

System Dynamics Modeling-Based Approach for Assessing Seismic Resilience of Hospitals:  
Methodology and a Case in China

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1 **System Dynamics Modeling-Based Approach for Assessing Seismic Resilience of Hospitals:**  
2 **Methodology and a Case in China**

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15  
16 **Abstract**

17 Hospitals play a crucial role in providing the badly needed medical care after earthquakes. Meanwhile, hospitals  
18 are themselves likely subjects to earthquake impacts and may fail to function, which highlights that there is  
19 significant need for enhancing the resilience of hospitals to earthquakes. Nevertheless, there lacks an effective

20 assessment approach of hospital seismic resilience, which makes it challenging for devising and benchmarking  
21 appropriate resilience enhancement measures. This study proposes a new functionality-based assessment  
22 approach of hospital resilience to earthquakes. A new indicator of hospital functionality is proposed, and a system  
23 dynamics model of hospital functionality after earthquakes (SD-HFE) is developed to simulate the hospital  
24 functionality. The resilience assessment can then be conducted based on the functionality curve, which considers  
25 both the loss and the recovery of hospital functionality. Based on a case study in China, the efficacy of the  
26 proposed approach is tested. The proposed approach advances the understanding on how hospital functionality  
27 evolves after an earthquake, and allows quantitative assessment of hospital seismic resilience. The outcomes of  
28 this study will contribute to the development of informed policies and effective engineering measures to enhance  
29 the seismic resilience of hospitals.

## 30 **Introduction**

31 Earthquakes are one of the most destructive natural disasters. From 1998 to 2017, earthquakes occurred 563  
32 times, which accounted for 7.8% of the numbers of all types of natural disasters but were responsible for 56%  
33 of all fatalities caused by natural disasters all around the world (Wallemacq and House 2018). Hospitals play a  
34 crucial role in the mitigation and recovery of disaster-hit regions, providing continued access to care (Arboleda  
35 et al. 2009, Cimellaro et al. 2018). Almost 97% of the injuries occur within the first thirty minutes after  
36 earthquakes (Gunn 1995), which requires a rapid and effective medical response. However, hospitals are  
37 themselves likely subjects to earthquake impacts (Li et al. 2019). For instance, the 1995 Great Hanshin  
38 earthquake resulted in 110 structurally damaged and 4 completely destroyed hospitals, out of the 180 hospitals

39 in the disaster-hit area (Ukai 1996). Damage to the hospitals, equipment and supplies, loss of staff will  
40 undoubtedly result in a loss of hospital functionality, which would substantially exacerbate disaster consequences  
41 (Albanese et al. 2008).

42 During disasters like earthquakes, hospitals are required to be more than structurally safe but to maintain  
43 their functions and continue to provide medical care. The resilience of hospitals, which is focused on hospitals'  
44 capability to resist, absorb and recover from disasters while maintaining necessary functionality, has attracted  
45 increasing attention (Zhong et al. 2014, Cimellaro et al. 2018). In 2005, “building hospitals with enough  
46 resilience level” was set as one practice to reduce the underlying risk factors in the Hyogo Framework for Action  
47 2005-2015 (UNDRR 2007). Then, the Sendai Framework for Disaster Risk Reduction 2015-2030, which was  
48 endorsed following the 2015 Third UN World Conference on Disaster Risk Reduction (WCDRR), also  
49 highlighted the enhancement of hospital resilience to disasters as an important part of “Priorities for action”  
50 (UNDRR 2015). There have also been an increasing volume of recent studies in academia that focus on various  
51 challenges related to the disaster resilience of hospitals (Cimellaro et al. 2010b, Achour et al. 2014, Zhong et al.  
52 2015, Hassan and Mahmoud 2019), among which the assessment of hospital disaster resilience is the most urgent.  
53 Quantifying hospital resilience to disasters is essential and fundamental to benchmarking hospitals' capability to  
54 cope with disasters and to identifying hospitals' vulnerability in face of disasters, which is crucial for the  
55 propositions of targeted and effective resilience enhancement measures. However, the need for an effective  
56 approach for quantifying hospital resilience to earthquakes has largely remained a gap in the literature. Current  
57 “indicator-based” resilience assessment approaches, which assess hospital disaster resilience with sets of

58 evaluation indicators (WHO 2015), are difficult to use for parametric analysis, which is crucial for evaluating  
59 possible resilience enhancement measures. Although “functionality-based” resilience assessment approaches,  
60 which assess hospital disaster resilience based on the functionality curve (Cimellaro et al. 2010a), can overcome  
61 this limitation, efforts are still needed in the development of an indicator of hospital functionality and an  
62 approach to analyze both the loss of hospital functionality after earthquakes and its recovery over time.

63 This study contributes to the existing body of knowledge by proposing a new functionality-based  
64 assessment approach of hospital resilience to earthquakes. Firstly, a new indicator of hospital functionality is  
65 proposed, and factors affecting the hospital functionality are identified and discussed in detail. Then, system  
66 dynamics (SD) modeling is employed to simulate the changes of hospital functionality after earthquakes, which  
67 considers both the loss and the recovery of hospital functionality. The simulation results provide the basis for  
68 seismic resilience assessment of the hospitals. Based on a case study in China, the efficacy of the proposed  
69 assessment approach is tested. The proposed approach can provide a tool to better understand how hospital  
70 functionality evolves after an earthquake and to quantitatively assess the overall seismic resilience of a hospital.  
71 The outcomes of this study are expected to contribute to the resilience management of hospitals by supporting  
72 the development of informed policies and effective engineering measures with the proposed resilience  
73 assessment approach, so that the resilience of hospitals in seismic-prone regions could be enhanced against  
74 possible seismic impacts in the future.

## 75 **Literature Review**

76 There are two types of assessment approaches of hospital disaster resilience that are available in the existing

77 literature, including “indicator-based” approaches and “functionality-based” approaches. Indicator-based  
78 approaches assess hospital disaster resilience with a series of evaluation indicators. The World Health  
79 Organization released the Hospital Safety Index Guide for Evaluators (Second Edition) in 2015, which provides  
80 a comprehensive checklist of indices for hospital safety and resilience assessment (WHO 2015). The checklist  
81 includes four modules covering hazard identification, structural safety, nonstructural safety, and emergency and  
82 disaster management. Each of the indices is evaluated qualitatively by professionals who check one of three  
83 options (low, average and high). Similarly, Zhong et al. (2015) established a conceptual framework of hospital  
84 disaster resilience and proposed a set of indicators for resilience assessment, which includes 8 domains, 17 sub-  
85 domains, and 43 indicators. Assessment of hospital resilience using “indicator-based” assessment approaches  
86 can be relatively comprehensive, because of the flexibility to introduce different evaluation indicators to cover  
87 various dimensions. However, these indicators such as the aforementioned ones are usually described  
88 qualitatively, which are inherently vague and subject to evaluators’ different interpretations when they are put  
89 into practice. Meanwhile, indicator-based approaches are usually used for the resilience assessment of the current  
90 status of the hospitals (WHO 2015). It is difficult to apply these approaches to different scenarios, which  
91 prohibits the comparison of the effectiveness of different resilience enhancement measures.

92       Functionality-based assessment approaches assess the resilience ( $R$ ) of a system of any type using a  
93 functionality curve (see Fig. 1). The functionality ( $Q(t)$ ) of a system varies within the range between 0 and  
94 100%. One hundred percentage means the system is fully functional, providing full service, while 0 means the  
95 system malfunctions with zero service availability. Mathematically,  $R$  can be calculated by integrating  $Q(t)$

96 from the occurrence of the event ( $t_0$ ) over a control time for the period of interest ( $t_{LC}$ ), as shown in Eq. (1)  
97 (Cimellaro et al. 2010a, Cimellaro et al. 2016). In comparison with indicator-based assessment approaches,  
98 functionality-based assessment approaches provide more details on the behavior of a system over time after  
99 being attacked by disruptions. Moreover, such formula-format definition of system resilience makes it much  
100 more feasible to be adopted in different application scenarios, especially with simulation tools (Cimellaro and  
101 Pique 2016, Khanmohammadi et al. 2018).

$$R = \int_{t_0}^{t_0+t_{LC}} \frac{Q(t)}{t_{LC}} dt \quad (1)$$

102 **[Insert Fig. 1 here]**

103 When applying functionality-based assessment approaches to assess hospital disaster resilience based on  
104 Eq. (1), it is essential to first define and calculate the hospital functionality. Yavari et al. (2010) divided a hospital  
105 into four major systems, namely structural, nonstructural, lifelines, and personnel systems, and defined the  
106 overall hospital functionality using a “functionality tree”, which covered all possible combinations of the  
107 performance levels of the four systems. Similarly, Jacques et al. (2014) used a “fault-tree” (Lee et al. 2009)  
108 structure to define and calculate hospital functionality, which was composed of three main components,  
109 including staff, structure, and stuff. However, the above two approaches do not clarify how much each system  
110 or each component affects the overall hospital functionality, which prevents the development of component-  
111 specific resilience enhancement measures and assessment of optimal quantities of resources prepared for  
112 disasters.

113 Rather than defining hospital functionality directly, some researchers proposed indicators to reflect the

114 overall level of hospital functionality. Different from indicator-based assessment approaches which contain sets  
115 of indicators, a single indicator is usually used for this purpose. For instance, “waiting time”, which is defined  
116 as the time between the receipt of care request by the hospital and the provision of care to the patient, is widely  
117 used to construct the indicator of hospital functionality (Cimellaro et al. 2011, Cimellaro and Pique 2016,  
118 Cimellaro et al. 2017). The hospital functionality based on waiting time can be determined based on Eq. (2)  
119 (Cimellaro and Pique 2016):

$$Q(t) = \frac{WT(n, \alpha)}{\max(WT(n = n_{tot} - 1, \alpha))} \quad (2)$$

120 where  $Q(t)$  is hospital functionality;  $WT$  is waiting time;  $n$  is the number of emergency rooms;  $n_{tot}$  is the  
121 total number of emergency rooms inside the emergency department;  $\alpha$  is an amplification factor of the patient  
122 arrival rate;  $t$  is time. The waiting time can be calculated using discrete event simulation (DES) models, by  
123 simulating patient flows and treatment processes (Cimellaro et al. 2011, Cimellaro and Pique 2016, Cimellaro et  
124 al. 2017). The DES models shed new light on studying hospital disaster resilience, by viewing the hospital as an  
125 integrated system rather than a simple aggregation of independent components. However, the DES models in  
126 prior studies bear two major limitations. First, these models were built based on the assumption that the hospital  
127 could remain operational as usual in the aftermath of disasters. In reality, the organizational system and the  
128 operation of the hospital can change significantly during disasters, which consequently lead to changes in waiting  
129 time compared with normal conditions. Hence, such an assumption inevitably introduces bias into the resilience  
130 assessment results. Second, the recovery process of the hospital, which is one of the key determinants of  
131 resilience (Cimellaro et al. 2010a), was not considered in prior studies using the DES models.

132 Khanmohammadi et al. (2018) built an SD model to calculate hospital functionality, which characterized  
133 the dynamics of the operation of a hospital during an earthquake. In comparison with the aforementioned DES  
134 models, the SD model considers both damage and recovery processes of the hospital. An indicator of hospital  
135 functionality for resilience assessment was proposed in their study. The indicator is determined by the number  
136 of patients waiting to be treated, as shown in Eq. (3) (Khanmohammadi et al. 2018):

$$Q(t) = \begin{cases} \frac{A}{P(t)} & A \leq P(t) \\ 1 & A > P(t) \end{cases} \quad (3)$$

137 where  $Q(t)$  is hospital functionality;  $A$  is the acceptable number of patients waiting to be treated;  $P(t)$  is the  
138 number of patients waiting to be treated at time  $t$ . The parameter  $A$  could be determined by hospital  
139 administrators based on a set of performance criteria. The proposed approach of assessing hospital disaster  
140 resilience based on SD modeling provided an inspiring perspective to analyze the “lifecycle” of the hospital  
141 functionality during disasters. However, there were still some limitations in this research. First, utilities such as  
142 electricity, water, and gas were simply aggregated as one type of component in the SD model, named as  
143 “technical systems”, which overlooked the specific effect of each type of utilities on hospital functionality. These  
144 utilities, in reality, play critical roles in supporting hospital functionality (Achour et al. 2014, Vugrin et al. 2015).  
145 In-depth analysis of the relationships between these utilities and hospital functionality will contribute to more  
146 comprehensive identification of vulnerability of hospitals. Second, the recovery of the components was  
147 considered to only depend on monetary resources, which was too simplistic and ignored technical feasibility,  
148 causing potential bias in the calculation of recovery time and hence the overall hospital resilience. Similarly,  
149 Choi et al. (2019) built an SD model to simulate the operations of an emergency room and used the “serviceability”

150 of the emergency room defined by the authors to reflect its functionality. A major limitation of this model,  
151 however, is that it did not consider the damage of the hospital in terms of damages to hospital buildings and  
152 losses of medical staff.

## 153 **Methodology**

154 Based on the literature review, there still lacks an appropriate indicator of hospital functionality after earthquakes  
155 and an approach of analyzing both the loss and the recovery of hospital functionality after earthquakes. This  
156 paper proposes a functionality-based assessment approach of hospital resilience to earthquakes by the following  
157 three steps:

- 158 1. Quantification of hospital functionality after earthquakes (i.e.  $Q(t)$  in Eq. (1)). A quantifiable definition of  
159  $Q(t)$  is needed, which should be able to reflect the desired outcome (Walden et al. 2015) that the hospital  
160 aims to achieve after earthquakes. In this paper, a new indicator of hospital functionality after earthquakes  
161 is proposed based on literature review and expert interviews.
- 162 2. Modeling hospital functionality after earthquakes. Given the complexity of hospitals and their risks of being  
163 destroyed by sudden and devastating earthquakes, assessing and predicting the loss and the recovery of  
164 hospital functionality after earthquakes via physical experiments could be highly challenging (Lu and Guan  
165 2017). In this paper, SD modeling, a widely used approach for describing processes of accumulation and  
166 feedback of a complex system using differential equations (Chang et al. 2017, Wang and Yuan 2017, Leon  
167 et al. 2018), is adopted to model hospital functionality ( $Q(t)$ ) after earthquakes. Key factors that affect

168  $Q(t)$  and their interactions are identified. These factors and their interactions form the basis of the variables  
169 and equations in the SD model.

170 3. Hospital functionality simulation and assessment of hospital resilience to earthquakes. Based on the SD  
171 model of hospital functionality, once the initial values of the variables (i.e. the inputs of the SD model) are  
172 set,  $Q(t)$  (i.e. the output of the SD model) can be obtained from model simulations. The inputs include two  
173 parts, including one part that describes the states of the factors affecting  $Q(t)$  right after the occurrence of  
174 the earthquake, and a second part that describes the variations of the factors affecting  $Q(t)$  over a certain  
175 time span. The former can be used to determine the loss of  $Q(t)$  and the latter can be used to determine the  
176 recovery of  $Q(t)$ . Then, after  $Q(t)$  is calculated and  $t_0$  and  $t_{LC}$  are set, the hospital resilience to  
177 earthquakes can be assessed based on Eq. (1).

178 Above provides an overview of the methodology to propose the functionality-based assessment approach  
179 of hospital resilience to earthquakes in this study. More details of the methodology will be discussed in next  
180 sections. In addition, to support the proposition of the functionality-based assessment approach of hospital  
181 resilience to earthquakes, a comprehensive review of prior studies was conducted. Moreover, expert interviews  
182 were carried out in Mianzhu, an inland Chinese city, in order to strengthen the validity of the proposed approach  
183 and gather information and data for an empirical case study. Mianzhu, located in Sichuan Province, China, was  
184 one of the worst-hit cities in the 2008 Sichuan Earthquake (also known as the Wenchuan Earthquake) that  
185 occurred on May 12, 2008, with a magnitude of 8.0 (Lu et al. 2012). Most hospitals in Mianzhu were destroyed  
186 in the earthquake and then reconstructed. The authors conducted a total of four rounds of interviews between

187 2017 and 2019. The qualifications of the interviewees are summarized in Table 1.

- 188 1. The first round (R1) was conducted in December 2017, which aimed at constructing an indicator of  $Q(t)$ .  
189 Four senior doctors and three senior nurses, who participated in the medical rescue in the 2008 Sichuan  
190 Earthquake, from four hospitals (one tertiary, two secondary and one primary hospitals) in Mianzhu, were  
191 interviewed. The interviewees were requested to reflect on the scenario of the medical rescue after the  
192 earthquake and provide their opinions on the definition of hospital functionality.
- 193 2. The second round (R2) was conducted in March 2018. Eighteen respondents including officials from the  
194 local Health Bureau and the medical staff from five local hospitals (one tertiary, three secondary and one  
195 primary hospitals) were surveyed. They were requested to evaluate a list of factors the authors extracted  
196 from the literature that may affect  $Q(t)$ .
- 197 3. The third round (R3) was conducted in August 2018. Six medical staff from four hospitals (the same  
198 hospitals as in R1) were interviewed and requested to give opinions on the indicator of hospital functionality  
199 and the preliminary SD model of hospital functionality proposed by the authors.
- 200 4. The fourth round (R4) was conducted in May 2019. Eleven medical staff from four hospitals (the same  
201 hospitals as in R1) were interviewed. They were requested to provide opinions on the modified indicator of  
202 hospital functionality and SD model after the R3 interviews. In the meanwhile, one of the hospitals was  
203 chosen for case study purpose. The medical staff in the case hospital were requested to provide additional  
204 information that was necessary to construct and run the SD model.

205

[Insert Table 1 here]

206 ***Indicator of Hospital Functionality after Earthquakes***

207 Hospitals are aimed to provide complete medical care for the population (Gilder 1957). During emergencies,  
208 such as earthquakes, the focus of their service may be changed compared with normal conditions. Although it  
209 may not be possible to find a single indicator that can perfectly represent the full functionality of hospitals, it is  
210 feasible to find one that reflects the main functionality of hospitals during earthquakes. During emergencies,  
211 minimizing mortality and morbidity has been seen as a primary objective of hospital services (West 2001,  
212 Hendrickx et al. 2016). Hospitals are expected to accept and treat as many patients as possible so as to meet the  
213 increasing care needs in disasters (Yi et al. 2010). During the R1 interviews, the medical staff also argued that  
214 they tried every means to save lives after the earthquake in spite of tough medical working conditions. Therefore,  
215 the capability of treating patients in hospitals is the main functionality of hospitals during earthquakes, which,  
216 hence, is used as an indicator of hospital functionality after earthquakes in this study.

217 Per Eq. (1), the system functionality should have a value range from 0 to 1. The indicator of hospital  
218 functionality, namely the capability of treating patients in hospitals, is mathematically defined as the ratio of the  
219 number of patients which a hospital is able to treat to the number of patients which the hospital is required to  
220 treat over a period, as shown in Eq. (4):

$$Q(t) = \begin{cases} \frac{\sum_{i=1}^n \beta_i \cdot N_i^a(t)}{\sum_{i=1}^n \beta_i \cdot N_i^r(t)} & N_i^a(t) \leq N_i^r(t) \\ 1 & N_i^a(t) > N_i^r(t) \end{cases} \quad (4)$$

221 where  $Q(t)$  denotes hospital functionality;  $t$  denotes time in days;  $N_i^r(t)$  denotes the number of patients with

222 disease  $i$  that the hospital is required to treat on day  $t$ ;  $N_i^a(t)$  denotes the number of patients with disease  $i$  that  
223 the hospital is able to treat on day  $t$ ;  $\beta_i$  denotes the weight of disease  $i$  based on its urgency;  $n$  denotes the  
224 number of the types of diseases considered for medical care during earthquakes.  $N_i^r(t)$  can be set by the hospital  
225 or by local health authorities according to the capability of the hospital and the historical data of patient arrivals  
226 during similar disasters;  $\beta_i$  can be set by medical experts.

### 227 ***Factors Identification***

228 A hospital is a complex system, whose functionality is subject to the impact of a variety of factors. In this section,  
229 these factors were firstly identified from literature and then discussed in detail. Major databases and search  
230 engines including Web of Science, Google Scholar and CNKI were searched and literature including academic  
231 papers, theses and working reports was retrieved. Snowballing method, i.e. identifying literature from the  
232 references of publications, was also applied. The factors were divided into three categories based on a trio-space  
233 framework proposed by Kasai et al. (2015), namely physical, social and cyber factors. Physical factors were  
234 those owning an entity, such as medical resources, utilities, and buildings; social factors were those related to  
235 human activities, such as professional knowledge of medical staff, emergency plans, and leadership of hospital  
236 administrators; cyber factors were those related to information and data such as Hospital Information System  
237 (HIS). During the R2 interviews, after a comprehensive introduction of the goal of the interview and the  
238 meanings of the factors, the interviewees were required to give advice on adjusting the list of factors and their  
239 opinions on how much these factors affected hospital functionality. A questionnaire survey followed the  
240 interviews to quantify the effects of the factors on hospital functionality, using a 5-point Likert scale from 1

241 (strongly disagree) to 5 (strongly agree). The average score of each factor was calculated and evaluated based  
242 on the rating scale proposed by Hansapinyo (2018). The validity of the results was enhanced by the rich field  
243 experience of the interviewees and a combination of interviews and questionnaire surveys (Khalili et al. 2015).  
244 Table 2 summarizes the finalized list of factors. These factors are further explained below.

245 **[Insert Table 2 here]**

### 246 **Medical Resources (Medical Staff, Supplies, and Equipment)**

247 A hospital is unable to function without medical staff. Human resource management is an essential part of  
248 hospital emergency management (WHO 2011, WHO 2015). During emergencies like disasters when there will  
249 be a surge of patients, the shortage of medical staff can be a critical issue (Ukai 1996, Ochi et al. 2016). Medical  
250 supplies like medicine, disinfectant, bandages, oxygen, and beds are also essential for medical treatment in most  
251 cases. During emergencies, continuity of the hospital supply and delivery chain plays a critical role in achieving  
252 the quality of service and saving lives (WHO 2011, Sabegh et al. 2017). Medical equipment such as X-rays and  
253 magnetic resonance imaging (MRI) is necessary for diagnosis or treatment. Operating rooms are also regarded  
254 as a type of medical equipment in this study since they need to be well equipped in order to function. In addition,  
255 the functioning of medical equipment almost always relies on utilities such as power and water.

### 256 **Utilities (Power, Water, Telecommunication, and Transportation)**

257 Power probably is the most important utility, which also supports other utilities such as water and  
258 telecommunication (Beatty et al. 2006). A power failure will result in various problems in a hospital, such as  
259 unavailability of equipment, loss of lighting, malfunction of information system and so forth (Milsten 2000,

260 Beatty et al. 2006, Prudenzi et al. 2017). To prepare for unexpected power outages, hospitals can be equipped  
261 with generators so as to guarantee uninterrupted power supply. Water also plays an important role in hospitals,  
262 as it supports many critical services in a hospital including surgery preparation, heating, ventilation, and air-  
263 conditioning (HAVC), sanitation, dialysis, sterilization and cooling some medical equipment (Milsten 2000,  
264 Roberson and Hildebrand 2010, Welter et al. 2013, Matsumura et al. 2015). Interruptions of water supply will  
265 significantly disrupt healthcare activities (UK Department of Health 2014). Without water, hospitals would not  
266 be able to function since hygiene and sterilization cannot be guaranteed. Many hospitals store water in tanks or  
267 reserve bottled water in case of water supply disruption. However, the stored water cannot solve the special water  
268 needs such as water used in dialysis (Klein et al. 2005), which needs secondary purification by specialized  
269 devices.

270 Telecommunication and transportation are not direct necessities in medical treatment but may affect the  
271 efficiency to deliver healthcare service. Information exchange is important in disaster rescue (Garshnek and  
272 Burkle 1999, Chen et al. 2018). Supplement of medical supplies may be delayed if the telecommunication is cut  
273 off as Mianzhu had experienced in Sichuan earthquake. Although the functioning of telecommunication systems  
274 is beyond the boundaries of hospitals, hospitals can rely on satellite phones for communication in case of  
275 disruptions of everyday telecommunication systems (Garshnek and Burkle 1999). Transportation also matters  
276 for the delivery of medical service. Damages of roads and bridges in earthquakes will badly affect the efficiency  
277 of patient transfer as well as emergency logistics (Ukai 1997, Caunhye et al. 2012). While road condition is also  
278 out of their control, hospitals are supposed to have vehicles (e.g. ambulances) to ensure successful patient transfer

279 on their sides.

## 280 **Buildings**

281 Hospital buildings always need to be available for medical activities, where the medical staff can perform the  
282 treatment and the patients can be protected. In Mianzhu, the hospital buildings were structurally damaged in the  
283 2008 Sichuan Earthquake and were hence unsafe to enter after the earthquake. The medical staff had to work  
284 outdoors, where the hygienic condition could not be guaranteed for treatment. Although they moved to tents and  
285 portable dwellings several days later, the medical staff argued that the tents and portable dwellings were all  
286 provided by the government, as the hospitals themselves were not able to prepare enough tents or portable  
287 dwellings in advance.

## 288 **Social and Cyber Factors**

289 Professional knowledge of disaster medical rescue is one of the basic requirements of disaster medical  
290 responders (King et al. 2019). The interviewees argued that a lack of knowledge in disaster medicine resulted in  
291 the inefficient performance of the medical staff in the face of such a sudden disaster. To improve the working  
292 performance of the medical staff during disasters, it is important to provide them with routine training (WHO  
293 2011, Zhong et al. 2015). A comprehensive emergency plan, which pre-specifies how each department of the  
294 hospital should respond in emergencies, will contribute to the preparedness of hospitals to cope with disasters  
295 (WHO 2015). However, the interviewees argued that effective implementation of emergency plans was more  
296 important – “without implementation, emergency plans are just pieces of paper”. Good leadership of hospital  
297 administrators is key to ensuring the efficient operation of hospitals during emergencies (Richardson et al. 2013,

298 WHO 2015). According to the interviewees, there was chaos in the operation of Mianzhu hospitals in the  
299 immediate aftermath of the 2008 Sichuan Earthquake due to an apparent lack of leadership.

300 As for cyber factor, the HIS has been an indispensable part of modern hospitals. It supports hospital affairs  
301 and helps to increase efficiency and reduce errors of medical service (Handayani et al. 2017, Handayani et al.  
302 2018). The HIS is also subject to damages during earthquakes. According to the R2 interviewees, the HIS is not  
303 a must for treating patients since it could be replaced by labor, however, in that case, the working efficiency of  
304 medical staff would be significantly impacted.

305 Based on the above discussions, some simplifications and hypotheses are made, as explained below, in  
306 order to quantify  $N_i^a(t)$  in Eq. (4) and ultimately to quantify  $Q(t)$ :

- 307 1. Only treatment in hospital is considered, while pre-hospital care is not.
- 308 2. Once a patient receives treatment, he or she will be cured and released from the hospital.
- 309 3. Medical staff, medical supplies, and medical equipment for the treatment of each disease are independent  
310 on each other, which means the staff, supplies, and equipment are disease-specific and cannot be shared  
311 across diseases.
- 312 4. Power is considered to affect medical treatment in two ways, namely supporting lighting, which is  
313 considered necessary for treatment at night, and supporting medical equipment such as X-rays, MRI, and  
314 operating rooms.
- 315 5. Drinking water, which does not need secondary purification, is considered necessary for all treatment.

316 Purified water from specialized devices, which relies on power, is only needed for some medical equipment  
 317 such as Dialysis Machines.

318 6. Telecommunication and transportation affect medical treatment indirectly, e.g. by affecting patient transfer  
 319 and the supplement rate of medical supplies.

320 7. Buildings are necessary for all treatment activities.

321 8. Social factors affect medical treatment indirectly through other impact factors: professional knowledge  
 322 affects the service capacity (the maximum number of patients who are able to be treated) of medical staff;  
 323 emergency plans affect the recovery rate of physical factors; leadership of hospital administrators affects  
 324 the implementation of emergency plans.

325 9. The cyber factor, i.e. the HIS, is regarded to affect the service capacity of medical staff.

326 Hence,  $N_i^a(t)$  can be calculated using Eq. (5) below:

$$\begin{aligned}
 N_i^a(t) &= \min\{[St_i^a(t)]_{min}, [Su_i^a(t)]_{min}, [E_i^a(t)]_{min}\} \cdot P_L(t) \cdot W_D(t) \cdot B(t) \\
 [St_i^a(t)]_{min} &= \min[St_{i,1}^a(t), \dots, St_{i,o}^a(t), \dots, St_{i,n_{St}}^a(t)], o \in (1, n_{St}) \\
 [Su_i^a(t)]_{min} &= \min[Su_{i,1}^a(t), \dots, Su_{i,p}^a(t), \dots, Su_{i,n_{Su}}^a(t)], p \in (1, n_{Su}) \\
 [E_i^a(t)]_{min} &= \min[E_{i,1}^a(t), \dots, E_{i,q}^a(t), \dots, E_{i,n_E}^a(t)], q \in (1, n_E)
 \end{aligned} \tag{5}$$

327 where  $St_{i,o}^a(t)$ ,  $Su_{i,p}^a(t)$  and  $E_{i,q}^a(t)$  denote the service capacity of each kind of medical staff, supplies and  
 328 equipment respectively for disease  $i$  on day  $t$ ;  $n_{St}$ ,  $n_{Su}$ , and  $n_E$  denote the number of kinds of medical staff,  
 329 supplies and equipment respectively;  $P_L(t)$  denotes the power supply for lighting (given that lighting power is

330 only necessary for the treatment in the night time,  $P_L(t) = 1$  when power is available for lighting and  $P_L(t) =$   
331  $0.7$  when power is not available for lighting);  $W_D(t)$  denotes the drinking water supply (binary, 1 when drinking  
332 water is available, while 0 when unavailable); and  $B(t)$  denotes the availability of hospital buildings, equaling  
333 to the percentage of residual capacity of the buildings after earthquakes.

### 334 ***SD Modeling***

335 Once the value variations over time of the factors in Eq. (5) are obtained,  $Q(t)$  can be obtained using Eq. (4)  
336 and Eq. (5). However, as aforementioned, some of these factors are interacted and their values are correlated in  
337 complicated, non-linear relationships. Therefore, the value variations of the factors are essentially a type of  
338 emergent property that cannot be predicted only by examining individual factors. The relationships of the factors  
339 play a fundamental role in determining the factors' values and therefore must also be considered. In order to  
340 model these dynamics and interactions of the factors, from which important inputs for calculating  $Q(t)$  can be  
341 obtained, an SD model of hospital functionality after earthquakes (SD-HFE) is proposed in this study. In the  
342 process of model development, the SD-HFE was revised and finalized by experts through two rounds of  
343 interviews (R3 and R4).

344 The structure of the SD-HFE is split into multiple parts shown in different figures for readability, among  
345 which Fig. 2 illustrates the high-level causal loops of the model (i.e. the overall structure of the model), while  
346 Figs. 3-9 further illustrate the detailed causal loops of the factors (i.e. parts of the model) included in Fig. 2.  
347 Variables in all figures follow the same naming convention, and the variables that appear in multiple figures are  
348 the proxies through which different parts of the model interact. Disease A is used as an example in these figures

349 for brevity. The overall structure of the SD-HFE is developed based on the following logic: after an earthquake  
350 happens, patients arrive at hospitals and are first triaged by disease type. Patients with different types of disease  
351 are treated separately. Those who have received treatment are cured and released from the hospital. Some  
352 patients waiting to be treated are transferred to other healthcare facilities by ambulance and some patients, who  
353 die during the waiting, are sent to morgues (Cimellaro et al. 2017). In the SD-HFE, two types of medical supplies  
354 are considered, namely medical consumables and beds. Medical consumables, such as medicine, bandages, and  
355 oxygen, can be consumed and supplemented, while beds are reusable medical supplies. According to Eq. (5),  
356 treatment of patients relies on “Service capacity of medical staff”, “Service capacity of medical consumables”,  
357 “Number of available beds”, “Service capacity of medical equipment”, “Power supply for lighting”, “Drinking  
358 water supply”, and “Availability of building”.

359 **[Insert Fig. 2 here]**

360 Figs. 3-6 illustrate the dynamics of different medical resources, including medical staff, medical  
361 consumables, beds, and medical equipment, respectively. Specifically, “Service capacity of medical staff”  
362 depends on both “Number of medical staff” and “Full service capacity per medical staff”. “Service capacity of  
363 medical staff” is also affected by “Availability of HIS” and staff’s “Knowledge of disaster medicine” (see Fig.  
364 3). “Number of medical staff” may decrease due to the staff’s deaths and injuries caused by the earthquake.  
365 Medical consumables are consumed while patients are being treated. They can be supplemented, and the  
366 supplement rate is affected by “Road state”, “Availability of communication”, and “Emergency plan effect” (see  
367 Fig. 4). In Fig. 5, the dynamics of beds mainly depend on “Hospitalization rate” and “Discharge rate” of the

368 patients who receive treatment. Beds can also be supplemented if they are not adequate. In addition, medical  
369 equipment (Fig. 6) may suffer damage during earthquakes and lose availability. “Service capacity of medical  
370 equipment” is also affected by “Medical water supply” and “Power supply”, which support the operation of  
371 medical equipment, and also affected by “Rate of equipment usage” and “Full service capacity of medical  
372 equipment”.

373 **[Insert Fig. 3 here]**

374 **[Insert Fig. 4 here]**

375 **[Insert Fig. 5 here]**

376 **[Insert Fig. 6 here]**

377 With regard to utilities, two parts are considered, including the municipal part (Fig. 7), which is beyond the  
378 boundaries of hospitals, and the hospital part (Fig. 8), which is within the boundaries of hospitals. The municipal  
379 part includes roads, telecommunication, municipal power, and municipal water; the hospital part includes  
380 ambulances, satellite telephones, power generators, fuel, and stored water. Each type of municipal part of utilities  
381 has a “state” to describe its availability, which then determines its serviceability. The utilities’ states may be  
382 worsened and their availability may be lost after the earthquake hit, while the states can also be improved after  
383 recovery measures are taken. For municipal water and telecommunication, their availability also relies on the  
384 availability of municipal power supply (Fig. 7). As aforementioned, the supply of power and water in the hospital  
385 mainly depends on the municipal supply, while the hospital can also prepare power generation instruments and

386 store water in case of accidents (Fig. 8). “Generator power supply” relies on both “Generators” and “Fuel  
387 storage”, which can be consumed and supplemented. In addition, electric power generation also requires water  
388 for cooling (Vugrin et al. 2015). The stored water, as another source of “Drinking water supply” in the hospital,  
389 can also be consumed and supplemented by hospital. “Medical water supply” relies on both “Drinking water  
390 supply” and “Power supply” as power is needed to run the purification equipment.

391 **[Insert Fig. 7 here]**

392 **[Insert Fig. 8 here]**

393 Fig. 9 shows the dynamics of the hospital buildings, social factors and cyber factors. The state of buildings  
394 determines their availability, which can be recovered by repair or reconstruction. “Availability of HIS” depends  
395 on “Power supply”. The HIS is also equipped with UPS. “Recovery rate of HIS” is considered to depend on  
396 “Recovery rate of building” where it is installed. For social factors, medical staff’s “Knowledge of disaster  
397 medicine” can be improved by “Training”, and “Emergency plan effect”, which can affect the recovery rate of  
398 some physical factors as aforementioned, is related to “Comprehensiveness of emergency plans” and  
399 “Leadership” of hospital administrators.

400 **[Insert Fig. 9 here]**

401 The relationships among different factors can be classified in two types: one is one-way relationships,  
402 namely one factor is affected by another; the other one is interactions, namely two factors are affected by each  
403 other. For one-way relationships, one example is that transportation condition affects the supplement of medical

404 consumables, which is modeled by the relationship between “Road state” (Fig. 7) and “Supplement rate of  
405 medical consumables” (Fig. 4); another example is that “Emergency plan effect”(Fig. 9) affects the recovery  
406 rates of some physical factors such as medical staff (Fig. 3), medical consumables (Fig. 4), medical beds (Fig.  
407 5), medical equipment (Fig. 6), fuel and stored water (Fig. 8), as the recovery processes of the factors are usually  
408 pre-specified in emergency plans of hospitals. As for interactions, one example is that two types of utilities,  
409 namely power and water, are interacted, where “Municipal power supply”, as one source of “Power supply”,  
410 affects “Municipal water supply” and further affects “Drinking water supply” (Fig. 7), while conversely  
411 “Drinking water supply” affects “Generator power supply” (Fig. 8), which is another source of “Power supply”.  
412 Some factors and the treatment activity are also interacted. For instance, “Service capacity of medical  
413 consumables” (Fig. 4) and “Number of available beds” (Fig. 5) contribute to “Treatment rate” of patients (Figs.  
414 4-5), which in turn determines “Consumption rate of medical consumables” (Fig. 4) and “Beds occupying rate”  
415 (Fig. 5).

#### 416 ***Simulation of the SD-HFE and Assessment of Hospital Resilience to Earthquakes***

417 Inputs are needed to run the SD-HFE. As aforementioned, the inputs include the ones describing the states of the  
418 factors right after the occurrence of the earthquake, which depend on potential loss or damage of the factors, and  
419 the ones describing the variations of the factors over time. Potential methods to determine the inputs are given  
420 in this section. FEMA (2012a) proposes the FEMA-P58 methodology for seismic performance assessment of  
421 buildings as well as an electronic calculation tool called “PACT” for implementing the methodology. By  
422 inputting the data on building information (story height, area etc.), occupancy, component fragilities, the

423 earthquake scenario and so forth, the PACT is able to perform loss calculations including repair cost, downtime,  
424 and casualty estimates (FEMA 2012b). Hence, the casualties of medical staff and the loss of the hospital  
425 buildings can be obtained using the PACT. The PACT can also potentially be used to determine the loss of the  
426 components located in the hospital building such as medical supplies, medical equipment, hospital part of  
427 utilities, and the HIS once their fragility data are obtained. With regard to the recovery of the above factors, the  
428 supplement of medical staff, medical supplies, fuel for generators, and drinking water, and recovery of medical  
429 equipment can be estimated according to the interviews with the hospital staff. The time needed for retrofitting  
430 the hospital building can be obtained using the PACT. In addition, the loss and recovery rates of municipal part  
431 of utilities can be estimated using Hazus - MH 2.1, which is also developed by FEMA (2018), if required data  
432 are made available. For social factors, the variables in the model can be set according to experts' opinions  
433 collected in interviews. The profile data of the hospital, such as the initial number of medical staff, initial service  
434 capacity of medical supplies and so on, can be obtained through surveys. For the inputs which require medical  
435 knowledge and historical experience, such as patient arrivals, death rates, hospitalization rates, and discharge  
436 rates and so on, can be estimated by experts.

437 When the simulation is performed using the SD-HFE, the variables in the model vary over time.  $N_i^a(t)$   
438 can be obtained based on Eq. (5) and then  $Q(t)$  can be calculated based on Eq. (4). Setting  $t_0$  as the time when  
439 the earthquake occurs and  $t_{LC}$  as a time window of interest, the resilience level of the hospital to earthquakes  
440 can be obtained based on Eq. (1).

## 441 **Case Study**

442 A case study was carried out using the proposed approach to quantify the resilience of a tertiary hospital in  
443 Mianzhu. The hospital, located in the city center, had 686 beds with annual patient arrivals of around 0.70 million.  
444 The hospital building, reconstructed after the 2008 Sichuan Earthquake, had 12 floors. The pharmacy was located  
445 on the first floor and the operating rooms were located on the fourth floor. The simulation scenario assumed that  
446 the reconstructed hospital suffered an earthquake similar to the 2008 Sichuan Earthquake at the present time. All  
447 data that were needed as inputs of the SD-HFE were obtained in the R4 interviews. The ground motion data of  
448 the 2008 Sichuan Earthquake with a peak ground acceleration of  $6.33 \text{ m/s}^2$  was used in this case study.

449 Residual “Number of medical staff” was set by taking into consideration the casualty of the medical staff  
450 estimated using the FEMA PACT. It was assumed that all the medical staff were working in the hospital when  
451 the earthquake occurred and hence there was no supplement of medical staff. Due to a lack of the fragility data  
452 which were necessary for damage analysis in the FEMA PACT, the loss of medical supplies and damage of  
453 medical equipment and the HIS was estimated based on the damage state of the hospital building, and it was  
454 assumed that there was no damage of hospital part of utilities. Using the method proposed by Xiong et al. (2016),  
455 the damage state (none, slight, moderate, extensive or complete) of each floor of the hospitals under the ground  
456 motion was obtained. Then, the loss or availability of the above components was estimated according to the  
457 damage state of the targeted floor using a lookup table (Table 3) developed by the authors in this study. For loss  
458 or availability estimation of medical consumables, beds, operating rooms, and the HIS, the targeted floor in Table  
459 3 referred to the floor where the pharmacies, wards, operating rooms, and HIS were located respectively. The

460 availability of the building equaled to the ratio of residual availability of floors. “Supplementary rate of medical  
461 consumables” was estimated based on data collected in the R4 interviews, which were adjusted by the “Road  
462 state”, “Availability of communication” and “Emergency plan effect”; the recovery rates of hospital part of  
463 utilities were assumed or estimated by the interviewees; “Recovery rate of building” was set based on the repair  
464 time of the building estimated using the FEMA PACT, and the repair process was assumed to be linear; the  
465 operating rooms and the HIS were considered fully recovered when the hospital building was fully recovered.

466         Since data required by Hazus - MH 2.1 for analyzing the damage and recovery of municipal part of utilities  
467 were not available, the damage and recovery rates were set as the actual rates that were observed in the 2008  
468 Sichuan Earthquake and reported in the interviews. This may lead to somewhat conservative assessment results  
469 because after the 2008 Sichuan Earthquake, there was a huge investment on the overall capability of the Mianzhu  
470 to cope with earthquake, therefore, the current municipal part of utilities should be more resilient to earthquakes  
471 than they were in 2008. There were four typical kinds of diseases considered in the case study: disease A (minor  
472 trauma like abrasion), disease B (severe trauma like fractures and brain injuries), disease C (upper respiratory  
473 infection and enteritis) and disease D (other diseases) (Liu et al. 2008). The weights of these four types of  
474 diseases ( $\beta_i$  in Eq.(4)) were set by the average death rate of each type of disease. Operations were only necessary  
475 for all patients with disease B and 10% of the patients with disease D, according to the interviews. Patient arrivals  
476 with different diseases after the earthquake were set after scaling the data from the 2008 Sichuan Earthquake  
477 according to annual patient arrivals.  $N_i^r(t)$  of each hospital was set according to the daily service capacity of  
478 the current medical resources. Gaussian noise was introduced to reflect the fluctuations of the service capacity

479 of the medical resources. Table S1 summarized the main inputs for the calculation of hospital functionality in  
480 the case study, and Table S2 provided the system dynamics equations used in the case study. The SD-HFE was  
481 run in Anylogic 8.4.0 PLE. The results are reported in the next section.

482 **[Insert Table 3 here]**

## 483 **Results**

484 Fig. 10 illustrates the functionality curve of the case hospital in Mianzhu. The curve reflects a pattern of “first  
485 decreasing and then recovering”. Immediately after the occurrence of the earthquake (Day 0),  $Q(t)$  dropped to  
486 0.65, which was mainly due to the loss of serviceability of the hospital building. In the meantime, there was  
487 municipal power failure caused by the earthquake. Although the hospital was equipped with power generators,  
488 the stored diesel fuel was only enough for one-day use. Hence,  $Q(t)$  fell to 0.26 at the end of Day 1.  $Q(t)$   
489 bounced back when the municipal power was restored on Day 2. Then,  $Q(t)$  began to increase gradually as  
490 measures were being taken to repair the hospital building. Since Day 19 when the hospital building was fully  
491 recovered,  $Q(t)$  had generally remained stable at 1.00 with slight fluctuations caused by the Gaussian noise  
492 introduced to the SD-HFE. Setting  $t_0$  as the day when the earthquake happened and  $t_{LC}$  as 60 days when the  
493 distribution of the diseases after the earthquake tended to be stable (Liu et al. 2008), the resilience level of the  
494 hospital using the SD-HFE was calculated as 0.91 based on Eq. (1).

495 **[Insert Fig. 10 here]**

496 In order to further explore the reasons behind the variations of the functionality curves, the performance

497  $(Per(t))$  of the hospital was assessed per each kind of disease, in other words,  $N_i^a(t)/N_i^r(t)$  was calculated for  
498 each value of variable  $i$ . The results are depicted in Fig. 11. As can be seen in the figure, after the earthquake  
499 occurred (Day 0),  $Per(t)$  for Disease A, B, C, and D fell to 0.68, 0.80, 0.90, and 0.41 respectively. The  
500 differences in the performance were due to the different initial service capacity of the medical resources. On Day  
501 1 when there was no lighting due to power outage after the generators ran out of fuel, the performance of the  
502 hospital for all diseases significantly dropped. Among the performance,  $Per(t)$  for Disease B fell to 0 and  
503  $Per(t)$  for Disease D fell to 0.29, as the operating rooms were not available due to the power failure. On Day  
504 2,  $Per(t)$  for all diseases bounced back when the municipal power was restored, which was consistent with the  
505 trend of  $Q(t)$  in Fig. 10. On Day 4, a decrease of  $Per(t)$  for Disease B was observed. It was due to the  
506 deficiency of medical consumables, which only lasted for one day as more medical consumables were  
507 supplemented. From Day 4, there was a significant drop in  $Per(t)$  for Disease C, when the hospital received an  
508 increasing number of patients and ran out beds. However, as the occupied beds were gradually released and the  
509 building was being restored,  $Per(t)$  for Disease C went back up over time. Nevertheless, the decrease of  $Q(t)$   
510 from Day 4 was not very obvious because  $Per(t)$  for Disease A and D kept increasing with the recovery of the  
511 building from Day 2 when the municipal power was recovered, which neutralized the effects of the decrease of  
512  $Per(t)$  for Disease B and C. As shown in Fig. 11,  $Per(t)$  for Disease B got fully recovered on Day 13 rather  
513 than on Day 19 when the building was fully recovered. It was due to that the storage of medical resources for  
514 Disease B was higher than it was actually needed so that  $Per(t)$  for Disease B could be at a relatively high level  
515 and be recovered earlier in spite of the impact of the damaged building. In addition,  $Per(t)$  for Disease D was  
516 generally the lowest among all four curves, because it was mainly restricted by the service capacity of medical

517 staff, which fell 50% due to the unavailability of the HIS. However, on Day 19 when the HIS was recovered and  
518 so was the service capacity of medical staff,  $Per(t)$  for Disease D bounced by to around 1.00, which contributed  
519 to the full recovery of  $Q(t)$  on the same day.

520 **[Insert Fig. 11 here]**

521 The results of the case study were provided for three experts in Mianzhu who had participated in the  
522 aforementioned interviews, including one associate chief physician and one senior nurse from the case hospital  
523 and one administration staff from the local Health Bureau. The experts all commented that the results were in  
524 line with their expectations and could well reflect the characteristics of the behavior of the hospital after  
525 earthquakes.

## 526 **Discussions**

### 527 ***Extreme Condition Test***

528 In order to ensure that the SD-HFE was structurally valid, extreme condition tests were conducted. The inputs  
529 of the variables in the model were set to zero or infinite (values large enough, around ten thousand times larger  
530 than other variables) individually, which examined the behavior of the model under various extreme conditions.  
531 The results of the extreme conditions tests showed that the SD-HFE behaved as expected. In this section, two  
532 tests were given as examples. One condition (Condition 1) was to assume that the roads around the hospital were  
533 totally impassable and “Recovery rate of roads” was zero with other conditions unchanged compared with the  
534 case study. Under such condition, the hospital had no access to supplement of medical supplies and could not

535 transfer patients to other locations (patient arrivals were considered unaffected by “Road state”). Another  
536 condition (Condition 2) was to assume that “Recovery rate of municipal power” was zero, which indicated that  
537 the municipal power would be continuously unavailable due to the damage caused by the earthquake. The results  
538 of the case study served as a reference (marked as Condition 0). Fig. 12 illustrates the results of the two tests.  
539 Under Condition 1, for the first two days,  $Q(t)$  was not impacted compared to Condition 0 due to the initial  
540 storage of medical consumables. However, when the hospital was running out of the medical consumables,  $Q(t)$   
541 began to decrease. The first decreases occurred on Day 4 and Day 5 when medical consumables for Disease B  
542 was running out; the second decreases occurred on Day 6 and Day 7 when medical consumables for Disease C  
543 was running out; the third decreases occurred on Day 20 and Day 21 when medical consumables for Disease D  
544 was running out. After then,  $Q(t)$  kept decreasing as medical consumables for Disease A were consumed. Under  
545 Condition 2, unlike Condition 0,  $Q(t)$  did not bounce back on Day 2, because the municipal power was not  
546 recovered. As power affected  $Q(t)$  through access to lighting and medical equipment, the hospital was able to  
547 maintain a low level of functionality. It was because that the treatment activities, which did not rely on medical  
548 equipment and happened in the daytime, were not affected. However, municipal power supply was also essential  
549 to municipal water supply, which in turn determined whether the hospital could have access to drinking water  
550 that was critical to  $Q(t)$ . Thus, from the curve in Condition 2, it could be seen that  $Q(t)$  was kept at a level of  
551 around 0.25 due to the storage of drinking water until Day 7, when the stored drinking water ran out and  $Q(t)$   
552 fell to zero. This curve of  $Q(t)$  also reflected the interactions among utilities.

553 **[Insert Fig. 12 here]**

554 ***Adaptation of the Hospital***

555 During the 2008 Sichuan Earthquake, the case hospital was severely damaged. The power and water supply was  
556 cut off for days and almost all the functional departments were unavailable. The medical staff the authors talked  
557 to during the R4 interviews were asked to recall and estimate  $Q(t)$  of the case hospital after the occurrence of  
558 the 2008 Sichuan Earthquake. In order to facilitate their understanding of  $Q(t)$ , it was simplified as “the  
559 percentage of patients the hospital was able to treat”. It should be noted that such a simplification ignored the  
560 weights of diseases, i.e.  $\beta_i$  in Eq. (4). According to the interviewees, the patients they were not able to treat then  
561 were usually those with life-threatening diseases. The weights of these diseases were supposed to be high because  
562  $\beta_i$  was set based on the death rate of the disease in the case study. Hence, the estimated  $Q(t)$  would be  
563 overestimated. The interviewees indicated that  $Q(t)$  showed three obvious stages, including treatment on site,  
564 treatment in tents and treatment in portable dwellings, where  $Q(t)$  was about 0.40, 0.60 and 0.90 respectively  
565 as shown in Fig. 13. Around two years later when the current hospital was reconstructed and put into use,  $Q(t)$   
566 recovered to 1.00 (not shown in Fig. 13). Setting  $t_0$  as the day when the earthquake happened and  $t_{LC}$  as 60  
567 days, the resilience level of the hospital to the 2008 Sichuan Earthquake was calculated as 0.61 based on Eq. (1).

568 **[Insert Fig. 13 here]**

569 In Fig. 13, both curves had significant decreases in the first few days after the earthquake occurred. It was  
570 because that the decreases were mainly caused by the failure of utilities like power and water and the inputs of  
571 the damage and recovery rate of municipal utilities in the case study were set to be the same as in the year 2008.  
572 Nevertheless, the decrease of  $Q(t)$  in the case study had a one-day lag due to the implementation of power

573 generators in the hospital. Moreover, the current hospital building suffered much less damage in the case study  
574 than the year 2008, contributing to fewer casualties of medical staff and less loss or damage of medical supplies  
575 and equipment, which in turn contributed to a less loss of  $Q(t)$  and a higher resilience level. Such results echoed  
576 the feedback collected during the R4 interviews. The medical staff in the hospital suggested that they had been  
577 much more prepared to cope with earthquakes than before – with a more robust building and more stored supplies.  
578 They were quite sure that the hospital could perform much better if the same earthquake in 2008 happened again.

579 According to Eq. (4),  $Q(t)$  depends on not only  $N_i^a(t)$  but also  $N_i^r(t)$ .  $N_i^r(t)$  reflects the expected  
580 serviceability of the hospital which is related to the resources it has. Obviously, a tertiary hospital is usually  
581 required to serve more people and handle more types of diseases than a primary hospital. From the year 2008 to  
582 the present time, the case hospital has become a tertiary hospital with an annual patient arrival of around 0.70  
583 million from a secondary hospital with an annual patient arrival of around ten thousand. The current  $N_i^r(t)$  is  
584 much higher than that in 2008. Therefore, the resilience level of the hospital increases by 49% from 0.61 to 0.91  
585 since the year 2008, while the number of patients the hospital is able to treat has increased by an even much  
586 larger percentage.

### 587 ***Policy Sensitivity Test***

588 In the case study, the decreases of  $Q(t)$  mainly due to three issues, namely power failure, deficiency of beds  
589 and the loss of serviceability of the hospital building. In this section, the authors tested the effectiveness of three  
590 policies that were supposed to address the above issues using the SD-HFE. Herein, the policies are: Policy 1 -  
591 the hospital reserves twice as much fuel as it does now; Policy 2 - the hospital shifts 40 beds from the departments

592 for Disease C to the departments for Disease D after the earthquake; Policy 3 - the hospital shortens the recovery  
593 time of the building from 19 days to 10 days by hiring more workers. The inputs of the model were adjusted  
594 according to each policy. The effects of the three policies based on simulation results were illustrated in Fig. 14,  
595 where the result of the case study was also shown marked as Policy 0.

596 **[Insert Fig. 14 here]**

597 Fig. 14 showed the effectiveness of the policies, which overall improved  $Q(t)$ . Policy 1's effectiveness  
598 indicated that a higher storage of fuel did work to avoid the abrupt loss of  $Q(t)$  caused by municipal power  
599 failure. However, a new drop in  $Q(t)$  occurred on Day 3. By backtracking the variables in the SD-HFE, it was  
600 found that medical consumables for Disease B happened to be deficient on Day 3 because they were consumed  
601 faster when the power was uninterrupted from the beginning. Such deficiency caused the drop. Hence, Policy 1  
602 should be accompanied by another policy of enhancing the storage of medical consumables for Disease B so as  
603 to better improve  $Q(t)$ . Policy 2's effectiveness indicated that proper distribution of medical supplies in different  
604 departments of the hospital were also important to enhance the hospital resilience to earthquakes. However, such  
605 a "distribution" is disease-specific and the distribution for earthquakes might not work for other types of disasters  
606 once the distribution of the diseases caused by the disaster was different. Policy 3's effectiveness indicated that  
607 a higher recovery rate of hospital building would contribute to a higher recovery rate of  $Q(t)$ , which was as  
608 expected. Nevertheless, it should be noted that the purpose of the policy test was to demonstrate the feasibility  
609 of using the SD-HFE to assess the effectiveness of possible resilience enhancement policies rather than develop  
610 feasible or optimal resilience enhancement policies. Hence, some factors such as structural repair and

611 reconstruction activities that may potentially cause interruptions to medical operations, were not considered in  
612 the policy test. Overall,  $Q(t)$  calculated using the SD-HFE was sensitive to the proposed policies and the  
613 evolution of  $Q(t)$  under the three policies headed for the same trend, which proved the reliability of the SD-HFE  
614 (Jiang et al. 2015).

## 615 **Conclusions**

616 This research proposes a new functionality-based assessment approach of quantifying hospital resilience to  
617 earthquakes. A new indicator of hospital functionality is proposed and the SD-HFE is developed to simulate and  
618 compute the hospital functionality after earthquakes, which considers both the damages and the recovery  
619 processes of the hospital. The validity of the approach is tested using a case study of a hospital in China. The  
620 proposed approach can contribute to analyzing the evolution of hospital functionality after an earthquake and  
621 assess hospital earthquake resilience. Moreover, the approach can serve as a tool for the decision makers of the  
622 hospitals to identify the weakness in hospital earthquake resilience and compare the effectiveness of different  
623 resilience enhancement measures so as to propose targeted solutions.

624 While the proposed approach provides a promising tool to enable the assessment of hospital resilience to  
625 earthquakes, there are several limitations in this study that should be acknowledged. A few assumptions were  
626 made for the proposed assessment approach. Some of those assumptions, however, may be strict. For instance,  
627 medical resources (medical staff, medical supplies, and medical equipment) for the treatment of each disease are  
628 considered independent on each other. In fact, different diseases may require common medical resources and  
629 hospitals themselves may arrange their medical resources flexibly so as to maximize their functionalities in

630 emergencies. Future research should look into the correlation of the medical resources needed in the treatment  
631 for different diseases, which may require more domain knowledge in medicine and pharmacy. Moreover, there  
632 could be other potential factors that may affect hospital functionality after earthquakes, in addition to the ones  
633 identified in the SD-HFE. These factors could be identified and examined in future research for further  
634 improvement of the SD-HFE. For a practical assessment of hospital resilience, it is also suggested to consider  
635 the uncertainties of the occurrences, as well as the intensities of earthquakes. In addition, while the feasibility of  
636 using the proposed approach to compare the effectiveness of possible resilience enhancement policies has been  
637 demonstrated, how to develop or optimize these policies, which should consider their costs, feasibility, and  
638 interactions, is worth further investigation in future research.

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649 **Supplemental Data**

650 Table S1 and S2 are available online in the ASCE Library ([ascelibrary.org](http://ascelibrary.org)).

651 **Data Availability Statement**

652 Some or all data, models, or code generated or used during the study are available from the corresponding author  
653 by request. The data, models or code are:

654 The raw data used to generate Figs. 10-14.

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802

## **Table List**

Table 1. Qualifications of the interviewees

Table 2. Factors identified to be influential to hospital functionality after earthquakes

Table 3. Lookup table for the inputs for the SD-HFE in the case study

**Table 1.** Qualifications of the interviewees

Items	Categories	Number of interviewees			
		R1	R2	R3	R4
Current titles	Associate chief physician	3	5	4	3
	Attending doctor	1	3	1	3
	Practitioner	0	3	1	2
	Senior nurse	3	2	0	3
	Nurses	0	1	0	0
	Administration staff	0	4	0	0
Years of professional experience	≥30 years	1	1	1	4
	20-29 years	5	11	4	5
	10-19 years	1	3	1	4
	≤9 years	0	3	0	0
Education	Bachelor or above	5	11	4	7
	Other	2	7	2	4
Worked during earthquakes?	Yes	7	15	6	11
	No	0	3	0	0
Total		7	18	6	11

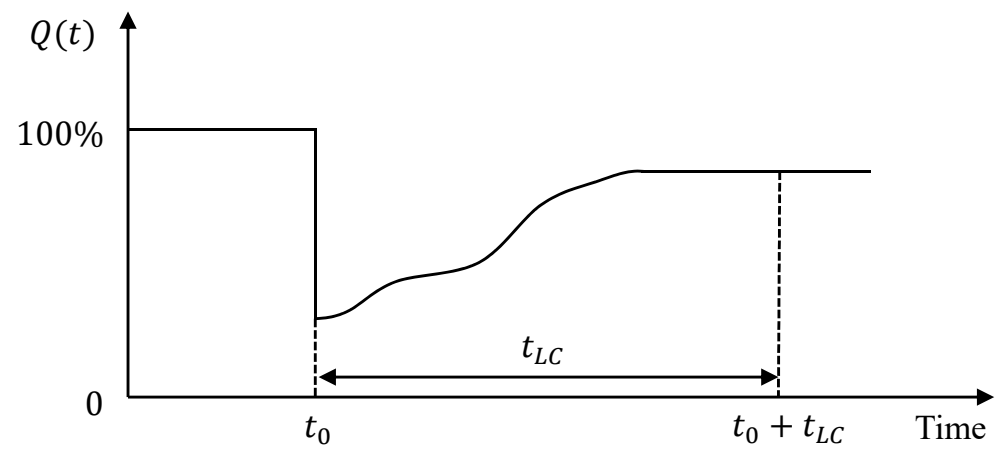
**Table 2.** Factors identified to be influential to hospital functionality after earthquakes

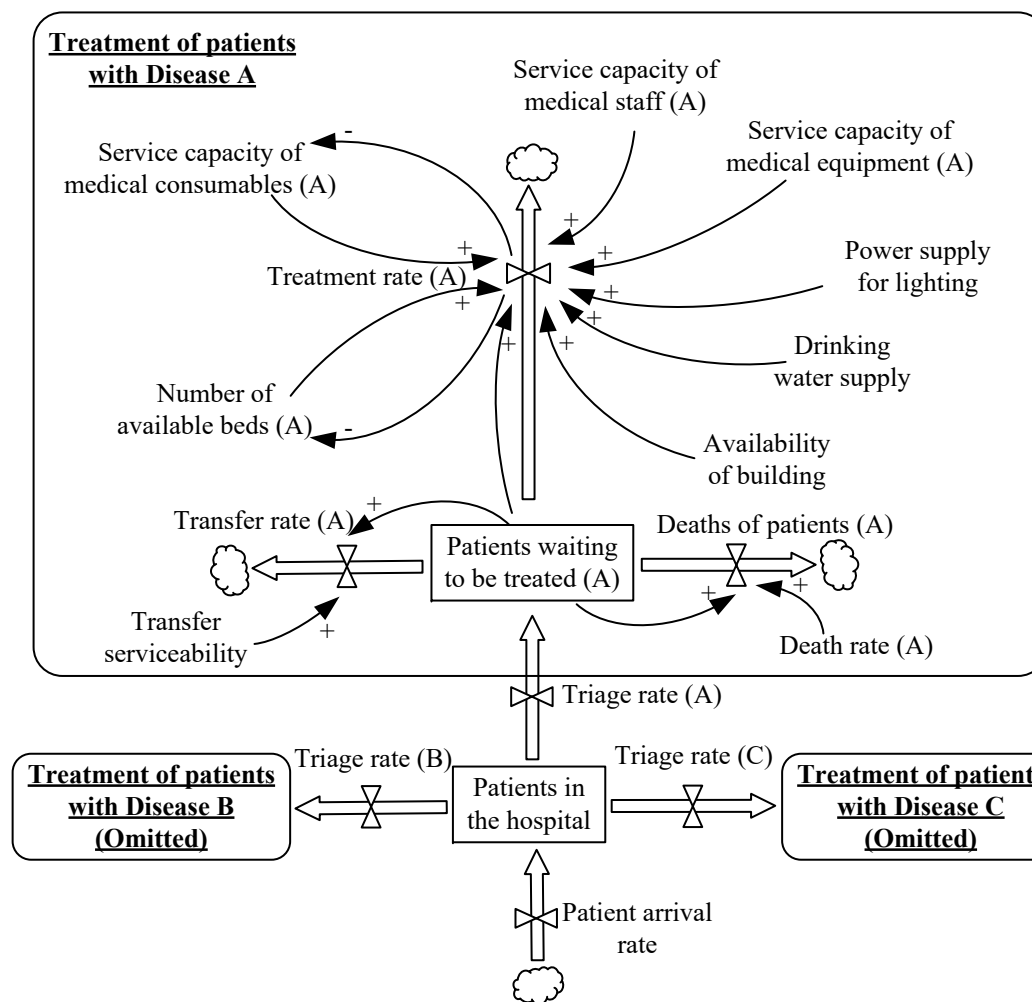
<b>No.</b>	<b>Factors</b>	<b>Categories</b>	<b>Results<sup>a</sup></b>
F1	Sufficient medical staff	Physical	Strongly agree
F2	Sufficient medical supplies	Physical	Strongly agree
F3	Available medical equipment	Physical	Strongly agree
F4	Available electricity supply	Physical	Strongly agree
F5	Available water supply	Physical	Strongly agree
F6	Available telecommunication	Physical	Strongly agree
F7	Available transportation for patient transfer	Physical	Strongly agree
F8	Safe buildings	Physical	Strongly agree
F9	Sufficient professional knowledge	Social	Strongly agree
F10	Comprehensive emergency plans	Social	Strongly agree
F11	Good leadership of hospital administrators	Social	Strongly agree
F12	Functional Hospital Information System (HIS)	Cyber	Strongly agree

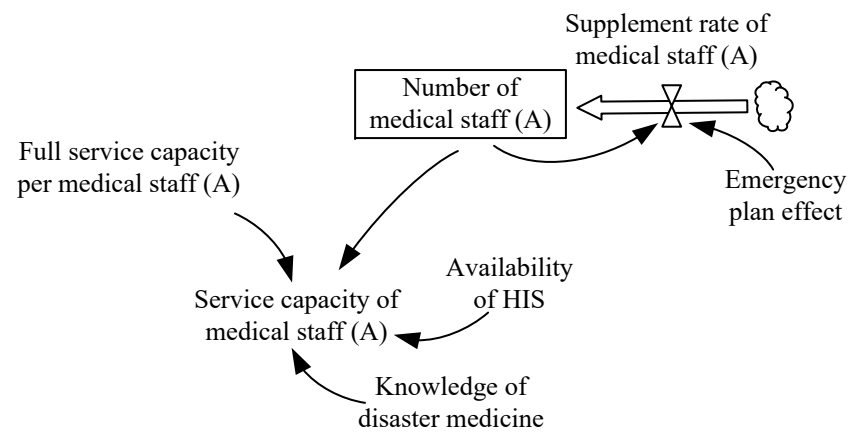
<sup>a</sup>“Strongly agree” means the average score of the factor falls within [4.21, 5.00] (Hansapinyo 2018).

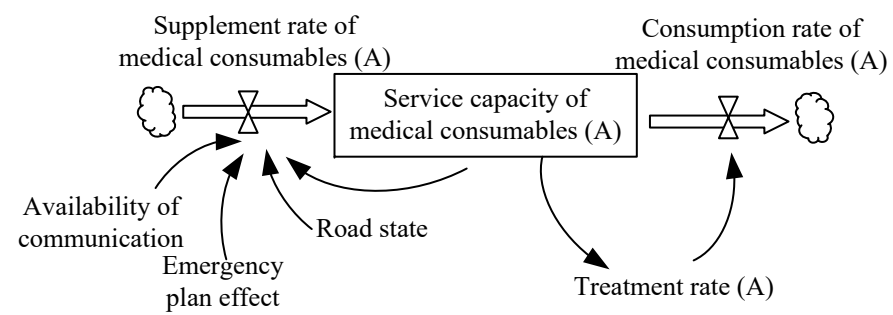
**Table 3.** Lookup table for the inputs for the SD-HFE in the case study

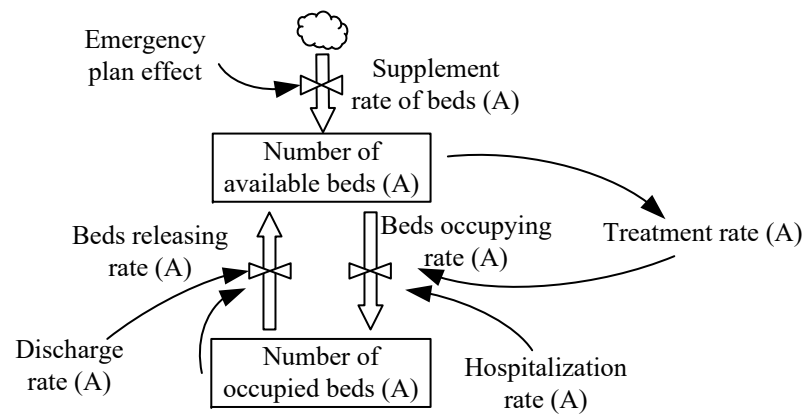
<b>Model input</b>	<b>Damage state of the targeted floor</b>				
	<b>None</b>	<b>Slight</b>	<b>Moderate</b>	<b>Extensive</b>	<b>Complete</b>
Loss of medical consumables	0	5%	10%	50%	90%
Loss of beds	0	0	20%	60%	100%
Availability of operating rooms	100%	100%	0	0	0
HIS state	100%	0	0	0	0
Availability of floor	100%	80%	0	0	0











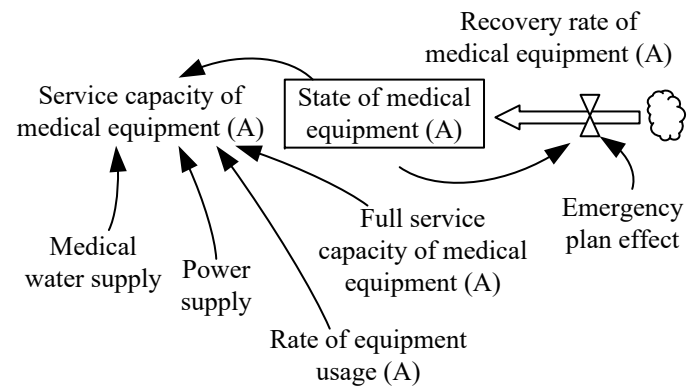


Fig. 7. Dynamics of utilities (municipal part)

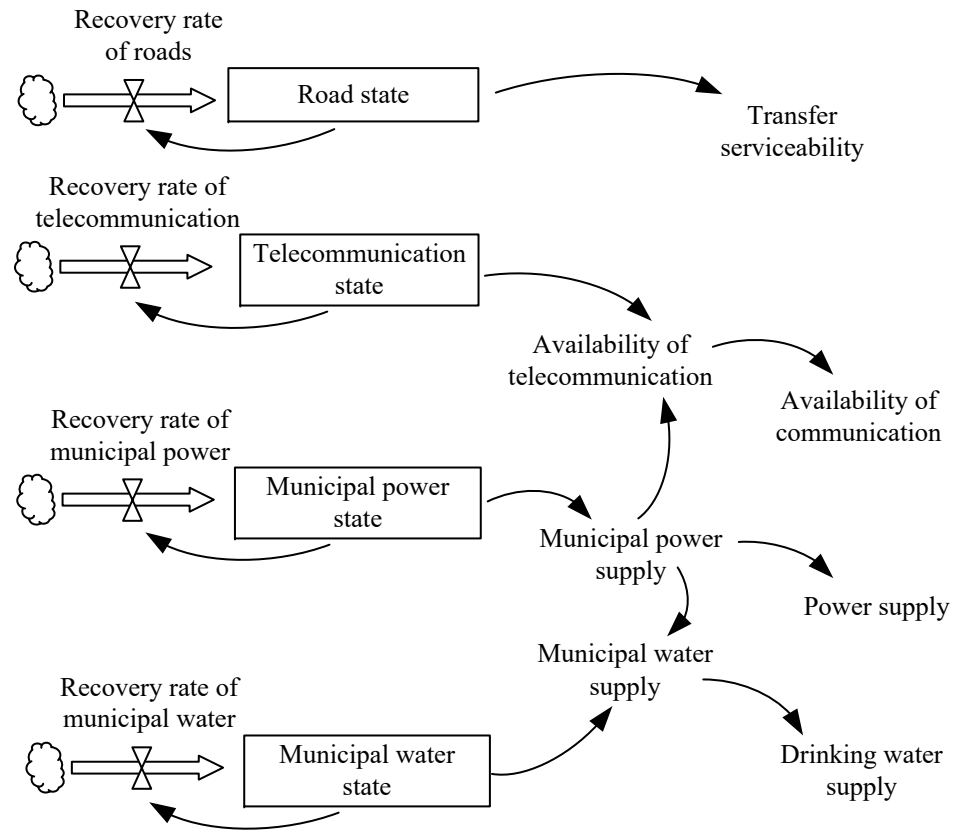


Fig. 8. Dynamics of utilities (hospital part)

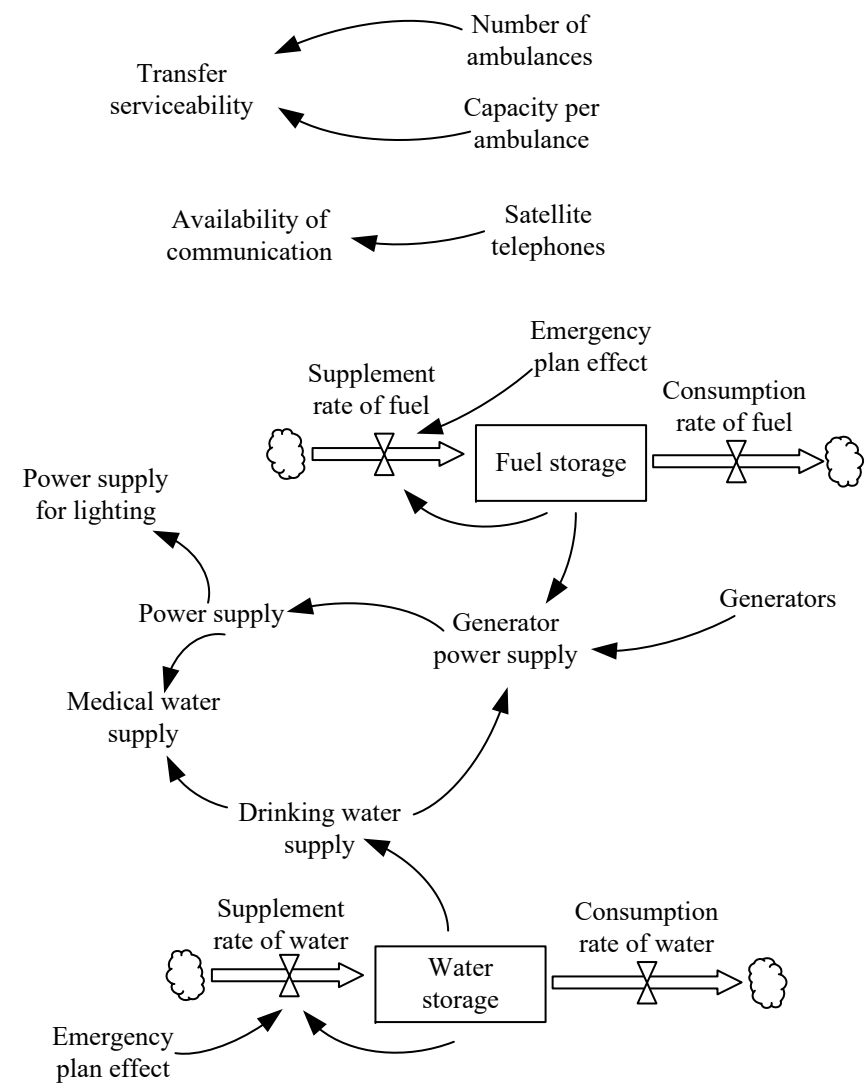


Fig. 9. Dynamics of the hospital buildings, social factors and cyber factors

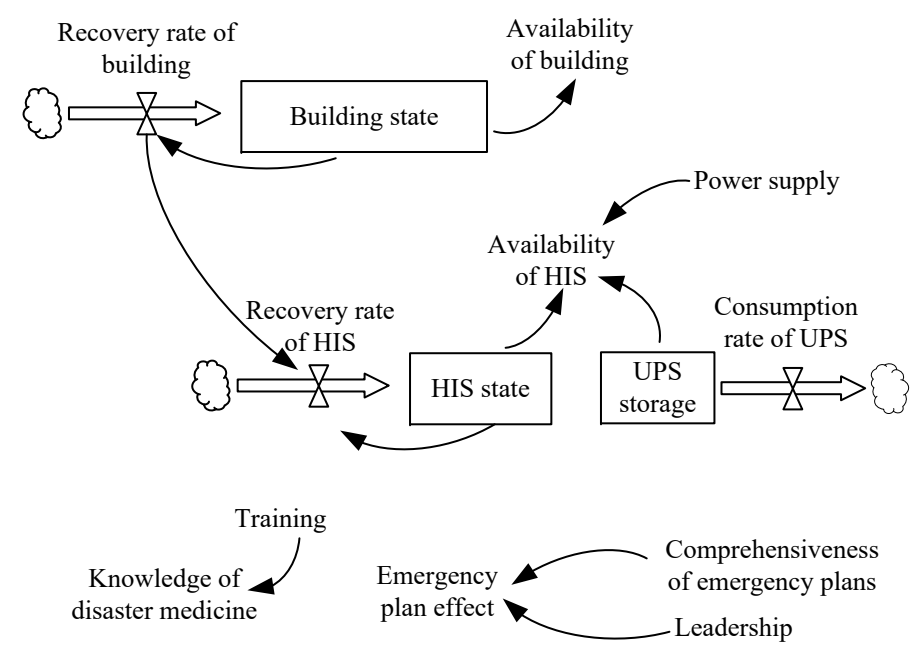


Fig. 10. Functionality curve of the hospital

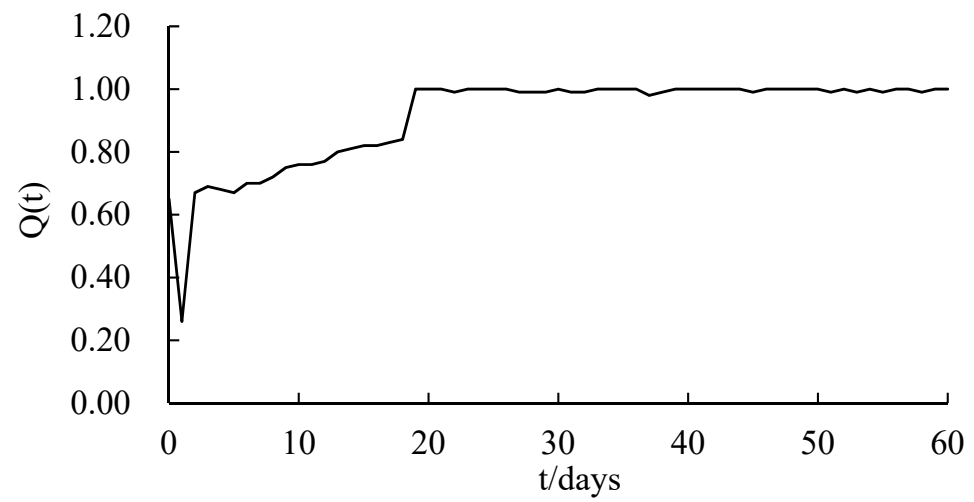


Fig. 11. Performance of treating each kind of disease of the hospital

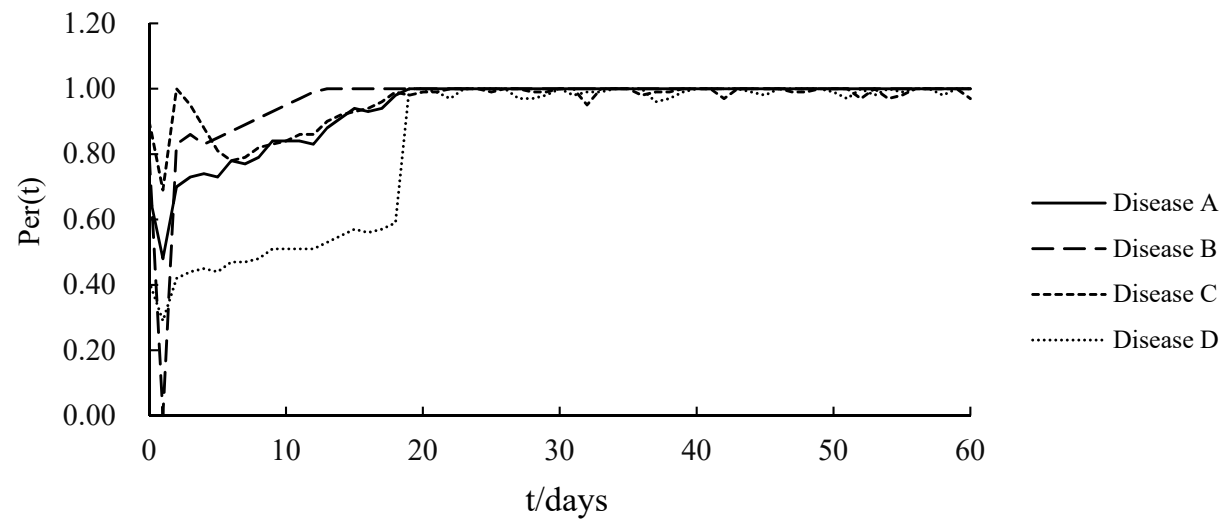


Fig. 12. Results of extreme condition test

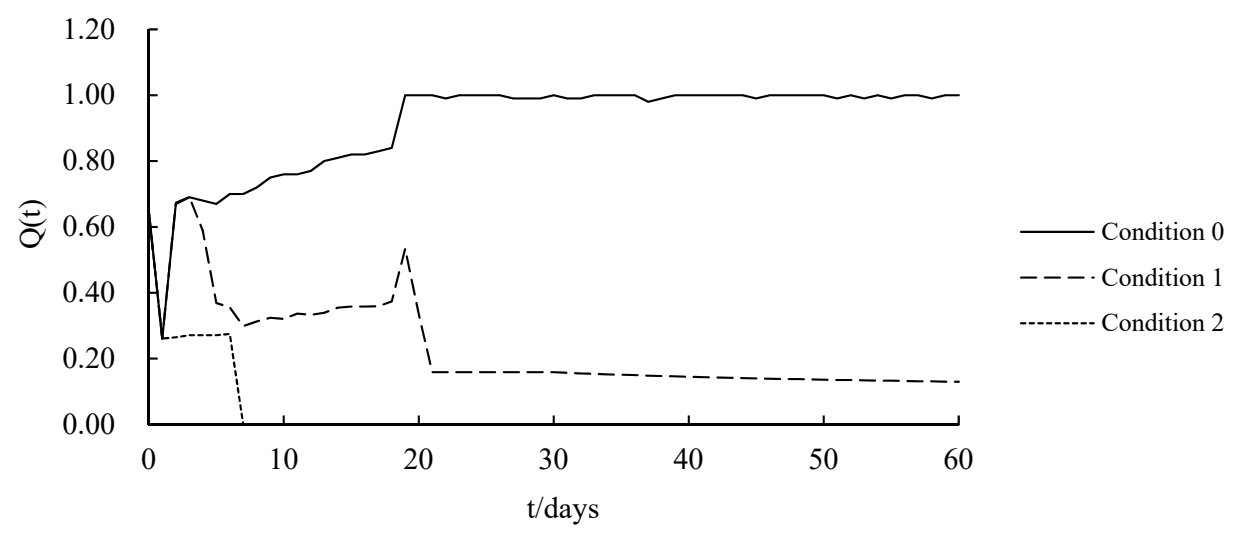
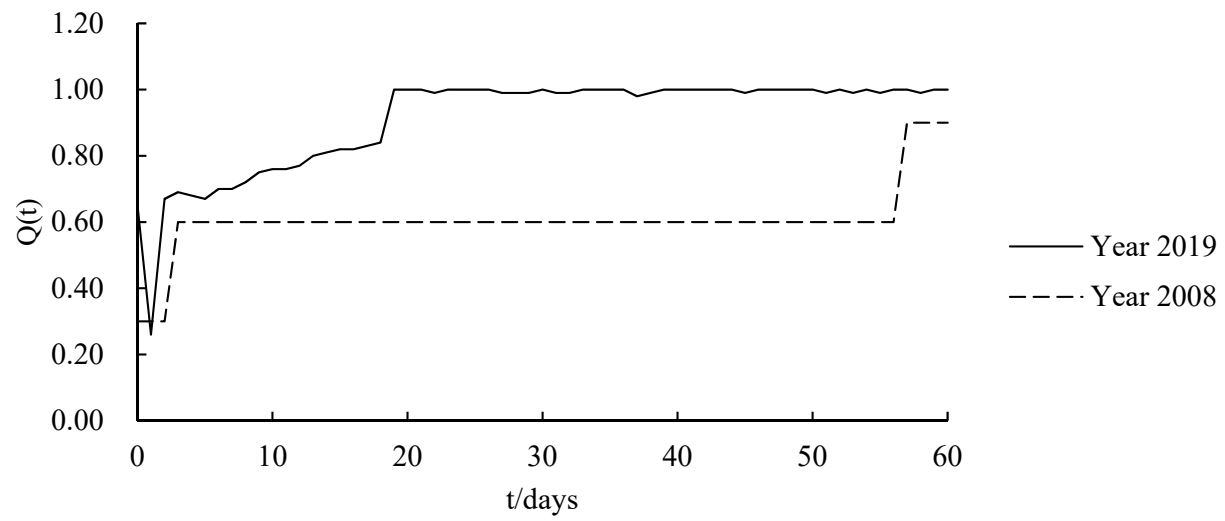
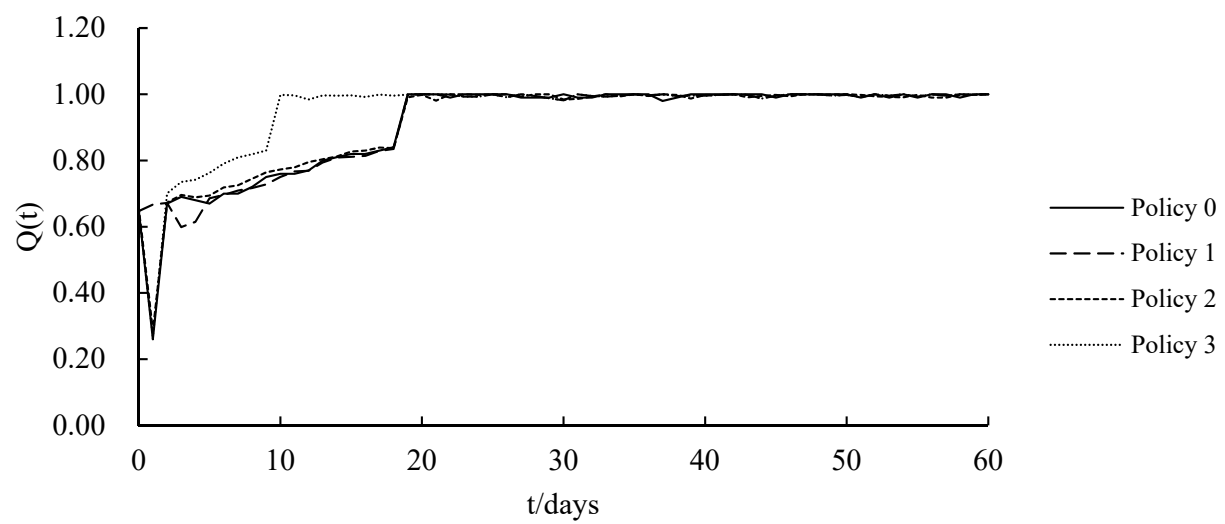


Fig. 13. Adaptation of the hospital





**Figure List:**

- Fig. 1. Disaster resilience (adapted from Cimellaro et al. (2010a))
- Fig. 2. Overall structure of the SD-HFE
- Fig. 3. Dynamics of medical staff
- Fig. 4. Dynamics of medical consumables
- Fig. 5. Dynamics of beds
- Fig. 6. Dynamics of medical equipment
- Fig. 7. Dynamics of utilities (municipal part)
- Fig. 8. Dynamics of utilities (hospital part)
- Fig. 9. Dynamics of the hospital buildings, social factors and cyber factors
- Fig. 10. Functionality curve of the hospital
- Fig. 11. Performance of treating each kind of disease of the hospital
- Fig. 12. Results of extreme condition test
- Fig. 13. Adaptation of the hospital
- Fig. 14. Results of policy sensitivity test