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Research article

Ensuring sufficient cabin hospital beds for curbing the spread of COVID-19 – Findings from petri net analysis

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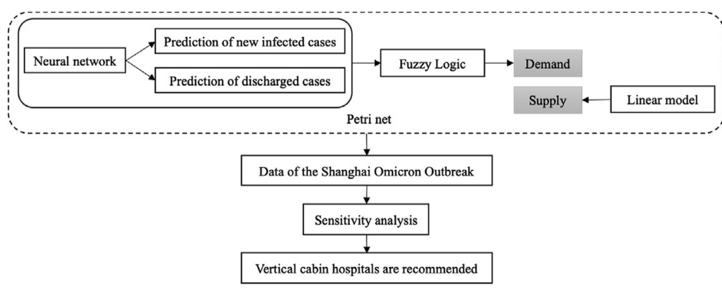
HIGHLIGHTS

- A Petri net analytical tool for studying cabin hospital demand and supply.
- The case of the Shanghai Omicron outbreak.
- Sensitivity analysis for the impact of manpower and impact of venue size.
- Vertical cabin hospitals are recommended to build post-pandemic resilience.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to the complexity of the virus and its rapid rate of spread, many countries face the same challenges of providing adequate medical resources. This paper provides an analytical approach for evaluating the possibility of the regional construction industry constructing a large number of cabin hospitals within a short time. The key idea is to compare the demand and supply of patient beds using a Petri net-based approach that incorporates a neural network for the prediction of demand, fuzzy logic for decision-making, and a linear model for predicting supply. The data reported in the Shanghai Omicron battle is used to validate the developed model. Our results show that the fastest conversion speed and the least manpower requirement are obtained from high-rise buildings. Then, preparing some high-rises for easy conversion into cabin hospitals seems a possible solution for future citywide preparedness toward pandemic resilience.

1. Introduction

The sudden and unexpected COVID-19 has turned our world upside down and we still don't know when the pandemic will end. Since its first confirmed case was reported in late December in Wuhan city, Hubei province of China, the virus has spread quickly from person to person. Millions of lives lost in the past two years. Almost all the countries in the world suffered and sacrificed. In the fight against COVID-19, strict prevention and control measures were adopted from time to time. These measures included lockdown, vaccine rollout, and centralized isolation. However, as the virus continuously mutates and becomes more transmissible, the pandemic is still raging today. Though the latest dominant variant of COVID-19, Omicron, causes less severe disease than infection with prior variants, there is still uncertainty about the virus. It is far too early to be optimistic about the end of the pandemic.

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A big metropolis like the city of Shanghai in China is well-known for its large population in a crowded environment. Reports show that population density and urban density have a stronger connection with the spread of COVID-19 (Pandey et al., 2021). Therefore, urban metropolises are more vulnerable than the rest of the world in wave after wave of the COVID-19 pandemic. The Omicron variant hit Shanghai hard during the second quarter of 2022, and the city carried a massive lockdown. Even though people with Omicron are much more likely to be asymptomatic after full vaccination, its death count is high because Omicron spreads quickly and is infecting a large number of people. To quickly and effectively cut all channels for the transmission of the virus in the community, it needs to separate those infected, including asymptomatic patients and close contacts with the confirmed cases, from healthy people. In this case, sufficient space is required.

The Chinese government resorted to the construction of the so-called cabin hospital, or "方舱" in Chinese, to solve problems with the hospitalization of COVID-19 patients in the previous pandemic wave in Wuhan (Wenlong Yao, 2020). The establishment of 16 cabin hospitals with a capacity of 13,000 beds largely alleviated pressure on the local healthcare system which was overwhelmed by patients flooding into local hospitals. Cabin hospitals first appeared as temporary military medical shelters in the American army in the Vietnam War that takes care of casualties on-site before they can be safely transported to more permanent facilities. After that, they were prevalent in the event of disasters and other emergencies. Generally, cabin hospitals are a kind of makeshift/mobile field hospitals that can be swiftly transported and built with the integration of modular sanitary equipment with multiple functions such as emergency aid, surgical treatment, clinical examination, etc. Cabin hospitals in Wuhan COVID-19 were mainly responsible for treating mildly ill patients (Zhang, Y. et al., 2021a). Researchers later evaluated their effectiveness in controlling the COVID-19 pandemic by retrospectively analyzing the correlation between available beds in cabin hospitals and epidemic data. The number of newly diagnosed cases showed a highly negative correlation with the availability of cabin beds by statistical analysis (Wenlong Yao, 2020).

The previous successful experience with cabin hospitals greatly encouraged the Chinese government to take the same measures though controversial to contain the Omicron outbreak in Shanghai. Within one-month time, Shanghai built over one hundred cabin hospitals, providing 300,000 plus beds. While we are so amazed by the Chinese construction speed, a question comes to mind: Can other countries copy this speed? Due to the complexity of COVID-19 and its rapid rate of spread, many countries have failed to prevent the virus from entering their territory. There is a need to race against time to increase capacity for the effective isolation of infected people (Gbadamosi et al., 2020). In this regard, this paper provides an analytical approach for estimating the potential capability of constructing a large number of cabin hospitals within a short period using a Petri net (PN) model. PNs are state-transition systems that offer a graphical notation for stepwise processes including choice, iteration, and concurrent execution. The PN technology is selected by the authors mainly because of its ease of programming. It can encapsulate the scattered functional units making them like a black box. As such, given the users' inputs, the outputs are automatically given.

The main research objectives are as follows: (1) to predict the future need for patient beds on the basis of current and previous daily numbers of newly diagnosed cases and hospital discharged cases; (2) to estimate the future available patient beds based on the construction speed considering different types of existing venues. The key idea is to compare the demand and supply of patient beds. Firstly, the prediction model, which is an artificial neural network (ANN), is developed. Secondly, it employs fuzzy logic (FL) to decide the number of patient beds that are required. Thirdly, it applies a linear functional relationship model to estimate the patient bed supply from the different venue types. Last but not least, the PN model is created, gluing together all the aforementioned separate components. The data reported in the recent Shanghai Omicron battle is used to validate the developed model. A sensitivity analysis is further performed by varying different system parameters to study the impact of construction manpower supply and the impact of different venue type supply. Insights from this research may aid future citywide preparedness toward pandemic resilience.

2. Literature review

In this section, the existing literature which concerns COVID-19 and cabin hospitals is reviewed. Using the keywords (TITLE-ABS-KEY "COVID-19" AND ("cabin hospital" OR "makeshift hospital")) searched in the database SCOPUS, we found a total of 85 articles during the past two years. The majority of them are in the subject area of medicine, and few are in the subject areas of engineering, computer science, and mathematics. Then, using the literature visualization software like CiteSpace to analyze the patterns and trends in the literature, we observed four main clusters: illness uncertainty-related, health policy-related, cabin hospital design and construction-related, and cabin hospital management-related.

2.1. Illness uncertainty-related

Majority of patients with COVID-19 exhibit mild symptoms. Observational studies show that more than 80% of patients can self-recover. Fewer than 20% of patients require hospital admission for advanced healthcare (Li, H. et al., 2021; Yan, B. et al., 2020a). However, development from mild symptoms to severe or critical illness can be very fast. Even young people with no comorbid conditions who initially exhibit mild symptoms may rapidly develop a severe or critical illness and even die (Bialek et al., 2020).

Though the natural selection process results in the evolution of virus variants with low severity and high transmissibility, researchers predicted that the total number of infections and deaths due to the pandemic would be more linked to the virus' transmissibility than its severity (Xu et al., 2021). Therefore, how to reduce the transmission risk of COVID-19 more effectively is a top concern in the battle. Li et al. (Li, M. et al., 2021) studied the New York case and concluded that the daily number of new cases could be significantly reduced if all infected patients were diagnosed in time. And if all confirmed cases were hospitalized in time, the total number of deaths could be significantly reduced.

The diagnosis of COVID-19 is made primarily by nucleic acid tests. However, the accuracy and predictive values of nucleic acid tests have not been systematically evaluated. False-positive results are sometimes reported. Meng (Meng et al., 2020) suggested the complementary use of chest computed tomography, especially for deciding on the discharge of patients.

2.2. Health policy-related

As the COVID-19 virus transmits quickly, the need for a timely response from governments emerges as a crucial factor. To present, governments worldwide have employed a series of non-pharmaceutical intervention (NPI) measures, including isolation, quarantine, social distancing, and community containment, to combat the transmission of the virus. Yet, there are noticeable country-to-country variations regarding the scale and scope of these measures (Yan et al., 2020b).

Chen et al. (Chen Haiqian et al., 2021), Wang et al. (Wang, X. et al., 2021), and Zhang et al. (Zhang, Y. et al., 2021b) analyzed the common points and discrepancies of NPIs in the first wave of COVID-19 between China and South Korea, China and Singapore, China and Germany, respectively. Compared to the other counties, China implemented more rigorous lockdown measures and a stricter quarantine strategy to eliminate the virus, while the other countries adopted more moderate measures based on maintaining a relatively normal social life and protecting high-risk groups to reduce losses. The authors also identified the similarities in different policies implemented in different countries. They found active case detection, early detection of patients, timely isolation, and treatment, and increasing medical capabilities are crucial factors to combat COVID-19. However, there is no answer given to which policy performs better. Turrini et al. (2020) researched the same type of intervention (i.e. conversion of convention centers into cabin hospitals) in two different geographical settings (i.e. New York and Milan). They revealed that there is no one best way to intervene in emergencies. Researchers thereby suggested a configurational approach to government intervention in emergencies, future studies may adopt a multidimensional and contingency perspective for different contexts.

2.3. Cabin hospital design and construction-related

Isolation at cabin hospitals is the most recommended approach for effectively halting the epidemic and pandemic in cases where the patient number has overwhelmed the existing healthcare system (Gbadamosi et al., 2020). In the development of cabin hospitals, it is vital to consider the specific building requirements, the availability of building resources, and the potential environmental impacts. A series of protocols and standards must be met to ensure standard expectations and patient safety. Overall speaking, cabin hospitals should be distant from densely populated urban areas and negative pressure ventilation is compulsory to minimize exposure to indoor pollutants in the surrounding areas. Besides, the architectural layout of a cabin hospital should meet the requirements of "three areas and two passages" (the contaminated area, potentially contaminated area, clean area; medical staff passage, and patient passage). The maximum number of patients that a cabin hospital can accommodate depends on the number of medical care and hardware capabilities (Wang et al., 2020).

Researchers (Gbadamosi et al., 2020; Li, T. et al., 2021) stated that rapid design and construction of a cabin hospital could be achieved through technologies such as modular and offsite construction, building information modeling (BIM), and computational fluid dynamics (CFD). Particularly, Chen et al. (2022) studied the location selection for a cabin hospital combining the best-worst method and data envelopment analysis. Vu et al. (2022) described the efforts taken in New York City to convert a rehabilitation center into a satellite hospital with a capacity of up to 425 patient beds in 10 days. Zhu et al. (2021) proposed the adaptive industrial construction method appropriate for developing a cabin hospital in a rural region. In addition, Bhagat and Linden (2020) recommended displacement ventilation to maintain a healthy indoor environment in cabin hospitals.

2.4. Cabin hospital management-related

The effectiveness of cabin hospitals in quickly containing the outbreak in Wuhan has attracted a lot of Chinese researchers as well as international researchers to take a closer look at them.

In general, patients are admitted to the cabin hospitals in a centralized manner, and cabin hospitals are usually large in scale and treat multiple patients at the same time. Therefore, to prevent and reduce the potential dangers of clustering infections, attention must be paid to the key points of monitoring inside and outside of the cabin, guaranteeing a clean and disinfected environment (Chen et al., 2021). In China, cabin hospitals are just simple temporary institutions without standard medical hospital facilities and a full complement of medical professionals, not like those in developed countries. They mainly serve accommodation and isolation of mile and ordinary COVID-19 patients. To improve the efficiency and standardize the management inside the cabin hospitals, protocol packages including admission criteria, management, and medications, as well as referral criteria and discharge criteria are established. Liu et al. (2021) described these protocols that were prevalent in Wuhan cabin hospitals in detail in their paper.

Inside cabin hospitals, patients are likely to exhibit depressed moods and anxiety. Therefore, in addition to providing medical treatment, cabin hospitals also need to offer psychological and physical interventions such as daily exercise, recovery diaries, emotional painting, etc. Wang (Wang, Y. et al., 2021) and Li et al. (Li, Z. et al., 2021) did survey questionnaires to investigate the stress, depression, and anxiety status of patients in Wuhan cabin hospitals. Their research found that all people (whether or not infected) showed a generally high level of stress, depression, and anxiety, regardless of age, gender, education level, and employment. According to Dong's study (Dong et al., 2022), COVID-19 patients suffer a moderate level of illness uncertainty. Litzinger and Ni noticed the positive effects of social media platforms (e.g., "Douyin") on the psychological recovery of cabin hospital patients though they also worried about the possible political intervention through these platforms. In addition, Zhang et al. (Zhang, X.B. et al., 2021) propagandized that a traditional Chinese qigong exercise – Baduanjin can alleviate anxiety and depression in patients.

2.5. Research gap

The literature concurs on the beneficial role of cabin hospitals in containing the COVID-19 spread. The modular and offsite construction method is also recommended as a rapid design and construction way. However, when the market demand is confirmed, there is still a lack of research on further studying the supply capability of the construction industry.

2.6. Our contributions

This paper contributes an analytical approach for evaluating the possibility of the regional construction industry constructing a large number of cabin hospitals within a short time. While a majority of the COVID-19 literature discuss pandemic control from the demand perspective, e.g., the beneficial role of cabin hospitals, this paper stands out by addressing the supply issue. The paper tries to answer not only the question whether enough qualified isolation space can be provided for affected patients and their close contacts on the verge of an epidemic breakout but also the question about how to provide such resources.

3. Methodology

In this paper, a PN model is proposed to simulate the decision-making and construction progress regarding cabin hospitals in the face of an explosive epidemic. Because the construction has a lead time, the current construction is in fact to fulfill future demand. So, we propose an ANN model to predict future demand. Meanwhile, the available patient beds are estimated according to the predicted hospital discharged cases using the same ANN model. Next, the need for extra patient beds is estimated taking into account the psychological effect. The value is adjusted by an FL model and quantized into discrete levels. At last, we estimate the patient bed supply by a simple linear forecasting model based on the knowledge of existing venues and the average construction speed. In the following, the models are elaborated.

3.1. Petri net model for the analytical system

PNs are a graphical and mathematical modeling tool applicable to the analysis of dynamic systems. A PN is a collection of directed arcs connecting places and transitions. Places and transitions are represented by circles and rectangles, respectively. The place that connects to a transition is called an input place of the transition. On the other hand, the place that is connected to a transition is called an output place of the transition. Places may hold tokens. Tokens are represented by dots. A transition is enabled for firing when there is at least one token on each of its input places. When a transition fires, it removes a token from each of its input places and puts a token in each of its output places. In addition to the instantaneous firing assumption, a time delay can be associated with a transition location, and consequently, it fires. The state or marking of the PN is its assignment of tokens to places.

In this study, we let tokens represent patient beds. The proposed PN model for the analytical system is illustrated in Figure 1. The first step is to decide the extra patient beds needed from the predictions of the number of newly infected cases and the number of available patient beds. Then, based on the site space of existing venues and average construction speed, we predict the number of patient beds that we can obtain. Delay firing is associated with the transitions of T5 to simulate the construction time. Construction speed varies between projects depending on the manpower available and the job complexity.

3.2. A neural network model for prediction of daily new cases and hospital discharged cases

ANN technique is applied to make forecast the new patient number and discharged patient number. The gap between them determines the extra patient beds needed. An ANN is an interconnected group of nodes, inspired by a simplification of neurons in the human brain. Each circular node represents an artificial neuron and an arrow represents a connection from the output of one artificial neuron to the input of another. The proposed ANN architecture is given in Figure 2. X_i is the input data, observed over successive periods and Y_j is the output data, predicted by this network. W and b refer to the weights and biases in the linear combinations, respectively, which can be calculated using the gradient descent method. Assuming the mean square loss function and sigmoid activation function are used, we have such a set of iterative equations as Eqs. (1), (2), (3), and (4). The number of hidden nodes is to be fine-tuned by the training data given.

$$W_{H_m,Y_j} = W_{H_m,Y_j} - \eta \sum_{j=1}^{n_j} \left(Y_j - Y_{j,target}\right) H_m, \forall m, j \tag{1}$$

$$W_{X_{i,Hm}} = W_{X_i,H_m} - \eta \sum_{j=1}^{n_j} \left(Y_j - Y_{j,target}\right) W_{H_m,Y_j} H_m (1 - H_m) X_i, \forall i, m \tag{2}$$

$$b_{Y_j} = b_{Y_j} - \eta \sum_{j=1}^{n_j} \left(Y_j - Y_{j,target}\right), \forall j \tag{3}$$

$$b_{H_m} = b_{H_m} - \eta \sum_{j=1}^{n_j} \left(Y_j - Y_{j,target}\right) W_{H_m,Y_j} H_m (1 - H_m), \forall m \tag{4}$$

in which η is the step-size and $Y_{j,target}$ is the target value of output variable Y_j. H_m can be calculated by Eq. (5)

$$H_m = f\left(\sum_{i=1}^{n_i} W_{x_i,H_m} X_i - b_{H_m}\right), \forall m \tag{5}$$

where $f(\bullet)$ is the Sigmoid function.

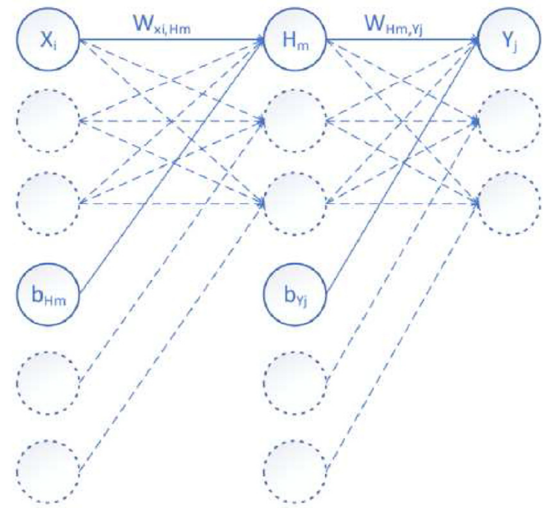

Figure 2. A neural network model for the prediction.

4. A fuzzy logic model for decision-making of patient beds needed

To absorb uncertainties in prediction and inference, an FL model is applied for the decision-making of the needed amount of patient beds. A pessimistic belief is hypothesized if there is an exponential increase in the number of new cases. When a pessimistic belief is held, the need for extra patient beds will be a little exaggerated. A psychological scale factor is applied to adjust the original figure. Likewise, an optimistic belief is hypothesized if there is a sharp drop in the number of new cases. When an optimistic belief is held, it is likely the need for extra patient beds will be understated. Figure 3 shows the proposed FL model.

Moreover, the needed amount of patient beds is quantized into discrete levels. For illustration, let x be the needed amount of patient beds, $m(> 1)$ indicates the width of the quantization level, $[\bullet]$ denotes the rounding quotient to its nearest integer number, then, the quantization index $q(x)$ is defined by Eq. (6).

$$q(x) = \left[\frac{x}{m}\right] \tag{6}$$

As such, the inference result is a rounding value that omits smaller digits, which seems a more natural way to our human beings.

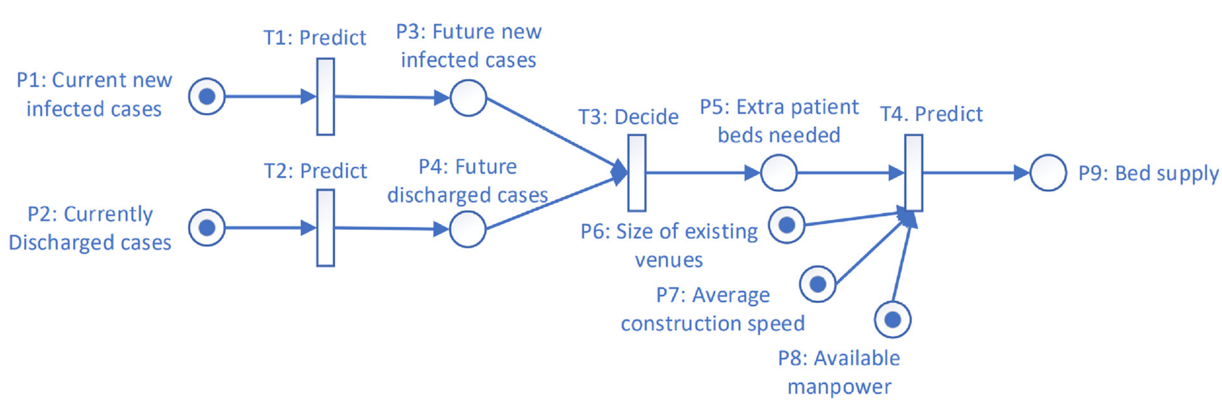

Figure 1. Petri net model for the analytical system.

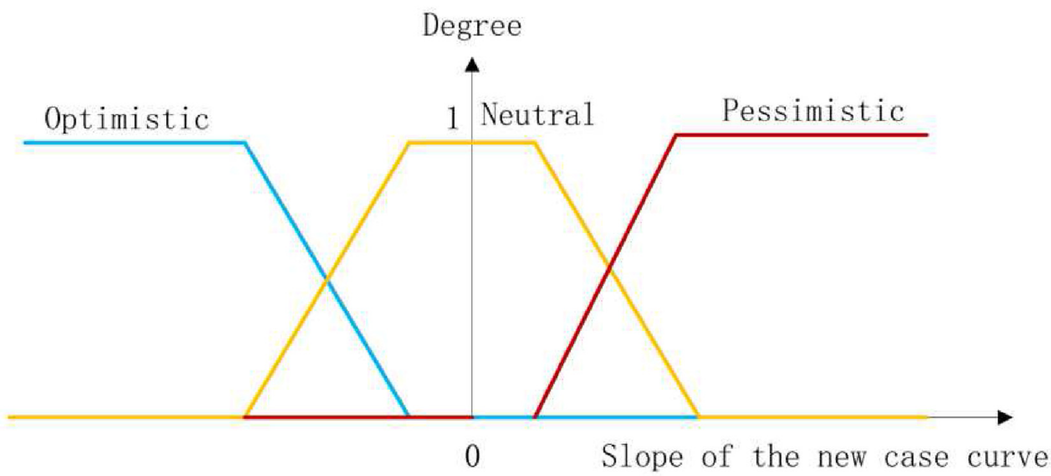

Figure 3. Fuzzy logic model for decision making.

4.1. A linear forecasting model for the prediction of patient bed supply from construction

Modular construction implies standardization. The standardization hereby refers to not only standard design but also standard construction. Therefore, based on the knowledge of site space and the average construction speed, we can forecast the approximate patient bed supply number. The proposed forecasting model is linear as depicted in Figure 4. The slope of the line, which refers to the progress of making a cabin hospital, is the construction speed. We assume the hospital can start to provide service in the middle of its construction as there are usually phase one projects, phase two projects, etc. The ward size is a scaled-down value of the entire constructed area size. Each bed in a ward occupies the same square space (often 2 × 2 square meters). The construction speed may either be constructed area per day or installed bed per day. Their transformation is by the scale factor. The construction completes when the constructed area reaches the original site space size.

5. Case study

The PN can be realized in a Stateflow chart in the MATLAB Simulink environment. MATLAB is an interactive computing environment and high-level programing language. Simulink is an extension to MATLAB that provides a block diagram environment for designing, modeling, and simulating reactive systems. Stateflow is an extension to Simulink that provides an environment for modeling and simulating combinatorial and sequential decision logic based on hierarchical state machines and flow charts. The transformation of a PN into the Stateflow model is a mature process.

In this section, the developed PN is verified using the case data in the 2022 Shanghai Omicron outbreak. A sensitivity analysis is performed by varying different system parameters to study the impact of construction manpower supply and the impact of different venue type supply. A discussion is further made on future citywide preparedness toward pandemic resilience.

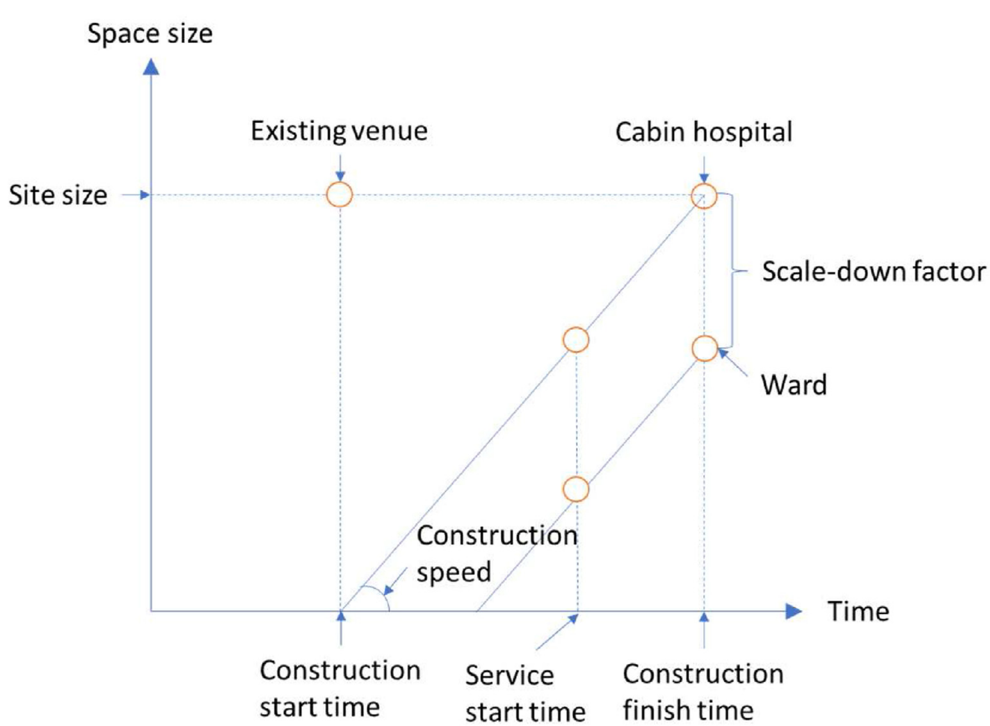

Figure 4. Linear forecasting model for the prediction of patient bed supply from construction.

5.1. Case data

The daily numbers of newly infected cases (including confirmed and asymptomatic cases), as well as newly cured cases (including discharged cases) in the 2022 Shanghai Omicron outbreak, are collected from the website of the National Health Commission of the PRC. According to the press briefing, the first Shanghai Omicron case was found on January 13 in a local milk tea shop. The channels of transmission were immediately cut off under precise and differentiated epidemic control strategies. Between February 7 and February 20, Shanghai reported zero new cases. Nonetheless, after February 25, the situation there got worse. An outbreak occurred at a local designated quarantine hotel – Hua Ting Hotel & Towers on March 11. Within the following ten days, more than five hundred asymptomatic cases were successively identified in the nucleic acid tests at communities. The city thereafter imposed a strict locked-down on March 28 to combat the Omicron surge. Although the initial plan was a two-phase lockdown, with the first five-day phase on the eastern side of the Huangpu River and the second five-day phase on the western side of the river, the lockdown period was eventually extended to almost the end of June as the central government was stepped in and reiterated the country's dynamic zero-COVID policy. During the lockdown time, Shanghai authorities conducted citywide antigen testing and nucleic acid testing every day to discover the high-risk population. The testing results were later released to the public. Figure 5 presents the Shanghai Omicron data between March 28 and May 15. Figure 5(a) shows the daily new infected patients and Figure 5(b) shows the daily discharged patients.

Despite Shanghai having some COVID-19-designated hospitals, the local healthcare system was soon overwhelmed in the wake of the outbreak. To alleviate the shortage of medical resources, Shanghai built up a lot of cabin hospitals for centralized isolation of those infected with mild and no symptoms. The Chinese government deemed the preparation for centralized quarantine facilities and the construction of the cabin hospitals as the paramount important thing to winning the battle against the pandemic. In Shanghai, five hundred thousand construction workers were working days and nights. Over one hundred cabin hospitals were constructed within one-month time, supplying 300,000 plus patient beds. The largest one was converted from National Exhibition and Convention Center with a capacity of about 50,000 beds, see Figure 6. Figure 6(a) shows the outdoor scene of the cabin hospital and Figure 6(b) shows the indoor scene of the cabin hospital.

Table 1 shows the average construction speed respecting the original venue type, in which "car park" and "empty space" indicate new construction. The construction speed mainly depends on the manpower available and the job complexity. Retrofitting existing residential or office buildings into cabin hospitals was the fastest as not many modifications were necessary. On the other hand, new construction, especially in car parks, took a long time because land leveling was needed and precast structure assembly was relatively complicated. New construction in empty space, however, was fast because wards were all prefabricated containers. Yet, production of these prefabricated containers in a factory was time-consuming, thus overall this is not a time-saving method compared to the renovation of existing venues using partitions. Table 2 shows the milestones of COVID-19 patient bed supply status over time. Also, we provide an appendix listing the construction details of some big samples.

5.2. The petri net platform

The proposed PN is made up of three main functional units, say the ANN module, the FL module, and the linear supply forecasting module. PN acts like a platform to glue these modules together, making them like a black box with only input and output ports. Figure 7 displays the developed PN platform in the Stateflow at Simulink Matlab. The toolbox in Matlab is convenient to use, saving us a lot of time in coding. Figure 7(a) shows the main PN structure, in which different colors correspond to different functional units. Firstly, the green color represents the ANN functional unit. Its inputs are the new affected cases and discharged cases in recent days. Its outputs are predictions. Next, the blue color represents the FL functional unit. It outputs the fuzzy degree. Then, the yellow color represents the general calculation unit for the extra beds needed. The demand for extra beds is calculated by subtracting the discharged cases from the existing total bed supply and multiplying the result with the fuzzy degree. At last, the red color represents the linear supply forecasting functional unit. Eight different building categories which have different construction rates are incorporated in the unit. The inputs include available venue sizes and available manpower. The numbers of beds that can be supplied from each building categories are calculated separately and then summarized on a daily basis to offer a total supply. In addition, Figure 7(b) shows the corresponding token generation logic flow. The logic flow contains so-called Compare-to-Constant Block (= = 0), Switch Block, Constant Block ("0" or "1"), and Logical Operator Block ("OR"). Compared-to-Constant Block checks whether zero value is encountered. If the data value is zero, it is treated as an error, case "0" is selected; otherwise, case "1". Switch Block checks whether any error occurs in the PN. If no error, PN proceeds to the next step; otherwise, terminates. Constant Block assigns case "0" or case "1" to the logical result from the

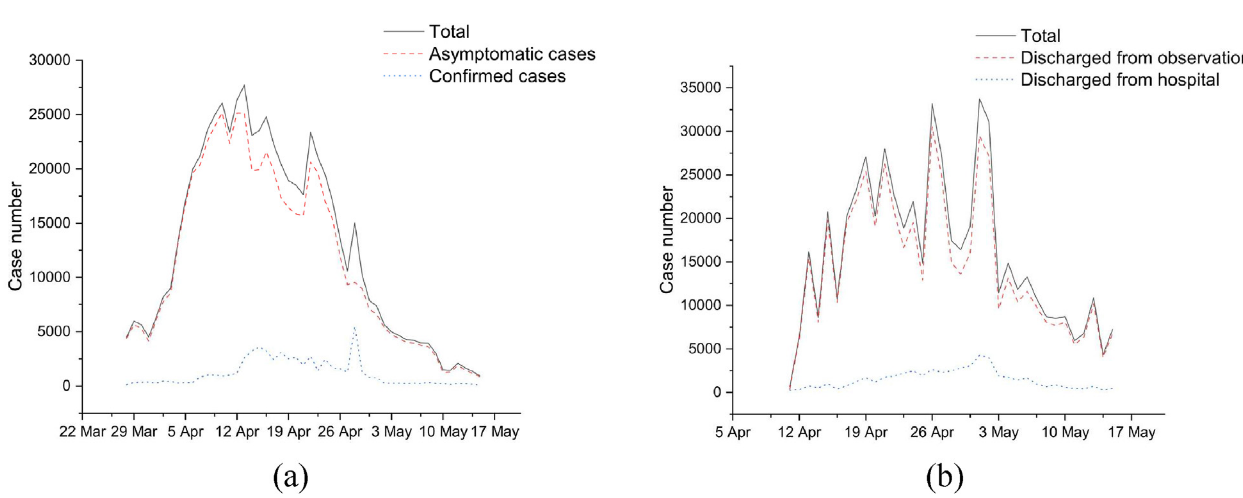

Figure 5. Shanghai Omicron data between March 28 and May 15: (a) new infected patients; (b) discharged patients.

(a) (b)

Figure 6. The photos show the cabin hospital in National Exhibition and Convention Center in Shanghai: (a) outdoor scene; (b) indoor scene (Source: Xinhua News).

Table 1. Average construction speed respecting original venue type.

	Car park	Convention center	Logistics warehouse	Industrial plant	Exhibition hall	Empty Space[3]	Cruise port	High-rise
Construction speed[1]	1.9	2.2	4.9	8.6	10.9	14.2	23.4	27.6
Construction speed[2]	0.2	0.2	0.6	0.8	0.2	0.8	0.9	2
Bed space ratio	10%	9.7%	11.5%	9.4%	7.5%	7%	3.8%	7%

[1] in the unit of square meters per person per day.
[2] in the unit of beds per person per day.
[3] using prefabricated containers.

Table 2. Milestone of COVID-19 patient bed supply status over time.

	Designated hospitals	Designated hospital bed	Cabin hospitals	Cabin hospital beds
March 28	1	1,100	0	0
April 2	n.a.	n.a.	1	10,000
April 5	n.a.	n.a.	n.a.	47,700
April 9	8	8,000	100+	160,000
April 30	44.	23,000	120	270,000
May 5	48	25,000	100+	195,000

n.a. indicates not available.

Switch block. And Logical Operator Block terminates the PN if any error in multiple logical results is obtained.

5.3. The results

Firstly, the ANN model needs to be trained on the real case dataset. Figures 8 and 9 show the parameter tuning process for the predictions of daily numbers of newly infected patients and discharged hospital patients. The training dataset is normalized to the range of [−1, 1]. Generally, more input nodes give more knowledge for the prediction. Yet, as the pandemic outbreak is an unexpected sudden issue and needs a fast response, the ANN is unlikely to have a big amount of input nodes. From the trial-and-error experiments, we decide the choice of 4 input nodes. Figures 8(a) and 9(a) show the input node number tests. Besides, increasing the number of hidden nodes improves the prediction accuracy, but a net with too many hidden nodes can cause an overfitting problem. A rule of thumb suggests the number of hidden nodes is chosen no bigger than the number of training samples. So, from the numerical experiments, we select 30 hidden nodes. Figures 8(b) and 9(b) show the hidden node number tests. We use different small fixed step sizes for iterations of the weights and biases. An extreme small step size such as 0.000001 is used for the bias iteration. Figure 8(c) (d) and 9(c) (d) show the step size value tests. Since the computational cost for long iterations is not high with this net, we set iteration times 30000. Figures 8(e) and 9(e) show the iteration number tests. Eventually, Figures 8(f) and 9(f) display the prediction errors using the suggested ANN parameters.

Secondly, the parameters of the FL model are decided based on the real case dataset as Figure 10 shows. The slope is calculated by $(new\ value - current\ value)/current\ value$. Figure 10(a) shows the slope values during the Shanghai Omicron outbreak period. Before April 19, positive values dominate which indicates the explosive growth in the new cases, while after April 19, negative values prevail implying the effective control of the pandemic. On April 12, the first batch of hospitalized patients was discharged. Figure 10(b) illustrates the curves of the accumulated new cases and accumulated discharged cases, respectively. It is interesting to see that the two curves present similar shape patterns. The reason behind this is that most Omicron patients can be recovered eventually. This increases people's confidence, and thereby people take a more optimistic view in the sight of more discharged patients. According to the hints given in Figures 10(a) and 10(b), we propose a fuzzy logic model as demonstrated by Figure 10(c). We assume that with an optimistic view the need will be under-estimated by a scale-down factor of 0.8. And on the other hand, with a pessimistic view, the need will be over-estimated by a scale-up factor of 1.2. Finally, Figure 10(d) gives the psychological scale factor results that are calculated from the FL model.

Thirdly, the prediction of the patient bed supply per person from retrofitting different types of existing venues is presented in Figure 11 using the real case dataset. The construction speed has a positive linear relation to the manpower size. Therefore, by providing more manpower the construction time is shortened. As the construction of cabin hospitals is usually divided into phases, we assume a cabin hospital can be put into use prorated from its full capacity when it accomplishes 50% project volume. This tallies with the real practice of some big cabin hospitals. For

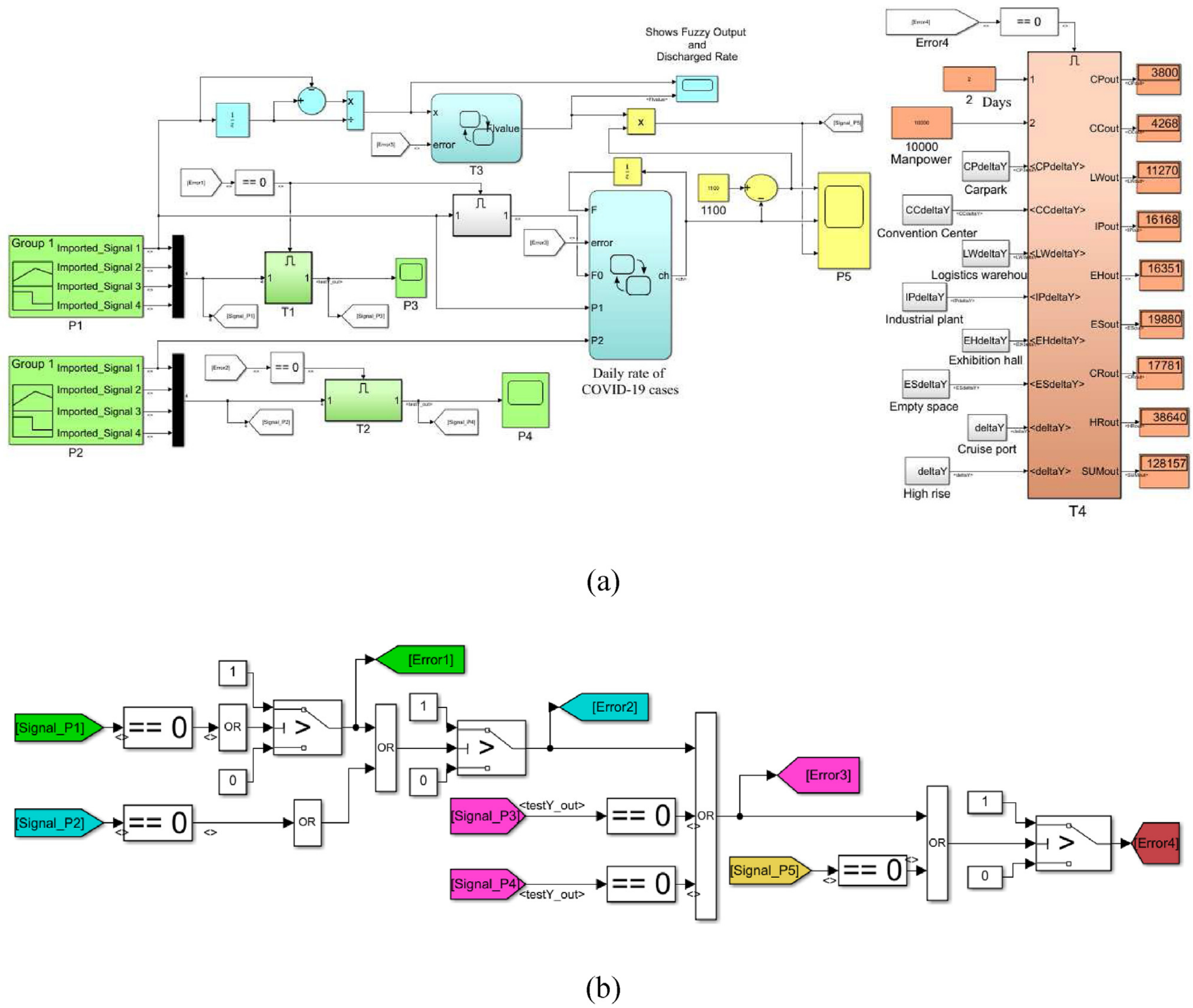

Figure 7. Petri net in the Stateflow at Simulink Matlab: (a) overview (Green: neural network functional unit, Blue: fuzzy logic functional unit, Yellow: extra bed demand calculation, Red: linear supply forecasting functional unit), (b) logic flow for generating the token.

example, on April 9, the National Exhibition and Convention Center Cabin Hospital project delivered the first batch of 6,748 beds after four-day construction and then continued delivering the remaining batches in the following days. The entire project construction took a total of eleven days and it finished on April 15.

Fourthly, Figure 12 shows the predicted demand and supply relation using Appendix A data. We assume all the projects start simultaneously on Day 1. The total manpower involved is 70,113 persons. The maximum supply is 169,481 beds from the big cabin hospitals. According to Table 2, we know the actual total bed supply at the peak reached 270,000 beds on April 30 in Shanghai.

5.4. Sensitivity analysis

A sensitivity analysis is conducted based on the PN platform to analyze the impact of construction manpower supply and the impact of different venue type supply.

Firstly, the impact of manpower supply on the total patient bed supply is studied by progressively reducing the labor size. When the manpower is not enough, either the start of a cabin hospital construction project will be postponed or the construction speed will be slowed down. Figure 13 shows the impact of manpower supply decreased from 70,113 to 31,000 in the case that projects are postponed. Figure 14 shows the impact of manpower supply decreased from 70,000 to 30,000 in the case that construction speeds slow down. In the case of Figure 13, the start sequence of the projects is arranged according to their size from big to small, which tallies people's psychology to place the treasurable resources on those most prospective projects, herein those can provide the largest number of patient beds. A slight adjustment of the manpower level among projects is allowed to fully utilize the labor. In the case of Figure 14, simultaneous projects start is assumed and the manpower resource is allocated pro-rata to their original arrangements. Then, the construction speeds are decreased due to the less manpower level.

Next, the impact of space supply of different venue types on the manpower requirement is studied by fixing the total patient bed supply and meanwhile progressively increasing the space size from 50% to 500%. Because the total patient bed supply is a constant number, varying the venue space size impacts the manpower requirement. As continuous supply is obtained from one venue type which has an increased size, supply from the other venue types is then suppressed. In this regard, the manpower levels in the other venue types are reduced with the decreased supply requirement. We assume the supply requirement is reduced pro-rata to the size portion of the venue type. Figure 15 shows the experimental results. Increasing the space supply of high-rise buildings and convention centers shows the most decreases in manpower requirement for the same supply amount.

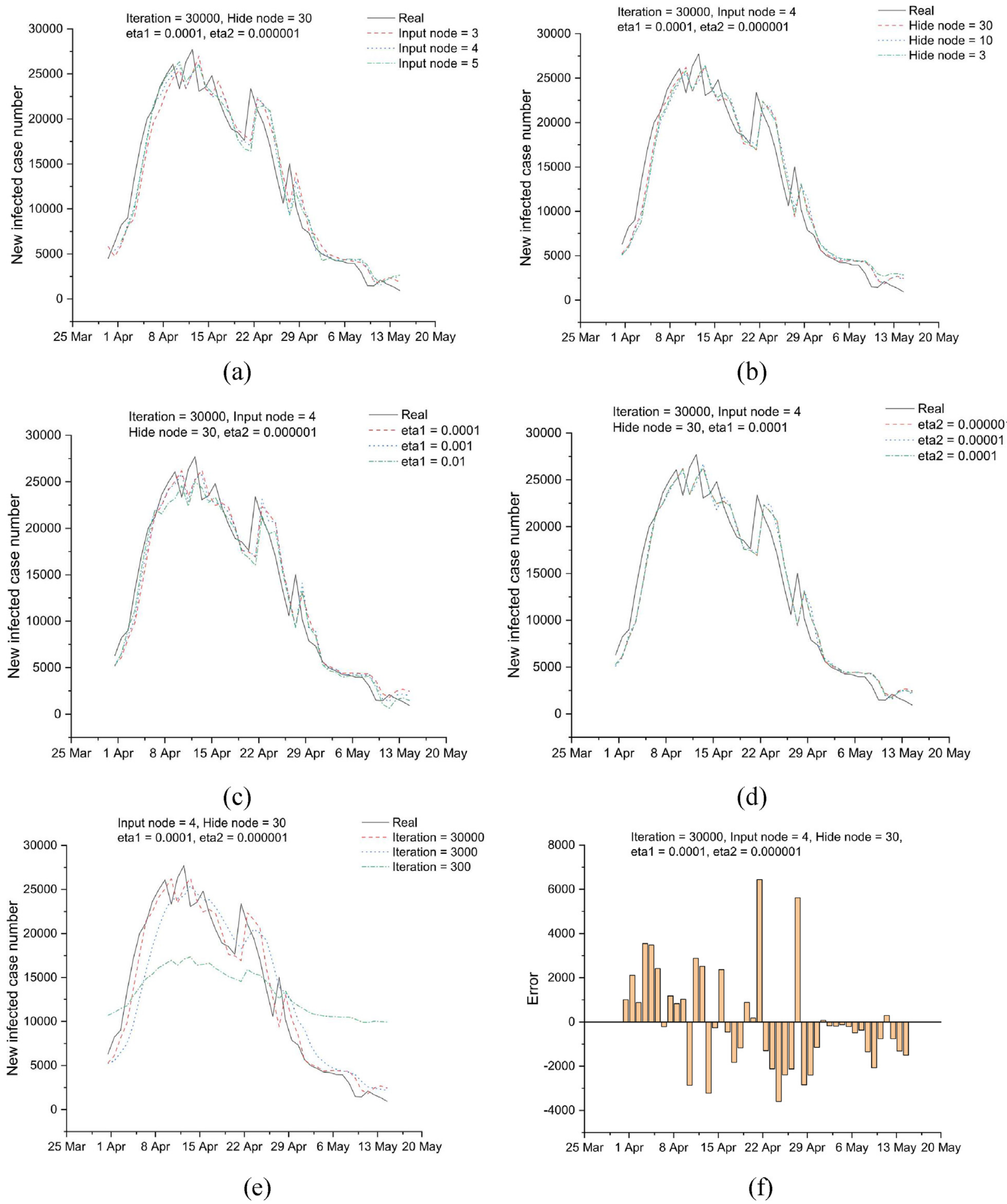

Figure 8. The predicted new case number from the neural network: (a) different input node; (b) different hide node; (c) different step-size of weights; (d) different step-size of biases; (e) different iteration; (f) prediction error.

6. Discussion

During March and June 2022, the city of Shanghai has been hit hard by the Omicron variant and the city carried out strict social isolation and lockdown measures. A large number of cabin hospitals were built within a very short time. The fast construction capability mainly relied on the huge manpower resource supported by China's whole nation system. The majority of the cabin hospitals were converted from the existing venues, such as convention centers, industrial plants, logistics warehouses, etc., by erecting lots of partition walls to divide the space into wards and installing negative air pressure ventilation systems to prevent viral pollution to surrounding areas. In empty spaces, prefabricated container wards were stacked into Lego-like buildings. Such offsite and modular construction improved construction efficiency and productivity. However, onsite assembly work so far cannot do without labor. In April 2022, a total of five hundred thousand workers participated in the construction projects. At the peak time, about seventy thousand workers were working at the same time. Then, for other countries that do not have sufficient

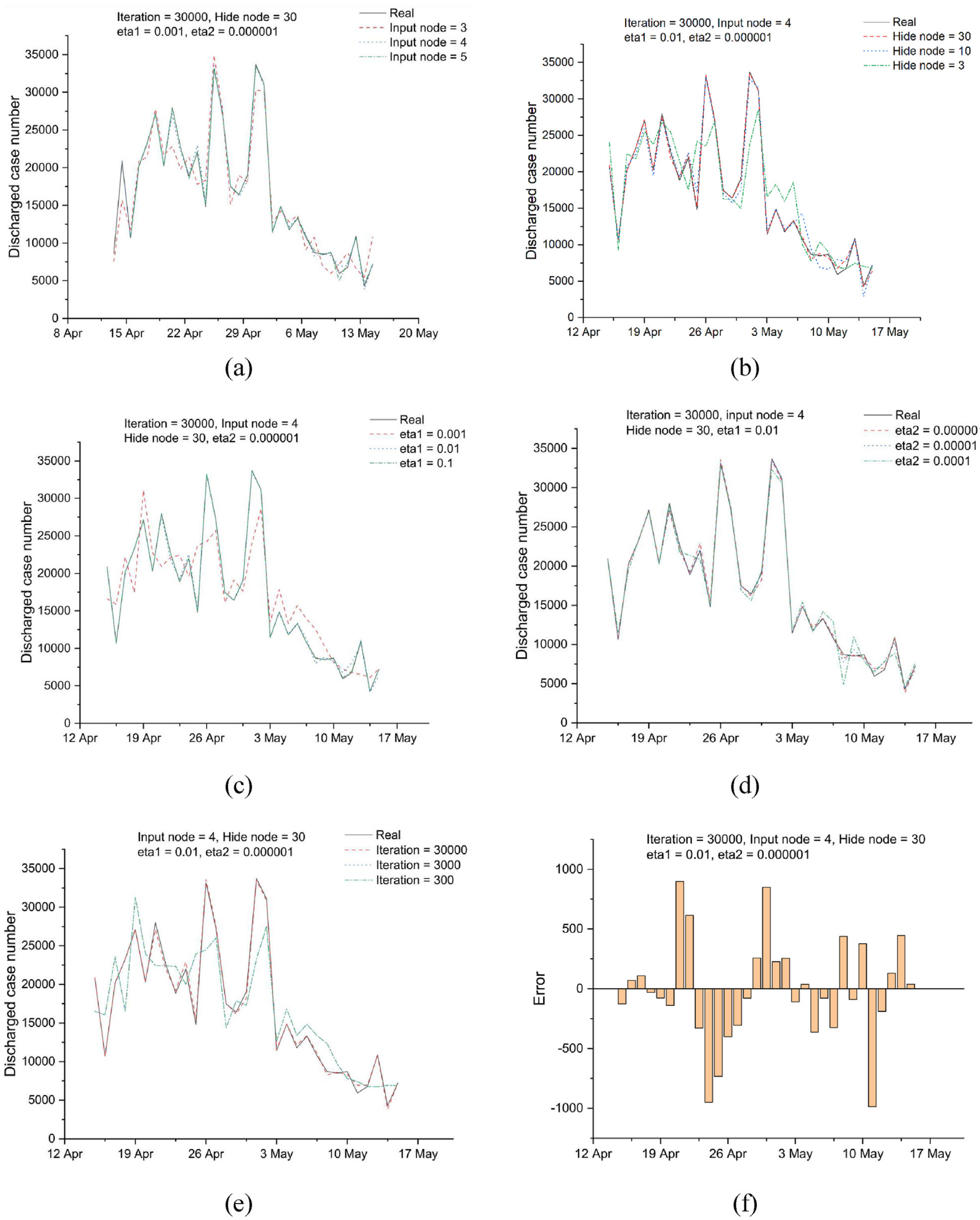

Figure 9. The predicted patient discharged number from the neural network model: (a) different input node; (b) different hide node; (c) different step-size of weights; (d) different step-size of biases; (e) different iteration; (f) prediction error.

manpower resources like China, how can they successfully supply enough patient beds within a short time window?

By taking a close look into conversion speeds from different venue types to cabin hospitals, high-rise buildings are found the fastest using the least manpower. Take the 19-storey Yingtong Tower project as an example, it took 200 persons 96 h to finish the project with the supply of 3,650 patient beds. High-rise buildings are usually for office and residential use. They are well equipped and have a friendly living environment. A small amount of retrofitting work can make them into a satisfactory hospital condition. Therefore, when manpower resource is

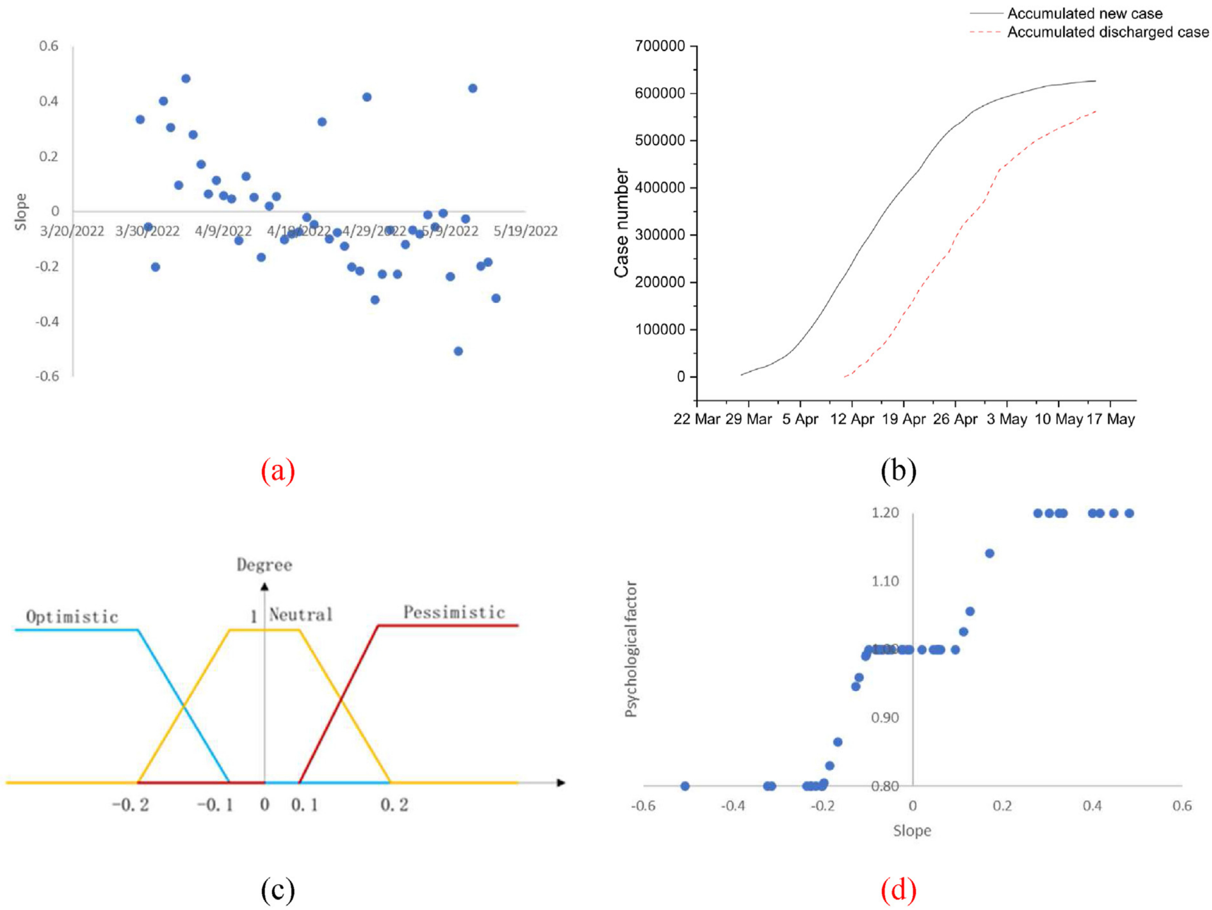

Figure 10. The predicted attitude toward status from the fuzzy logic model: (a) slope value; (b) discharged patients; (c) fuzzy logic model; (d) psychological factor.

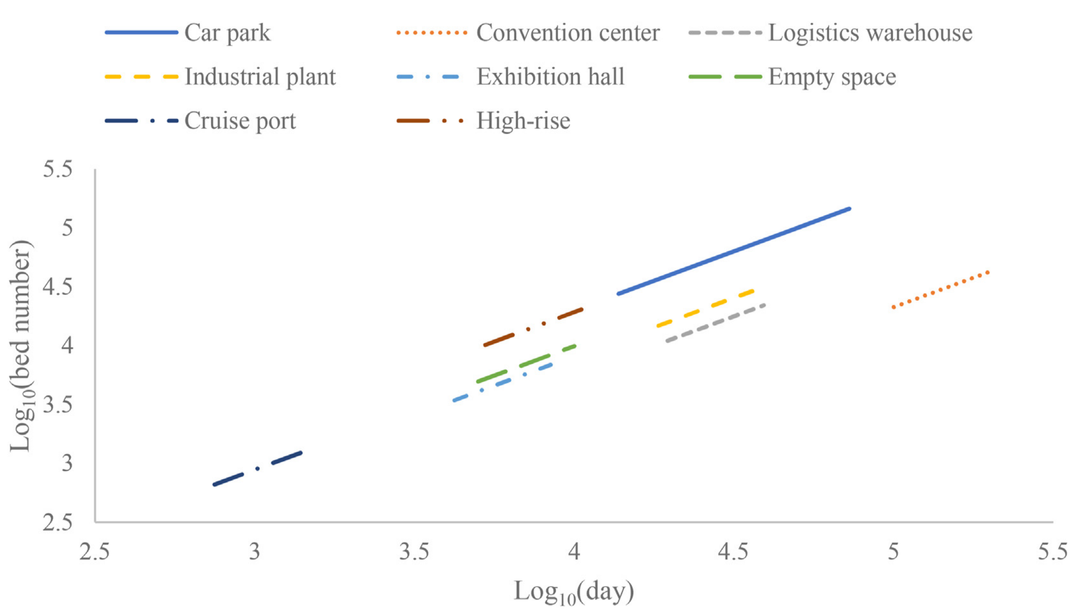

Figure 11. The predicted supply results from the linear model.

constrained, building vertical cabin hospitals helps alleviate the manpower shortage. Results from the sensitivity analysis prove this statement.

While construction efficiency is placed at the top concern, construction quality should not be compromised. In Shanghai's Omicron battle, low-quality wards hesitated people's willingness to go for the centralized isolation. The widely circulated photos of leaking roofs during the rainy days of the cabin hospitals not only increased the tension between doctors and patients but also decreased the credibility of the government. On the contrary, those cabin hospitals retrofitted from high-rise buildings won a good reputation for their comfortable living conditions, beautiful window sceneries, and comprehensive amenities.

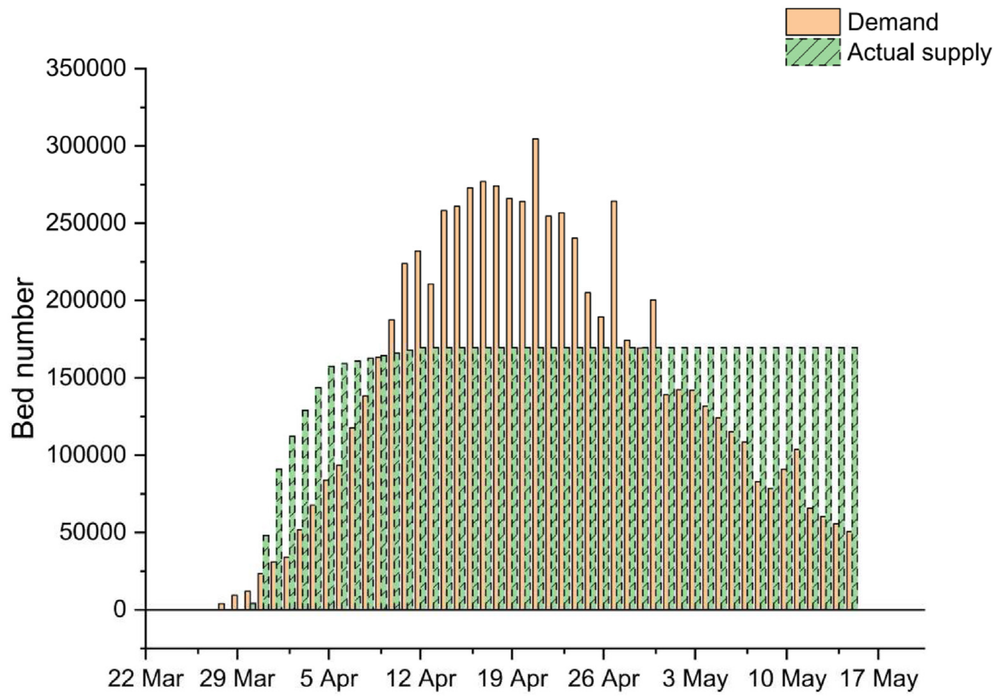

Figure 12. The demand and supply chart.

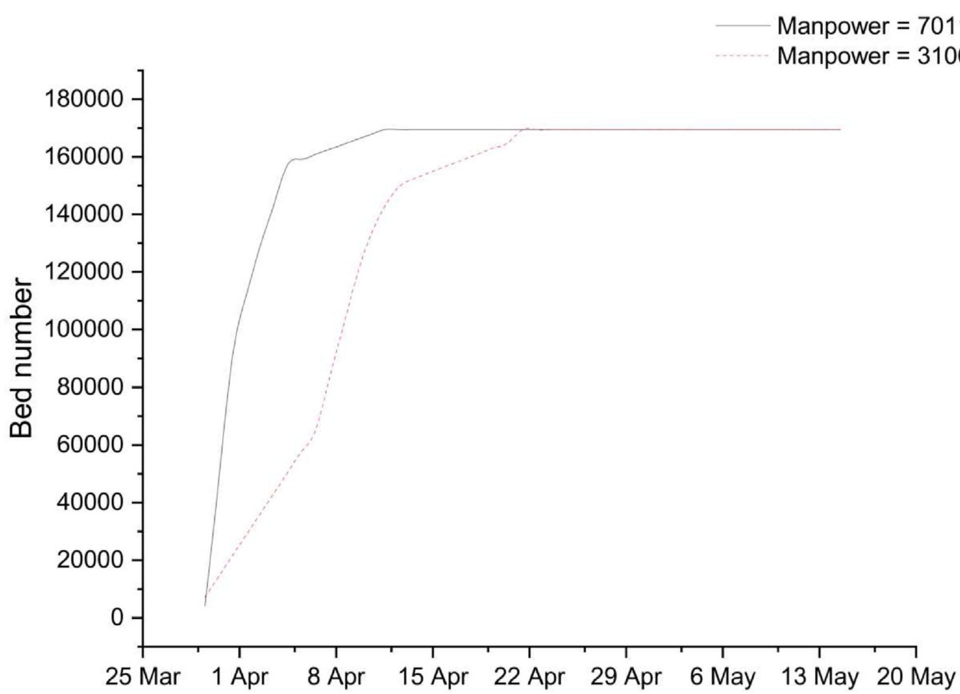

Figure 13. The impact of manpower supply in the case that projects are postponed.

Last but not least, big high-rise multifunction buildings are not only expensive to build but also expensive to demolish. In a metropolis like Shanghai, there are thirty thousand over 24-story high-rise buildings. Their functionality is not always fixed in their service life. Because of the volatile social needs, adding more functionality to existing buildings is likely to enhance their values, contributing to low carbon and sustainable future. In this regard, adaptive reuse of high-rise buildings attracts interest. The adaptive reuse project requires complete and accurate historical information about the building, which emphasizes the importance of life cycle building information modeling (BIM). BIM provides a level of transparency and archival insight into a building or precinct, which paper-based plans cannot. Though we didn't see the use of any IT technology in the construction of cabin hospitals in Shanghai this time, we believe IT technologies, including information systems, communication technologies, and digital technologies, will play a significant role in future cabin hospital construction, especially for those developed countries where manpower costs are high. The big variability of manpower used in the different cabin hospital construction projects in Shanghai

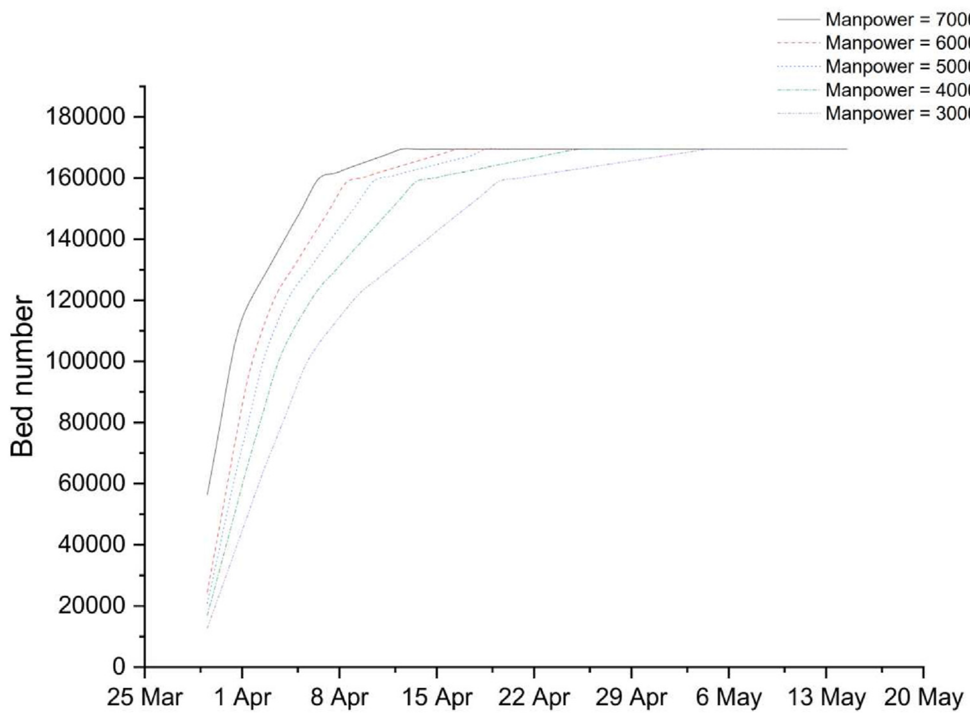

Figure 14. The impact of manpower supply in the case that construction speeds slow down.

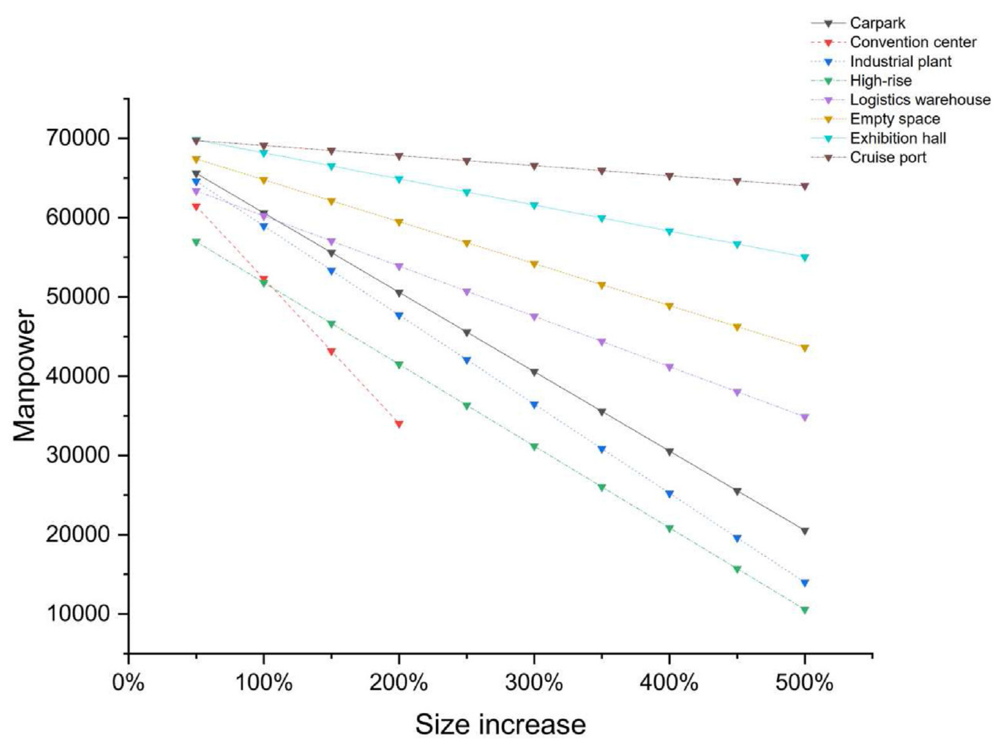

Figure 15. Sensitivity analysis results for the impact of venue size supply.

reveals there is still room for better work arrangements. With the help of IT technologies, the manpower requirement for a project is possible to be reduced. By enhancing the readiness of high-rise buildings to transform into cabin hospitals with the help of IT technologies, citywide preparedness toward pandemic resilience can be achieved.

7. Conclusion

PN is a powerful tool for system modeling and analysis. This work innovatively uses PN technology to propose an analytical tool for evaluating the possibility of the regional construction industry building up a large number of cabin hospitals within a short time. Through centralized isolation and treatment for patients with mild symptoms, the cabin hospitals will avoid cross-infection in communities, as well as reduce the severity and certain death cases. The key idea of the proposed approach is to forecast the dynamic balance between demand and supply. ANN is adopted as the prediction model for future new infected cases and hospital discharged patients. FL is applied to quantify the psychological impact on decision-making. And a linear model is proposed to estimate the patient bed supply from different venue types. PN glues together these separate components, making an automated process for our analytical study.

We verified the developed model using the data of a recent Omicron hit in the city of Shanghai. In April 2022, Shanghai transformed hundreds of its existing public venues, including convention centers, exhibition halls, industrial plants, logistics warehouses, car parks, office buildings, schools, and other places, into cabin hospitals. Averagely after three days, a new cabin hospital was put into use. Achieving such a speed relies on the huge crowd strategy. Around five hundred thousand construction workers participated in the battle. We used the PN model to analyze the impact of manpower resources. When manpower resource is constrained, either the start of some projects will be postponed or the construction speed will be slowed down. The sensitivity analysis results show that the fastest conversion speed and the least manpower requirement can be achieved from the high-rise buildings. Then, the idea of building vertical cabin hospitals helps the countries that do not have sufficient manpower resources to obtain a large number of isolation places within a short time window. This incurs a new requirement for future building design. Also, adaptive reuse of high-rise buildings is nowadays a front in city sustainability research. Rather than advocating such an idea of creating permanent cabin hospitals proposed by some Chinese politicians, we emphasize the capability of fast conversion. So, in the future, we will look into this problem from a designer's point of view.

Declarations

Author contribution statement

Chen Chen, Ph.D: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Zijie Xing: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Yonghui Xi; Robert Tiong: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Appendix A – Construction details of some big cabin hospitals in Shanghai Omicron outbreak

	Chinese names	Beds	Area (m^2)	Methods	Venue type	Manpower (person)	Built time (day)
National Exhibition and Convention Center	国家会展中心	50,000	420,000	Retrofit	Convention center	25,000	11
Shanghai new International Expo Center	上海新国际博览中心	15,000	200,000	Retrofit	Convention center	6,000	12
Lingang Yangshan Special Area	上海临港洋山特保区	13,956	158,000	Retrofit	Logistics warehouse	7,000	7
International Circuit	上海国际赛车场	13,801	105,880	New	Car park	4,380	10
Zhoudenggong Road	周邓公路	12,000	170,000	New	Car park	5,000	25
Yaohua Second Phase	耀华2期	7,104	162,000	Retrofit	Residential building	650	11
Jinshan	金山	5,030	50,000	Retrofit	Industrial plant	2,700	5
Kaiqing Road	凯庆路	4,800	50,500	Retrofit	Industrial plant	1,100	5
Jingcan Road	泾灿路	4,000	34,000	Retrofit	Industrial plant	600	7
Yingtong Tower	瀛通大厦	3,650	42,500	Retrofit	Office building	200	4
Yuanshen Road Research Building	源深路研发楼	3,500	51,000	Retrofit	Office building	1,500	2
Changxing Island	长兴岛	3,120	30,000	Retrofit	Industrial plant	1,000	8
Songzhenggong Road	松蒸公路	2,866	25,000	Retrofit	Industrial plant	1,000	10
Wuxuan Road	武宣路	2,800	35,000	Retrofit	Commercial building	400	5
Huaboyuan Revival Hall	花博园复兴馆	2,752	30,000	Retrofit	Exhibition Hall	3,500	3
Xiechun Road	谢春路	2,735	18,000	New	Empty space	600	4
Zhudai Road	朱戴路	2,500	17,000	Retrofit	Logistics warehouse	500	5
World Expo Footprint Pavilion	世博足迹馆	2,318	21,900	Retrofit	Exhibition Hall	480	6
Fuchang Road	富长路	2,000	70,000	New	Empty space	1,400	12
Shengang Road	申港路	1,967	30,646	Retrofit	Industrial plant	1,000	3
Luojing Jingdong	罗泾京东	1,860	17,000	Retrofit	Logistics warehouse	630	6
Nanxiang	南翔	1,790	20,000	Retrofit	Industrial plant	284	2
Beicai Yuqiao	北蔡御桥	1,690	54,000	New	Empty space	250	7
Baimao	白猫	1,590	20,000	Retrofit	Industrial plant	2,100	13
Shilong Road	石龙路	1,548	30,000	Retrofit	Industrial plant	600	5
Xingrong Road	兴荣路	1,500	1,2000	Retrofit	Industrial plant	500	3

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(continued)

	Chinese names	Beds	Area (m^2)	Methods	Venue type	Manpower (person)	Built time (day)
Cruise port	邮轮港	1,324	35,000	Retrofit	Cruise port	500	3
Liantang	练塘	1,200	13,487	Retrofit	Industrial plant	639	7
Zhangjiang Science Hall	张江科学会堂	1,080	40,000	Retrofit	Exhibition Hall	600	3

(Source: internet news).

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