Modeling and simulation of in-hospital medical processes for training and the evaluation of BCP in the event of a disaster

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Abstract: This study is aimed at the development of a highly realistic computer simulation of the complete disaster medicine process used in disaster base hospitals that can be used for training and an evaluation of a business continuity plan (BCP). By analyzing the relevant documents, observing actual disaster response training, and interviewing the medical staff members in charge of hospital disaster management, we identified important medical processes and response tasks, the critical resources and decision-making required for each task, movement of staff members and patients within the hospital, and communication among different hospital areas. In addition, we developed a patient model that describes detailed patient information. We developed a process-based simulation using these models and conducted simulations under various scenarios considering the patient arrival time, resource supply, and staff gatherings. By analyzing the simulation results obtained under different scenarios, we found several bottlenecks and potential problems in the current disaster response rules and resource allocation policy. The proposed simulation is expected to be applicable to simulation-based optimizations for achieving better BCP designs and discovering challenging scenarios for training. Furthermore, we intend to extend it to a human-in-the-loop simulation and use it for both training and exercise.

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1. INTRODUCTION

In Japan, disaster base hospitals (DBHs) [1] are expected to play a key role in regional medical care in the event of a disaster. The requirements for such hospitals include preparing a business continuity plan (BCP) [2] and regularly conducting drills.

DBHs, such as EMERGO, typically conduct either desktop or live drills or both together [3]. However, there are limitations and problems in the current training system; for example, a large amount of labor is required to prepare such drills, and participation is limited owing to conflicts with normal hospital operations. In addition, there are few methods available to quantitatively evaluate a BCP.

To solve these problems, the use of computer simulations that can reproduce a hospital response to a disaster is promising. For example, Sasanfar et al. [4] modeled the flow of patient care in the emergency department (ED) of a real hospital in Iran and explored the optimal hospital staffing and geographic layout allowing for the most rapid response to injured patients with the lowest labor costs. In addition, Basaglia et al. [5] conducted simulations of the hospital response when considering the flow of patient treatment and the time required under both normal and disaster situations and evaluated the results from the viewpoint of patient mortality. However, few studies have considered the use of various resources such as staff members and medical equipment. In addition, most studies did not consider the detailed processes needed, such as medical examinations. Moreover, they have lacked a detailed patient model that describes not only the triage level but also other detailed information such as vital signs, specific names of different injuries and illnesses, and the necessary medical care.

To develop a more realistic simulation that can be used for training and a BCP evaluation, it is necessary to consider the above aspects. Therefore, we aim to develop a more realistic hospital disaster response model and simulation, evaluate the response performance, and find bottlenecks in the BCP.

2. MODELING OF IN-HOSPITAL DISASTER RESPONSE

Through a document analysis, the observation of actual drills, and interviews with disaster response staff members working at a hospital, we identified the following modeling information: the detailed response processes, the various types of resources required, and the information exchanged in and among different areas throughout a hospital. In addition, we developed a patient model that can describe basic patient information, vital signs, the severity of illness or injury, and the appropriate treatment process in XML format. By combining the above elements, we then developed a prototype of a disaster response process model.

2.1. Patient Flow

Patients arriving at a hospital are triaged at a triage post. The patients are then taken to the appropriate consultation area according to their triage level. If a patient requires a detailed examination such as X-ray photography (XP) or computed tomography (CT), a request for the examination is sent to the examination room. The order of examination is determined based on the patient's physical condition and the number of resources available in the room. Patients approved for these requests are transported to the proper examination rooms to undergo XP or CT. If a patient requires blood testing, the specimen is sent to the laboratory for examination. During and after these examinations, the patient receives necessary treatment. If a patient requires surgery or hospitalization, the patient is transferred to the waiting room. At the same time, a request for surgery or hospitalization is sent to the medicine command post, where the surgery or hospitalization order is determined when considering the patient's medical condition and the number of available operating rooms and beds. Patients approved for these requests are operated on or hospitalized. Patients who have undergone surgery are taken directly to the waiting room for hospitalization. Patients who do not require surgery or hospitalization are discharged. The patient flow is shown in Figure 1.

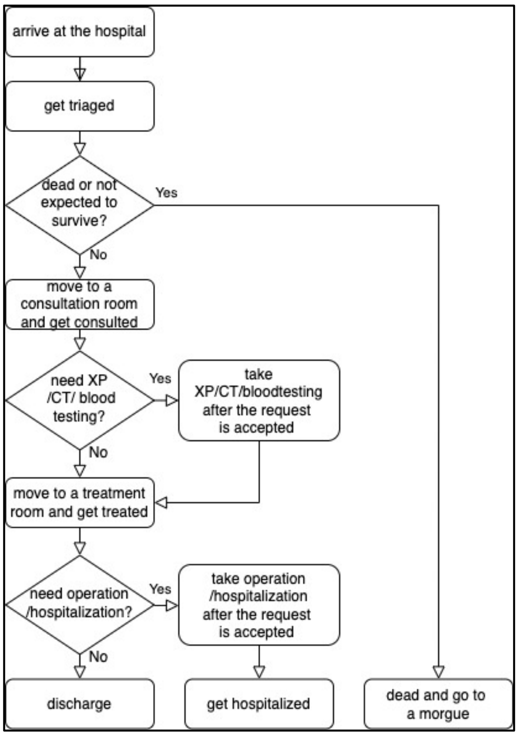

Figure 1. Patient Flow of In-Hospital Disaster Medicine

2.2. Resources

The resources required for the medical process are classified into non-recoverable and unconsumable. Non-recoverable resources are consumed when used. There are 48 types of this resource classification, including gauze and IV fluids. Unconsumable resources are occupied during use, after which they are released. There are 28 types of this resource category, including doctors, nurses, transport staff, stretchers, and XP equipment.

2.3. Patient Model

A detailed patient model was created in XML format based on the patient data created for training purposes. This patient model describes basic information such as the patient's name and age, vital signs such as blood pressure and transcutaneous arterial blood oxygen saturation, severity such as triage level and the injury name, and details of the medical processes required for the patient. Examples of patient information used in the model are shown in Table 1.

Table 1. Information Described in the Patient Model

Category	Example of content
Basic information	ID/name/age/sex/accident
Vital signs	Conscious level/BP/SPO_2/Pulse rate
Patient condition	Triage level/Injury name
Details of required treatment	Medicine processes required/Resources and time required for each process

2.4. Medical Process

As shown in Figure 2, each medical process is described in an input–process–output format. Each process is initiated by the arrival of the patient, under the conditions of resource and room availability and approval (for XP, CT, surgery, or hospitalization). Once a medical process is initiated, non-recoverable resources are consumed, and recoverable resources are occupied. The patient is transferred to the next area, and the non-recoverable resources become unoccupied. The process ends when the time required for the process, as described in the patient model, has elapsed.

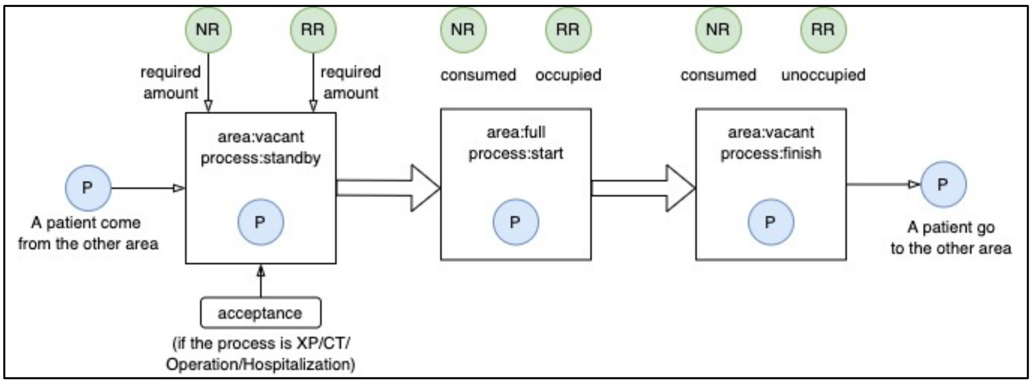

Figure 2. Medical Process

3. CASE STUDY

3.1. Simulation Settings

We implemented the model and conducted simulations using 80 patient models. These 80 patients consist of 13 patients with a primary triage level of red, 23 patients with a level of yellow, 11 patients with a level of green, and 3 patients with a level of black (deceased or unlikely to survive). Each patient has different basic information, injury and disease names, and required treatment processes and resources. The hospital response for a 10-h period, with a time step of 10 s, is simulated.

The arrival time of each patient was set as shown in Table 2 (Scenario 0). This scenario is based on an empirical assumption that it takes a relatively long time for severely injured patients to reach the hospital.

In addition, because some doctors, nurses, and other staff members may have entered from outside the hospital after a disaster, six doctors, nurses, and transportation staff became available. They were assigned to each area at t = 0, and an additional doctor, nurse, and other staff member were added at t = 180 and 720. Other resources became available and were assigned according to the predetermined time.

Table 2. Arrival Time of Patients for Each Triage Level

Triage level	Distribution of arrival time
Red	An exponential distribution with $\lambda = 0.005$ plus 360
Yellow	An exponential distribution with $\lambda = 0.005$ plus 180
Green	An exponential distribution with $\lambda = 0.005$
Black	An exponential distribution with $\lambda = 0.005$ plus 180

3.2. Length of Stay of Each Patient under Scenario 0

The length of stay of each red, yellow, and green patient under Scenario 0 is shown in Figures 3–5. The blue bars indicate the total treatment time required for each patient, and the orange bars indicate the wait time. Patients who arrive late are likely to have longer wait times because there is already a shortage of resources, such as doctors and treatment staff, during each medical process.

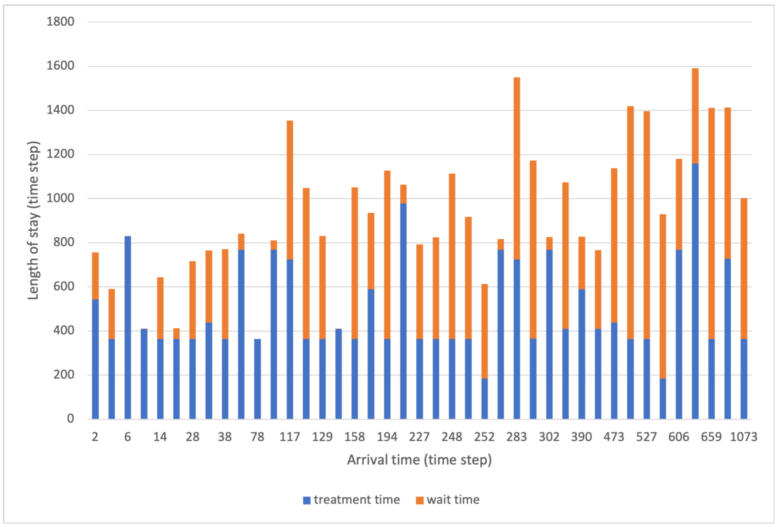

Figure 3. Length of Stay of Green Patients (Scenario 0)

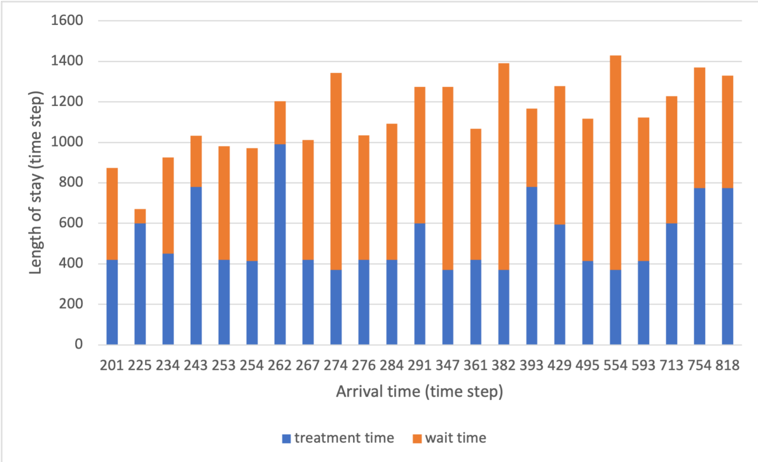

Figure 4. Length of Stay of Yellow Patients (Scenario 0)

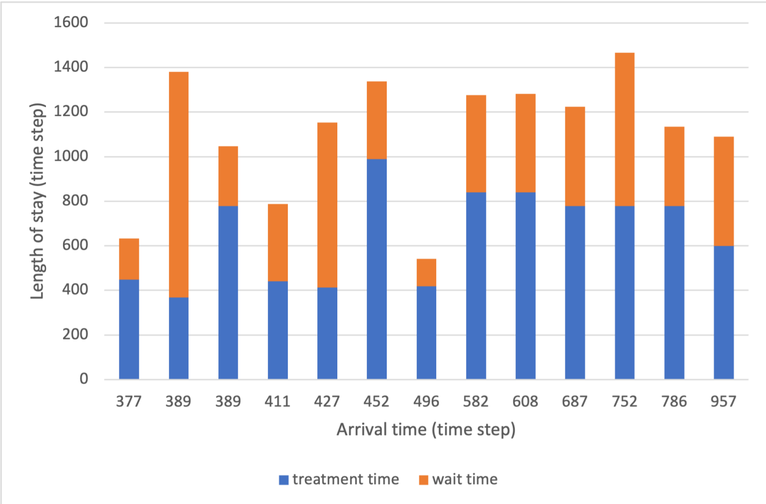

Figure 5. Length of Stay of Red Patients (Scenario 0)

3.3. Number Of Patients in Each Room under Scenario 0

Figure 6 shows the number of patients in the XP room over time. The blue bars show the number of patients receiving XP at that time, whereas the orange bars represent the number of patients waiting to receive XP. Because extra doctors and nurses arrive at the hospital, and the capacity of the XP room increases from 7 to 8, the number of patients waiting decreases to approximately t = 720. However, even with additional staff, many patients are still waiting for XP because 59 of the 80 patients need an XP examination under Scenario 0.

As shown in Figure 7, by contrast, in the red patient consultation room, almost no patients are waiting throughout the simulation. This indicates that the process is running smoothly because the time required for an examination is shorter than that of the other processes such as treatment and XP, and unconsumable resources are often left unused.

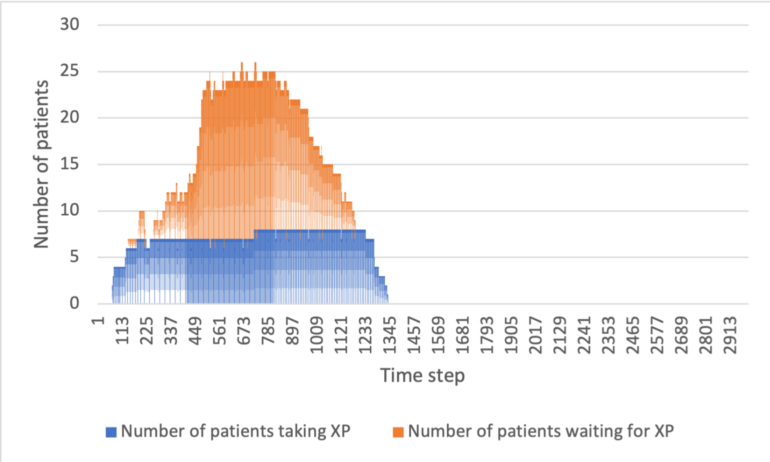

Figure 6. Number of Patients in XP Room (Scenario 0)

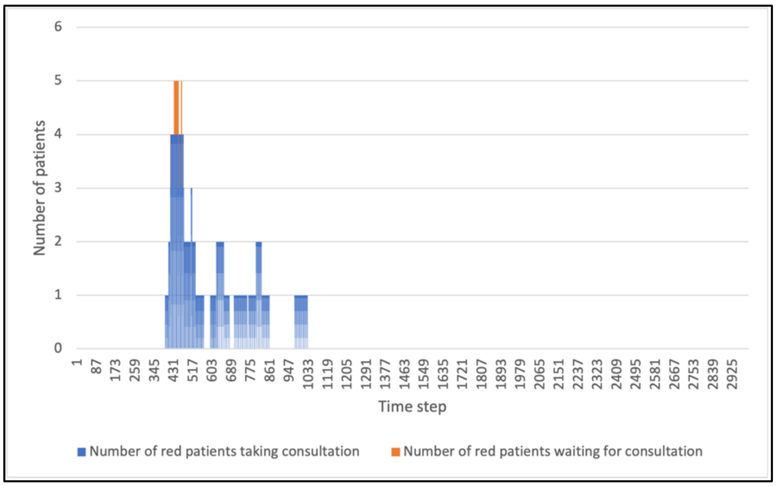

Figure 7. Number of Red Patients in Consultation Room (Scenario 0)

3.4. Simulation under a More Severe Scenario

This subsection shows the simulation results under a different scenario (Scenario 1), which was designed to consider a more severe case in which patients visit the hospital within a shorter interval. Under Scenario 1, the arrival time of red patients follows an exponential distribution with $\lambda = 0.005$ plus 180 (which is 180 time steps shorter than under Scenario 0), whereas that of the yellow patients follows an exponential distribution with $\lambda = 0.005$ plus 90 (which is 90 time steps shorter than under Scenario 0).

A comparison of the mean length of stay (LOS) between Scenarios 0 and 1 is shown in Table 3. The time-series behavior of the number of patients in the XP rooms under Scenarios 0 and 1 is shown in Figure. 8. It was confirmed that the concentration of patients within a short period resulted in a longer average LOS.

Table 3. Average Length of Stay (Scenarios 0 and 1)

Patients	Average LOS (Scenario 0)	Average LOS (Scenario 1)
All	989	1018
Red	1103	1162
Yellow	1139	1162
Green	939	964
Black	28	29

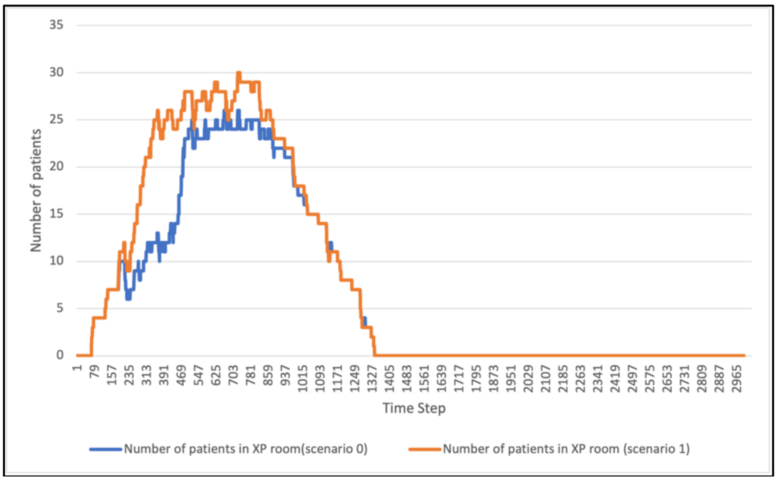

Figure 8. Number of Patients in XP Room (Scenarios 0 and 1)

3.5. Simulation under a Scenario with Staff Reallocation

To confirm the effects of a resource allocation, we conducted a simulation under a staff reallocation scenario (Scenario 2). Under this scenario, some staff members are reallocated from one room to another to reduce the shortage of human resources, i.e., two physicians, nurses, and transportation staff members are reduced in the triage room and one of each is reduced in the consultation rooms of the red, yellow, and green patients. However, one physician, one nurse, and one transportation staff member are increased in the XP room, CT room, and the treatment rooms of the red, yellow, and green patients. The number of staff in each scenario was set as shown in Table 4.

Table 4. Number of Staff (Scenarios 0 and 2)

Room	Number of physicians/nurses/ transportation staff (Scenario 0)	Number of physicians/nurses/ transportation staff (Scenario 2)
Triage room	6/6/6	4/4/4
Consultation room for red patients	6/6/6	5/5/5
Consultation room for yellow patients	6/6/6	5/5/5
Consultation room for green patients	6/6/6	5/5/5
XP room	6/6/6	7/7/7
CT room	6/6/6	7/7/7
Treatment room for red patients	6/6/6	7/7/7
Treatment room for yellow patients	6/6/6	7/7/7
Treatment room for green patients	6/6/6	7/7/7

The average LOS under Scenarios 0 and 2 are shown in Table 5. The time-series behaviour of the number of patients in the XP rooms under Scenarios 0 and 2 are also shown in Figure. 9. It was observed that the average LOS and the number of patients waiting in each area decreased, suggesting that the staff reallocation was effective at alleviating the resource shortages.

Table 5. Average Length of Stay (Scenarios 0 and 2)

Patients	Average LOS (Scenario 0)	Average LOS (Scenario 2)
All	989	965
Red	1103	1054
Yellow	1139	1070
Green	939	947
Black	28	29

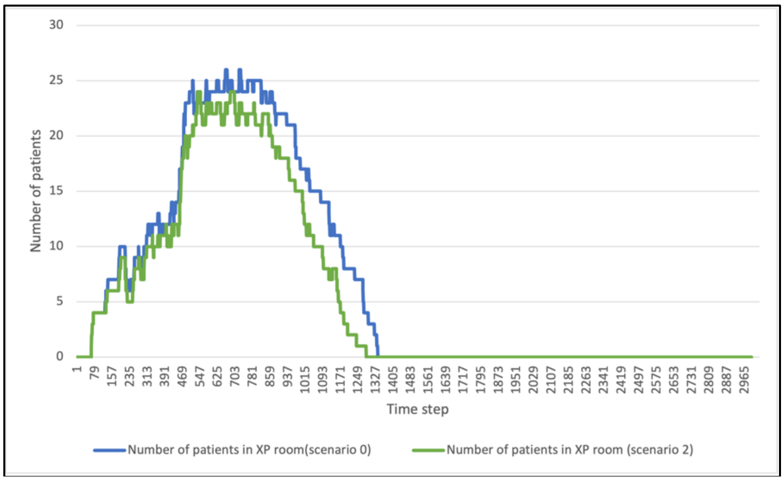

Figure 8. Number of Patients in XP Room (Scenarios 0 and 2)

4. DISCUSSION

Regarding the number of patients in each area, it was shown that the number of staff members was insufficient under all scenarios, particularly in the XP and CT rooms and in the treatment rooms, resulting in long waiting times for many of the patients. Thus, it is possible to identify bottlenecks in the current hospital response using this simulation.

By comparing the average LOS of the patients under Scenarios 0 and 1, as well as the number of patients in the XP rooms over time, it was found that when more patients arrive within a shorter period, as in Scenario 1, patient care is delayed, and the likelihood of preventable death increases. In this way, using this simulation model, it is possible to identify severe patient scenarios and examine the extent to which patients can be treated under each scenario by varying the time of the patient visits, the number of patients, or the degree of patient injury or illness.

By comparing the average LOS of the patients under Scenarios 0 and 2 with the number of patients in the XP rooms over time, it was found that appropriate resource allocation makes the patient treatment more efficient. Thus, it is possible to use the results under various scenarios to improve the existing response plans and BCPs applied during the simulation.

5. CONCLUSION

Based on previous studies and data, a simulation model of an in-hospital disaster medical process was developed to reproduce a hospital response during a disaster. We conducted simulations under several scenarios and compared the results to evaluate the severity of the situation and the effectiveness of the resource reallocation. As the next step, we will extend the model to include the activities of the command post of medicine and the disaster response headquarters. We will also consider normal operations and interactions with in-hospital disaster medicine. Then, after creating a model that can reproduce the communication and interaction between different areas and the command and control within a hospital, we will develop human-in-the-loop simulations, in which some parts of the simulation are conducted by real staff members, allowing new insights to be gained from their behavior as well as proper skills training for a disaster response.

References

[1] Ministry of Health, Labour and Welfare, "Partial Revision of Requirements for Designation as a Disaster Base Hospital," 2020, available: https://www.mhlw.go.jp/content/10800000/000749617.pdf(accessed 2022.4.1).

[2] ISO 22301:2019, "International Standard—Security and resilience—Business continuity. management systems—Requirements," 2019

[3] NPO Medical Crisis Management Support Organization, "What is Emargo—Medical Crisis Support Organization," available: https://meccso.jp/emergo/about-emergo.html(accessed 2022.4.1).

[4] S. Sasanfar, M. Bagherpour, A. Moatari-Kazerouni, "Improving emergency departments: Simulation-based optimization of patients waiting time and staff allocation in an Iranian hospital," *International Journal of Healthcare Management*, 14(4), 1449–1456, 2021

[5] A. Basaglia, E. Spacone, J.W. van de Lindt, T.D. Kirsch, *"A discrete-event simulation model of hospital patient flow following major earthquakes*," *International Journal of Disaster Risk Reduction*, 71, 2022