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A BIM-Based Simulation Approach for Life-Cycle Quality Control in Post-Pandemic Hospitals

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Abstract: The outbreak of COVID-19 has engendered extensive challenges for conventional hospital operations. To adapt to this problematic issue, a mixed-use hospital functioning system for normal and epidemic situations is proposed. However, the inherent complexity of a hospital embedded with a function of epidemic prevention and control renders a restrained construction process that may compromise quality. In this stance, we developed a BIM (building information modelling)-based simulation approach addressing life-cycle quality control in post-pandemic hospitals. An illustrative case study approach, which draws on the grey literature, was used to address the research question. BIM forward design was employed to integrate with such elements as functional streamline, emergency site, and ward conversion in the process of transformation from normal to epidemic-related operations. Computational fluid dynamics-based fluid simulation was conducted to obtain the most suitable air supply and exhaust solutions for negative pressure wards. BIM forward design method contributed to improving design efficiency and quality. The results of ventilation simulation and environmental analysis showed that the design scheme met all the functional requirements and technical specifications. Meanwhile, the best pipeline synthesis scheme was obtained, which reduced the rework and saved on construction time. The proposed method is beneficial to improve the efficiency of design information sharing and business collaboration. Implications generated from this study can be used as a significant reference for the future construction of various healthcare facilities.

Keywords: mixed-use hospital; functional transformation; BIM forward design

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1. Introduction

COVID-19 has hindered the global public health system [1]. The confirmed cases worldwide reached 559 million by July 2022. Since the outbreak in Wuhan, the acute shortage of admissions and treatment resources in designated hospitals have engendered huge pressure on local medical and health systems [2]. COVID-19 is highly contagious, and spreads fast through the air. Therefore, people are vulnerable to this new type of invader, resulting in an exponential growth of confirmed cases over a short period. The contagion of the virus has collapsed conventional medical facilities, which failed in functioning to stop the outbreak. With this in mind, more specialized hospitals are needed to accommodate the pandemic in terms of providing effective quarantine and preventing viral spread. However, the building of specialized hospitals for certain epidemics only, such as COVID-19, would overuse the public budget and medical resources, thereby compromising the service quality of the entire public health system. Therefore, rehabilitating conventional healthcare facilities in terms of architectural design would be a more optimized approach to deal with unexpected epidemics. Not only will it balance the medical facilities' operation efficiency with serviceability, but it will also avoid the waste of medical resources (i.e., wards with extra medical instruments for infectious diseases).

Equipping conventional hospitals with a full function of epidemic prevention and control will enable them to be more capable of withstanding a public health emergency

crisis. In this stance, developing a new mode of hospital (i.e., a mixed-use hospital), robust in functioning within dual contexts (e.g., regular medical services and epidemic control), is urgently needed. It will be the development direction to deal with uncertain epidemics, which can be realized according to the principle of the transformation of epidemic control functions, namely, the mixed-use hospital. Put simply, mixed-use hospitals are more adaptable than conventional ones by offering a wider range of medical services. For example, it can treat regular patients under normal circumstances, while functioning as an infectious disease hospital during an epidemic period. However, developing such a 'hybrid' hospital will not only require a large amount of medical resources and monetary investment, but will also be subjected to financial and technical challenges from the perspective of design.

The National Health Commission of the People's Republic of China has issued the 'construction technical guidelines for the convertible wards of general hospitals combined with epidemic prevention and control (trial implication)' on 17 August 2020, attempting to provide technical support for mixed-use hospital development. This guideline specifies a set of requirements such as planning and layout; architectural design; water supply and drainage systems; heating, ventilation, and air conditioning; electrical systems; and daily operation and maintenance. In this stance, the design and construction of this kind of hospital are more complex and require intensive engagement with all stakeholders. Despite these complexities, there is an absence of engineering design methods and relevant case studies that function as a reliable reference point. This void necessitates overturning the traditional ways of designing the functions of healthcare facilities and proposes a new design method, so that headway can be made to efficiently and promptly have the mixed-use hospitals in place. Notably, multiple simulations are needed to ensure the reliability and stability of multi-system cooperative work in different scenarios.

Developing the mixed-use hospital requires cross-disciplinary cooperation. The professional designers need to communicate and cooperate with the construction practitioners, medical staff, and management operators to understand the functions of the facility and the hospital's operation processes so that the delivery of the project can address and meet key stakeholder interests and expectations. Notably, the development of the mixed-use hospital is under stricter regulations for space function zoning, airflow control, building airtightness requirements, rain, and sewage diversion treatment. Furthermore, it is subjected to a variety of on-site construction procedures and cross operations, thereby requiring a more complicated quality management system. As such, design methods need to be developed for the mixed-use hospitals, for example, a BIM-based forward design. Essentially, BIM is robust in controlling design and construction quality by reducing operational risks and ensuring construction consistency.

BIM can serve as a basis for data during the construction of the mixed-use hospital and enhance the efficiency of the design process according to the forward design theory. For example, the rapid construction of Huoshenshan Hospital was as a result of the application of BIM technology in the design stage [3]. By integrating the design concept of epidemic response with the forward design method based on BIM, efficient and timely information creating and sharing, and management and communication based on the design information, can be achieved for stakeholders.

Against the contextual backdrop presented above, we aim to generate new knowledge of the building design approach by addressing the following research question: what is the ontology of BIM in redeveloping healthcare facilities to enhance their adaptability to pandemics? To address this, a mixed-use hospital was selected for the case study to verify the proposed method. The proposed method is beneficial to improve the efficiency of design information sharing and business collaboration.

The remainder of the paper is structured as follows. Section 2 introduces the implementation of BIM in medical facilities, while Section 3 provides details of the case study. The challenges for life-cycle quality control are identified in Section 4. Section 5 presents the BIM-based simulation approach applied to the case project. Section 6 discusses the

results of the proposed BIM-based forward design. Section 7 describes the lessons learned from this case study. Finally, the research conclusions are provided.

2. Review of the Literature

The mixed-use hospital is associated with a higher complexity in design and technical criteria than that of conventional hospitals [4]. The design of medical facilities is pivotal, determining hospitals' operation efficiency, productivity, staff safety, as well as patients' physical and mental health [5–9]. BIM technology is a data tool that has been widely applied in engineering design, construction, and asset management. It efficiently shares and transmits information throughout the project's life cycle, thereby improving production efficiency, budget, and schedule controls [10]. With BIM, a set of intangible elements can be visualized such as design coordination, installation, and progress simulations, which contributes to minimizing the risks of delivery [11].

The literature is replete with studies attempting to identify how BIM can improve the design and construction quality of healthcare facilities (Table 1). For example, Ref. [12] discussed the successful implementation of BIM in a hospital project. They demonstrated the mechanism of BIM in dealing with the high complexities and details of the project's design phase and then enhancing construction efficiency. Continuing with this theme, Ref. [13] reported that the application of BIM during the conceptual design stage of healthcare projects could provide more detailed project information and save time.

Table 1. Simple review on the application of BIM-based technology in medical facility projects.

References	Phase of the Project	Conclusion/Contribution
[3]	Design	Improve communication of information
[12]	Design	Improve the construction efficiency
[13]	Design	Save time and reduce the cost
[14]	Design	Improve collaborative work efficiency
[15]	Design	Improve green performance
[16]	Construction	Improve efficiency process
[17]	Construction	Improve efficiency Improve efficiency process
[18]	Construction	Improve project quality
[19]	Construction	Satisfy rapid construction requirements
[20]	Maintenance	Enhance the decision-making process of the facility managers
[21]	Maintenance	Facilities management
[22]	Maintenance	Facilities management

Ref. [14] proposed a BIM-based system to improve the efficiency of collaborative design by addressing a variety of extant problems, such as the loss of data, communication barriers, and poor work efficiency within the context of a hospital project. Additionally, there were also extensive studies focusing on the field application of BIM during construction. The rationality of doing so is because design collisions and changes are common problematic issues delaying the construction and depressing project quality. Efficient coordination between design and construction is therefore needed to ensure that information is fully accessible and exchangeable among all stakeholders over the construction process [16,17]. With this perspective, Ref. [19] identified an innovative 'site BIM' system that enables on-site workers to use mobile tablet or personal computers to access design information to ensure work quality.

Furthermore, existing studies also relate to the maintenance and management of the medical facilities [20–22]. With the widespread adoption of BIM-based systems, having appropriate standards and procedures in place to support BIM workflow is essential. The actuality of BIM application, notably, is that a 3D model is usually built based on 2D construction drawings. However, the BIM forward design method discussed in this paper employs BIM 3D modelling throughout the entire process cascading from design to delivery. In this stance, design concepts are presented in a BIM 3D space, for the purpose of: (1) ensuring the consistency of drawings and models; and (2) eliminating mistakes

and omissions in construction drawings. Consequently, design quality will be improved. For the mixed-use hospital project, the forward design method proposed in this paper is beneficial to enable higher delivery quality and ensure a limited project schedule can be met.

3. Case Study

3.1. Research Approach

This study aims to develop new knowledge for healthcare facilities to withstand a pandemic. An illustrative case study approach, which draws on the grey literature identified in technical reports, pre-prints, and the media is therefore used to address the research question proposed above [23]. The use of grey literature to examine policy and technology-related matters is deemed a valid inquiry line [24].

3.2. Case Project Background

A mixed-use hospital was selected for the case study of this paper, as it can be transformed into an infectious disease hospital to deal with an uncertain epidemic. This requires designers to consider functional transformation during the design phase. It is located in the Huangpi District, which is about 40 km away from Wuhan City Centre. This hospital occupies a total site and construction area of 14,400 m^2 and 240,000 m^2, respectively. The Architectural Design Institute is responsible for the BIM design of this hospital. The estimated investment of the project is RMB ¥2.79 billion, and it is required to be delivered within 15 months. The hospital was designed in October 2020, and opened in December 2021. The hospital consists of three main zones, including an infection isolation area, a comprehensive medical campus, and an administrative logistics area. It has 1200 beds, with 1000 beds for regular patients and 200 beds prepared for the treatment of infectious diseases. The overall layout of the hospital is shown in Figure 1.



Figure 1. The overall diagram of the mixed-use hospital.

A total of five buildings were newly built. These include the: (1) five-story medical technology facilities with a height of 23.9 m; (2) seventeen-story 74.25-m-high inpatient building; (3) four-story scientific research centre (19.5 m high); (4) seven-story infection building (31.6 m high); and (5) six-story duty apartment building (23.95 m high). Furthermore, the basement is designed to serve as a car park and facility room. By rationally planning and organizing the streamlining between different functional modules to protect both patients and medical personnel, the efficiency of medical services of this hospital is higher than that of traditional hospitals.

4. Challenges for Life-Cycle Quality Control

As an important mixed-use medical facility designed for dealing with possibly severe infectious diseases, the development of the selected hospital confronted multiple challenges.

First, it is challenging to ensure the project's information accuracy (especially the design information) and delivery efficiency. The hospital consists of different zones and

each of them has unique and special functions. Thus, designers must comply with the corresponding design specifications. For example, the ventilation system of the infection wards needs to follow the principle of negative pressure to prevent the spread of viruses. In addition, different scenarios, i.e., normal or epidemic situations, must be taken into consideration. Furthermore, the project is required to be delivered in fifteen months, which requires all stakeholders to cooperate efficiently to deliver this project. Therefore, the project management is extremely challenging due to multiple participants, overwhelming information, and incompatible file formats. Failing to obtain accurate and timely information may lead to substantial schedule over-run.

Second, the construction of a mixed-use hospital relies on a flexible and functional streamline layout to enable the rapid function transformation required with the outbreak of an infectious disease. To avoid cross-infection, separate entrances and exits are set for medical staff members, and suspected or confirmed patients. In addition to the clean and contaminated zone, buffer zones should also be set up. The design of the medical treatment area of the hospital should comply with the 'three zones and two passages' principle [3] and national design code for an infectious disease hospital (see Figure 2). By rationally planning the overall functional streamline layout, the hospital's admission capacity will not drop sharply during an epidemic, thereby maintaining the operation of the hospital. For this reason, the relationship between various streamlines must be considered during the design process to ensure the relative independence of patient streamline, medical personnel streamline, and waste streamline, as shown in Figure 3.

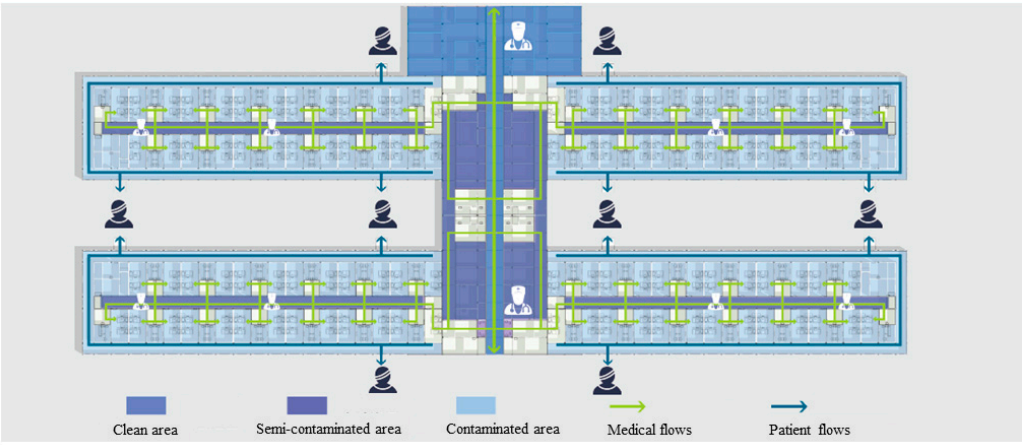


Figure 2. The design of the 'three zones and two passages'.

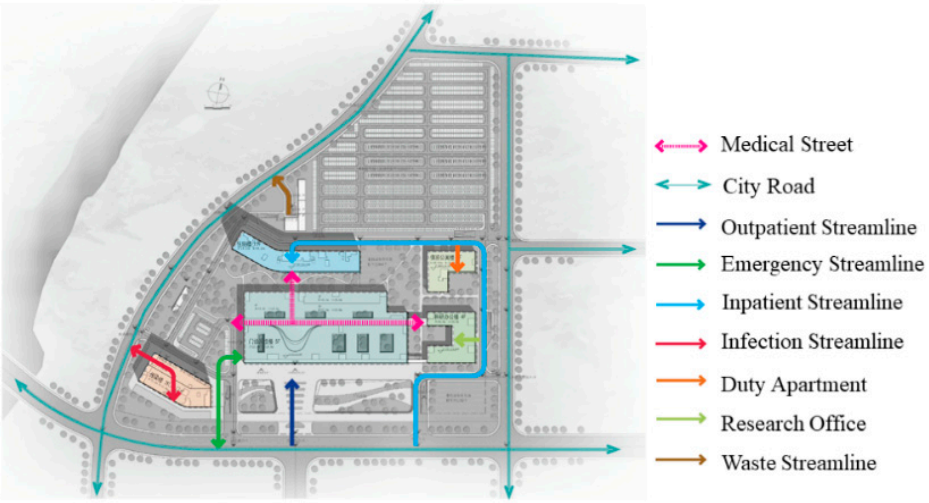


Figure 3. The streamline distribution of the hospital.

Third, the irregular surface structure is highly complex. The use of this complex curve design is mainly for aesthetic reasons, but it also leads to difficulties in the expression of the structure design and construction. As noted from Figure 4, the partial form of the roof of the medical technology building is sophisticated, where a double-layer grid structure with numerous nodes and complicated spatial relationships was adopted. The traditional design method presented by CAD 2D drawings cannot address the design concepts, so it is essential to use BIM to combine structural design with architectural aesthetics.



Figure 4. Three-dimensional view.

To address the challenges mentioned above, the designer played a strong leadership role in the information creation, management, and communication of BIM implementation. According to the characteristics of the project and the design requirements, the BIM workflow of the project was developed. Specifically, the main modeling scope, benchmark coordinates, and model naming of the different disciplines at each stage of the project were clarified, and the process of design coordination among all participants was also displayed clearly. The technical roadmap was split into three steps, namely implementation planning, design and application, and digital project management. Each step comprises several sub-processes to form a main task (Figure 5). Designers conducted collaborative design based on the virtual machine software VmWare platform [25] to integrate the software tools and data management process. Owing to the data basis for design analysis, the information model was used to conduct functional division, streamline organization and airflow analysis, and the different schemes can be further compared and optimized to enable a higher management efficiency. To ensure the reusability of the model, the components utilized in the modeling were all derived from the standardized model database that were independently developed, maintained, and were conducive to improve the BIM standardization in the construction and the design efficiency of the hospital.

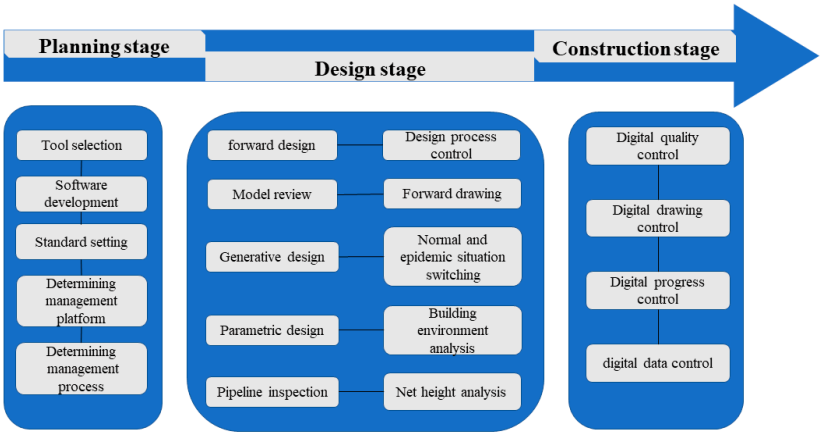


Figure 5. The technical roadmap of BIM application implementation.

5. BIM-Based Simulation Approach

5.1. BIM-Based Forward Design

This project adopts BIM forward design method, self-developed mechanical engineering BIM (CE-BIM) electromechanical design software and other secondary developing tools to maximize design efficiency and improve project delivery quality (see Figure 6). The coordinated BIM model developed at the design stage contains information not only about the building itself but also the model details (e.g., structural, mechanical, electrical, and plumbing (MEP) components). The BIM components reach a level of development (LoD) of 400 according to the Delivery Standard of Architectural Engineering Design Information Model of China, which contains information concerning classification, size, materials, methods of operation, technical specifications, etc. With the assistance of enhanced information in BIM, the design can be validated and optimized to meet functional requirements. This part is essential so that the health condition of patients and staff members can be ensured, and a safe working environment can be guaranteed as well. The overall design of this project conformed to the practice code of a mixed-use hospital, and the design tasks were decomposed to determine the functional layout, streamline organization, and air flow direction. The main challenge of a BIM forward design is from project management, which plays a guiding role in the construction process. The project stakeholders do not necessarily have the same commonality of interests but are expected to cooperate as a team. Meanwhile, design details are updated frequently with the transformation of the building life cycle and environmental changes. Based on the forward design concept, a series of BIM tools is introduced in the planning and design stage, so that all stakeholders can be involved in the project implementation process as soon as possible and with deeper perception. Hence, the quality and efficiency of the project will be kept at a high level.

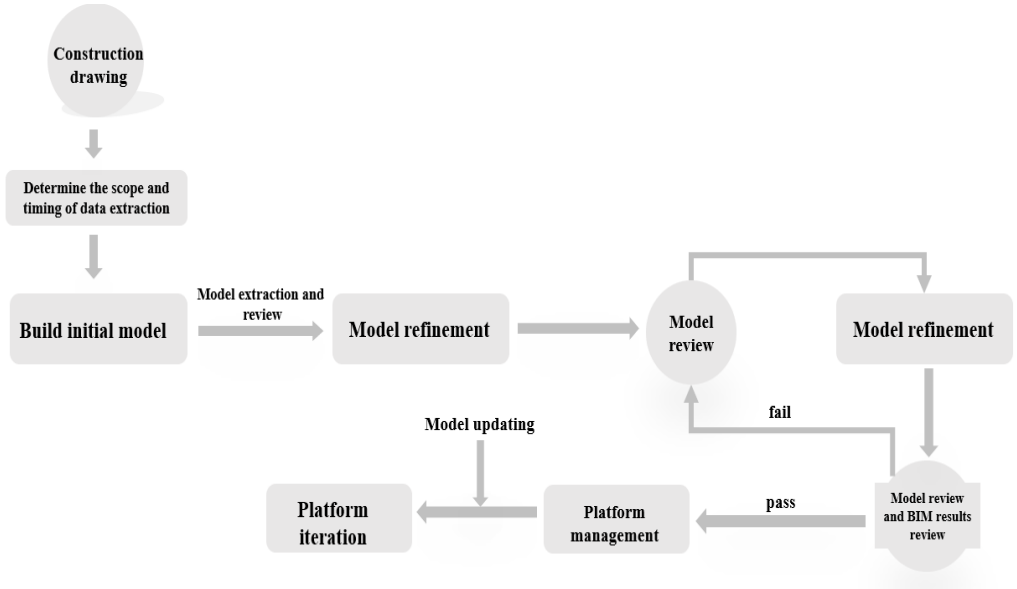


Figure 6. The BIM-based forward design process.

5.2. Combination of Normal Time and Epidemic Period

5.2.1. Changes in Hospital Functional Streamline

During the epidemic period, with the changes on the ward, the streamlines of the doctor–patient passage will change. The way to scientifically set up the passage streamlines to avoid cross-infection and effectively ensure the safety of medical staff members will be the key to the epidemic transformation design. The functional streamline of this project is divided into three categories: the normal time, the second, and third-level response state of the epidemic, and the first-level response state of the epidemic.

By contrast, the hospital is divided into two areas during normal functioning. One is the quarantine area (polluted area) including the infectious building, and the other is the general area (clean area) including the outpatient, inpatient, and administrative areas (Figure 7). In addition, the operation of the hospital has four main streamlines: the passage for infected patients, the passage for outpatients, the passage for logistics, and the passage for inpatients to prevent the contact of multiple groups of people. There is a separate outlet for the waste in the polluted area, which is isolated from clean area.

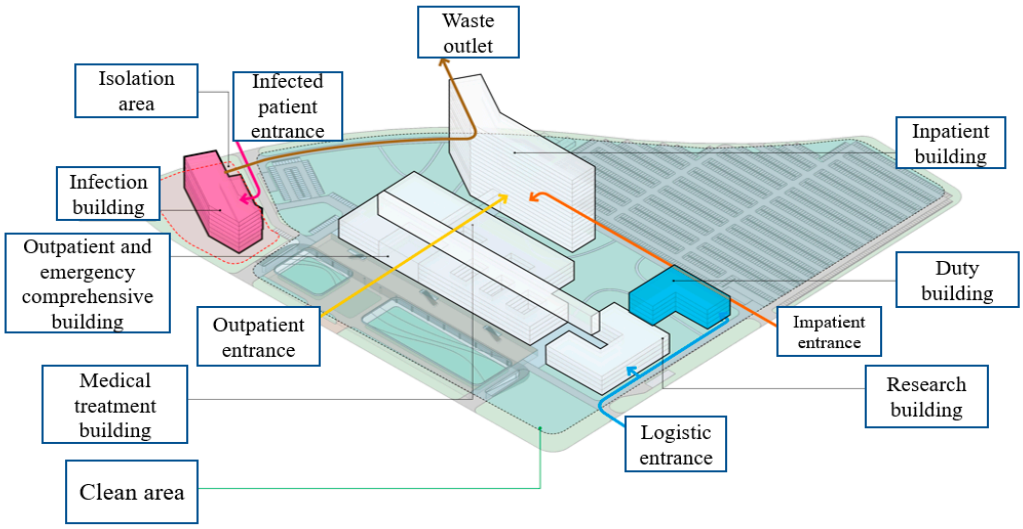


Figure 7. Functional streamlines in normal time.

Under the second and third-level response state of the epidemic, the quarantine area will be expanded, and an emergency response site will be prepared outside of the infectious building. Additionally, the outpatient and emergency departments (in normal time) are switched into fever clinics, as shown in Figure 8. The medical supplies are moved to the polluted area through the medical technology building. Under this situation, the high-rise standard wards in the inpatient building are rearranged into an infectious disease area step by step, and staff members can use the entrance in logistics area.

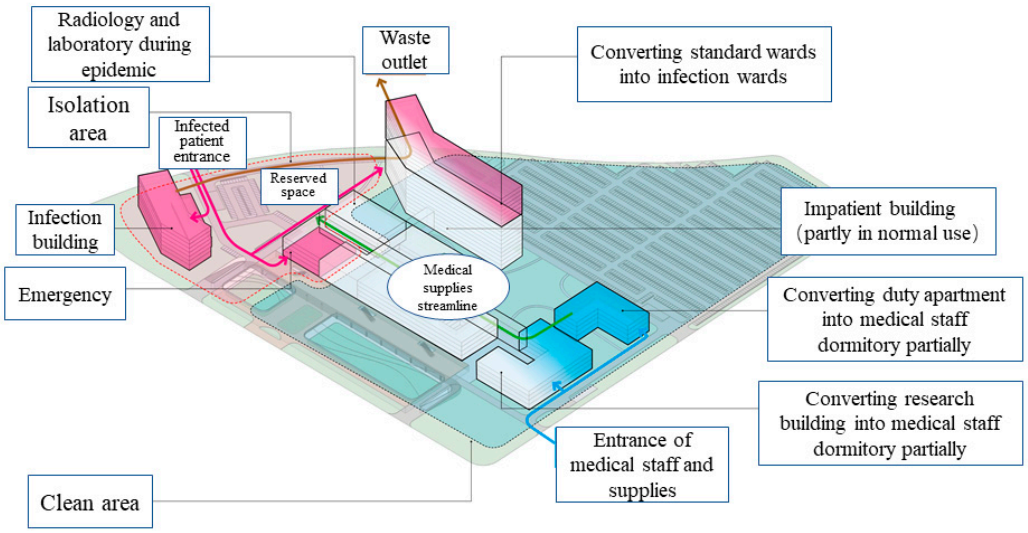


Figure 8. Functional streamlines under the second and third-level response state of the epidemic.

Under the state of first-level response to the epidemic, the overall layout of the hospital will change drastically and will be primarily used to deal with the public health emergency crisis, as shown in Figure 9. First, in terms of the overall layout of the site, a larger part

of the hospital will be devoted to treat confirmed cases. At the same time, the reserved emergency response site will be quickly transformed into an emergency hospital to increase admission capacity. The parking lot will then be renovated into a site for incinerators, temporary waste storage, and vehicle disinfection to enhance the hospital's emergency response capability.

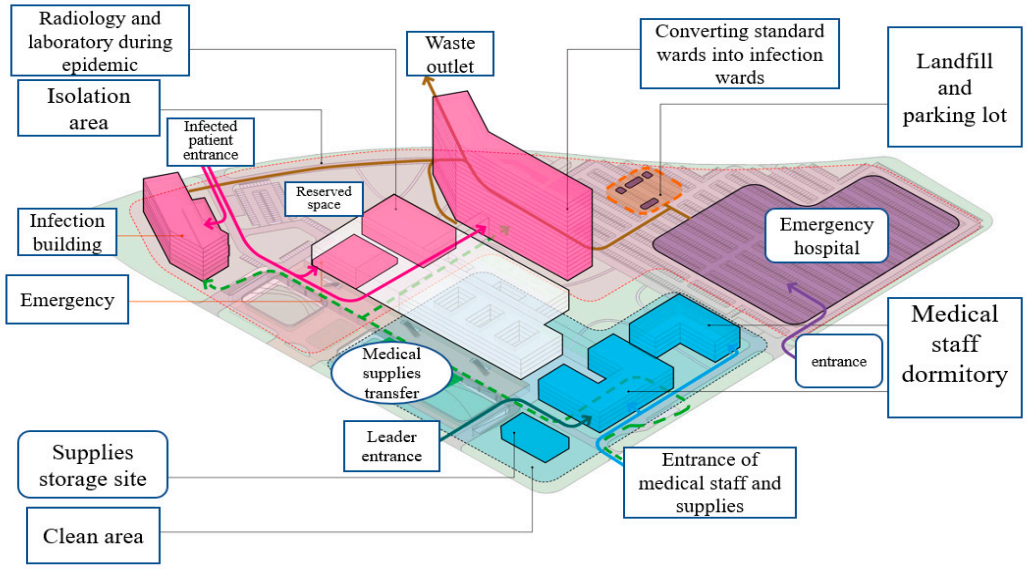


Figure 9. Functional streamlines under the state of first-level response to the epidemic.

5.2.2. Emergency Site Construction

Referring to the modular design of Huoshenshan and Leishenshan hospital, prefabricated construction is expected to be adopted to achieve the rapid construction of the emergency hospital. The electromechanical interface will be reserved under the emergency site. During the epidemic, the parking space will be removed, and the lightweight modular steel structure combined house (box-type house) will be selected, which can be easily spliced. As shown in Figure 10, using isolation wards and the medical dormitory as an example, light steel modular structures (container type) could be applied. Each unitized module consists of flooring, ceiling, and wall, while pipeline, doors, windows, and decorative parts are integrated in the module. Modules can be flexible in size and can be transported to site for assembling after being manufactured in the factory as a whole.



Figure 10. Emergency hospital construction.

5.2.3. Passage Streamlines Changes

During normal times, the doctor–patient passages cross each other. When the epidemic occurs, the function of the overall area will be adjusted according to the 'three zones and two passages' to effectively avoid cross-infection, as shown in Figure 11. The use of BIM visualizes the transfer path, which can be used for staff training and conversion implementation guidance to increase the efficiency of information exchange.

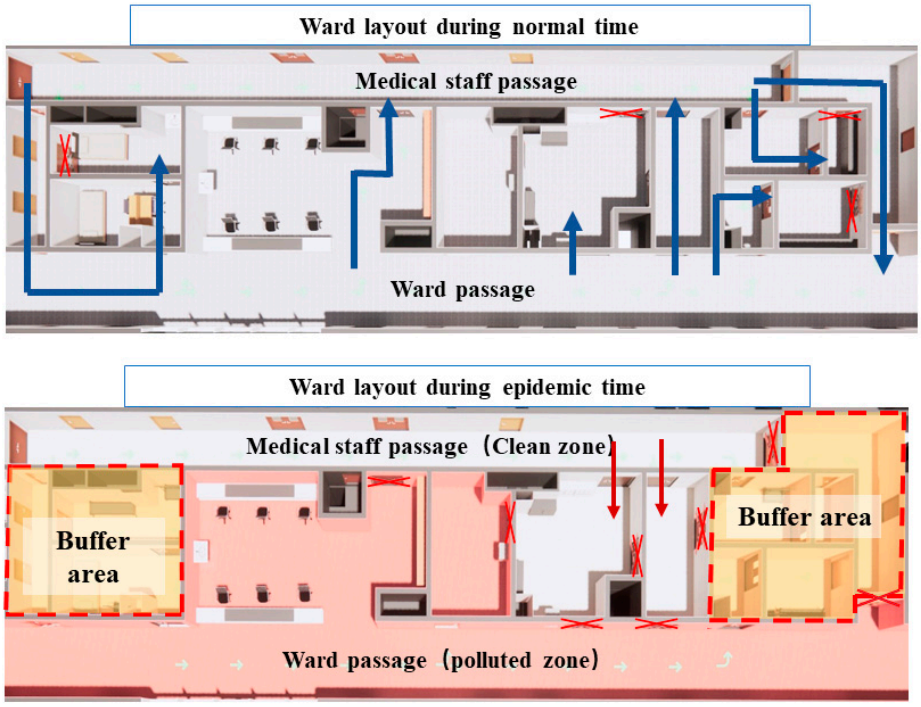


Figure 11. Passage streamlines changes in the ward.

5.3. Computational Fluid Dynamics-Based Simulation

According to the requirements of the respiratory infectious disease wards, it is necessary to set up a negative pressure ward to adjust the airflow in the process of ward function transformation. Therefore, the air supply and exhaust system of the infectious building and gastrointestinal ward were carefully designed in this project. Based on the information provided in BIM, the air circulation and virus contamination in the negative pressure ward were simulated, and the XFLOW software was used for fluid simulation to compare all schemes to ensure the safety of the hospital.

6. Implementation and Evaluation

6.1. Design Phase

6.1.1. Environment Analysis

An analysis of the wind environment of the mixed-use hospital was conducted to verify the rationality of the design scheme. We concluded that the construction zone is well ventilated, and the area of vortex is in an acceptable range. The simulation results for summer and winter were shown in Figure 12. The sunshine simulation analysis was conducted with the Ladybug tool based on Rhino/Grasshopper [26], and the sunshine conditions were set based on the meteorological database. The cumulative duration of the sun exposure of each analysis point in the space was calculated by the software. As shown in (Figure 13), the sunshine duration and radiation amount in the construction zone are moderate, which complies with the sunshine specification and is acknowledged as being beneficial to patients' rehabilitation.

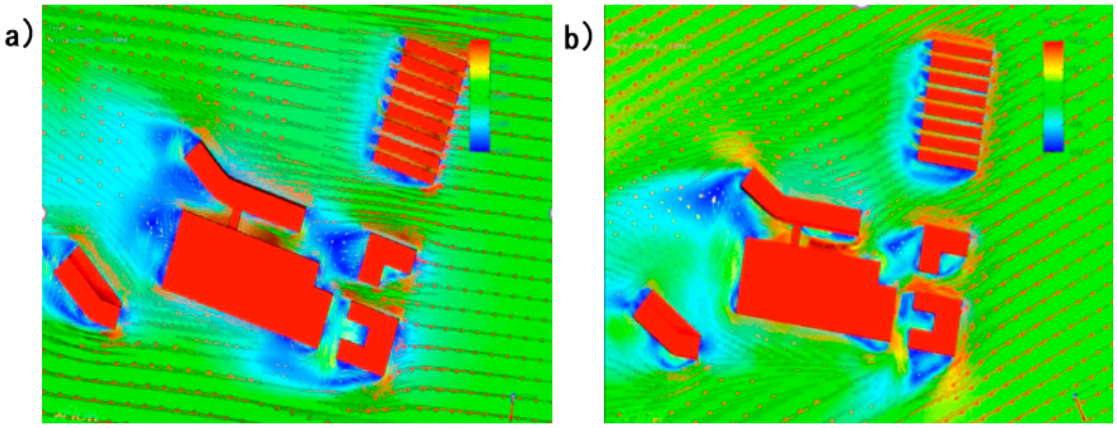


Figure 12. The simulation results of the wind environment of the hospital: (**a**) summer, (**b**) winter.

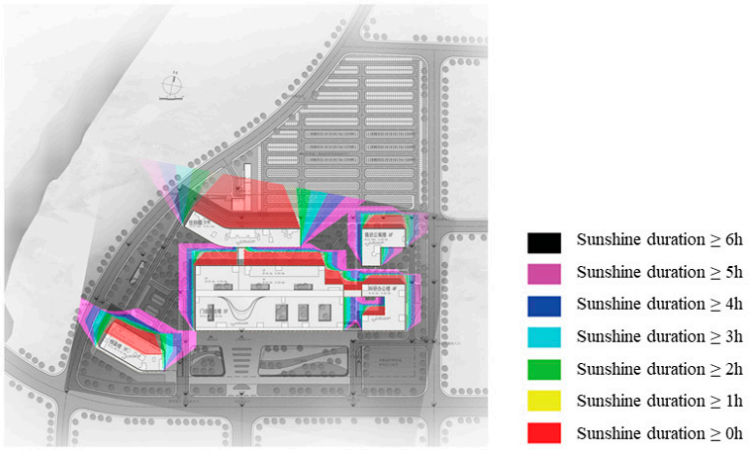


Figure 13. The analysis of the sunshine of the hospital.

6.1.2. Ventilation Simulation

Considering that the majority of infectious diseases spread by close contact through breathing and remain active and infectious for several hours in the air, the ventilation system of the mixed-use hospital follows the principle of negative pressure to isolate pathogenic microorganisms. The air pressure in the isolation ward is required to be lower than the air pressure outside the ward. By this way, air flows from outside into the ward, and the virus-contaminated air in the ward is discharged only after receiving special treatment. Furthermore, the concentration of pathogenic microorganisms in the ward is diluted by ventilation to ensure that the area outside of the ward is virus-free. The air circulation within the mixed-use hospital is extremely important and has been carefully designed to meet the relevant standards and requirements.

BIM was used to simulate and analyze the air circulation and virus contamination to select the most suitable solution for negative pressure wards, and the simulation was conducted by using SIMULIA XFLOW, which is a professional software for computational fluid dynamics. Three representative operation conditions were selected for simulation, and the grid discretization method of the computing domain directly affected the calculation accuracy and efficiency. Two grid discretization schemes were adopted, with the grid number of 2 million and 3 million, respectively. In order to balance the calculation accuracy and efficiency, a more refined grid was finally selected for calculation. The velocity boundary conditions of the air supply in the ward were 3.93 m/s and 1.57 m/s, respectively. The design relative pressure of the ward and the bathrooms were −15 Pa and −20 Pa, respectively. Additionally, the pressure outlet boundary condition was adopted. The patient was assumed to be the release source of the virus in the air. Since the release

source was patient related, the relative concentration was used for analysis. Therefore, the concentration of virus-containing air released by the patient was assumed to be one, and the initial concentration field in the room was set to zero. The calculation time was set as 300 s and the time step was set as 0.0001 s. The scheme comparison has been achieved on this platform to ensure the safety of medical personnel and patients. During normal time, there is only one air inlet in a negative pressure ward, with a ventilation rate of 225 m^3/h. The air outlet in the bathroom remains open to ensure daily ventilation, as shown in Figure 14a. During the epidemic period, the digestive tract ward in the infectious building is switched into a negative pressure isolation ward. In addition, a sub-high efficiency particulate air filter is installed, with the air inlet and outlet open at the same time. The inflow and outflow rates of the ventilation system are 450 m^3/h and 600 m^3/h, respectively. As mentioned above, the air outlet in the bathroom remained open to form stable negative pressure and prevent viral diffusion, as shown in Figure 14b. At the same time, the gastrointestinal ward in the infectious building could also be switched into an intensive care unit (ICU) negative pressure ward during the epidemic period, as shown in Figure 14c.

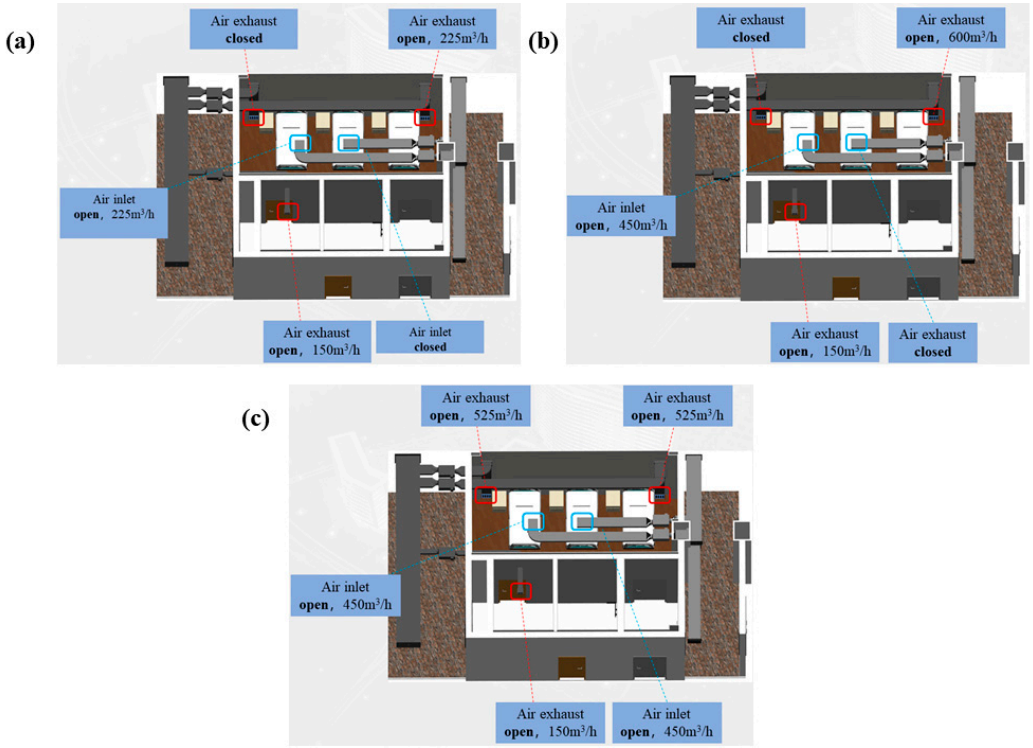


Figure 14. Air inlet and exhaust solutions for the isolation ward: (**a**) normal time, (**b**) isolation ward for infectious diseases during the epidemic period, and (**c**) ICU ward for infectious diseases during the epidemic period.

6.1.3. Analysis of Logistics System

The hospital has adopted an intelligent medical service system and intelligent logistics system to effectively enhance treatment experience and increase efficiency. Based on indoor IoT base stations and platforms, various business data can be collected and processed to ascertain the precise positioning of hospital personnel and interconnection of equipment information, which will support the development of the intelligent mixed-use hospital, build an intelligent healthcare platform, and ultimately comprehensively improve the quality of medical treatment. Intelligent logistics systems include pneumatic and box-type logistics. To be specific, pneumatic logistics can quickly transmit drugs, reagents, and documents to the terminal through pneumatic pipelines, while box-type logistics can pack heavy drugs or medical supplies through packing boxes and send them to the logistics elevator for centralized vertical transportation.

BIM has been employed to simulate the operation state of the box-type logistics system, so that the shaft setting, transportation route, and station setting can be reasonably arranged. The vertical shaft (1.6 m × 1.6 m) and the horizontal transfer pipe (0.7 m × 1.4 m) of the medium-sized box logistics lead time sorter are considered in this project. The simulation results based on BIM show that setting 46 box-type logistics sites and 11 reciprocating vertical elevators would be the best solution, as shown in Figure 15. The horizontal transmission facilities in the hospital are connected through the first and fifth floors. The material warehouse and pharmacy are connected to the first floor through an independent elevator to improve the transmission efficiency of key departments.

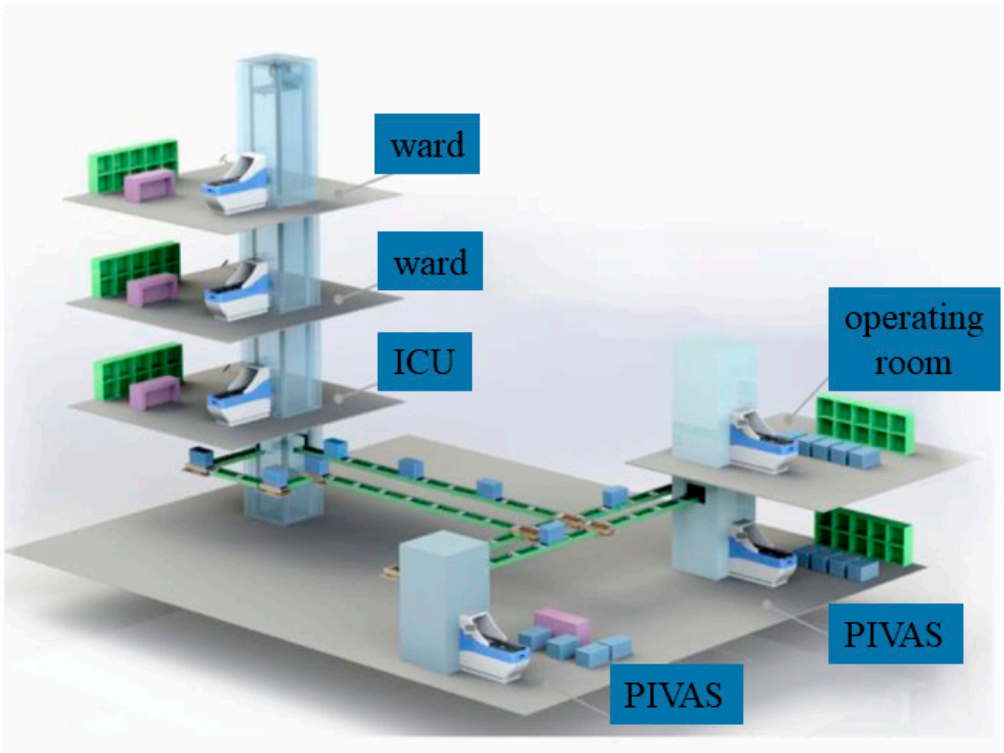


Figure 15. Medium-sized box logistics solution.

6.2. Construction Phase

Engineering construction projects require the high-quality comprehensive ability of management personnel to take the overall control of the project. BIM technology can play an important role in this process. Thus, the engineering procurement construction management platform was developed based on webGL, which enables stakeholders to share information through a mobile App and update project progress in real time, including quality management, safety management, schedule management, and drawing updates. It can ultimately improve the overall management efficiency through digital technology. For example, after the completion of the pipeline design, the self-developed automatic pipeline bending algorithm was used to carry out the overall automatic pipeline synthesis. Through pipeline adjustment, the results of pipeline synthesis could be quickly obtained. Therefore, the best scheme could be selected after thoughtful comparison, which could reduce the rework and save construction time and cost, as shown in Figure 16. In addition, we evaluate clash detection as well using BIM. Examples have been presented in Figure 17.

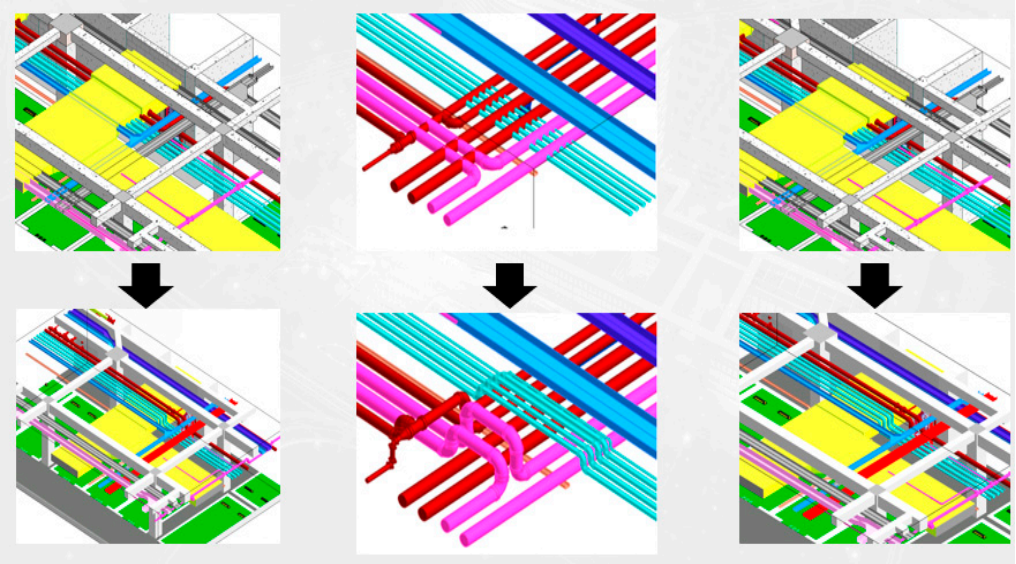


Figure 16. The results of pipeline synthesis.

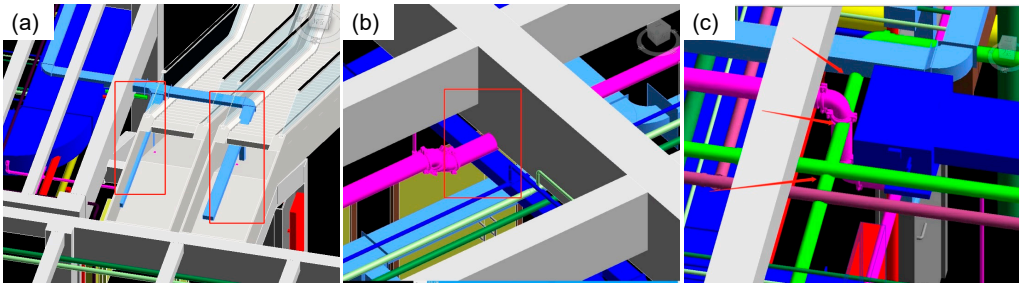


Figure 17. (**a**–**c**) Examples of clash detection.

6.3. Operation and Maintenance Phase

The implementation of the new medical re-form leads to the integration of more information technologies, such as artificial intelligence and sensing technology, in medical industry; thus, it promotes the prosperity and development of the industry. The mixed-use hospital is proposed to enable the normalization of epidemic prevention in the post-pandemic period, and an intelligent medical system is introduced to effectively improve the treatment experience and efficiency of these hospitals. Through indoor IoT base stations and platforms, telemedicine integrated platform, smart energy management platform, and smart traffic guidance system, various IoT data will be collected and processed to achieve the precise positioning and interconnection of hospital personnel and equipment information. It provides support for the development of intelligent innovative business within the hospital and builds an intelligent medical health platform to improve the quality of medical service.

As mentioned above, we have established the intelligent medical system, including a patient temperature monitoring system, environmental monitoring system, vital signs monitoring system, intelligent nursing system, etc., as shown in Figure 18. At the same time, the intelligent ward provides the IoT platform for patients and medical staff, so that the needs of patients can be transferred to the medical staff more quickly, and the medical staff can rely on the intelligent nursing system to quickly deal with the needs of patients and provide a more efficient medical service. In addition, the patient data collected through the clinical data acquisition system can be scientifically and systematically extracted to provide a reference for medical staff to make decisions.

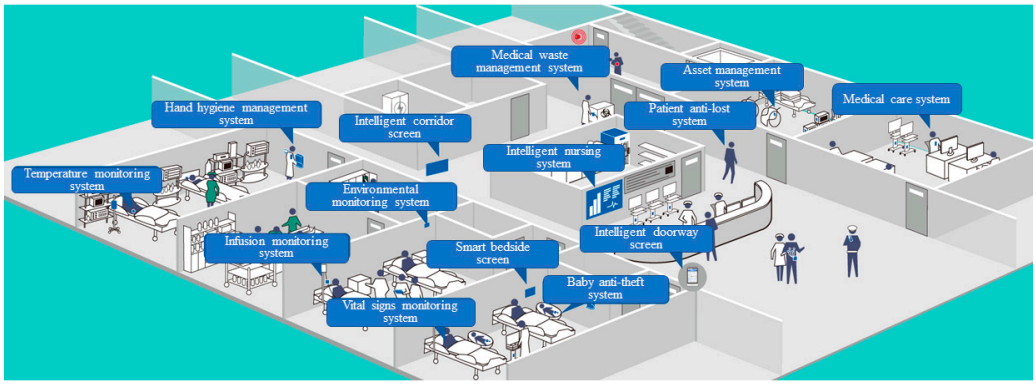


Figure 18. Schematic diagram of intelligent medical system.

6.4. Economic Analysis

As mentioned above, mixed-use hospitals are multi-functional and are usually associated with a series of challenges in design. As such, the complex functions and design specifications of the mixed-use hospitals will increase the construction cost. This study used a traditional hospital as a reference, Yangxin County People's Hospital in Huangshi, China, which is a general hospital completed in 2021 and compared the construction and installation cost of two hospitals, as shown in Table 2. The cost per unit area of the mixed-use hospital is 11.6% higher than that of the reference hospital, which is a reasonable and acceptable result. As the design of wards and functional streamlines must meet the requirements of an infectious disease hospital, it results in the higher cost of construction materials and mechanical and electrical equipment. It should be emphasized that once the mixed-use hospital is built, there will be no need to build large amounts of temporary infectious disease hospitals in the event of an outbreak of an infectious disease, which can save unnecessary cost.

Table 2. Comparative evaluation of construction and installation cost for two hospitals.

	The Mixed-Use Hospital	Yangxin County People's Hospital
Construction and installation cost (million yuan)	1773.57	794.64
Built area (m^2)	240,000	120,000
Cost per unit area (yuan)	7390	6622

7. Discussion and Conclusions

The outbreak of COVID-19 has had a significant impact on public health globally, and hospitals require proactive and systematic planning to better deal with potential crises. This study documented the first case study of a BIM-based simulation approach for life-cycle quality control in a post-pandemic hospital. The use of BIM forward design supports accurate information gathering at an early stage, which saves time for subsequent tasks and promotes information exchange between stakeholders to optimize production and construction, reducing overall construction time and cost. Additionally, various architectural design and construction specifications of hospitals need to be reorganized and special attention paid to public building inspection and environmental safety, which are highly sensitive to public health.

To improve the operational efficiency of hospitals and create a more comfortable and convenient medical environment, smart hospital design needs to be focused on information technologies. The application of artificial intelligence and big data will become essential in the design and operation of hospitals in the future. The extensive use of non-contact smart technology can minimize cross-infection. The management of epidemic prevention personnel needs to be strengthened, and a normalized training mechanism for infectious disease prevention needs to be established to improve the ability of medical staff to respond to public health emergencies.

With the normalization of COVID-19 prevention and control, mixed-use hospitals have become an effective solution to deal with public health emergencies. The construction of mixed-use hospitals needs to consider general layout, functional and channel streamline transformation, and ward renovation. BIM's advantages in data integration and efficient information exchange have been considered in this case to manage overwhelming construction information. The collaborative work efficiency has been greatly improved through the BIM-based forward design method, ensuring high-quality project delivery with an intensive schedule.

This research paper provides an important reference for cities and countries under the threat of COVID-19. Future studies are expected to advance life-cycle quality control in post-pandemic hospitals and strengthen public health systems' adaptation to epidemics through the use of information technologies.

A limitation of this study is that only the COVID-19 pandemic scenario has been analyzed, and other types of infectious diseases were not analyzed to verify the effectiveness of our proposed analytical framework. In future studies, we will use digital technologies [27,28] to automatically collect data and further conduct more detailed analyses based on the transmissibility of infectious diseases to improve the resilience of our analytical framework.

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References

1. Sohrabi, C.; Alsafi, Z.; O'Neill, N.; Khan, M.; Kerwan, A.; Al-Jabir, A.; Iosifidis, C.; Agha, R. World Health Organization declares global emergency: A review of the 2019 novel coronavirus (COVID-19). *Int. J. Surg.* **2020**, *76*, 71–76. [CrossRef] [PubMed]
2. Cao, Y.; Li, Q.; Chen, J.; Guo, X.; Miao, C.; Yang, H.; Chen, Z.; Li, C.; Li, L. Hospital Emergency Management Plan during the COVID-19 Epidemic. *Acad. Emerg. Med.* **2020**, *27*, 309–311. [CrossRef] [PubMed]
3. Leon, I.; Sagarna, M.; Mora, F.; Otaduy, J.P. BIM application for sustainable teaching environment and solutions in the context of COVID-19. *Sustainability* **2021**, *13*, 4746. [CrossRef]
4. Lavikka, R.H.; Smeds, R.; Jaatinen, M. Coordinating collaboration in contractually different complex construction projects. In *Supply Chain Management: An International Journal*; Emerald Group Publishing Limited: Bingley, UK, 2015; Volume 20, pp. 205–217.
5. Hareide, P.J.; Bjørberg, S.; Støre-Valen, M.; Haddadi, A.; Lohne, J. Strategies for Optimization of Value in Hospital Buildings. *Procedia-Soc. Behav. Sci.* **2016**, *226*, 423–430. [CrossRef]
6. Kannampallil, T.G.; Schauer, G.F.; Cohen, T.; Patel, V.L. Considering complexity in healthcare systems. *J. Biomed. Inform.* **2011**, *44*, 943–947. [CrossRef] [PubMed]
7. Mackrill, J.; Marshall, P.; Payne, S.; Dimitrokali, E.; Cain, R. Using a bespoke situated digital kiosk to encourage user participation in healthcare environment design. *Appl. Ergon.* **2017**, *59*, 342–356. [CrossRef]
8. Setyowati, E.; Harani, A.R.; Falah, Y.N. Green Building Design Concepts of Healthcare Facilities on the Orthopedic Hospital in the Tropics. *Procedia-Soc. Behav. Sci.* **2013**, *101*, 189–199. [CrossRef]
9. Støre-Valen, M.; Kathrine, L.A.; Bjørberg, S. Buildings' impact on effective hospital services: The means of the property management role in Norwegian hospitals. In *Journal of Health Organization and Management*; Emerald Group Publishing Limited: Bingley, UK, 2014; Volume 28, pp. 386–404.

10. Shi, W. Framework for Integration of BIM and RFID in Steel Construction. Ph.D. Thesis, University of Florida, Gainesville, FL, USA, 2009.
11. Becerik-Gerber, B.; Jazizadeh, F.; Li, N.; Calis, G. Application Areas and Data Requirements for BIM-Enabled Facilities Management. *J. Constr. Eng. Manag.* **2012**, *33*, 431–442. [CrossRef]
12. Zeidan, M.N.; Hershberg, M.A.; Reynolds, A.D.; Gavan, J.R.; Nazareno, R.; Kuznik, T.; Hazleton, B. Successful Implementation of Design Assist on a Large California Hospital Project. In *Structures Congress 2010*; American Society of Civil Engineers: Orlando, FL, USA, 2010; pp. 3375–3386.
13. Manning, R.; Messner, J.I. Case studies in BIM implementation for programming of healthcare facilities. *Electron. J. Inf. Technol. Constr.* **2008**, *13*, 446–457.
14. Oh, M.; Lee, J.; Hong, S.W.; Jeong, Y. Integrated system for BIM-based collaborative design. *Autom. Constr.* **2015**, *58*, 196–206. [CrossRef]
15. Zhan, Z.; Xu, W.; Xu, L.; Qi, X.; Song, W.; Wang, C.; Huang, Z. BIM-based green hospital building performance pre-evaluation: A case study. *Sustainability* **2022**, *14*, 2066. [CrossRef]
16. Motamedi, A.; Hammad, A. Lifecycle management of facilities components using radio frequency identification and building information model. *J. Inf. Technol. Constr.* **2009**, *14*, 25.
17. Goedert, J.D.; Meadati, P. Integrating Construction Process Documentation into Building Information Modeling. *J. Constr. Eng. Manag.* **2008**, *134*, 509–516. [CrossRef]
18. Davies, R.; Harty, C. Implementing 'Site BIM': A case study of ICT innovation on a large hospital project. *Autom. Constr.* **2013**, *30*, 15–24. [CrossRef]
19. Chen, L.; Yuan, R.; Ji, X.; Lu, X.; Xiao, J.; Tao, J.; Jiang, L. Modular composite building in urgent emergency engineering projects: A case study of accelerated design and construction of Wuhan Thunder God Mountain/Leishenshan hospital to COVID-19 pandemic. *Autom. Constr.* **2021**, *124*, 103555. [CrossRef] [PubMed]
20. Irizarry, J.; Gheisari, M.; Williams, G.; Roper, K. *Ambient Intelligence Environments for Accessing Building Information: A Healthcare Facility Management Scenario*; Facilities, L.S., Ed.; Emerald Group Publishing Limited: Bingley, UK, 2014; Volume 32, pp. 120–138.
21. Lucas, J.; Bulbul, T.; Thabet, W.; Anumba, C. Case Analysis to Identify Information Links between Facility Management and Healthcare Delivery Information in a Hospital Setting. *J. Arch. Eng.* **2013**, *19*, 134–145. [CrossRef]
22. Yalcinkaya, M.; Singh, V. Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis. *Autom. Constr.* **2015**, *59*, 68–80. [CrossRef]
23. Paez, A. Gray literature: An important resource in systematic reviews. *J. Evid. Based Med.* **2017**, *10*, 233–240. [CrossRef]
24. Farace, D.J.; Schöpfel, J. (Eds.) . *Grey Literature in Library and Information Studies*; De Gruyter Saur: Berlin, Germany; New York, NY, USA, 2010.
25. Barr, K.; Bungale, P.; Deasy, S.; Gyuris, V.; Hung, P.; Newell, C.; Zoppis, B. The VMware mobile virtualization platform: Is that a hypervisor in your pocket? *ACM SIGOPS Oper. Syst. Rev.* **2010**, *44*, 124–135. [CrossRef]
26. Ajouz, R. Parametric design of steel structures fundamentals of parametric design using Grasshopper. *Steel Constr. Des. Res.* **2021**, *14*, 185–195. [CrossRef]
27. Fang, W.; Love, P.E.; Ding, L.; Xu, S.; Kong, T.; Li, H. Computer vision and deep learning to manage safety in construction: Matching images of unsafe behavior and semantic rules. *IEEE Trans. Eng. Manag.* **2021**, 1–13. [CrossRef]
28. Fang, W.; Love, P.E.; Luo, H.; Ding, L. Computer vision for behaviour-based safety in construction: A review and future directions. *Adv. Eng. Inform.* **2020**, *43*, 100980. [CrossRef]

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