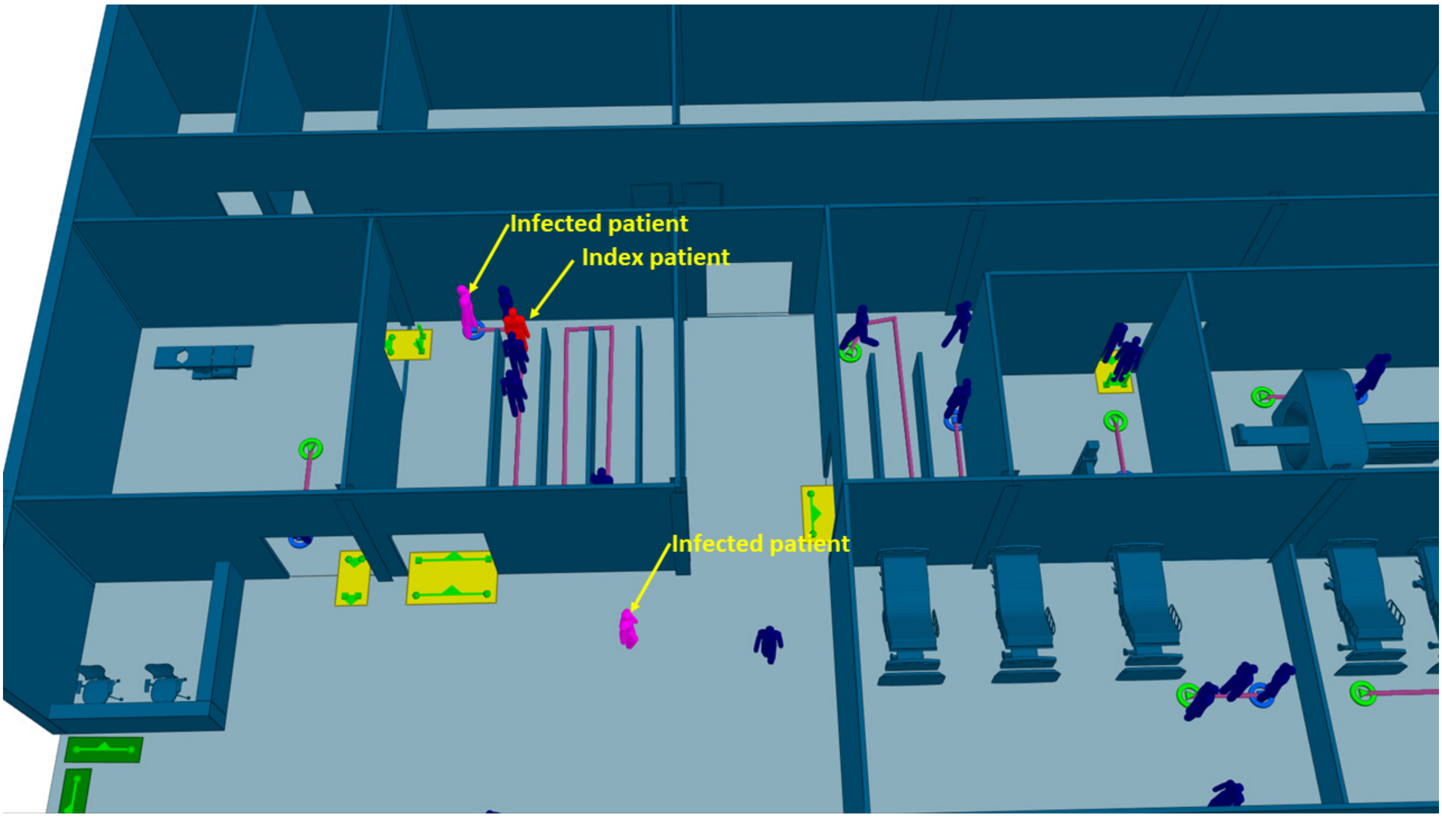
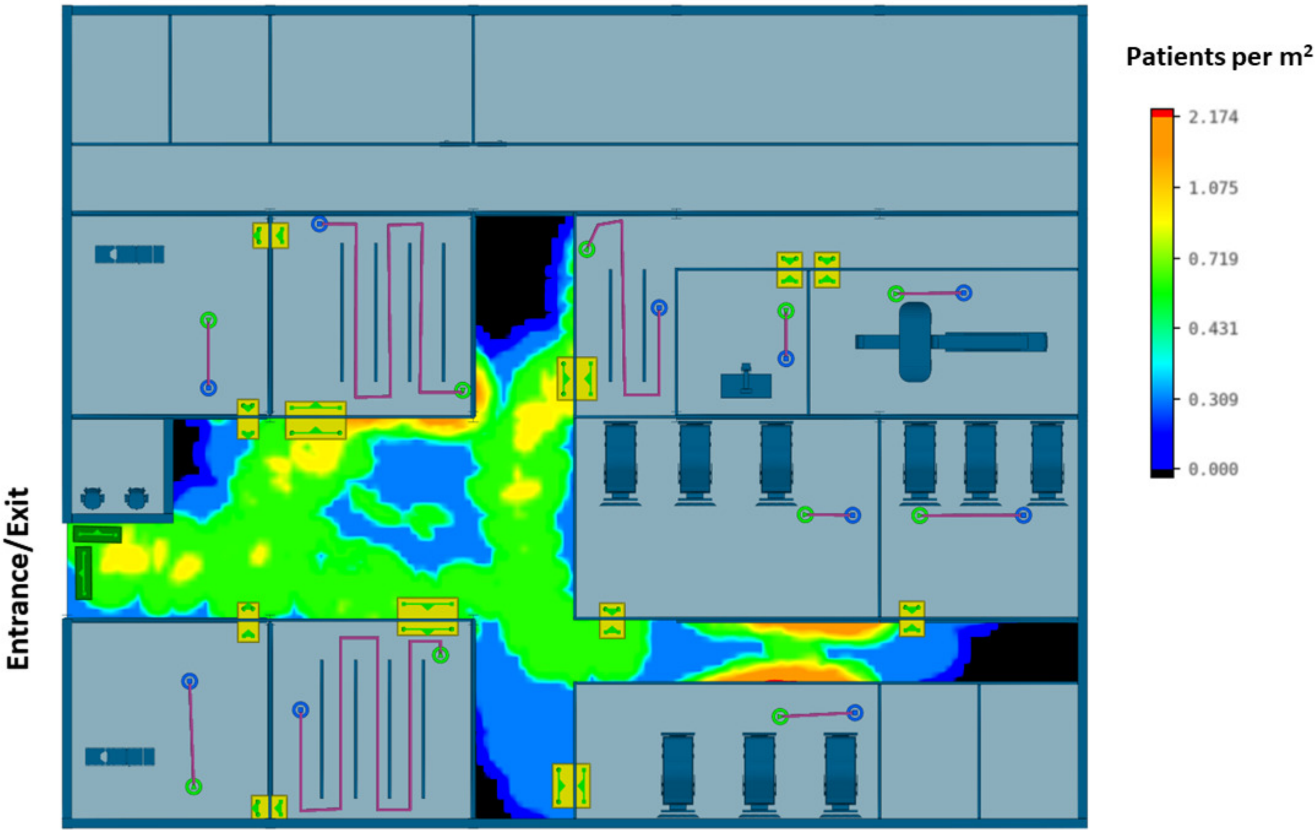
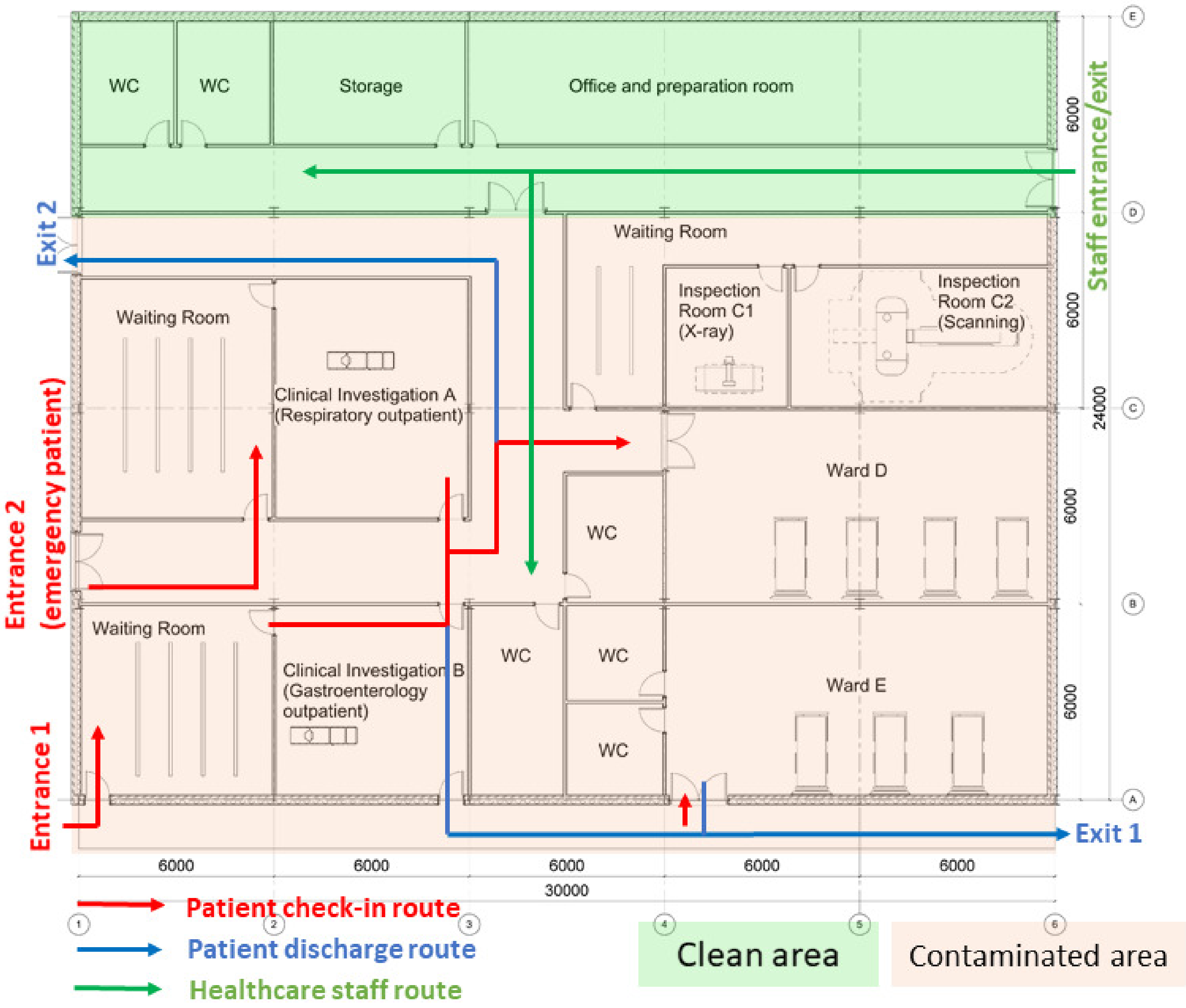
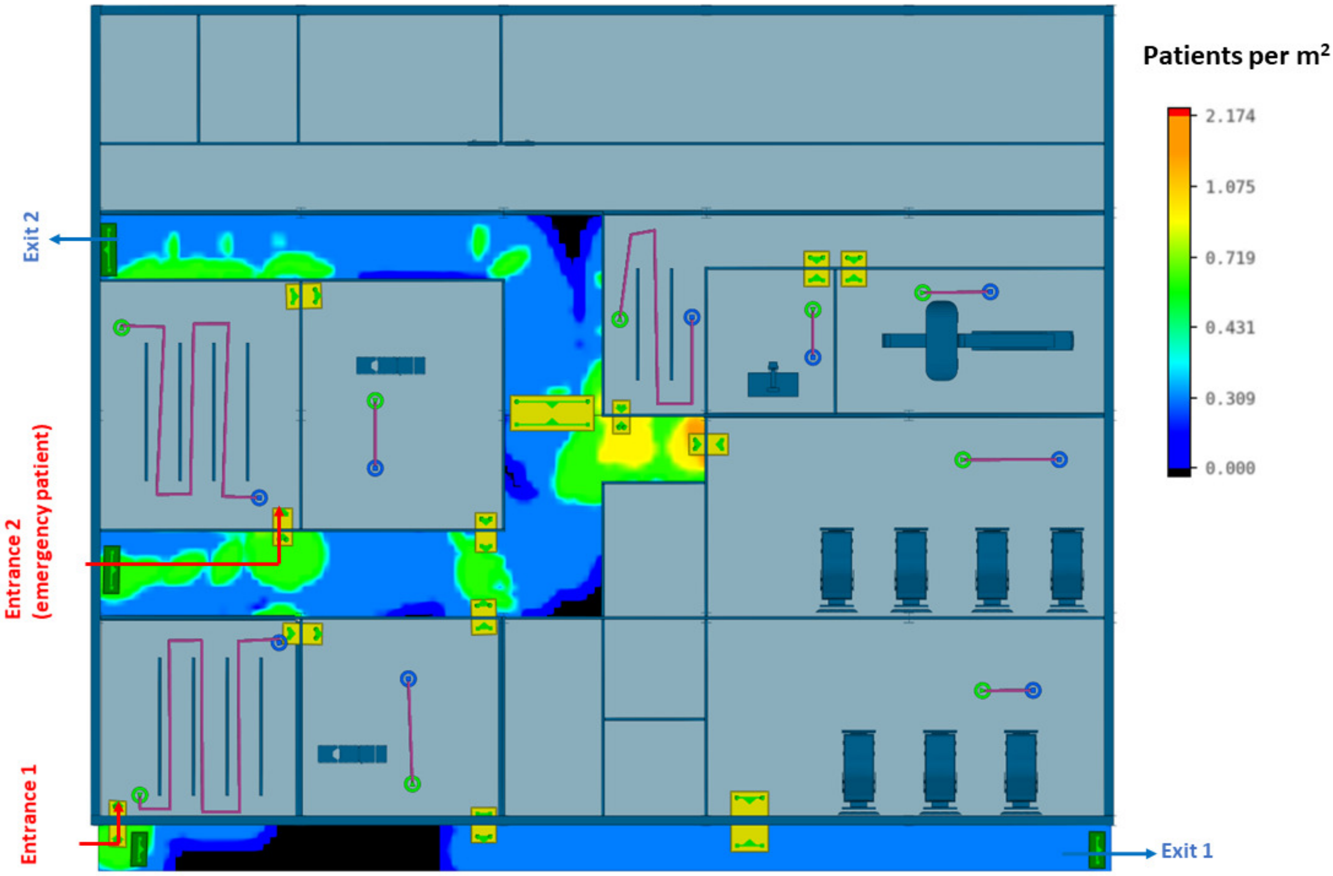


Figure 6a.tif $Figure$


Entrance/Exit
Patients per m²
2.174
1.075
0.719
0.431
0.309
0.000


WC
WC
Storage
Office and preparation room
Staff entrance/exit
Exit 2
Waiting Room
Inspection Room C1 (X-ray)
Inspection Room C2 (Scanning)
Waiting Room
Clinical Investigation A (Respiratory outpatient)
Ward D
WC
Entrance 2 (emergency patient)
Waiting Room
Clinical Investigation B (Gastroenterology outpatient)
WC
WC
WC
Ward E
Entrance 1
Exit 1
6000
6000
6000
6000
6000
30000
24000
Patient check-in route
Patient discharge route
Healthcare staff route
Clean area
Contaminated area


Patients per m²
2.174
1.075
0.719
0.431
0.309
0.000
Exit 2
Entrance 2
(emergency patient)
Entrance 1
Exit 1