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OPERATIONS ANALYSIS OF HOSPITAL WARD EVACUATION USING CROWD DENSITY MODEL WITH OCCUPANCY AREA AND VELOCITY BY PATIENT TYPE

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ABSTRACT

This study conducts an operational analysis of horizontal evacuation in a hospital using a crowd density model to simulate patient evacuation. The proposed discrete-event simulation model considers three types of patients assigned with specific moving speed and areas from which to evacuate; the moving speed also varied according to the area's crowd density. We evaluated the effect of the ratio and transfer priority for each patient type on evacuation time in the ward. During night shifts, the evacuation time increased with the ratio of type 1 patients transferred by two nurses with sheets or blankets. The results showed only slight differences in evacuation times when transfer priority changed between type 1 and type 2 patients. The hospital required only one additional staff member to shorten the evacuation time during night shifts.

1 INTRODUCTION

Amid the increasing occurrences of natural and man-made disasters, emergency evacuation has become an important issue in healthcare facilities. During the Great East Japan Earthquake in 2011, 10 of the 380 hospitals in the Tohoku area were completely destroyed, while 290 hospitals were partially destroyed (Health Policy Bureau in Ministry of Health, Labour and Welfare (Japan), 2013). The worst case involved 75 casualties—72 inpatients and three nurses—in a 107-bed public hospital, adjacent to the Sanriku Coast, as a result of the earthquake and accompanying tsunami (Kahoku-Shinpo, 2013). The hospital's staff members transferred the patients to the upper floor using bed sheets or wheelchairs, but the tsunami rose to the fourth floor, sweeping the staff members and patients away. Neighbors swarmed the five-story hospital building seeking shelter from the tsunami, thus crowding the hospital with patients, staff, and neighbors. Healthcare facility evacuation differs in difficulty depending on patients' mobility. Hence, hospitals require effective evacuation plans to mitigate casualties.

This study analyzes a horizontal evacuation plan in a hospital ward using a discrete-event simulation model that considers different patient areas and movement velocities (moving speed) by patient type. Three patient categories related to emergency evacuation are generally employed in hospitals: type 1 for patients transferred on stretchers, type 2 for patients transferred on wheelchairs, and type 3 for patients who can walk without assistance. The model also includes moving speed parameters that vary according to the crowd density in the ward passage. We evaluate the effect of ratio and transfer priority for each patient type on evacuation time.

2 BRIEF LITERATURE REVIEW

Evacuation plans in healthcare facilities are a very important issue in disaster preparedness, risk management, and business continuity. Computer-based evacuation simulations are an attractive method to develop and evaluate such plans (Childers and Taaffe, 2010; Longo, 2010; Taaffe, Kohl, and Kimbler, 2005). Taaffe (2005) conducted a modeling and simulation of a whole hospital evacuation caused by emergencies, such as hurricanes, floods, hazardous material spills, and terrorist incidents, while Golmohammadi and Shimshak (2011) addressed the issue of patient evacuation from hospital floors and buildings. There are three categories of modeling and simulation for evacuation in healthcare facilities: whole hospital evacuation (or large-scale evacuation), partial evacuation (or small-scale evacuation), and specific patient evacuations, such as from an intensive care unit or operation theater (Childers and Taaffe, 2010; Kader, 2008; Lango, 2010).

In the case of whole hospital evacuation caused by disasters, researchers frequently adopt traffic models to detect mass evacuation in simulations (Duanmu, Taaffe, and Chowdhury, 2010; Taaffe, Johnson, and Steinmann, 2006; Tayfur and Taaffe, 2007). Other studies use an agent-based model to analyze the effects of route selection due to social behavior or decisions about the evacuation process, or apply cellular automaton to simulate partial evacuation in hospitals (Aritomo, Shiraki, and Inomo, 2008; Johnson, 2007). Fire evacuation is a typical situation in which many people in one specific area—such as a theater, stadium, building floor, or station yard—evacuate the area following an emergency alert (Alginahi, Kabir, and Mohamed, 2013; Johnson, 2007; Miyazaki et al., 2002; Zheng, Zhong, and Liu, 2009). Studies also use agent-based modeling to examine the effects of crowd behavior on evacuation. In hospital simulations, evacuation routes are generally assigned to guide patients, thus removing the need for agent-based models in such simulations.

Modeling and simulation of evacuation in hospitals require proper specifications according to the hospital's occupants. Many patients in a hospital need the assistance of medical staff to evacuate, so modeling patient mobility is especially important in evacuation time estimates. Taaffe (2006) classified patients into three categories according to their acuity in a model of full hospital evacuation. Full hospital evacuation, which involves traveling significant distances to other facilities or cities or towns, is possible with vehicles and ambulances. However, models of small-scale evacuation require a patient mobility classification because patients' moving speed play a more important role in these cases.

There are some classifications according to patient mobility for building evacuation modeling. In these classifications, patients are categorized as ambulant or non-ambulant (Rahouti, Datoussaïd, and Lovreglio, 2016); walking wounded, less critical, or critical (Childers and Taaffe, 2010; Golmohammadi and Shimshak, 2011); and mobile, mobile with some assistance, immobile but transferred by wheelchair, and immobile because of need for critical care (Golmohammadi and Shimshak, 2011). In practice, the three categories of mobile, transferred by wheelchair, and transferred by sheets or blankets are valid for modeling horizontal or vertical evacuation in hospital buildings. These three categories are generally employed in Japanese hospitals to manage patient safety (Health Policy Bureau in Japanese Ministry of Health, Labour and Welfare (Japan), 1988; 2013). Horizontal evacuation means to move on a floor from a room to emergency exit, while vertical evacuation is to move from a story to an upper or lower stories in multi-story buildings.

Some studies have addressed evacuation models for hospital buildings. Golmohammadi (2011) proposed a predictive model for evacuation from a hospital building that focuses on resources, including medical staff who transfer patients and equipment, such as elevators. This study represents the horizontal movement of patients only by a simple parameter for constant speed. The moving speed of patients transferred or assisted are very important factors in evacuation time. The crowd density of an exit area is also a considerable factor because it affects the patients' use of transfer devices such as wheelchairs and stretchers (Hunt, Galea, and Lawrence, 2015; Miyazaki et al., 2002; Morita, 2010; Tsuchiya and Yuji, 2009). Each patient occupies a specific area on a floor of a hospital according to the device used for their transfer. Although fire evacuation simulators, such as EXODUS, adopt a cellular automata model, no models consider the different areas occupied by different patient types. In addition, no model includes crowd density, along with specific moving speed and areas for each patient type in a hospital evacuation.

3 METHODS

3.1 The Hospital and Ward

The hospital in this study, Iwasa Hospital and Maternity, is a unit of Yuai-kai Medical Corporation in Gifu, Japan. The corporate planning office of the hospital is a pioneer in the development of the Business Continuity Plan for hospitals in Japan. The staff members conduct disaster preparedness training several times a year, and modify the plan. Evacuation training in wards is regularly carried out according to a variety of scenarios.

This hospital has 132 beds in three wards for inpatients, including beds for internal medicine, rehabilitation, and maternity. The hospital building has five floors. The outpatient department provides medical services, such as internal medicine, pediatrics, gynecology, and maternity, for about 250 patients per day on the 1st floor. There are 50 patients, on average, who are admitted in internal medicine or rehabilitation in a ward located on the 4th floor, called the 4th Ward. Patients who receive rehabilitation services and maternity delivery services are admitted on the 3rd and 2nd floors, respectively. The administration offices are located on the 5th floor of the building.

In this study, we address an evacuation plan for the 4th Ward in the case of a fire emergency. The ward has 60 beds divided into 27 rooms, comprised of 11 multiple-bed rooms and 16 single-bed rooms. Multiple-bed rooms with four beds per room are common in Japanese hospitals. A layout of the ward is shown in Figure 1. Emergency exits are located on both the east and west sides of the floor, and there are two fire shutters in the center of both the north and south blocks. The administration staff supposes that the most likely case of a fire emergency would be the hospital kitchen located northwest on the 1st floor. In such an emergency, the west side exit would not be available, because the smoke would travel to the west block of the ward. Therefore, the staff has a plan to evacuate all patients to the east exit.

3.2 Performance Measurement and Data Collection

We aimed to identify the effect of the ratio and transfer priority for each patient type on evacuation time using a discrete-event simulation technique to determine a horizontal evacuation plan corresponding to the patient transfer demand. Hence, the indicators below were used to analyze the evacuation performance according to the ratio and transfer priority for each patient type.

1. Total evacuation time of patients to the east exit on the 4th floor
2. Number of evacuated patients during a certain period

The data were collected from administration records and a computer-aided design drawing of the hospital. The patient-related data that were collected were the number of patients staying in the

Patient Type		Ratio	Velocity	Preparation Time	Occupied Area	Depth	Width
		%	m/s	sec	m^2/a person	m	m
Type 1	Transferred with Sheets or Blankets	21.0	1.60	26.10	2.110	3.317	0.633
Type 2	Transferred with Wheelchairs	56.0	2.43	14.10	1.378	1.548	0.890
Type 3	Walk without Assistance	23.0	1.20		0.688	0.774	0.890

Table 1: Parameters for each type of patient

hospital per day, and the ratio of patient types per day during a certain period. The number of nurses allocated in each day and night shift during the period was also collected. The representative values of the data were used in the simulation model, and distances and widths of passages were measured in the scale drawing.

3.3 Simulation Model

We created a set of simulation models for the ward using the simulation package, Arena version 14.5. Sixty patients—the maximum number of patients staying in the ward in a day—were divided into three transfer types according to the actual mean ratio of patient types in the primary model. We defined the three patient categories according to patients' evacuation ability: type 1 for patients transferred on stretchers, type 2 for patients transferred in wheelchairs, and type 3 for patients who can walk without assistance. The patients started in each room, then began evacuating via the east exit simultaneously.

The primary model included 12 nurses allocated in a day shift as human resources. Each type 1 and 2 patient was transferred by two nurses and one nurse, respectively. Type 3 patients evacuated without assistance. Type 1 and 2 patients needed a specific amount of preparation time to move from their beds to

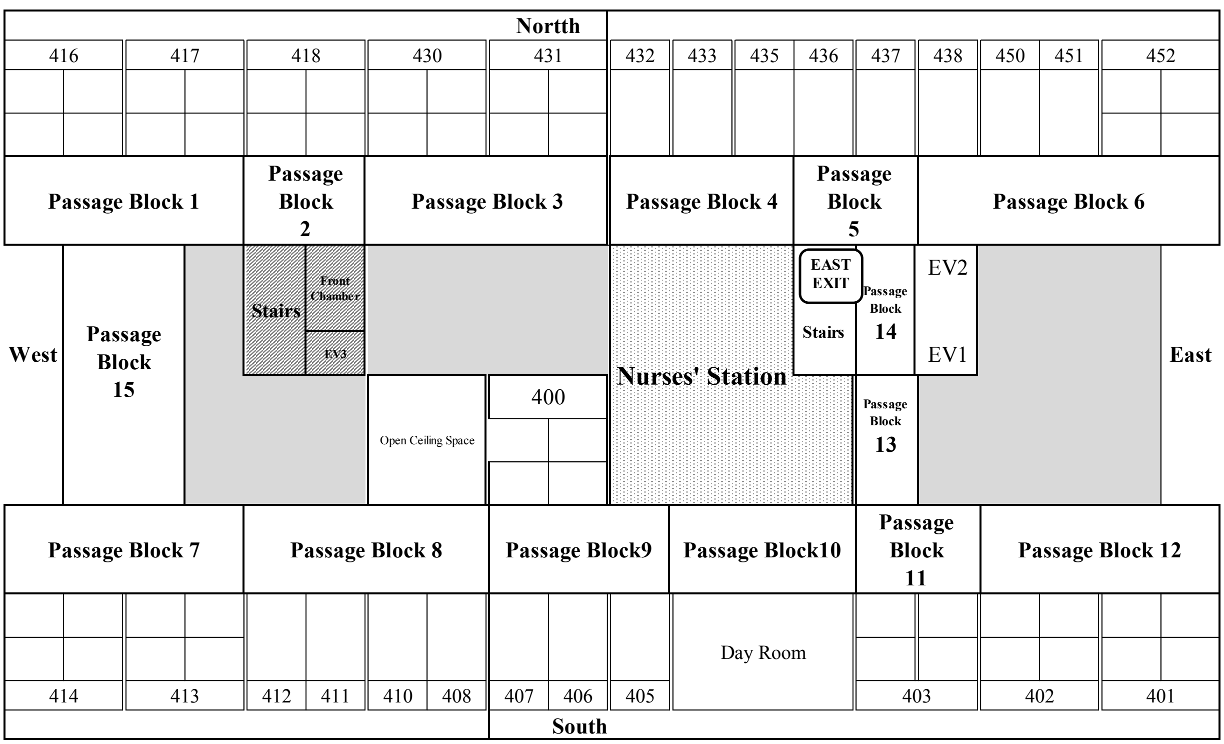

Figure 1: Layout of the 4th ward

their transfer devices with nurses' assistance (Ohnishi, Murozaki, and Kujime, 1986). In the model, each type of patient had a specific area and moving speed, based on past research data (Ohnishi, Murozaki, and Kujime, 1986). The parameters of patient types are indicated in Table 1.

The passages in the ward were divided into 15 blocks according to the ward's layout (Figure 1). Each patient evacuated by passing through a definite route to the east exit according to the location of the room in which they stayed. For example, a patient who stayed in room 416 moved to passage block 1 first, then passed through block 2, block 3, block 4, block 5, and block 14, before arriving at the east exit. If the area of the next block was full of other patients, the patient would not be able to move to the next block of passage. Consequently, the movement of the patients depended on the area of the next block calculated by the sum of areas occupied by all patients in the block. In addition to the movement conditions, patients moved according to the calculated speed based on the crowd density of the block through which they were passing (Togawa, 1958).

Togawa (1958) had proposed a simple crowd flow model, as in expression (1) below. The value 1.5 is a coefficient of crowd density indicated by the observational data, and refers to standard moving speed with which a healthy adult person walks. We modified the expression according to the moving speed of each patient type. Hence, type 1 and 2 patients were transferred according to v_1 in expression (2) and v_2 in expression (3), respectively. This design makes the models unique. The reason why type 1 and 2 patients have faster speed than healthy adults is that type 1 and 2 patients are transferred by nurses moving about busily.

$$v = \frac{1.5}{\rho} \qquad \rho = \frac{n}{m^2} \tag{1}$$

v : Moving speed, ρ : Crowd Density

$$v_1 = \frac{1.6}{\rho} \qquad \rho = \frac{n}{m^2} \tag{2}$$

$$v_2 = \frac{2.43}{\rho} \qquad \rho = \frac{n}{m^2} \tag{3}$$

ρ : Crowd Density, n : Number of patients in a block of passage, m^2 : Area of a block of passage

The primary model has no process for obtaining experimental data to estimate the simple horizontal evacuation time after the patients arrive at the east exit. Thus, we designed a secondary model for the experiments that included an evacuation process through to the east stairs to the 1st floor. We used an estimated normal distribution from prior studies for convenience to determine the process time to evacuate via stairways (Ohnishi, Murozaki, and Kujime, 1986; Okada, 2011).

3.4 Experiments

The patients started in rooms allocated to them at random, and then would begin to evacuate simultaneously when the accident occurred. Second, all patients evacuated through their assigned route to the east exit with or without assistance from medical staff according to patient type. There was no warm-up period, because of getting simple data for evacuation. Type 1 and 2 patients were transferred by two nurses and one nurse, respectively, while type 3 patients had no assistance. The patients requiring assistance moved with nurses from their room to the east exit. Patients' movements through the passage were controlled by space and moving speed, as in the previous sections. Third, the number of nurses for day shifts and night shifts were 12 and 4, respectively. One nurse served as the supervisor, while the other nurses provided assistance to the patients. The tentative time for evacuation on the stairs from the 4th to the 1st floor had a normal distribution, referring to the literature (Ohnishi, Murozaki, and Kujime, 1986).

In our preliminary experiments, the evacuation time for all patients to the east exit on the 4th floor was investigated using the primary model. The resulting value was an indicator, that is, a hypothetical evacuation time in an absolute horizontal evacuation. We conducted experiments to evaluate the property of crowd density according to different scenarios in which the number of nurses varied from 3 to 60, using the secondary model. The core experiments were conducted according to patient type using the secondary model to explore the effects of ratio and transfer priority for each patient type on evacuation time. We created the scenarios as below.

1. Increasing the ratio of type 1 patients from 10% to 70%, while the ratio of type 3 patients was fixed at 20% of all 60 patients (the maximum number of patients allowed) in the ward.
2. Changing the transfer priority between type 1 and 2 patients under the same condition.

The model design and the analysis were adjusted and modified by the co-author, an expert in industrial engineering. One hundred replications were simulated in all scenarios.

4 RESULTS

4.1 Preliminary Experiments

The completion time of a horizontal evacuation to the east exit on the 4th floor had a mean value of 4.66 minutes during a day shift, to which 12 nurses were allocated. Patient type 3 evacuated to the east exit in 0.16 minutes after the accident, and the slowest patient type, type 1, reached the exit in 4.66 minutes under the preliminary experiment conditions using the primary model. The mean evacuation time per patient was 3.48 minutes, 2.29 minutes, and 0.33 minutes for type 1, 2, and 3 patients, respectively.
The mean evacuation time of the last patient to the east exit was 28.17 minutes during a day shift using the secondary model. The slowest patient type, type 1, transferred to the exit in an average of 35.56 minutes during a night shift. Figure 2 shows the mean time for patients to reach the exit for each time interval. Type 3 patients, who walked without assistance from medical staff, finished the horizontal evacuation faster than the other types of patients. The number of type 1 patients transferred by two nurses with sheets or blankets increased in each successive time interval.

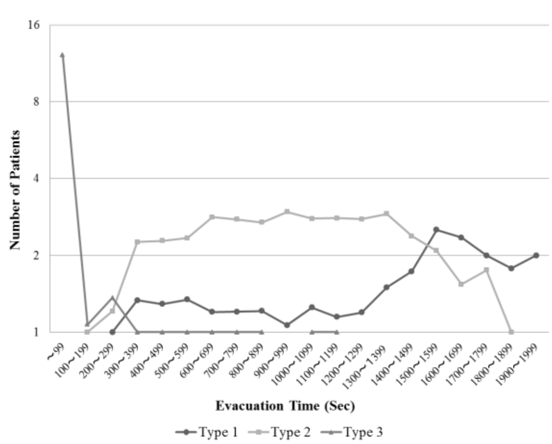

Figure 2: Mean number of patients evacuated at each time interval

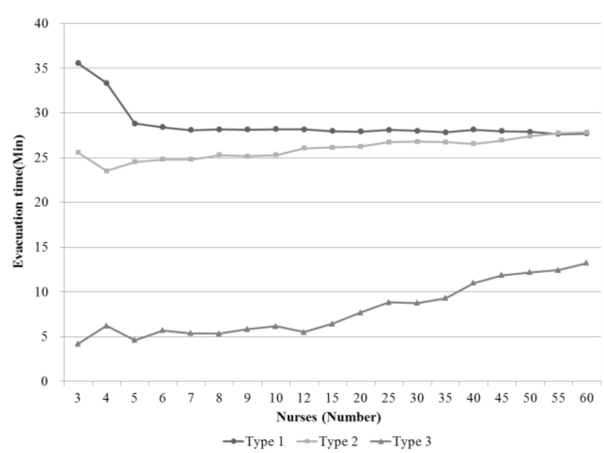

Figure 3: Mean evacuation time by number of nurses

The differences in evacuation time to the exit by number of nurses is shown in Figure 3. Type 1 and 2 patients were transferred by two nurses and one nurse, respectively, while type 3 patients had no assistance. The evacuation time of type 1 patients shortened as the number of nurses increased. A turning point in the evacuation time was clearly observed when the number of nurses decreased from five (28.79 minutes) to four (33.34 minutes). On the other hand, the evacuation time of type 2 patients gradually increased with the number of nurses, as did the evacuation time of type 3 patients.

4.2 Effect of Ratio of Patient Type and Transfer Priority on Evacuation Time

There were seven scenarios in which the ratio of type 1 patients varied from 10% to 70% of all 60 patients, while the ratio of type 3 patients was fixed at 20%. (Figure 4). The mean evacuation time was 28.24 minutes when 10% of the 60 patients were type 1 patients during day shifts. When 40% of the patients were type 1 patients during day shifts, there was little difference between the maximal (28.91) and minimal (28.24) mean values. Conversely, mean evacuation times were extended from 30.97 minutes to 45.99 minutes owing to the increased ratio of type 1 patients during night shifts. The coefficient of the linear approximation curve for the increase of evacuation time is 2.34 for night shifts.

When transferring type 2 patients before type 1 patients, the mean evacuation time was 32.43 minutes during day shifts and 42.27 minutes during night shifts. When transferring type 1 patients before type 2 patients, evacuation time decreased only slightly during both day and night shifts (Figure 5).

5 DISCUSSION

The results from our crowd density model showed that having too many nurses prolonged the evacuation time for types 2 and 3 patients, providing evidence of the validity of our model. Normally, having adequate resources is assumed to reduce evacuation time if the passage is not crowded. However, type 2 patients, who accounted for 56% of all patients, caused crowding in the passage when they evacuated simultaneously. Crowding also influenced the evacuation time of type 3 patients, who usually evacuated quickly because they could walk without medical assistance. This finding is in line with that of Tsuchiya and Hasemi (2009), who experimented with transferring patients in a real hospital using transfer devices, and found that crowding had a strong effect on the evacuation of type 3 patients due to crowding in the areas occupied by patients who are transferred with devices.

The evacuation time of type 1 patients, who were the last to reach the exit on the 4^{th} floor, became significantly longer when there were fewer than five nurses. Conversely, having more than 12 nurses

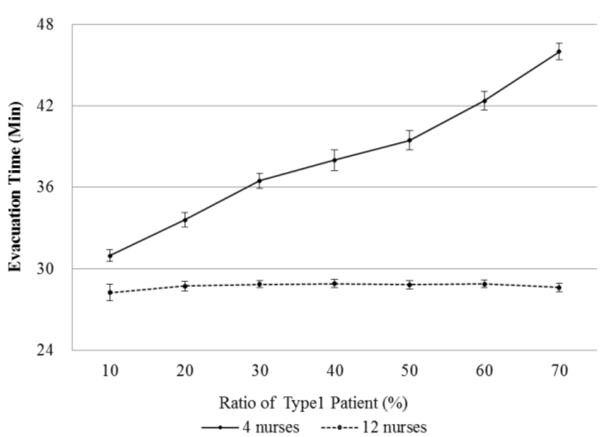

Figure 4: Differences in evacuation time by ratio of Type 1 patients

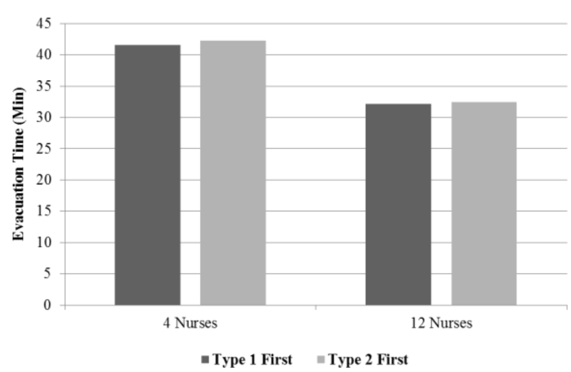

Figure 5: Differences in evacuation time by transfer priority for patient types

prolonged the evacuation time of type 2 and 3 patients. In this hospital, having 12 nurses in a day shift may be appropriate to assist patients in an evacuation, and having two additional nurses to assist patients would dramatically shorten the evacuation time in a night shift. Although the results show the importance of sufficient staffing, exhaustion would also be a considerable factor of the effectiveness of the staff. However, this factor was not considered in this study's model. Nevertheless, our study's most important finding is that having too many staff members is not always effective in evacuating a combination of different types of patients.

A significant impact of the ratio on evacuation time for type 1 patients was detected for night shifts. Type 1 patients needed to be transferred by two nurses using sheets or blankets, and the staff was overwhelmingly insufficient during night shifts, so that only three nurses transferred all type 1 and 2 patients. When the ratio of type 1 patients increased, evacuation time was prolonged by the lack of human resources. Increasing the ratio of type 1 patients in the ward prolonged the evacuation time to 2.34 times the baseline evacuation time. This value is a useful indicator to predict the scale of damage, and to prepare effective evacuation plans.

This study revealed that transfer priority had little influence on evacuation time. Childer and Taaffe (2010) discussed a priority transfer strategy according to patient type in a large-scale evacuation. Staff can adopt a triage to determine which patients to transfer first. While the results of our study, which focused on horizontal evacuation in a ward, show that transfer priority has only a small effect on evacuation time for both day and night shifts, the field still requires further discussion to examine ethical issues in transfer priority. Preparation time may also influence evacuation time. Type 2 patients need a shorter preparation time than type 1 patients because nurses move the former from their beds to wheelchairs. If nurses transfer type 1 patients prior to type 2 patients, they would complete the evacuation only slightly faster than in the reverse transfer priority due to the longer preparation time for type 1 patients.

In conclusion, the crowd density model provides a useful enhancement to simulations of horizontal evacuation in hospital wards. In this case study, the evacuation time was longer during night shifts at 2.43 times the baseline evacuation time per a 10% increase in type 1 patients. Only two additional staff members were needed to shorten evacuation time, and too many staff members hindered evacuation due to crowding. However, further research is necessary to determine the influence of other human factors, such as fatigue, in the evacuation process.

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