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Rapid construction delivery of COVID-19 special hospital: Case study on Wuhan Huoshenshan hospital

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Abstract. Infectious disease emergency hospitals are usually temporarily built during the pneumonia epidemic with higher requirements regarding diagnosis and treatment efficiency, hygiene and safety, and infection control. This study aims to identify how the Building Information Modeling (BIM) + Industrialized Building System (IBS) approach could rapidly deliver an infectious disease hospital and develop site epidemic spreading algorithms. Coronavirus-19 pneumonia construction site spreading algorithm model mind map and block diagram of the construction site epidemic spreading algorithm model were developed. BIM+IBS approach could maximize the repetition of reinforced components and reduce the number of particular components. Huoshenshan Hospital adopted IBS and BIM in the construction, which reduced the workload of on-site operations and avoided later rectification. BIM+IBS integrated information on building materials, building planning, building participants, and construction machinery, and realized construction visualization control and parametric design. The delivery of Huoshenshan Hospital was during the most critical period of the Coronavirus-19 pneumonia epidemic. The development of a construction site epidemic spreading algorithm provided theoretical and numerical support for prevention. The agent-based analysis on hospital evacuation observed "arched" congestion formed at the evacuation exit, indicating behavioral blindness caused by fear in emergencies.

Keywords: BIM+IBS; COVID-19 special hospital; epidemic spreading algorithms; huoshenshan hospital; rapid construction delivery

1. Introduction

Hospital construction projects are highly specialized in publicity, public welfare, professionalism, systematicness, complexity, group dynamics, and non-replicability. The application of Building Information Modeling (BIM) in hospital construction projects has received particular attention (Talento *et al*. 2019). There are more than 40 kinds of pipelines in large hospitals, and the traditional design, construction, operation, and maintenance management model could hardly adapt to the current hospital construction (Mousavi *et al*. 2020). For example,

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Careggi Hospital in Italy combined BIM and Geographic Information System (GIS) to optimize building energy efficiency design; Al Ain Hospital in Arabia applied BIM throughout the construction process; Shanghai Chest Hospital successfully optimized the building function through BIM application in the design and construction stage, improved the quality of design results, and solved a series of problems in the construction process; The Fourth Affiliated Hospital of Zhejiang University School of Medicine applied BIM in the later stage of construction and established a hospital building operation and maintenance management system; Ruijin Affiliated Hospital of Shanghai Jiaotong University School of Medicine used BIM simulation to smooth the key components of the project (Choi *et al*. 2020, Merschbrock and Munkvold 2015, Davies and Harty, 2013, Lin *et al*. 2018). In early 2020, since the outbreak of Coronavirus-19 pneumonia, the number of confirmed cases in Wuhan increased dramatically every day. The number of beds in more and more designated hospitals was far behind the spread of the epidemic. The Coronavirus-19 pneumonia epidemic has inspired BIM application in the medical field (Segars *et al*. 2020). To some extent, the Coronavirus-19 pneumonia epidemic exposed the need to accommodate enough patients in an emergency, which could cause an unavoidable delay and a significant infection in the epidemic (Mazinani 2020). BIM could assist in establishing a good space and resource management system in analyzing and managing the functional flexibility and expansion feasibility of various spaces and form the rapid adjustment and flexible expansion capabilities of the hospital functional unit system (Choi *et al*. 2020).

Compared with general hospitals or other types of specialized hospitals, infectious disease hospitals such as the emergency hospitals are typically temporarily built during the pneumonia epidemic with higher requirements in terms of diagnosis and treatment efficiency, hygiene and safety, and infection control (Isikdag 2012). Reasonable medical process design can effectively avoid crossing routes inside the hospital, thereby effectively avoiding the gathering and congestion of doctors and patients. Especially considering the high incidence of epidemics such as Coronavirus-19 pneumonia, if suspected patients, confirmed patients, and medical staff is high-density cross-mixing, the possibility of nosocomial cross-infection will significantly increase. Therefore, it is necessary to carry out the refined design of infectious disease hospitals, such as the first-level process of the hospital, the second-level process of each medical unit, and the third-level process of the function rooms (Merschbrock and Munkvold 2015). Under such a refined design, the characteristics of BIM, such as integration, digitization, and visualization, could play a beneficial role in simulating and optimizing the medical efficiency of infectious disease hospitals (Choi *et al*. 2020). The prefabricated construction mode or Industrialized Building System (IBS) has been widely used and vigorously promoted, which has not only changed the construction method but also has made corresponding changes in processing, procurement, design, installation, and transportation as challenges for the construction of a relatively complex infectious disease hospital (Zhou *et al*. 2020). Emergency hospitals such as the Wuhan Huoshenshan hospital were given a brief construction period, thus, the prefabricated module design and optimization, the integrated design of emergency hospitals, and the 4D simulation of on-site installation needed assistance from BIM (Ferdous *et al*. 2019). The vitality of the Coronavirus-19 pneumonia is strong, and various media such as water, aerosols, and air are its infectious agents, thus, it is necessary to study the infection path in the hospital systematically. However, in an actual analysis process, the infection path is complex, invisible, and nonlinear, as an enormous challenge for infection control. BIM can assist hospital engineering projects to carry out visual simulation of aerodynamics, topological structure analysis on water supply and drainage flow, central air-conditioning flow, the rules of airflow in various regions and spaces, and aerodynamics parameterization and visualization (Segars *et al*. 2020). Though some experiences could be learned from the construction of Beijing Xiaotangshan Hospital during the SARS epidemic in 2003, that hospital's diagnosis and treatment capacity were insufficient for the Coronavirus-19 pneumonia epidemic evaluated by the digital integration feature of BIM (Zhou *et al*. 2020). The newly built Huoshenshan Hospital focused on treating patients with the epidemic to ease the pressure on other hospitals and reduce cross-infection. The construction of Huoshenshan Hospital was a challenge with many questions: Can a rapidly built hospital be put into operation efficiently? Will it cause cross-infection and environmental impact? How do BIM and IBS help? This study aims to use a case study to identify how the BIM+IBS approach could rapidly deliver an infectious disease hospital and develop site epidemic spreading algorithms for emergency hospital construction.

2. Latest development on emergency hospital construction aided by BIM

BIM was introduced into the design process of hospital construction projects to promote the informatization and modernization of hospital buildings (Merschbrock and Munkvold, 2015). The scope of BIM application has gradually evolved from being only used in the design stage to the entire life cycle (Shirowzhan *et al*. 2020). BIM contributes to the sustainable development of medical buildings, contributes to space design during the delivery period, and improves energy management and equipment update management in the operation phase (Li *et al*. 2009). In the modern environment with multiple risks, the medical and health field is vulnerable to various threats. Healthcare projects are defined as projects for designing and building healthcare facilities where healthcare is provided (Kahn 2009). In general, they are highly complex compared to other types of building projects due to technological sophistication, regulatory requirements, and many users and workers, including patients with identifiable vulnerabilities (Enache-Pommer *et al*. 2010). Healthcare projects, thus, have adopted various strategies that add value to their facility delivery (Kahn 2009). Among them, benchmarking has been perceived as an effective technique to improve project outcomes, which allows for identifying performance gaps with other peers and thus promoting changes during the life cycle of projects (Choi *et al*. 2018). These days, performance assessment and benchmarking are considered critical components of the successful delivery of healthcare projects (Choi *et al*. 2016).

In order to control the repeated spread of the epidemic, the rapid construction of emergency hospitals is needed. The process of building a hospital is inherently full of complexity, especially emergency hospitals have higher requirements for construction technology, requiring that the quality and efficiency of the hospital to avoid cross-infection among confirmed patients, suspected patients, and medical staff (Suzuki *et al*. 2020), which is expected to be solved by BIM simulation. BIM could simulate the entire life cycle of emergency hospital construction and the spreading and infection path of the epidemic and store in building information data (Ambat and Vyas 2020). In the meantime, the utilization of Building Information Modeling (BIM) is a prevailing trend in the healthcare sector. BIM has transformed the process by at buildings are designed and delivered in diverse ways, particularly when it comes to constructing highly complex buildings such as healthcare facilities (Manning and Messne 2008). The data-richness nature of BIM allows for producing, storing, and processing building information. With this functionality of BIM, researchers began to discuss an opportunity to leverage BIM data for performance assessment and benchmarking by investigating its feasibility and functional requirements for realizing such a tool (Choi *et al*. 2018). The study outcomes reported that BIM standards and technologies could be leveraged to streamline the benchmarking practice due to the large amount of project information required to implement the benchmarking program stored in BIM models (Choi *et al*. 2016). While BIM-based benchmarking was identified as an alternative approach to streamline the current benchmarking process, previous studies lack a robust and consistent approach to obtaining valuable and reliable benchmarking data from heterogeneous models. Instead, they were focused on exploring the potential of leveraging the models for benchmarking through the analysis of contents embedded in models and deducing the measurability of benchmarking metrics (Merschbrock and Munkvold 2015). In the comprehensive building project of the Maternal and Child Branch of Jiangsu Provincial People's Hospital, the hospital's engineering infrastructure department found a certain degree of visual expression through BIM was essential to a high degree of participation from decision-makers, medical staff, and other supporting staff during the project planning and design stage (Choi *et al*. 2020). During an epidemic, many patients and medical staff would gather in an emerging infectious disease hospital. If an accidental fire occurs in the hospital, its destructiveness is unimaginable (Paul, 1987). Therefore, before the hospital is formally put into operation, it is necessary to simulate the fire evacuation and optimize the hospital safety evacuation plan (Alizadeh 2011).

3. Research methods and procedures

In this case study, the entire construction process of Huoshenshan Hospital was virtually constructed through BIM, and corresponding isolation and fire evacuation were analyzed to ensure the construction of the Huoshenshan Hospital project was completed in time and put into use efficiently. In addition, epidemic spreading algorithms for emergency hospital construction sites were developed. The construction of Wuhan Huoshenshan Hospital was used to conduct an empirical study using the Pathfinder finite element meshing method to mesh the existing Revit model, adding a crowd grid model to numerically calibrate the kinematic characteristics of the crowd, using its built-in solver to solve the motion route. The interfaces used mainly included Revit 2017, Navisworks 2017, Revit Zuku Master, Modeling master, and MS-Excel. The BIM modeling was divided into three phases: architectural modeling, structural modeling, and Navisworks4D construction scheduling. The architectural modeling included: Step 1: Create a new building template, Step 2: Set elevation and generate elevation in the plan, Step 3: Draw the grid, Step 4: Draw the wall, Step 5: Draw doors and windows, Step 6: Draw the stairs, Step 7: Draw the floor slab, Step 8: Draw the railing, Step 9: Medical facilities and conventional model layout, and Step 10: Draw the venue and scenery. The structural modeling included: Step 1: Create a construction template, Step 2: Create an elevation grid, Step 3: Draw foundation with wall and strip foundation functions, and Step 4: Draw columns, plates, and beams. Navisworks4D construction scheduling included: Step 1: Import Revit, Step 2: Create a collection, Step 3: Time-liner, and Step 4: Export animation. Navisworks was employed to make a virtual roaming animation to display the exterior and interior of the hospital fully.

One key factor for the highly efficient delivery of the Huoshenshan Hospital was the simplicity of the structural design. For sections with repeated functions, the design of Huoshenshan Hospital adopted an asymmetrical arrangement and a matrix arrangement, which saved time in designing and delivery. This hospital was assembled with a box-type modular to save concrete curing time. From January 23rd, 2020, when the Huoshenshan Hospital was confirmed to be delivered, the increasing number of beds in designated hospitals was far from keeping up with the spread of the epidemic. Huoshenshan Hospital was expected to ease the pressure on other hospitals greatly and to reduce cross-infection. It took less than 12 hours from accepting the task to the beginning of construction. Operations were parallel or inverted. The hospital focused only on treating patients with Coronavirus-19 pneumonia. The hospital had a total construction area of 33,900 square

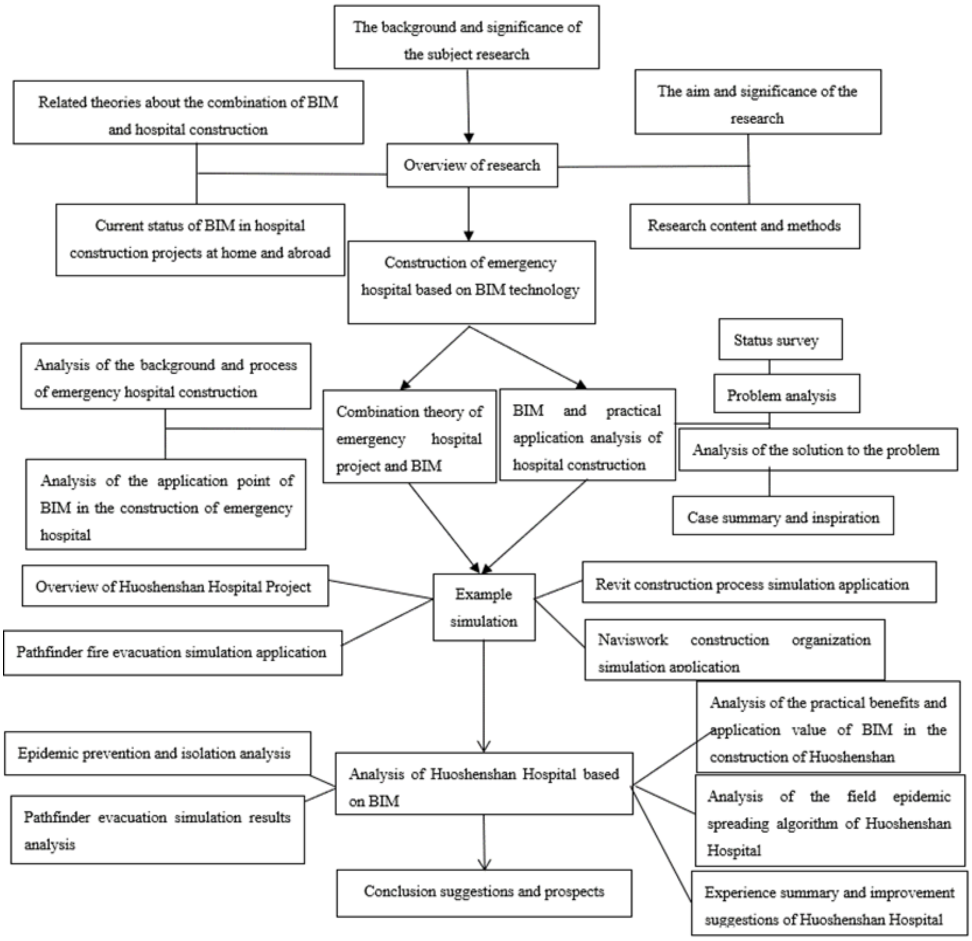

Fig. 1 A research framework

meters with 1,000 beds. As of the evening of January 24, 2020, Wuhan Huoshenshan Hospital flattened all the grounds at 50,000 square meters, equivalent to the size of 7 football fields, and transferred 150,000 cubic meters of earth to fill 57 swimming pools. One goal of the hospital was to have the highest cure rate, the lowest mortality rate, zero infections among medical staff, and zero complaints from patients admitted. The Huoshenshan Hospital project relied on BIM to quantify and simulate the full-specialized construction process and to coordinate the decomposition of various professional tasks to ensure that the participating units were perfectly integrated into the construction rhythm. The project utilized the advantages of EPC management, the overall sanitary ware, and the same-layer drainage method. The project rationally planned the hoisting equipment operation zone, arranged the hoisting sequence, and maximized the efficiency of prefabricated construction. The research framework is presented in Fig. 1.

3.1 Evacuation analysis

The emergency hospital accommodated not only a large number of patients who were in urgent need of treatment but also a large number of medical staff, thus, it was necessary to set up a safe

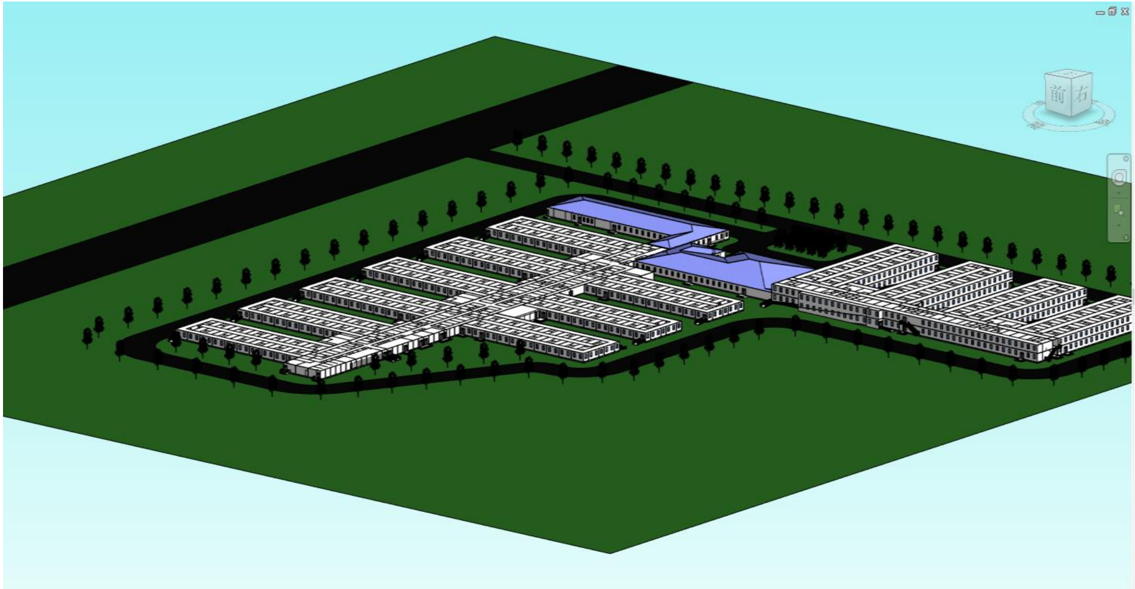

Fig. 2 Model simplified rendering

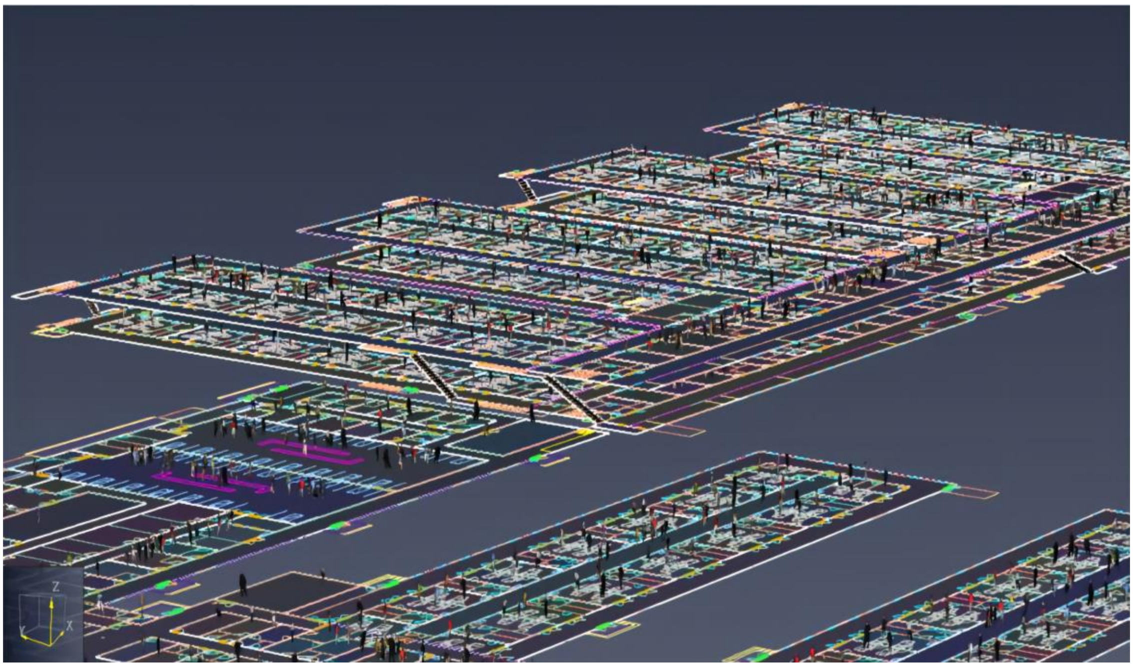

Fig. 3 Agent-based simulation using BIM model built in Revit

evacuation plan for a newly-built emergency hospital. An agent-based approach was used to analyze the evacuation of Huoshenshan Hospital in emergencies. It provided a specific relevant theoretical basis for the safe evacuation of emerging infectious disease hospitals. The BIM model was built in the Revit interface as in Fig. 2. The Dxf format model was loaded into Pathfinder to

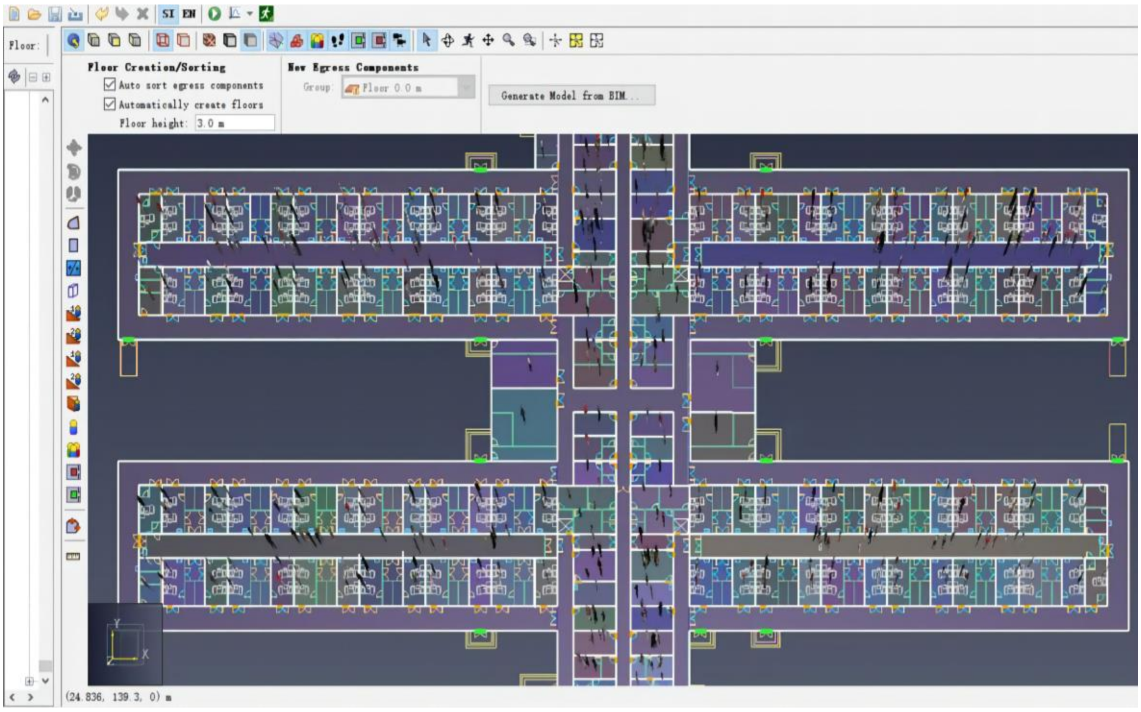

Fig. 4 Top view of agent-based simulation using BIM model

determine the evacuation plan for people in the building in an emergency. The evacuation plan also considered how the safety evacuation instructions inside the building could guide people to evacuate reasonably and efficiently. Evacuees were distributed according to the evacuation areas, and evacuation routes were set according to the locations of exits with different peaks of migrants. The BIM model used for the agent-based simulation is shown in Fig. 3, and its top view is in Fig. 4.

The parameters of human height, body shape, walking speed, evacuation speed, and human response speed and response behavior in emergencies were collected from the latest accurate statistic data in another hospital. The parameters were continuously adjusted until the parameters finally reached reliable standards, and then relatively accurate evacuation simulation exercises were carried out to obtain a higher reference value. There were two evacuation modes in the agent-based simulation, including SFPE personnel sport mode and Steering personnel sport mode. The SFPE model led all personnel to the nearest exit, assuming no collision behavior among people. On the other hand, in the Steering mode, the evacuation route was guided artificially, and the entire evacuation process was combined with the collision behavior among people. The total number of people in the Huoshenshan Hospital was about 2,200, and the hospital density was about 0.16 people/m^2. Because the collision behavior among people could be ignored in a hospital for infectious diseases, the SFPE mode was used. The animation displayed the evacuation trajectory of people at different time points, the number of people safely evacuated, exits causing crowding and exits evacuated well. This intuitive animation allows designers to optimize the design more targeted. Fig. 5 presents the dynamic flow of people in rooms 159 and 175. Fig. 6 shows the simulation results of all rooms.

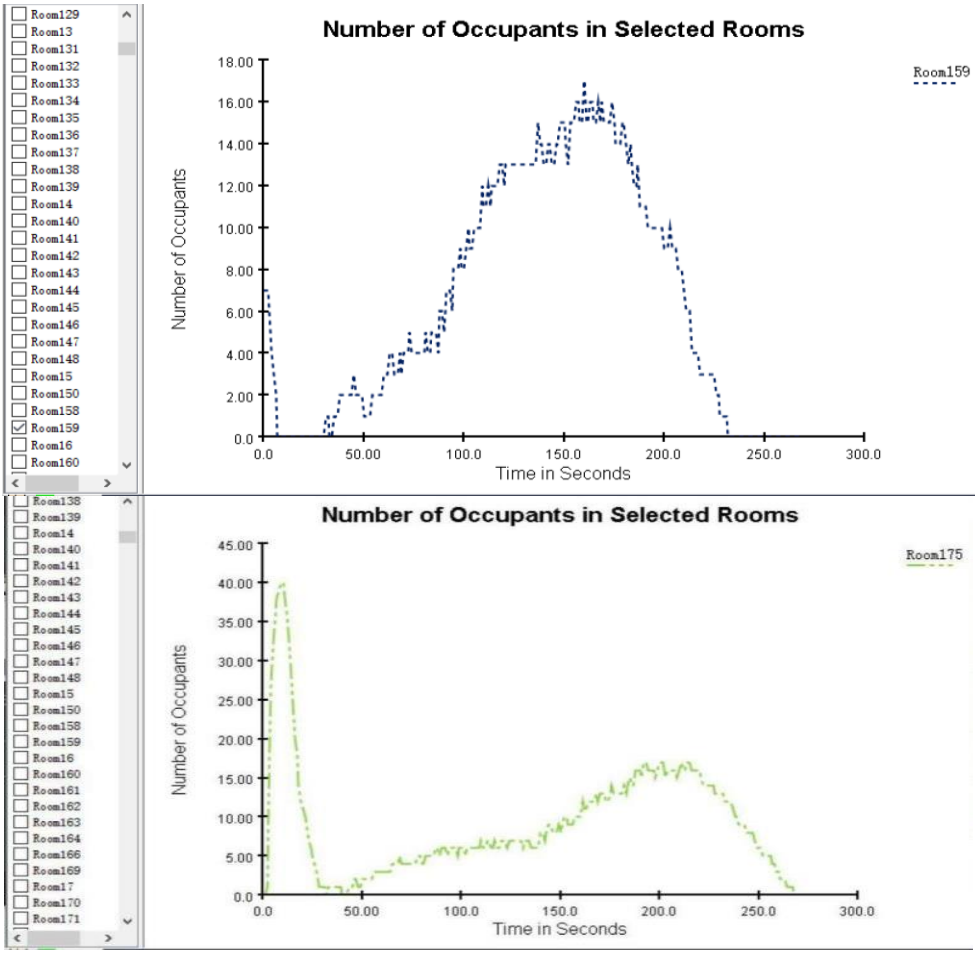

Fig. 5 Dynamic flow of people in Rooms 159 and 175

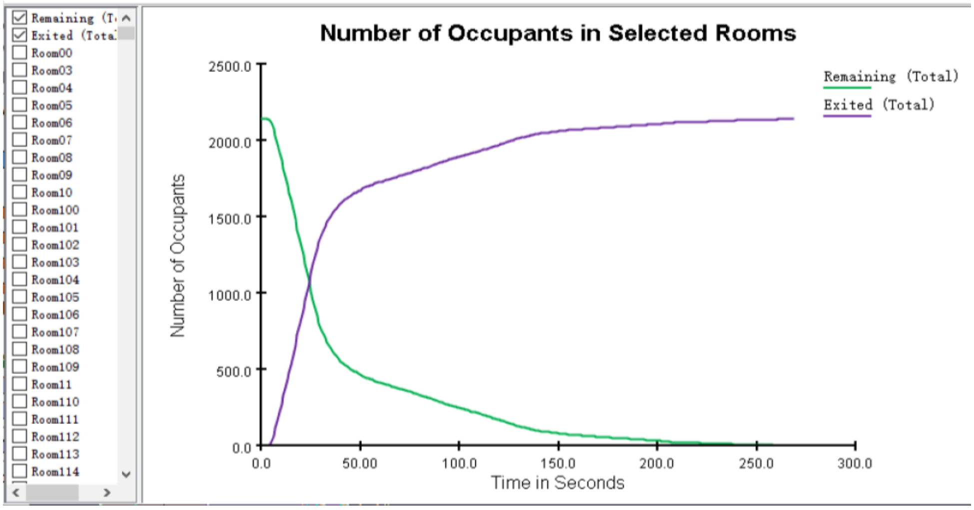

Fig. 6 Simulation results of all rooms

The safe evacuation mainly depended on two types of critical times, namely: RSET and ASET. RSET referred to the necessary time for a safe evacuation, and ASET referred to the available time for a safe evacuation. The premise of safe evacuation was RSET<AEST. The fire detection alarm time T_1 was the response time after fire identification to the start of evacuation as in Eq. (1).

$$T1 = \frac{RTI}{\sqrt{\mu \max}} ln(\frac{T\,max - T0}{T\,max - T}) \tag{1}$$

where $\mu\,max = 0.197Q^{1/3}H^{1/2}r^{5/6}(r > 0.15H), \mu\,max = 0.946(Q/H)^{1/3}(r \leq 0.15H)$. Q is the heat release rate of the flame, r is the height of the fire detector from the roof, T is the induced temperature of the fire detector, RTI is the characteristic response index of the fire detector. The personnel reaction time T_2 was the decision time for personnel to perform psychological activities when they decided to evacuate to a safe area as in Eq. (2).

$$T2 = 120 + \sqrt{A0} + 0.4H \tag{2}$$

where A_0 is the floor area, and H is the floor height. The personnel Evacuation movement time T_3 was the evacuation movement time consumed from the evacuation to the safe area as in Eq. (3).

$$T3 = 0.68 + 0.081P^{0.73} \tag{3}$$

where T_3 is the time required for evacuation, P is the number of people taking the stairs per unit of effective width. The available safe evacuation time T_H is the time from the disaster started to the time disaster developed to threaten the personal safety of personnel as in Eq. (4).

$$TH = T1 + T2 + T3 \tag{4}$$

The required safe evacuation time T_E was the evacuation time required from the start of the disaster to the evacuation of personnel to a safe area. In order to ensure the safe evacuation of personnel, the remaining time $T_H \geq T_E$ was required. Because the length of the evacuation movement time T_3 directly affected whether the evacuees could be safely evacuated, the safety factor α was used to correct the available safe evacuation time T_H as in Eq. (5):

$$TH = T1 + T2 + \alpha T3 \tag{5}$$

where α is the safety factor, and α≥1.0. After considering the safety factor, if the available safe evacuation time T_H was greater than the required safe evacuation time RSET, it was considered that the building met the requirements of safe evacuation.

3.2 Building organizational structure of the BIM-based cooperation model

The construction unit was the general organizer, general coordinator, and general successor of the Huoshenshan hospital construction project. The builder set the BIM requirements, integrated resources from all parties, and coordinated BIM applications, including pre-decision management, implementation project management, and operation facility management. Fig. 7 presents the organizational structure of the BIM-based cooperation modelled by the builder by breaking out the identity differences of each unit and establishing a de-identified professional team from the technical level. The BIM model of this project was optimized by the BIM integration team, which significantly promoted the transformation of the traditional construction thinking mode of the participating units.

Fig. 8 presents the hierarchical analysis of BIM application driving and hindering factors in the

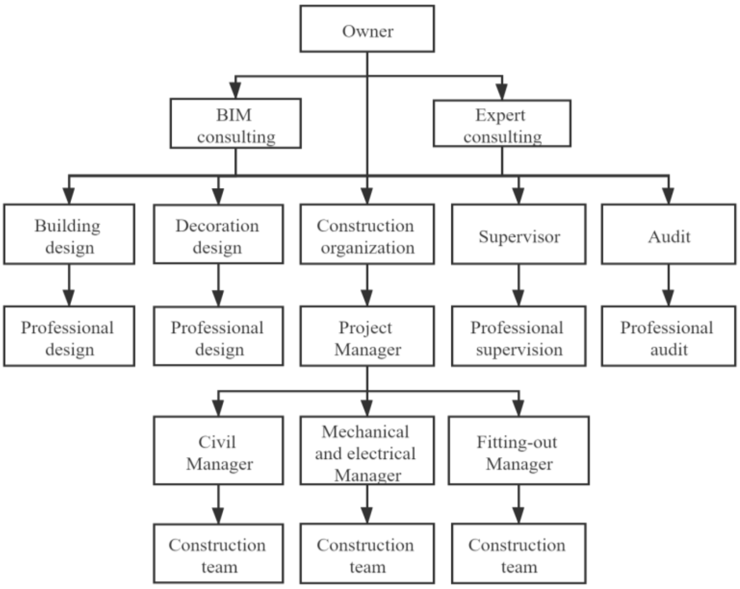

Fig. 7 Organizational structure of the BIM-based cooperation mode led by the builder

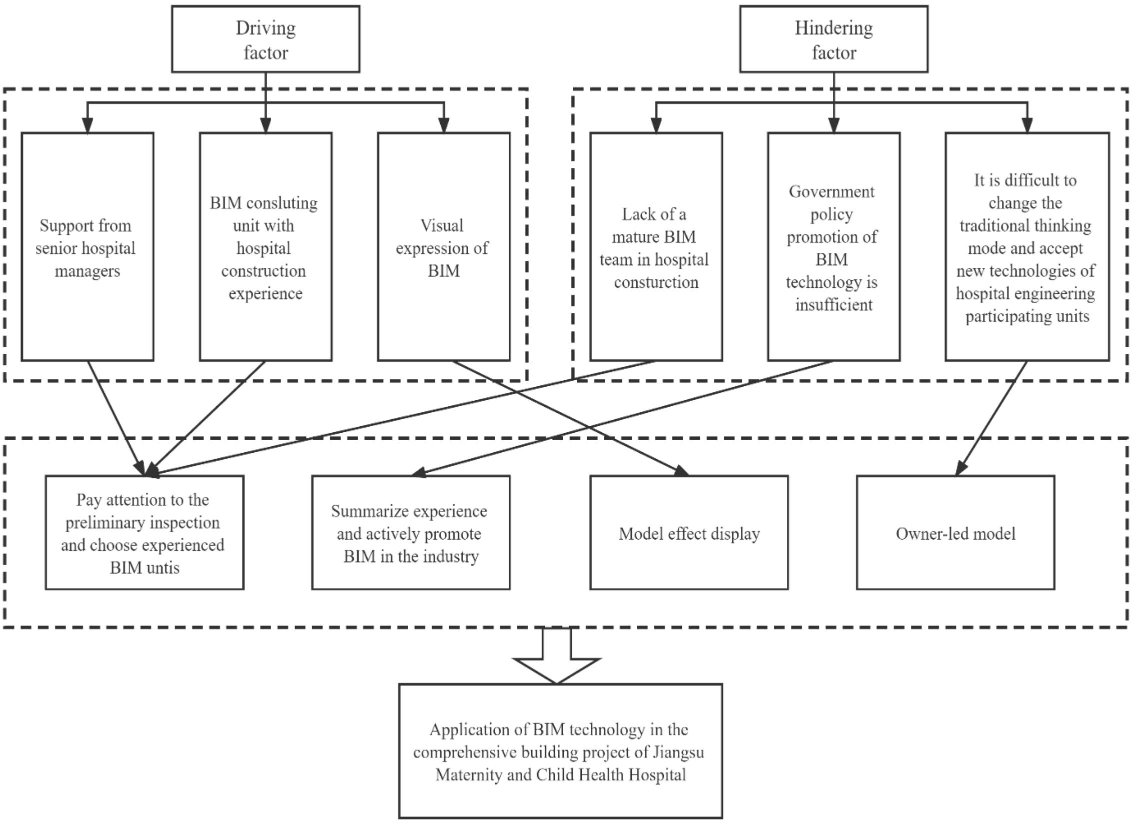

Fig. 8 Hierarchical analysis on driving and hindering factors of BIM application in the inpatient complex project

inpatient complex project. Hospital builders strengthened their understanding of BIM consulting units before the project started. During the project implementation, hospital builders conducted organizational learning among other related hospitals. They jointly carried out the planning, implementation, organization, and coordination of the BIM application in this hospital construction project.

4. Case study analysis on huoshenshan hospital based on BIM simulation

4.1 Analysis on epidemic prevention and isolation

Considering that the prevailing wind direction in Wuhan was from the northeast, Huoshenshan Hospital was located in the city's leeward belt with southwest-facing water, thereby minimizing the possibility of pollution to the city. When the task was urgent, some countries might choose to requisition a gymnasium as a temporary hospital directly, yet this was not the case in Wuhan this time. In this Coronavirus-19 pneumonia epidemic, the main flow of people in the corresponding disease diagnosis and treatment hospitals was divided into three types: confirmed patients, medical staff, and suspected patients. The hospital was to protect the suspected patients and medical staff from infection on the corresponding diagnosis and treatment of confirmed patients. A gymnasium could indeed achieve the external isolation of the entire hospital. Nevertheless, actual internal isolation was utterly impossible in a pneumonia epidemic such as Coronavirus-19, because if the confirmed patients, medical staff, and suspected patients were all in a spacious internal space at the same time, it would significantly increase the probability of infection and the number of cured patients would be far behind the increase in the number of infections. The failure of the doctor-patient separation without the buffer zone could also significantly increase the chance of infection. Therefore, the most feasible way was to requisition a hotel-style hospital where the rooms were separated from each other. A critical analysis of the layout plan design of Huoshenshan Hospital was conducted. As shown in Fig. 9, from the zoning map of Huoshenshan Hospital, the blue rooms were the medical and technical departments of the hospital. The red area was the intensive care ICU. The green area was general wards. The grey part in the middle was the corridor and the medical wards, which separated each ward area and separated the patient activity areas from the medical staff activity areas. The fishbone arrangement or H-shaped treatment area played a crucial role in isolation and epidemic prevention. A nursing unit in the hospital contained fifty beds, and an H-shaped treatment area was composed of four nursing units with a total of 200 beds. The hospital was equipped with a specific number of medical equipment, facilities, and medical staff to serve the corresponding 200 patients in an H-type treatment area connected with common areas for laboratory tests and inspections between each treatment area. The distance between rooms was 15 meters, as in Fig. 10.

Huoshenshan Hospital set up corresponding transitional and semi-contaminated zone in the clean and contaminated areas. The ward set up in Huoshenshan Hospital was a negative pressure ward. The air pressure in the clean area was the highest, followed by the semi-contaminated area, and the lowest was the contaminated area. Based on this principle, the airflow direction was from the clean area to the semi-polluted area and the polluted area. Such a negative pressure device was placed in a negative pressure ward. As a result, the air pressure outside the ward was higher than the air pressure inside the ward, and the airflow was more conducive to epidemic prevention and isolation. In addition, the contaminated air in the ward did not leak but was collected by the

Fig. 9 Partial plan of Ward 1

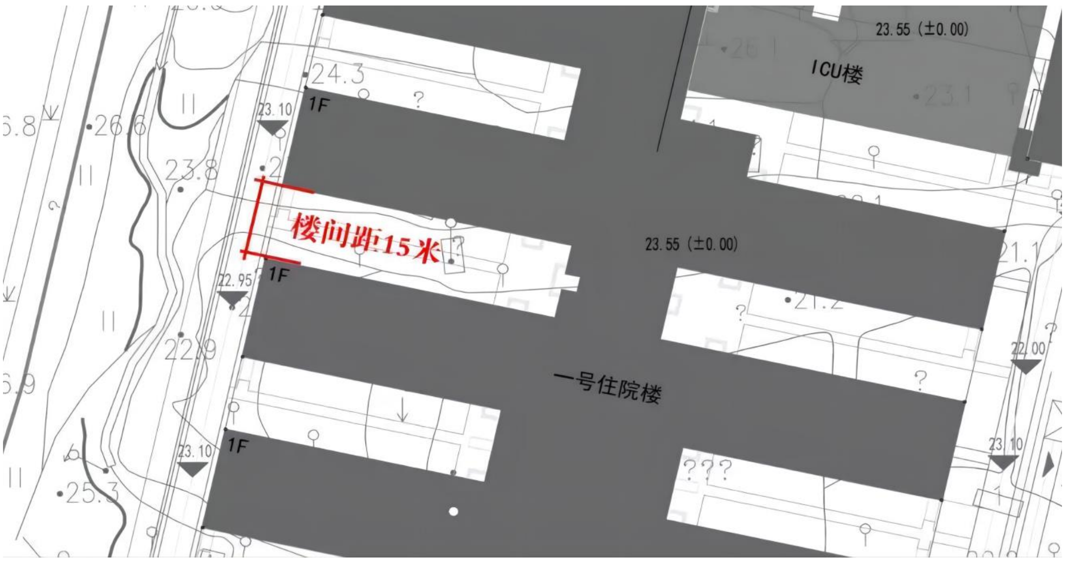

Fig. 10 Schematic diagram of design key points of Ward 1

corresponding negative pressure device for centralized processing. Compared with the wards of ordinary infectious disease hospitals, Huoshenshan Hospital was equipped with air disinfection machines in each ward and provided more fresh air in its wards. The clean medical passage was located in the middle of the entire building, and the medical passage was located at the horizontal passage on both sides of the building. The red arrows instructed the flow direction of medical staff, and the purple arrows instructed the flow direction of the patient, and the two types of flow lines

Fig. 11 Schematic diagram of simulated crowded places

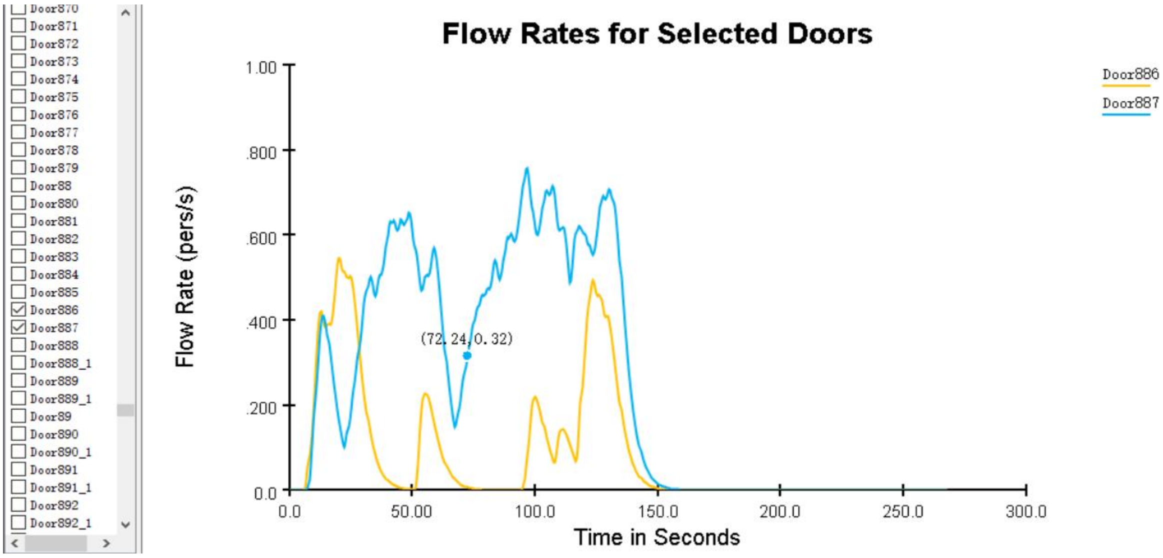

Fig. 12 Schematic diagram of the Congestion gate flow of Door 886 and 887

did never cross. The office and living areas of the medical staff were arranged in a clean area. If medical staff needed to enter the contaminated area with patients, they needed first to go through the changing room and sanitary through the last second dressing, then enter the buffer zone, the corridor of the semi-contaminated area, and finally the contaminated area. Similarly, if medical staff needed to return to the clean area, the same process was required. The patients in the contaminated area were never allowed to enter the clean area.

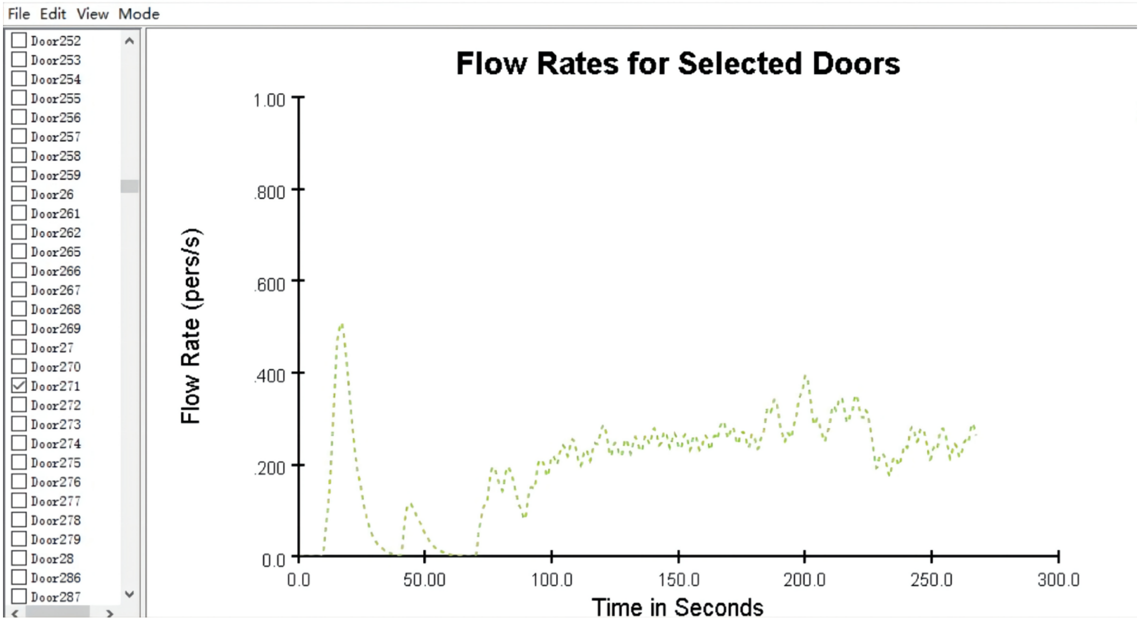

Fig. 13 Schematic diagram of the Congestion door flow of Door 271

4.2 Evacuation analysis

The agent-based analysis on evacuation in Huoshenshan Hospital observed "arched" congestion formed at the evacuation exit as in Fig. 11, indicating behavioral blindness caused by fear in emergencies, which led to faster actual reaction and movement speed.

This type of evacuation exit caused a rapid increase in the number of people in the room and multiple fluctuations indoor flow. As shown in Fig. 12, the two doors on the west side of the Ward 2 building reached an extreme value of human flow in 75 seconds. Then the human flow again raised to another peak due to the congestion, repeatedly fluctuating until about 155 seconds when all the personnel in the fire zone were evacuated.

The evacuation time of most rooms and doors was concentrated between 100-200 seconds, and most fireproof areas were evacuated in about 150 seconds. The door in the middle of the south side of the intensive care ICU building shown in Fig. 13 was more congested due to the human flow. The congestion began at about 74s and completed at 268s. The total duration of the congestion was 194s. More than 3/5 of the evacuation time was spent on the evacuation of people in this fire compartment. As time increased, the evacuation speed of this exit first increased, then decreased, and then increases again. The main reason for the decrease in evacuation speed was the congestion caused by the gathering of people.

Fig. 14 shows the overall evacuation situation of Huoshenshan Hospital, where at 268s, the number of personnel inside the Huoshenshan Hospital building was 0, which means that the safe evacuation time for all personnel in the entire fire evacuation area of Huoshenshan Hospital was 268s.

The fire detection alarm time was T_1=60s. Since the storey heights of various areas in the hospital were different, the storey height of the hospital was 3m except for Building 2, and the storey height of Building 2 was 6m. Building 2 was a fire compartment, and the rest of the hospital was another fire compartment. The results of the available evacuation time of the two districts

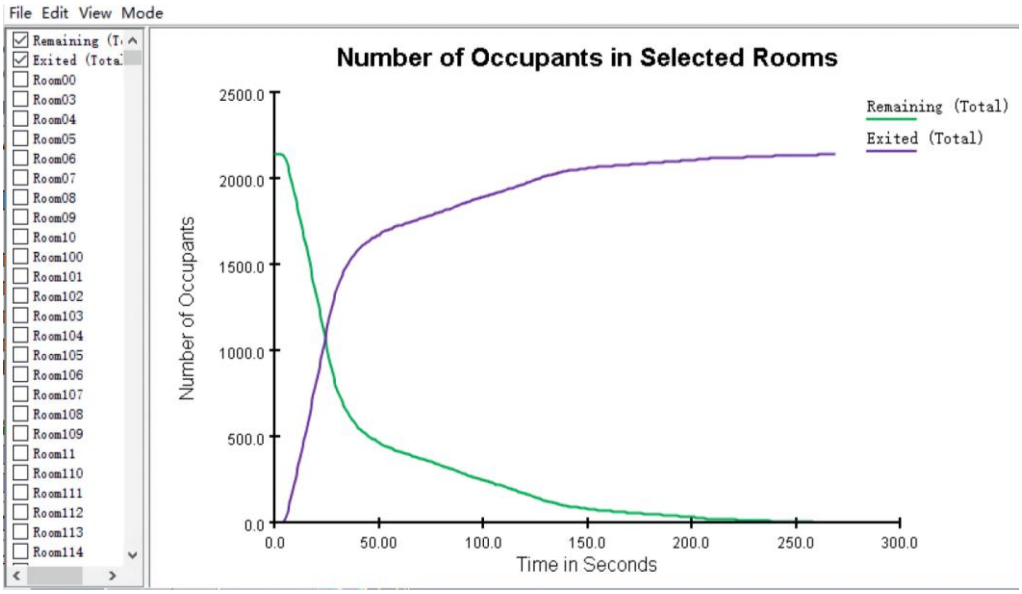

Fig. 14 Complete simulation process flow diagram

were compared, and the lower value was compared with the overall required safe evacuation time of Huoshenshan Hospital to verify whether it met the safety standards. The floor area of Building 2 was 7500, and the response time of personnel was calculated in Eq. (6):

$$T2 = 120 + \sqrt{A0} + 0.4H = 120 + \sqrt{7500} + 0.4 \times 6 = 209s \tag{6}$$

The evacuation movement time T_3 considered the safety factor α=1.2, and the final available evacuation time was calculated in Eq. (7).

$$TH = T1 + T2 + \alpha T3 = 60 + 209 + 1.2T3 = 269 + 1.2T3 \tag{7}$$

The evacuation time T_3 of each floor was 25.8 s on the first floor and 58s on the second floor. Therefore, the available safe evacuation time was calculated in Eqs. (8) and (9). Because 299.96s < 338.6s, a smaller value at 299.96s was taken as the safe evacuation time for Building 2.

$$\text{First floor } TH = 269 + 1.2 \times 25.8 = 299.96s \tag{8}$$

$$\text{Second floor } TH = 269 + 1.2 \times 58 = 338.6s \tag{9}$$

The floor area of other fireproof areas in the hospital was 18900, and the response time of personnel was calculated in Eq. (10).

$$T2 = 120 + \sqrt{A0} + 0.4H = 120 + \sqrt{18900} + 0.4 \times 3 = 258.68s \tag{10}$$

The evacuation movement time T_3 considered the safety factor α=1.2, and the final available evacuation time was calculated in Eq. (11). The evacuation time for each floor was 25.8s. Therefore, the available safe evacuation time T_H = 318.68+1.2×25.8=349.64s.

$$TH = T1 + T2 + \alpha T3 = 60 + 258.68 + 1.2T3 = 318.68 + 1.2T3 \tag{11}$$

The available safe evacuation time ASET for Ward 2 of Huoshenshan Hospital was 299.96 s,

Fig. 15 Photo taken on the actual construction of Huoshenshan Hospital site

and the SSET for other fireproof areas was 349.64s. The required safe evacuation time RSET was 268s. No matter what the fireproof area was, the available safe evacuation time was longer than all the required safe evacuation times of Huoshenshan Hospital, thus meeting the requirements. The safety exits of certain fireproof areas of Huoshenshan Hospital were congested when facing emergencies such as fires, resulting in decreased evacuation efficiency, thus, its width could be appropriately increased to meet evacuation requirements.

4.3 BIM + IBS approach in Huoshenshan hospital delivery

The construction of Huoshenshan Hospital adopted Industrialized Building System (IBS) and BIM to reduce on-site operations' workload and avoid rework and rectification in the later stage. In addition, IBS enhanced the structural integrity and installation convenience. Huoshenshan Hospital made full use of BIM-related technologies in the construction process, which played a beneficial role in strictly monitoring the construction progress, ensuring the high quality of the project, reducing labor costs, and improving waste recycling and utilization. This project incorporated information on building materials, building planning, building participants, and construction machinery based on actual conditions. The deliverables of BIM5D and BIM4D were based on architectural models, which were used in managing material requirements, existing capabilities, project delivery plans, pipeline layout, energy consumption analysis, and daylighting. BIM+IBS enabled the visualized control and parameterized design in the construction of Huoshenshan Hospital. In the design and construction process of Huoshenshan Hospital, there was a different theme core, which was the delivery speed because faster delivery meant more lives to be saved. In this context, the traditional construction model was replaced by modular splicing of container-type mobile board houses as an IBS technique. The container-type prefabricated units adopted in Huoshenshan hospital used each container unit as a separate room.

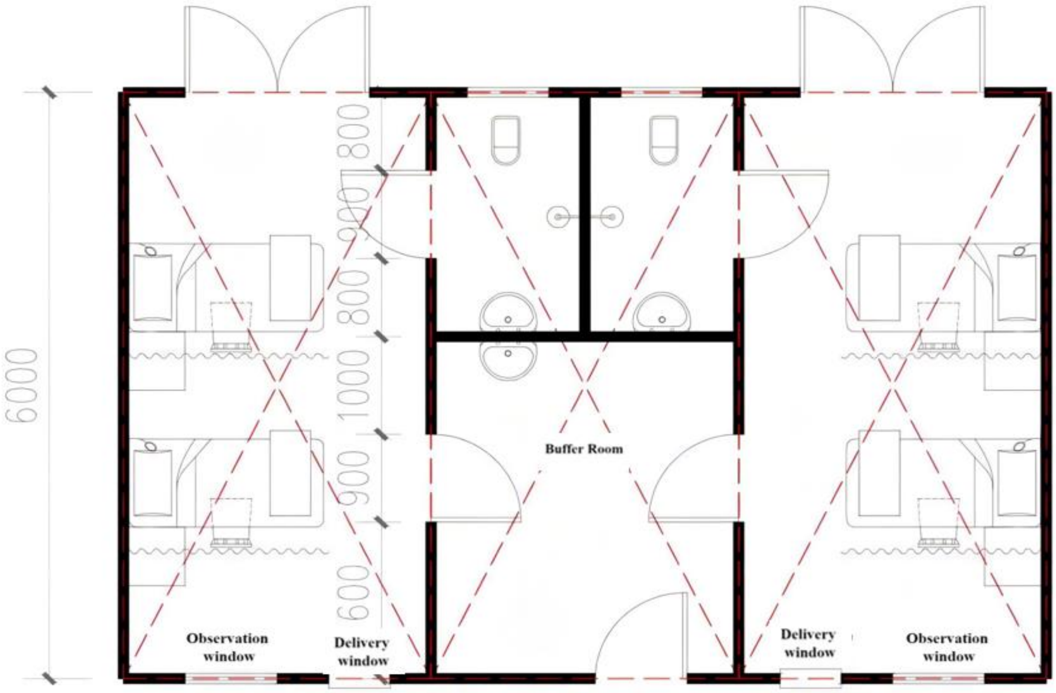

Fig. 16 Layout of the buffer room in the diagnosis zone

The size of the container was uniform, which was suitable for mass duplication and quick assembly. Such a box-type modular splicing building saved civil construction time, and concrete was only used in the lower cushion of the building, which reduced the use of a large amount of concrete, thereby saving time for concrete curing. In each unit, the weight of all the beams and slabs was borne by the four pillars, and not all weight of the building was borne by a group of pillars like traditional buildings did, and the newly added room would have independent pillars. Each room had an independent column, and multiple columns were spliced at the intersection, as in Fig. 15. This design did not need to wait for all the columns to be installed before laying the floor slab, which satisfied large-area simultaneous operations. Huoshenshan Hospital adopted a relatively simple structure. The rooms with repetitive functions were arranged in a symmetrical and matrix manner, which greatly simplified the design and construction phases of the project and saved time. In order to solve the problem of factory production standardization, the "modulus" was specified while designing. The Huoshenshan ward area used modulus sized 3 m × 3 m. The smallest unit of the corridor was 3 m × 3 m, and the smallest unit of the ward was 3 m × 6 m. Only one buffer room was needed in a diagnosis ward between the two wards, as in Fig. 16.

In order to avoid mutual infection, two independent buffer rooms were needed to separate suspected wards, as in Fig. 17.

The structure of the medical-tech zone was relatively the most complicated with a high requirement for flexible changes in space so that the 1.8m modulus instead of the 3m modulus was used as in Fig. 18.

Although modular, many components, especially those with doors and windows, were quite different in shape, such as the three walls circled in Fig. 19. BIM+IBS was to maximize the repetition of reinforced components and to reduce the number of particular components. BIM+IBS

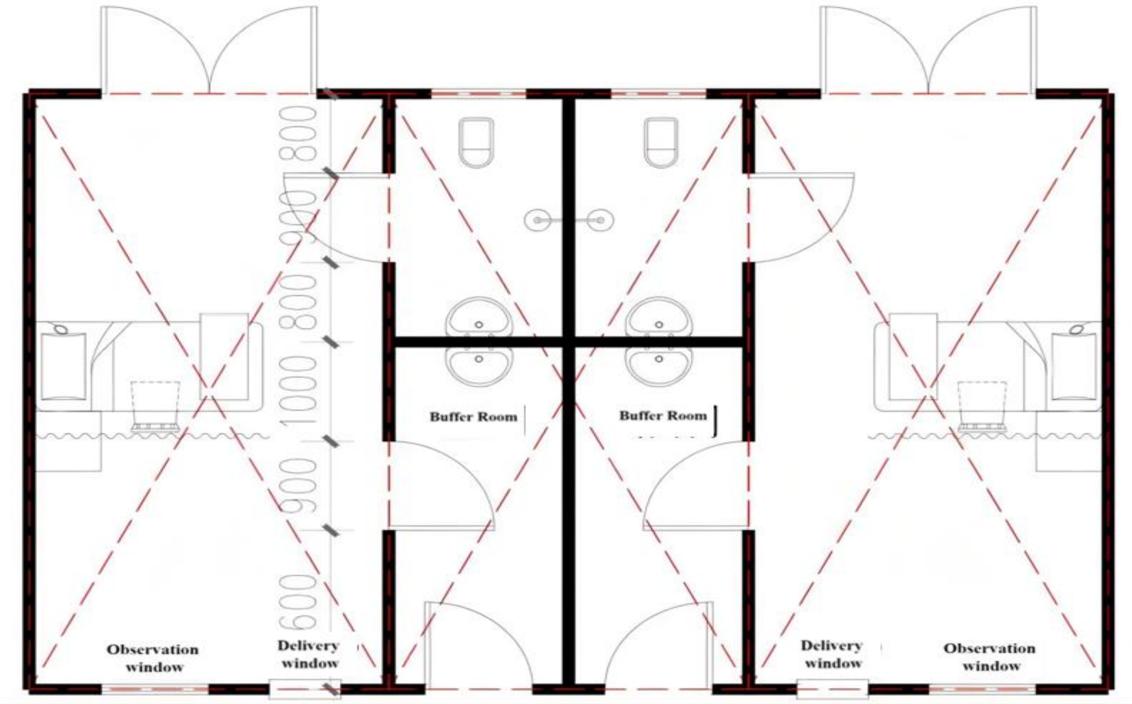

Fig. 17 Plan of setting up buffer room in the suspected ward

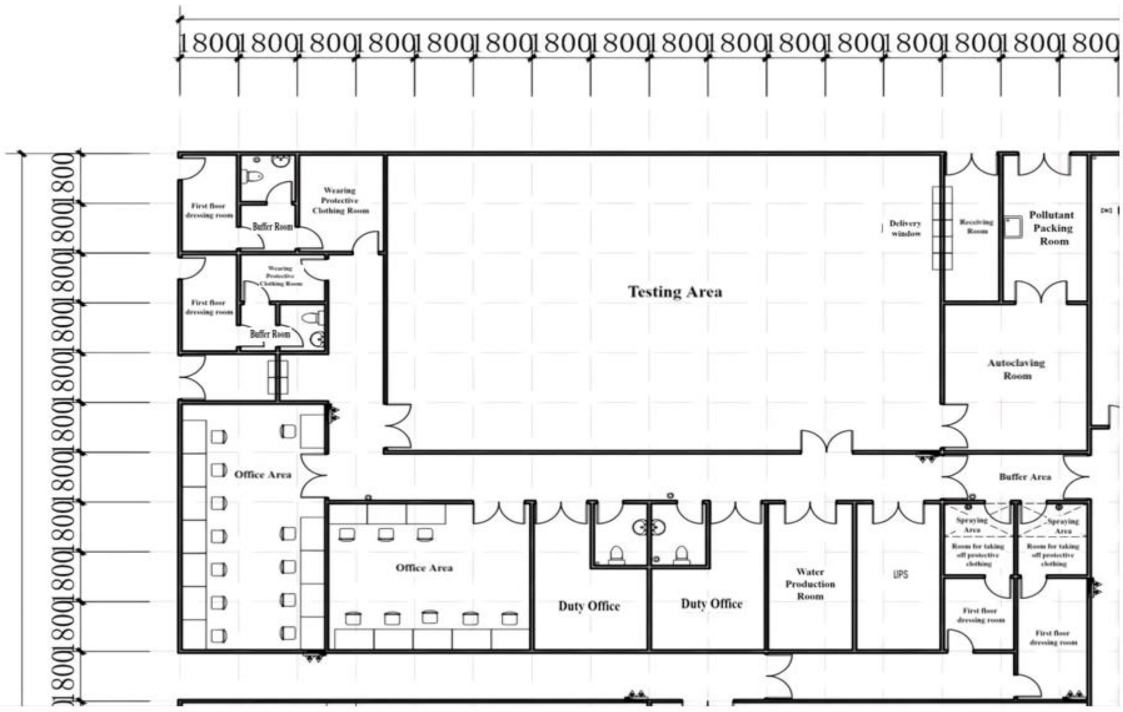

Fig. 18 Design plan of medical-tech zone

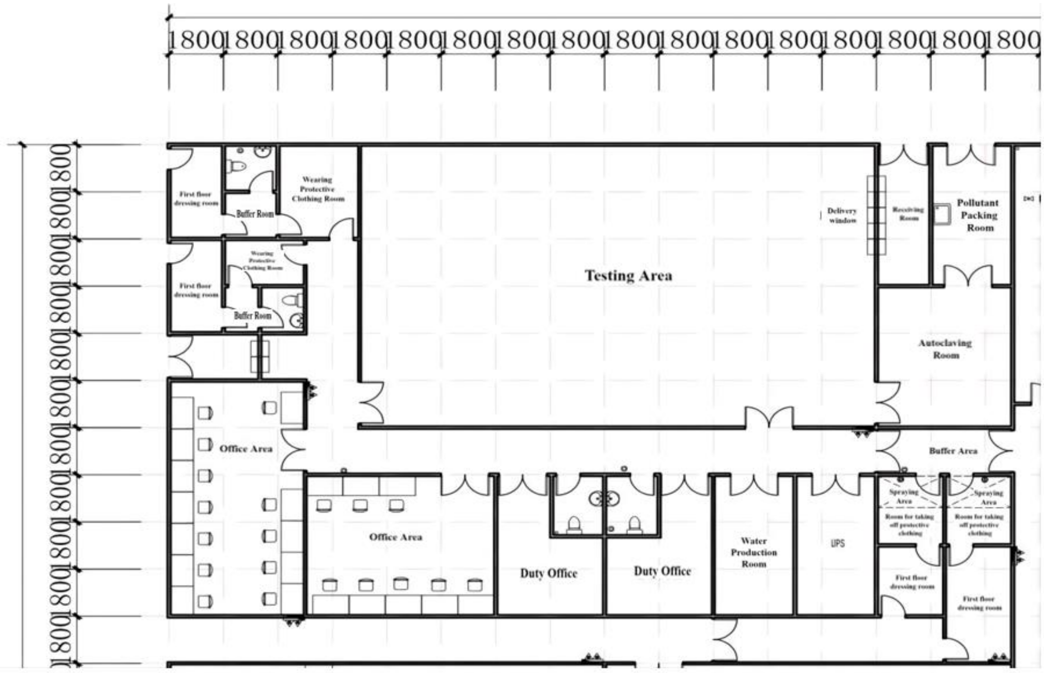

Fig. 19 Distribution plan of a particular wall

adjusted measures to obtain all construction materials from local suppliers due to the extremely tight schedule.

Hundreds of excavators started the land leveling work on January 24, 2020. Huoshenshan Hospital officially started construction on January 25, 2020. On January 26, the six nursing units' basic maps and general water and electricity maps were completed and summarized. On January 27, 2020, the land levelling work was completed, and the first batch of box-type container houses was hoisted. On January 28, the steel structure of the double-layer ward area took shape. The electromechanical pipeline work was carried out on January 29, and more than 300 box-type board houses were installed on the same day. On January 30, the hoisting operation of equipment in the sewage treatment room started, and the laying of the HDPE film was fully completed. On January 31, 90% of the container splicing was completed. In addition, the installation of the frame of the movable board room was about 3000 square meters. Medical supporting facilities were installed on February 1. On February 2, Huoshenshan Hospital was officially put into use. The construction of Huoshenshan Hospital was completed on schedule and delivered smoothly in such a short time because of the following key points for schedule management: a) A reasonable balance between cost, quality, and time, b) Respond to project risks and changes in advance, c) Ingenious cloud online supervision mode with billions of netizens assisted monitoring the construction process of Huoshenshan Hospital online, and d) Jiewei's iMIS-PM was used for project progress management.

4.5 Developing construction site epidemic spreading algorithm

The vertical displacement load with constant speed of displacement is applied at RP-1 point. When the maximum principal stress of the element in the middle straight-line zone reaches the

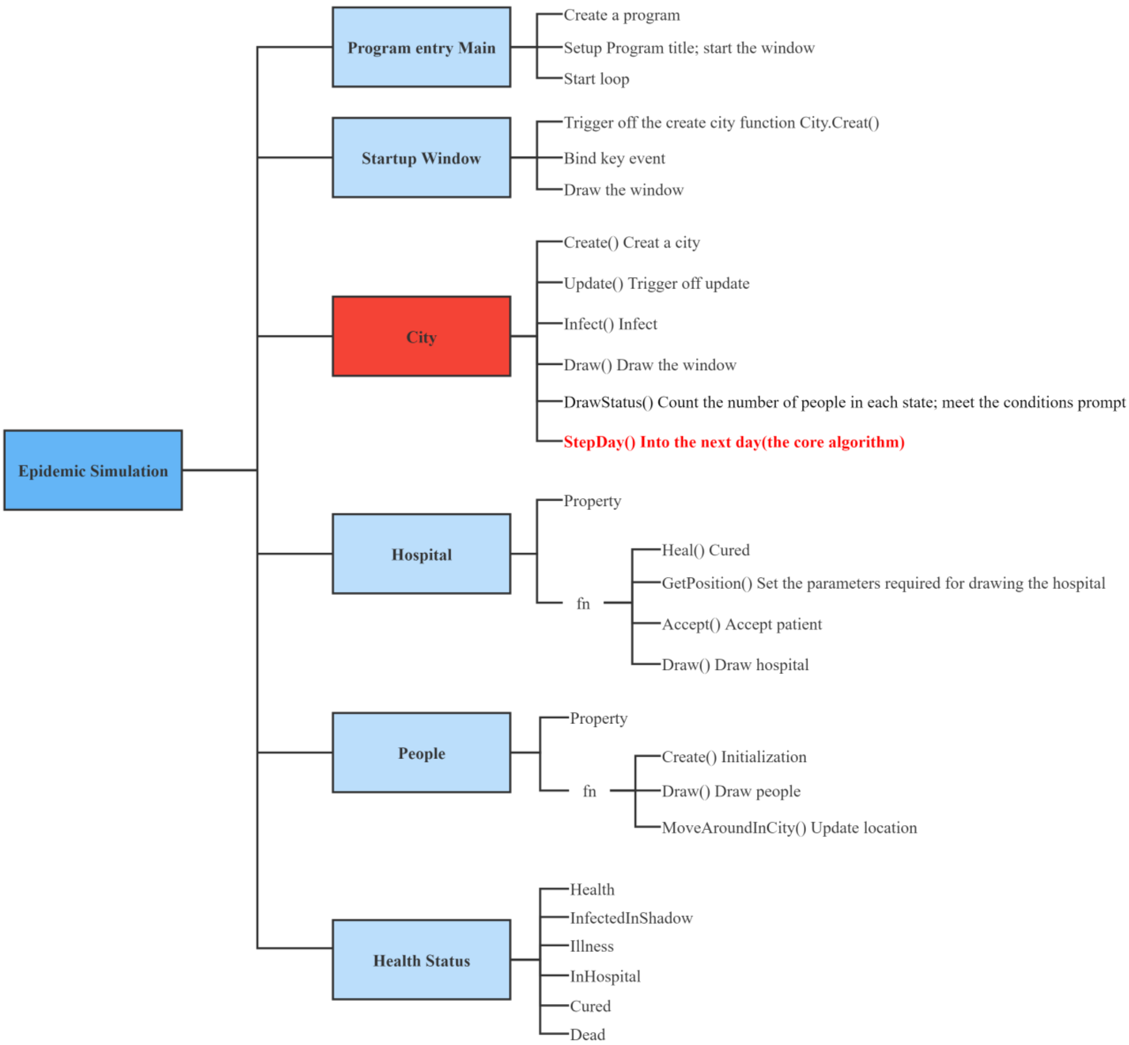

Fig. 20 Coronavirus-19 pneumonia construction site spreading algorithm model mind map

tensile strength, the test is broken off.

The delivery of Huoshenshan Hospital was during the most serious period of the Coronavirus-19 pneumonia epidemic, thus, the construction site epidemic spreading played a vital role in the successful delivery. The development of the construction site epidemic spreading algorithm provided theoretical and numerical support for prevention. We conducted a semi-structured interview survey among 17 first-line epidemiologists and explored the coefficient R0 that reflected the ability of the virus to transmit, and analyzed whether the asymptomatic infected person could transmit. Fig. 20 presents the Coronavirus-19 pneumonia construction site spreading algorithm model mind map. Epidemiologists proposed the parameter R_0 which referred to how many people an infected person carrying the virus could transmit the virus to. When $R_0>1$, that measure needed to be taken to curb the spread of pathogens. In January 2020, the WHO Emergency Committee issued an estimated R_0 from 1.4 to 2.5, which was similar to the R_0 values of the initial stage of the SARS outbreak in 2002-2003 and similar to the R_0 of the new strain of H1N1 influenza that caused the pandemic in 2009. However, these R_0 values were higher than that of the Middle East Respiratory Syndrome caused by a coronavirus similar to SARS. R_0 changed dynamically over time and was affected by prevention measures.

One interviewee stated that asymptomatic infections were also contagious, and the virus infection period could reach up to 29 days. Another interviewee proposed that the infectivity of asymptomatic infections in various situations was different, and people carrying Coronavirus-19 pneumonia had very low infectivity after being isolated for seven days in Wuhan. However, asymptomatic infections found in people returning from epidemic areas abroad were highly contagious. There were two types of asymptomatic infections. One type was the incubation period and asymptomatic confirmed patients with Coronavirus-19 pneumonia, and they were usually included in the confirmed case management. The other type only took a positive nucleic acid test, without any symptoms or image changes, and was not a patient but an actual asymptomatic infection. Interviewees argued that symptoms such as sneezing and coughing could cause virus-carrying droplets to be discharged from the respiratory tract. However, without the above symptoms, the probability of transmission was significantly reduced. All interviewees agreed that Coronavirus-19 during the incubation period was also infectious, and it was meaningless to introduce the concept of incubation period into this model. In this algorithm model, we directly assumed that each infected person with Coronavirus-19 pneumonia could spread the virus to 2.2 people during the incubation period, making $R_0 = 2.2$. We evenly distributed the value of R_0 to each day of the incubation period, and those who carried the virus during the incubation period were infectious. Once the incubation period passed the clinical symptoms, would be isolated and non-infectious. On average, each carrier of Coronavirus-19 pneumonia infected 2.2/4.75=0.46 people every day, and the infection multiplier increased randomly between 0-0.92.

There were about 7,500 construction workers participating in the Huoshenshan Hospital construction site, thus, we assumed that the initial number of infections on the construction site was 10. The fatality rate of confirmed cases in Hubei Province was 3.1%, the national case fatality rate was 2.1%, and the case fatality rate in Wuhan City was 4.9%. Therefore, interviewees assumed that the fatality rate of confirmed cases at the construction site in this algorithm model was 2.1%. Interviewees discussed the hospital discharge time for the algorithm model to be developed. One interviewee stated that the average hospital discharge time was from 5 days (as in Hainan province) to 12.75 days (as in Guangdong province). However, other interviewees argued that the average hospital discharge time confirmed Coronavirus-19 pneumonia in Wuhan was as high as 20 days because the clinical diagnosis and discharge standard outside Wuhan was that after the patient was cured. The relevant clinical symptoms disappeared, the patient could be discharged after being negative in two nucleic acid tests at an interval of 24 hours. However, the discharge standard in Wuhan needed an additional 12 days of pre-discharge observation. In this algorithmic model, interviewees suggested Wuhan's discharge time of 20 days as the algorithm model standard. Fig. 21 presents the block diagram of the construction site epidemic spreading algorithm model. The programming language used in this algorithm model was the C# program.

Figs. 22 and 23 present Huoshenshan Hospital construction site epidemic spreading algorithm running results on Day 2, Day 17, Day 27, Day 51, and Day 65, where the blue circle on the left represents the boundary of the construction site, the green moving square in the circle represents uninfected workers. The yellow moving square represents workers whose virus has infected their bodies. Fig. 22 presents the situation two days after the construction site officially started,

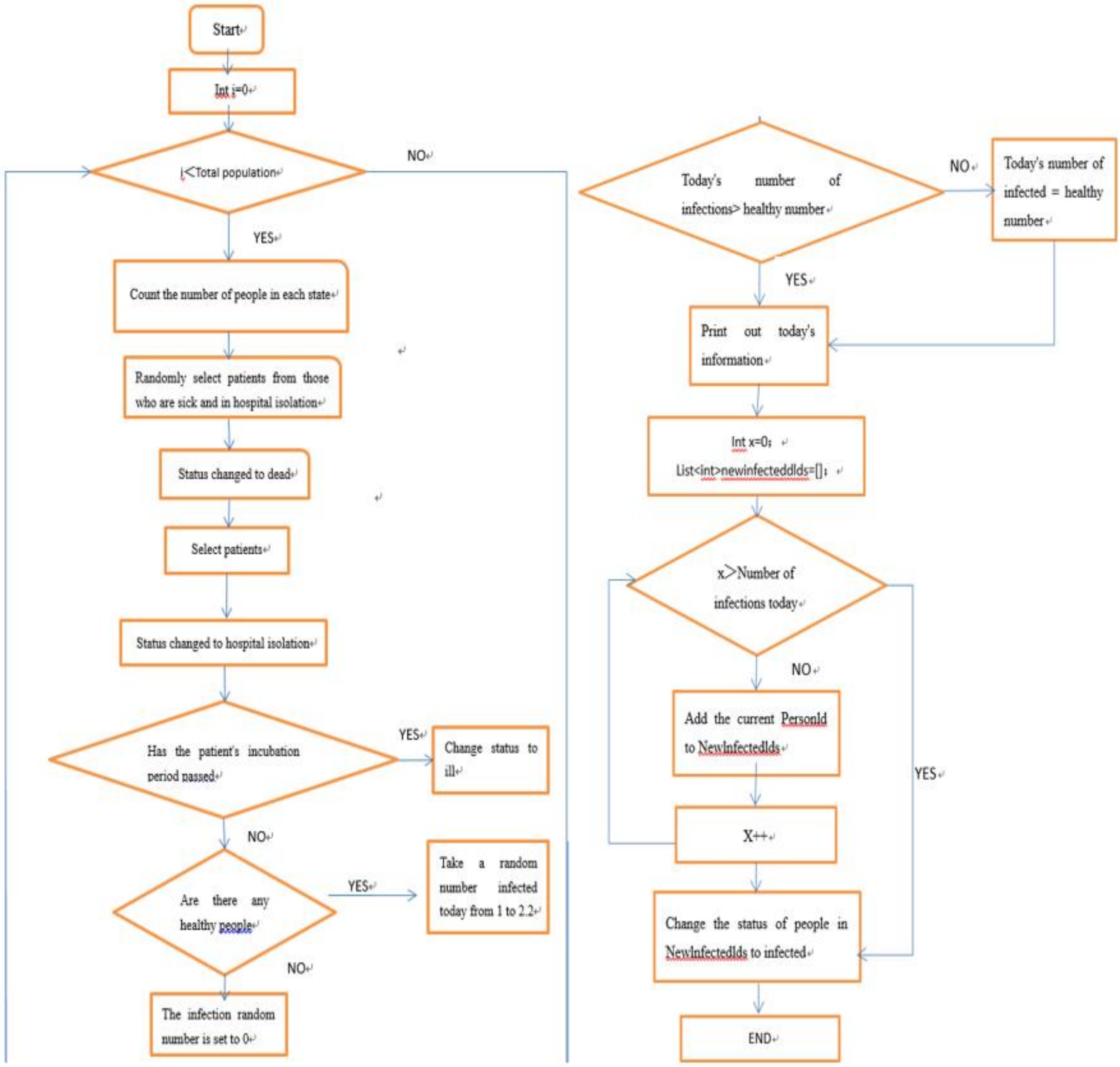

Fig. 21 Block diagram of the construction site epidemic spreading algorithm model

and there were only 18 virus carriers among 7500 workers, and none showed symptoms.

According to Fig. 23, on Day 17, orange squares and black squares appeared in the left circle. The orange squares represent workers who began to show symptoms after the incubation period, and the black squares represent workers who died. The red dots in each small square in the black box on the right represent workers who were sick and sent to the hospital. There were 351 virus carriers, with 166 showing symptoms, among which there were 133 admitted to the hospital and ten deaths. On Day 27, white squares began to appear in the circle on the left, representing the workers who were cured and discharged from the hospital. The black box on the right was full of hospitalized patients. At this time, all people on the construction site were infected with the virus. There were 3315 new virus carriers with 4038 showing symptoms, among which there were 3325 admitted to hospital, with 13 recovered and 134 deaths. On Day 51, there were 0 new virus carriers

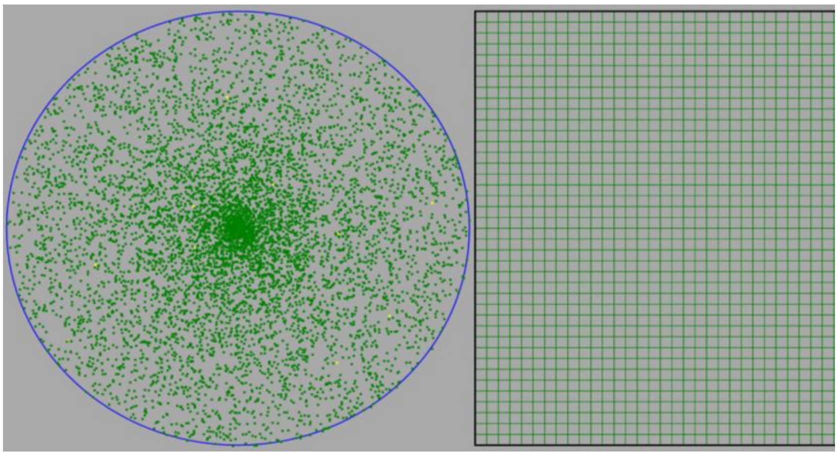

Fig. 22 Huoshenshan Hospital construction site epidemic spreading algorithm running result on Day 2

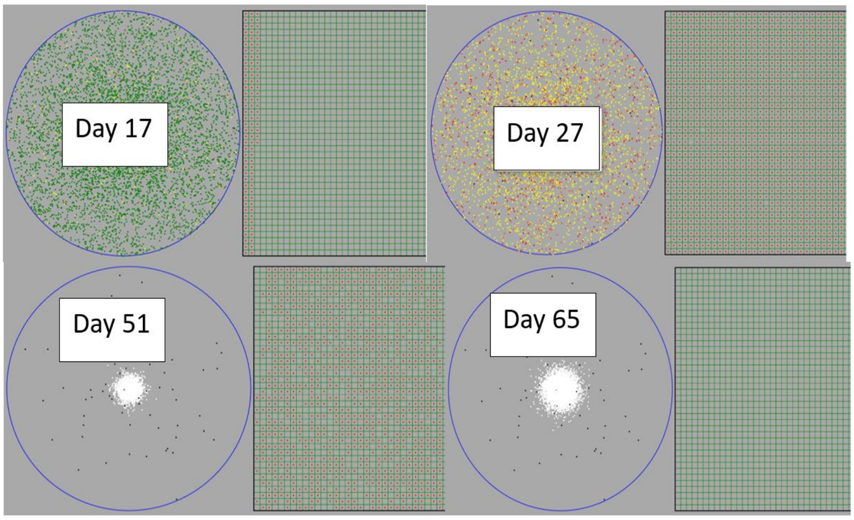

Fig. 23 Huoshenshan Hospital construction site epidemic spreading algorithm running result on Day 17, Day 27, Day 51, and Day 65

with 1305 showing symptoms, among which there were 1305 admitted to hospital, with 5168 recovered and 1027 deaths in total. On Day 65, there were 0 new virus carriers with 0 showing symptoms, among which there were 0 admitted to hospital, with 6459 recovered and 1041 deaths in total.

5. Conclusions

This study conducted a case study in Huoshenshan Hospital to identify how the BIM+IBS approach could ensure rapid delivery of an infectious disease hospital and develop site epidemic spreading algorithms for emergency hospital construction. Coronavirus-19 pneumonia construction site spreading algorithm model mind map and block diagram of the construction site epidemic spreading algorithm model was developed. BIM+IBS approach could maximize the repetition of reinforced components and reduce the number of particular components. BIM+IBS adjusted measures to obtain all construction materials from local suppliers due to the extremely tight schedule. The construction of Huoshenshan Hospital adopted IBS and BIM to reduce on-site operations' workload and avoid rework and rectification in the later stage. In addition, IBS enhanced the structural integrity and installation convenience. Huoshenshan Hospital made full use of BIM-related technologies in the construction process, which played a beneficial role in strictly monitoring the construction progress, ensuring the high quality of the project, reducing labor costs, and improving waste recycling and utilization. This project incorporated information on building materials, building planning, building participants, and construction machinery based on actual conditions. The deliverables of BIM5D and BIM4D were based on architectural models, which were used in managing material requirements, existing capabilities, project delivery plans, pipeline layout, energy consumption analysis, and daylighting. BIM+IBS enabled the visualized control and parameterized design in the construction of Huoshenshan Hospital. In the design and construction process of Huoshenshan Hospital, there was a different theme core, which was the delivery speed because faster delivery meant more lives to be saved. In this context, the traditional construction model was replaced by modular splicing of container-type mobile board houses as an IBS technique. The container-type prefabricated units adopted in Huoshenshan hospital used each container unit as a separate room. The size of the container was uniform, which was suitable for mass duplication and quick assembly. Such a box-type modular splicing building saved civil construction time, and concrete was only used in the lower cushion of the building, which reduced the use of a large amount of concrete, thereby saving time for concrete curing. The delivery of Huoshenshan Hospital was during the most serious period of the Coronavirus-19 pneumonia epidemic. Thus, the construction site epidemic spreading control played a vital role in the successful delivery. The development of the construction site epidemic spreading algorithm provided theoretical and numerical support for prevention. The agent-based analysis on evacuation in Huoshenshan Hospital observed "arched" congestion formed at the evacuation exit, indicating behavioral blindness caused by fear in emergencies. Future studies are expected to explore the built environmental and behavioral reasons behind the "arched" congestion.

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