Automatic generative design and optimization of hospital building layouts in consideration of public health emergency

Chenshuang Li, lics@hust.edu.cn
Center for Smart and Healthy Buildings, Huazhong Univ. of Science and Technology, Wuhan, Hubei 430074, China.
School of Civil and Hydraulic Engineering, Huazhong Univ. of Science and Technology, Wuhan, Hubei 430074, China.

Ying Zhou*, ying_zhou@hust.edu.cn
Center for Smart and Healthy Buildings, Huazhong Univ. of Science and Technology, Wuhan, Hubei 430074, China.
School of Civil and Hydraulic Engineering, Huazhong Univ. of Science and Technology, Wuhan, Hubei 430074, China.

Cong Wang, conghust@163.com
Center for Smart and Healthy Buildings, Huazhong Univ. of Science and Technology, Wuhan, Hubei 430074, China.
School of Civil and Hydraulic Engineering, Huazhong Univ. of Science and Technology, Wuhan, Hubei 430074, China.

Abstract
The COVID-19 pandemic has resulted in significant social and economic losses worldwide. The pandemic puts forward great challenge and higher requirements for future hospital construction especially for building layouts. How to conduct reasonable hospital building layouts design to meet different requirements building performance for peacetime (high efficiency) and emergency (low risk) has coming to be a highlighted problem. This study proposed a performance-oriented approach of automatically generative design and optimization of hospital building layouts in consideration of peacetime and emergency in the early design stage. Firstly, the key points and parameters of hospital building layout design are analyzed and summrized. Then, to meet the requirement of high efficiency and low risk performance, adjacent preference score and infection risk coefficient are constructed as constraints. On this basis, automatic generative design is conducted to generate building layouts schemes. Finally, the comprehensive score of schemes was calculated by normalization formula to obtain the optimal scheme. The method proposed in this study has been applied and verified in an actual hospital building layout design, which was proven to be its reliabe and practicabe and can help systematically explore the solution for better decision making.

Keywords
Generative design and optimization, hospital building layouts, performance, public health emergency

*Corresponding author. School of Civil and Hydraulic Engineering, Huazhong Univ. of Science and Technology, Wuhan, Hubei 430074, China. E-mail address: ying_zhou@hust.edu.cn

1 Introduction

The COVID-19 pandemic has spread to almost all countries around the world, resulting in significant social and economic losses. Hospitals are special public buildings with high hygiene and comfort requirements. During the early stages of the pandemic, it is difficult for general hospital to quickly transform building layouts into the 'three zones and two passages' pattern, which includes a contaminated zone, a semiclean zone and a clean zone, passages for health workers, and passages for patients (Fang, *et al*. 2020). Therefore, most hospitals do not have the ability to treat a large number of respiratory infectious patients and nosocomial infections occurred frequently because of the limitations of building layouts (Wang, *et al*. 2020). In order to effectively control the epidemic, the government built new temporary hospitals such as Huoshenshan hospital for fixed-point treatment of patients (Chen, *et al*. 2021). However, these newly built temporary hospitals were gradually vacant or demolished resulting in lots of medical resources waste. The pandemic puts forward great challenge and higher requirements for future hospital construction especially for building layouts (Chen, *et al*. 2020; Chen, *et al*. 2021). In order to improve medical ability in respond to public health emergencies in future, solve possible problems like bed shortages and frequent nosocomial infections, and reduce the waste of medical resources, the idea of building "combined peacetime and emergency" hospitals was proposed (Chen, *et al*. 2020; Chen, *et al*. 2021). Hospitals based on the combination of peacetime and emergency were required to efficiently provide medical services and reserve necessary temporary land in "peacetime", and effectively reduce infection risk by making full use of open space in "emergency", as shown in Figure 1. In the early design phase, building layouts design of hospitals is one of the most important design tasks, which plays a key role in ensuring building performance. Therefore, how to conduct reasonable hospital building layouts design to meet different requirements building performance for peacetime (high efficiency) and emergency (low risk) has coming to be a highlighted problem, which must be regarded with great interest and urgently be solved.

As a decision-making tool, machine learning techniques, have recently been applicated in many fields (Turrin *et al*. 2011; Chang *et al*. 2019). Generative design based on machine learning technique has enabled designers to generate numerous alternatives by adjusting design parameters under constraints (Vjlg *et al.* 2019; Du *et al*. 2020; Ao and Er 2020). Although well developed, such parametric modelling tools was only as computer-aided tools in hospital building layouts design (Jamali *et al*. 2020). Building layouts design of hospitals are complicated involving a wide range of functional units, each serving for different activities such as clinical, nursing, administration, service (food, laundry, etc.), research, and teaching (Cubukcuoglu *et al.* 2021). To effectively generate hospital building layouts meeting both high efficiency performance in peacetime and low risk performance in emergency is a challenging task. This paper presents the development of a novel methodology to automatic generative design and optimization of hospital building layouts in consideration of peacetime and emergency, which can help support decision making for architects and designers.

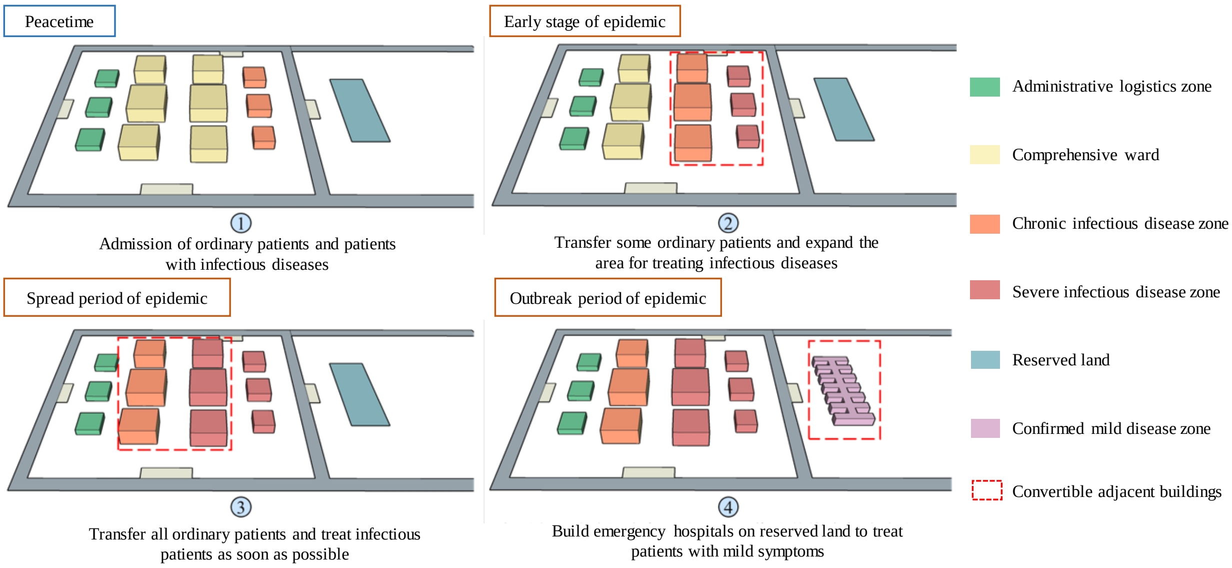

Fig. 1. Hierarchical epidemic prevention and control measures

2 Literature Review

Over the last few decades, when computational design became popular, many researchers attempted to solve the layout generation problem by exhaustively generating all possible results (Dino I *et al*. 2017). Some researchers have proposed approaches for the automatic generation of hospital building layouts (Jamali *et al*. 2020). To solve a 3D space planning problem, Cubukcuoglu et al. proposed a quadratic assignment problem with geodesic distances to conduct hospital layout design renovation (Cubukcuoglu *et al*. 2021). Based on generative adversarial networks, Chao et al. proposed an intelligent functional layout generation method for emergency departments of general hospitals (Zhao *et al*. 2021). Ines et al. proposed an approach of multi-period layout planning for hospital wards by using variable ward layout model (Arnolds and Nickel 2013). Jamali et al. reviews an area of interdisciplinary collaboration in the optimization design of hospital space-planning using automated statistical techniques (Jamali *et al*. 2020). They found most studies focused on flow efficiency and do not consider broader contextual, relational, social, or salutogenic design values. Additionally, for the design of Wuhan Huoshenshan Hospital, Chen et al. analyzed and summarized key designs of building layout for COVID-19 emergency hospital (Chen *et al*. 2021). Overall, previous research on the layouts of hospital building is inadequate. Most works focus on individual departments layout optimization in the hospital such as nursing units. Considering the whole set of hospital departments in layout optimization is scarce in the literature. Another challenge for the layout optimization of hospital buildings is the different performance requirements in peacetime and emergency. These critical problems have not yet been solved in the literature, and therefore a new optimization strategy is required for exploring the optimal layout plan for hospitals in consideration of peacetime and emergency.

3 Research Methodology

To meet different performance requirements in consideration of peacetime and emergency, this research proposes a methodology for automatic generative design and optimization of hospital building layouts, as shown in Figure 2. First, key points and specific parameters of hospital building layouts were analysed and stored as input data. Second, automatic generative design was conducted to generated hospital building layout schemes by using Generative Design plugin of Dynamo.

Automatic generative design includes two main steps: 1) objective functions of adjacency preference and infection risk score were generated as constraints; 2) random and optimized generative design based on machine learning were done after model was established. Third, based on the performance evaluation of schemes, comprehensive score of schemes were calculated by normalization formula, and the scheme with the lowest comprehensive score is the optimal scheme.

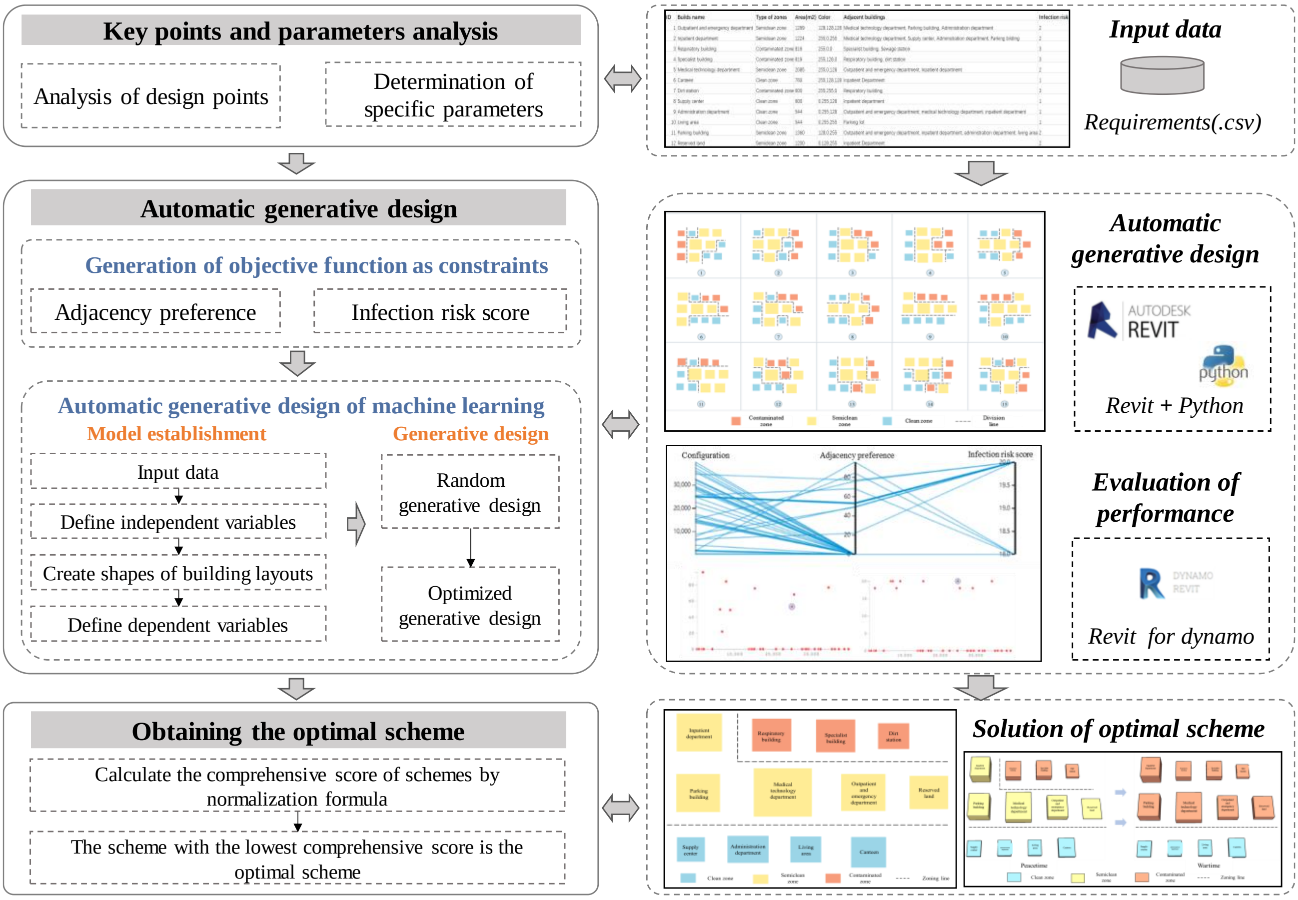

Fig. 2. Methodology workflow.

3.1 Generation of objective function as constraints

In view of the combination of peacetime and emergency, different performance of the hospital building layouts design should be considered as the optimization goal. Adjacent preference score and infection risk coefficient are used as constraints to measure the operational efficiency during peacetime and the risk of infection in emergency of hospital.

3.1.1 Adjacency preference

Adjacency preference score is the sum of the center distance of buildings with adjacency preference relationship, which considers both adjacent states and distances. The lower score means shorter total moving path among each building in the workflow, indicating higher work efficiency. The formula of adjacent preference score is as follows:

$$S_A = \sum_{i=1}^{n}\sum_{j=1}^{n} \alpha_{ij} d_{ij} \tag{1}$$

S_A is adjacency preference score. n is the number of buildings. d_{ij} is the centre distance between the buildings i and j. α_{ij} is the adjacency preference coefficient. When there is adjacency preference between buildings i and j, α_{ij} is set to 1, otherwise, it is set to 0.

3.1.2 Infection risk score

The risk coefficients of contaminated zone, semiclean zone and clean zone, are defined as 3, 2 and 1 respectively. To reduce the risk of cross infection by optimizing the layout of building, an infection risk function is calculated. The infection risk score is the sum of the difference between the risk coefficient of each building and the maximum coefficient of the buildings around it. The formula is as follows:

$$S_R = \sum_{i=1}^{n} (r_{imax} - r_i) \quad (2)$$

S_R is the infection risk score. n is the number of buildings. r_i is the risk coefficient of building i and r_{max} is the maximum risk coefficient of the buildings around i.

3.2 Solution of optimal scheme

The aim of this research is to obtain a hospital building layout with the lowest adjacency preference score and the lowest infection risk. To satisfy both requirements, the normalized formula is adopted to select the hospital building layout scheme with the minimum comprehensive deviation, which is the optimal hospital building layout in consideration of peacetime and emergency. The normalized formula is as follows:

$$\xi_i = (S-S_{min}) / (S_{max}-S_{min}) \ (i = A, R) \quad (3)$$

$$\xi = (\xi_A+\xi_R) / 2 \quad (4)$$

S is the score of indexes in each alternative plan, and S_{max} and S_{min} are the maximum and minimum values of corresponding indexes respectively. A, R represent adjacency preference and infection risk. ξ_i *is* the relative deviation, ξ is comprehensive deviation.

4 Case study

A case study is used to demonstrate the proposed new approach for automatic generative design and optimization of hospital building layouts in consideration of peacetime and emergency. The selected case is a medical center building for a tertiary hospital in Wuhan, China, which will be designed and constructed with the aim of peacetime and emergency combination.

4.1 Project overview

The medical center was designed to be built on the north side of the hospital. The outpatient department, children's hospital, parking building and other functional zones were located at the south side of the hospital, as shown in Figure 3. In peacetime, the medical center was an ordinary inpatient building which can achieve efficient connection with other buildings. In emergency, the medical center can be quickly transformed into an infectious disease hospital to treat infectious disease patients independently. The medical center is composed of two mirrored units, and the unit on the west side is selected as the research object in this study.

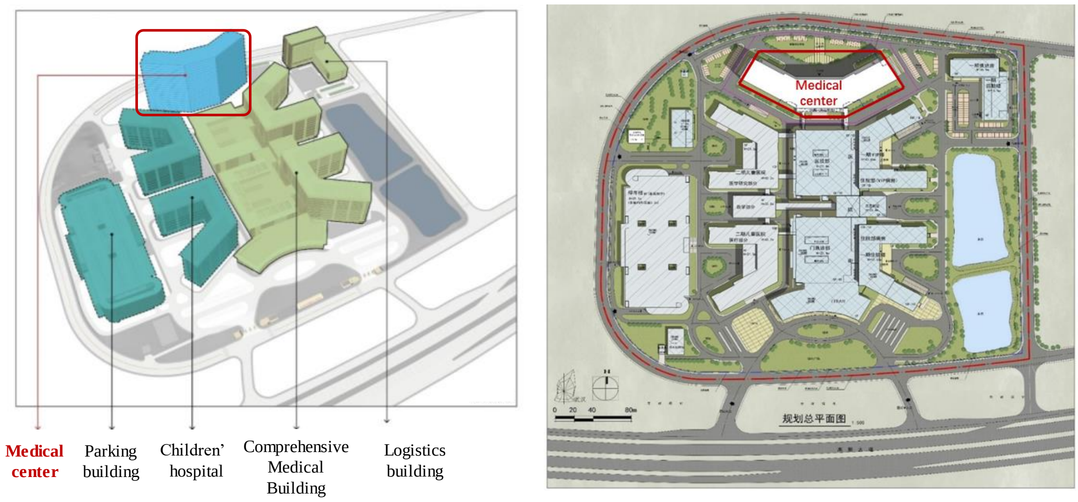

Fig. 3. Building layout and functional zone of the hospital

4.2 Identify key points and parameters of building layouts design

According to the current standards and specifications of nosocomial infection management, the key points and parameters of building layouts design in consideration of peacetime and emergency are extracted based on the requirements of project composition, functional zone, streamline organization, isolation and sewerage disposal. Key points and parameters of building layouts design of the medical center include: room components, area type, building area and floor area of each, as well as adjacency preference and risk coefficient as shown in Table 1.

Table 1. Key points and parameters of building layouts design of the medical center

No.	Functional zone	Area type	Area (m^2)	Size (mm*mm)	Adjacency zone	Risk coefficient
A	Medical staffs' corridor	semiclean zone	187	62400*3000	K, L, M, N	2
B	Patient zone 1	contaminated zone	568	62400*9100	F, P, Q	3
C	Patient zone 2	contaminated zone	254	27900*9100	F, P, Q	3
D	Balcony 1	contaminated zone	162	62400*2600	B	3
E	Balcony 2	contaminated zone	73	27900*2600	C	3
F	Patients' corridor	contaminated zone	79	3000*26400	B, C, O	3
G	Office	clean zone	45	7500*6000	G, M	1
H	Medical staffs' elevator	clean zone	27	4500*6000	G, I	1
I	Duty room	clean zone	50	8400*6000	H, M	1
J	Linen room	semiclean zone	26	4000*6600	A	2
K	Pantry	semiclean zone	26	4000*6600	A, B, C	2
L	Treatment room	semiclean zone	55	8400*6600	A, B, C, N	2
M	Buffer room	semiclean zone	40	6000*6600	A, G, I	2
N	Nurses station	semiclean zone	66	10000*6600	A, B, C, L	2
O	Contaminant elevator	contaminated zone	12	3000*4000	F, P, Q	3
P	Patients' elevator	contaminated zone	22	5400*4000	B, C, O	3
Q	Contaminant room	contaminated zone	12	3000*4000	B, C, O	3

4.3 Automatic generative design of machine learning

Automatic generative design of machine learning includes two steps: model establishment and generative design. In the process of model establishment, the key parameters data of building layout were imported into Dynamo. Then, the locations of different functional zone were defined as independent variables, and the shapes of different functional zone were created based on area and size. Further, the adjacency preference score and infection risk score are defined as dependent variables. Finally, after random and optimized generative design, the repeated results are eliminated, and six schemes with smaller adjacency preference score and infection risk score were obtained, as shown in Figure 4.

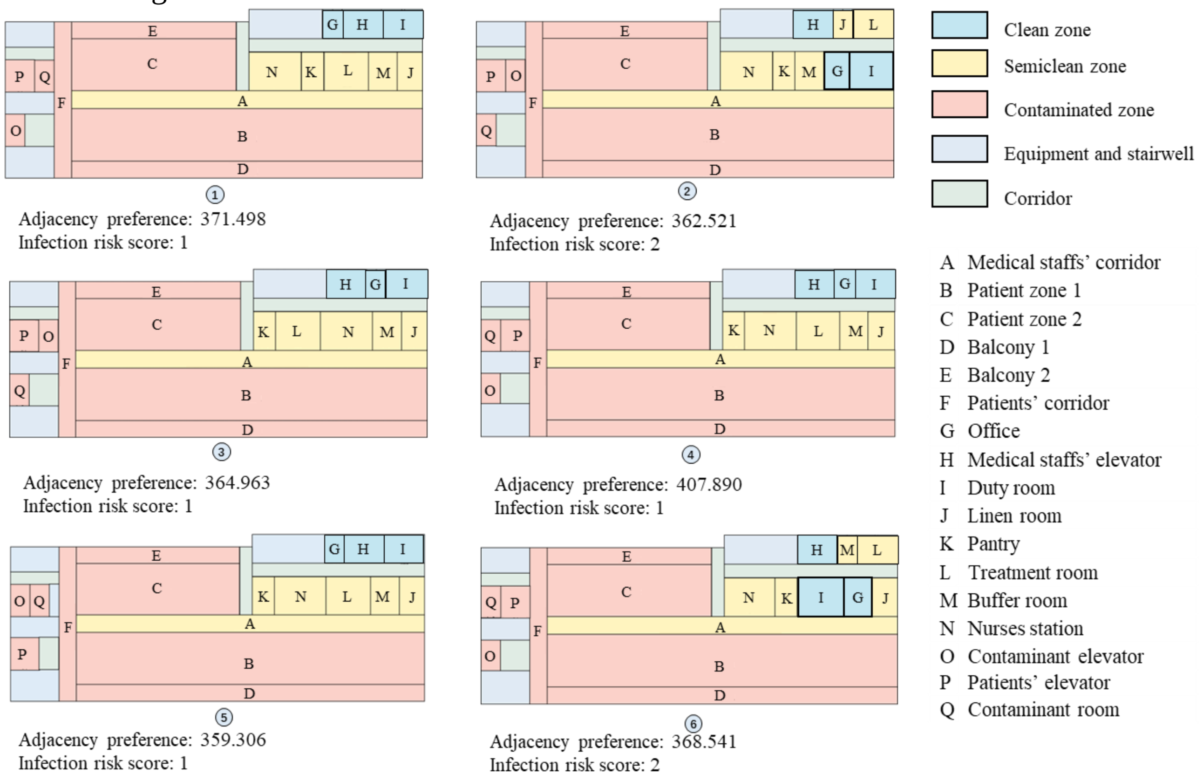

Fig. 4. The results of automatic generative design

4.4 Solution of optimal scheme

The west unit of the medical center standard floor was research object in this study. After normalization, scheme 5 got the lowest total score (Table 2) and selected as the optimal scheme for the medical center layout. As shown in Figure 4, the north area on the east side is the public area for medical staffs including offices, medical staffs' corridor and duty room, which is the clean zone. Near the public area is the treatment area for both patients and staffs including pantry, therapy, nurse station, buffer room and linen room as well as medical corridor, which is semiclean zone. There are two patients' zones and balconies at the north side of standard floor, which are contaminated zone. The generated building layout of medical center can effectively achieve the transition from peacetime to emergency. The medical center can treat ordinary patients and effectively improve the working efficiency of the medical staffs in peacetime. In emergency, the balconies can be transformed into patients' corridor, which meet the requirements of "three zones and two passages". The medical center can treat infectious patients and reduce the risk of infection in emergency, as shown in Figure 5. Compared with the original scheme, the generated optimal scheme changes the locations of the medical elevator, the office, the nurse station and the therapy, so that the adjacency preference score of the scheme is reduced. Therefore, the obtained scheme can effectively improve the operation efficiency and is better than the original scheme.

Table 2. The adjacency preference and infection risk score of alternatives.

Scheme	Adjacency preference	Infection risk score	ξ
1	371.498	1	0.13
2	362.521	2	0.53
3	364.963	1	0.06
4	407.89	1	0.50
5	**359.306**	**1**	**0.00**
6	368.541	2	0.60

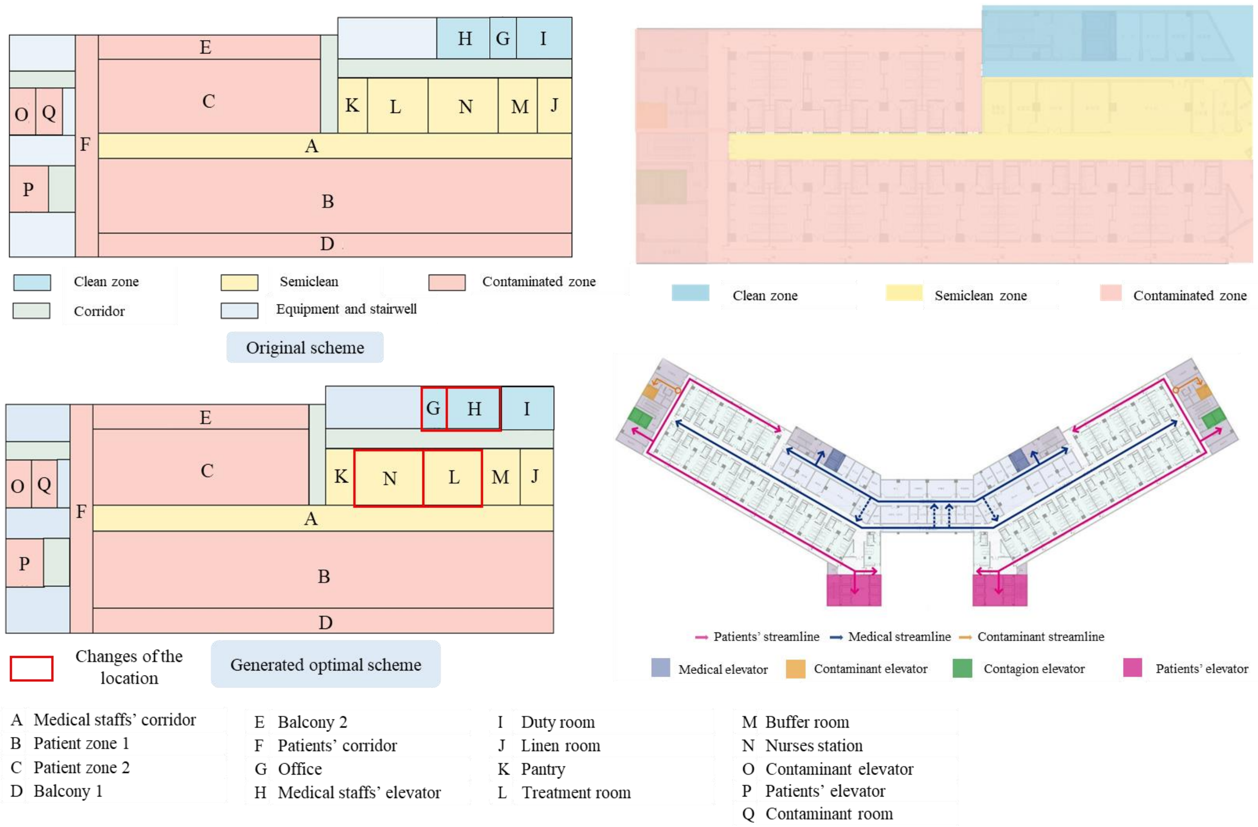

Fig. 5. The generated optimal scheme

5 Conclusions and Further Research

COVID-19 has put forward higher requirements for the performance of future hospital. How to design reasonable layout of hospital buildings to meet different performance requirements in peacetime and emergency has become a critical issue. This study proposes a performance-oriented approach of automatically generative design and optimization of hospital building layouts in consideration of peacetime and emergency in the early design stage.

Firstly, key points and parameters of hospital building layout design are analysed, and then adjacency preference score and infection risk score are constructed as constraints. On this basis, automatic generative design of machine learning is carried out to generate better schemes. Finally, the optimal scheme is obtained by normalization. Based on the different performance requirements of hospital buildings in peacetime (high efficiency) and emergency (low risk), this study creatively propose two indexes as constraint conditions, adjacency preference score and infection risk score during the hospital building layout generation process. The proposed approach has been applied and verified in practical hospital building layout design and proven to be of high reliability and practicability, which can contribute to systematically explore the solution for better-supported decision making.

There are several possible limitations of this study. Firstly, in the optimization process of hospital layout design, this study only takes high operation efficiency and low infection risk as the goal by considering adjacency preference and infection risk scores. In the future, indexes such as construction cost and operating benefit can be introduced to conduct a more comprehensive multi-objective design optimization of hospital building space layout (Jamali *et al*. 2020). Additionally, the form of building layouts in the scheme is limited to rectangles, and another exciting area of future work involves conducting irregular space layouts and facility layouts into optimization for the framework of generative design (Hao 2016; Ahmadi *et al*. 2016).

6 Acknowledgement

The presented work has been supported the National Natural Science Foundation of China (NSFC) [Grant numbers. No.72071089].

7 References

Ahmadi A., Jokar M., 2016. An efficient multiple-stage mathematical programming method for advanced single and multi-floor facility layout problems. *Applied Mathematical Modelling*, 40(9-10):5605-5620.

Ao A., Er B., 2020. Automated generation of optimal thematic architectural layouts using image processing. *Automation in Construction*, 117: 103255.

Arnolds I., Nickel S., 2013. Multi-period layout planning for hospital wards. *Socio-Economic Planning Sciences*, 47(3):220-237.

Chang S., Saha N., Castro-Lacouture D., et al., 2019. Multivariate relationships between campus design parameters and energy performance using reinforcement learning and parametric modeling. *Applied Energy*, 249: 253-264.

Chen S., Zhang Z., Yang J., et al., 2020. Fangcang shelter hospitals: a novel concept for responding to public health emergencies. *Lancet*, 395:1305–14.

Chen Y., Wang Q., Lei J., et al., 2021. Design characteristics on the indoor and outdoor environments of the COVID-19 emergency hospital. *Journal of Building Engineering*, 45: 2352-7102.

Cubukcuoglu C., Nourian P., Tasgetiren M., et al., 2021. Hospital layout design renovation as a Quadratic Assignment Problem with geodesic distances. *Journal of Building Engineering*, 44:102952.

Dino I., et al., 2017. Multiobjective Design Optimization of Building Space Layout, Energy, and Daylighting Performance. *Journal of Computing in Civil Engineering*, 31(5):04017025.

Du T., Turrin M., Jansen S., et al., 2020. Gaps and requirements for automatic generation of space layouts with optimised energy performance. *Automation in Construction*, 116: 103132.

Fang D., Pan S., Li Z., et al., 2020. Large-scale public venues as medical emergency sites in disasters: Lessons from COVID-19 and the use of Fangcang shelter hospitals in Wuhan, China. *British Medical Journal Global Health*, 5(6):e002815.

Hao H., 2016. Irregular architectural layout synthesis with graphical inputs. *Automation in Construction*, 72(3): 388-396.

Jamali N., Leung R., Verderber S., 2020. A review of computerized hospital layout modelling techniques and their ethical implications. *Frontiers of Architectural Research*, 9(3): 498-513.

Turrin M., Buelow P., Stouffs R., 2011. Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. *Advanced Engineering Informatics*, 25(4):656-675.

Vjlg A., Hkw A., Ktt A., et al., 2019. Simulation-based evolutionary optimization for energy-efficient layout plan design of high-rise residential buildings. *Journal of Cleaner Production*, 231:1375-1388.

Wang D., Hu B., Hu C., et al., 2020. Clinical Characteristics of 138 Hospitalized Patients With 2019 Novel Coronavirus-infected Pneumonia in Wuhan, China. JAMA, 323(11): 1061-1069.

Zhao C., Yang J., Li J., 2021. Generation of Hospital Emergency Department Layouts Based on Generative Adversarial Networks. *Journal of Building Engineering*, (1):102539.