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Estimation of the evacuation time in an emergency situation in hospitals

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ABSTRACT

In this paper, a prediction model is presented that estimates the evacuation time in an emergency situation for hospitals. The model is generic enough to be used in various hospital settings. This model can provide incident managers with estimates of the evacuation times of different types of patients and can offer support to the managers with their resource allocation decisions in emergency situations. The major advantage of the prediction model is that the computation time is very short and the model does not need a lengthy and costly design. The model was applied for several different evacuation scenarios and the results were compared with those of a simulation model which had already been designed for use by the hospital. The comparison shows that the prediction model can provide estimates of the evacuation time that are similar to the results found by using costly and time-consuming simulation models.

1. Introduction

In accordance with the rules and regulations of the Federal Emergency Management Agency (FEMA) and Joint Commission on Accreditation of Healthcare Organizations (JCAHO), all hospitals and healthcare facilities need to have a plan in place to be able to respond to internal and external emergencies. This plan is usually activated and supervised by a designated incident manager (Jafari, Golmohammadi, & Seyed, 2008). For this plan, the decision to allocate and assign available resources (such as medical and non-medical staff, elevators, and so on) to the floors and units in need of help during the course of evacuation highly depends on the emergency type and the estimated evacuation time. This decision making is vital when multiple floors are in danger and all of the patients, together with their family members, medical records and necessary medications need to be vacated to some safe locations. Some of these floors may have patients with critical conditions and therefore the incident manager may need to determine an estimate of the evacuation process time to assign more resources to those floors to make the operation faster, safer and more efficient.

Although the Joint Commission does not require estimated evacuation times, the estimation can help managers evaluate and measure the efficiency of their resources, level of utilization and response times. The ultimate goal is to save more lives in hospitals and healthcare facilities at the time of emergency and the determination of evacuation times demonstrates how a facility can accomplish this task with minimum loss.

In most major hospitals and clinics, there is a Division of Emergency Preparedness (DEP). The major goals of this division are to:

- Evaluate the current performance of operations and executive plans for potential disaster events.
- Educate medical and administrative staff about their roles and responsibilities in potential disaster events.
- Work with state and local partners to improve policies and plans for emergency response to health threats.

The use of quantitative decision making tools can provide insight for hospital managers to run what-if scenarios in order to estimate the evacuation response time in different situations and to evaluate their plans and resources. The results may impact on improving the training programs and improve policies and plans for a real emergency event.

With respect to emergency planning, a large number of research studies suggest alternative methods to deal with the evacuation of people from disaster areas through the use of the roadways. Computer programs have been developed to simulate various alternative traffic management strategies under different scenarios in order to improve highway network performance during an evacuation process (Hobeika & Jamei, 1985; Sheffi, Mahmassani, & Powell, 1982). Some researchers link geographic or real-time information systems with simulation models (Franzese & Joshi, 2002; Pidd, de Silva, & Eglese, 1996). Further studies evaluate other methods that can be used to identify evacuation routing plans in road networks, such as the network flow model by Cova and Johnson (2003) or the use of contraflow segments of the interstate freeway by Wolshon (2001). Fewer studies have been involved with the issue of building evacuation.

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There are a number of reasons why the emergency evacuation of a building may be necessary. One of the most compelling reasons is the threat of smoke or fire may require evacuation of a building. Other reasons may include the threat of an earthquake, a toxic or natural gas leak, a power blackout, elevator failure, a bomb threat, and civil defense emergencies. Large buildings undergo practice evacuations on a regular basis. It is understandable to plan evacuations in advance such that practice evacuations and, ultimately, actual evacuations will be successful (Chalmet, Francis, & Saunders, 1982).

A particularly difficult evacuation process involves high-rise buildings which can accommodate large amounts of people and have long vertical transport distances. In case of an emergency, occupants need time to escape from their current floor in the building to a safe place. The compelling question here is how long is the evacuation time of the occupants in these high-rise buildings? Accurate data on the evacuation time for occupants in a high-rise building are difficult to acquire because an investigation during a real emergency will endanger the occupants of the building. Fire drills serve as an alternative approach to simulate the real situation of a fire. Nevertheless, information acquired in such drills cannot incorporate the complex behavioral reaction of evacuees. Moreover, the arrangement for an evacuation exercise in a large building is difficult.

Some recent articles have discussed emergency preparedness in healthcare facilities as a result of a wide variety of disasters such as hurricanes (Castro, Persson, Bergstrom, & Cron, 2008; Gray & Hebert, 2007; Hyer, Brown, Christensen, & Thomas, 2009), tornados (Lewis, 2007), wildfires (Barnett, Dennis-Rouse, & Martinez, 2009), earthquakes (Schultz, Koerig, & Lewis, 2003), and bomb threats (Augustine & Schoettmer, 2005). Emergency planning in hospitals is particularly important due to the risk to the lives of the patients. While most of the emergency response plans focus on a hospital being able to accommodate the input of patients resulting from some type of a disaster situation, there are few studies that are concerned with the issues that a hospital faces when their occupants must be evacuated (Taaffe, Kohl, & Kimbler, 2005). An evacuation process in a hospital is a particularly difficult and complex task that requires a strategy, well-trained staff, and careful execution.

Due to the complexities involved in hospitals and in other buildings, numerical simulation can be employed as an alternative approach for studying the evacuation problem. Gwynne, Galea, Owen, Lawrence, and Filippidis (1999) report that scientists and architectural engineers using high-speed digital computers have developed numerous different building evacuation models. One simulation model entitled EVACSIM (Drager et al., 1992) attempts to measure the performance of the evacuation system under conditions as realistic as possible, including human behavior and the possibility of accidents. Some of the simulation models that have been developed can successfully simulate the process of evacuation in low-rise buildings with limited populations (Lo, Fang, & Chen, 2001).

Other simulation models focus directly on the means of egress, such as exits that are used during evacuation. A simulation model called MOBILIZE (Weinroth, 1989) considers the evacuation of a complex building with thousands of people on a large campus. This model considers different evacuation patterns and total exit times with alternative occupancy levels. While attempting to reduce the variance of the total numbers of occupants who exit through individual doorways, Bakuli and MacGregor Smith (1996) study the effect of circulation widths on throughput during evacuation. Choi's (1991) combined analytic and simulation model evaluates evacuation congestion effects by including branching rules as people come to a decision point in the egress network. Tayfur and Taaffe (2009) consider the evacuation of hospital patients who have to compete with the general population for transportation resources including vehicles and routes.

While simulation models are capable of analyzing the evacuation processes and estimating the evacuation time, building simulation models are costly and time consuming. The requirements of simulation modeling may include such expenses as purchasing simulation software (for example, Arena Basic Edition costs several thousands of dollars) and using simulation experts to help with various aspects of the modeling process (generally an expensive resource). In addition, simulation is a time consuming process that includes such functions as model development, testing and validation, data gathering, and data interpretation. Even simple models even take months to complete. In addition, these models have an overreliance on the specific layout and conditions of the building.

Due to the problems and complexities of using simulation modeling to study building evacuations, we have developed a quantitative prediction model. Our prediction model is applied to a hospital building in order to estimate evacuation times. In this paper, the evacuation time results from the model for 19 different hospital evacuation scenarios are compared with the results of a previously designed simulation model. While this work specifically focuses on evacuation, the methodology can also be extended for other types of surge capacity analysis.

2. Model design

As we have discussed earlier, implementing a simulation model for the evacuation of a hospital is costly and involves a time consuming design process. Hospital administrators would prefer to have an evacuation time estimate of a building or a floor that could be generated quickly, that would be in an acceptable range of accuracy, and that is flexible enough to incorporate different conditions, such as the number and type of patients and the number of available staff, elevators and other resources.

A prediction model is presented here that estimates the evacuation time based upon the different conditions on each floor of a hospital building. The possible choices for input data have a critical role in determining the existing conditions. The model considers the most likely possible scenarios that a hospital might face in an evacuation situation. A major advantage of this model is that it is not restricted to specific layouts; rather, it can be applied in any hospital setting.

The model assumptions and parameters are as follows: Based on hospital terminology, three types of patients are considered: "walking wounded" (referred to as Type 1 patients), "less critical", such as patients in wheelchairs (referred to as Type 2 patients), and "critical", such as patients confined to beds (referred to as Type 3 patients). The two types of staff available are medical and non-medical.

The concern in an evacuation situation is whether patients can safely move out of the building. In other words, the patients' classification depends on the ability of the patients' mobility and not necessarily on the condition or type of disease. Interested organizations, such as the Agency for Healthcare Research and Quality (AHRQ) have made contributions in this area. Recently the Agency for Healthcare Research and US Department of Health (2009) developed a Mass Evacuation Transportation Model to classify patients based on their transportation requirements. The patient classification scheme used in our paper was defined by the emergency and disaster preparedness group of the local hospital in our original case study. If the patient classification differs from this research and perhaps staff requirements increase, then our approach is still valid, but the impact of these new requirements would have to be incorporated in the model.

For the evacuation operation in our study, patients from their current floor are evacuated to a safe location. After their arrival

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at this location, some staff members will stay with the patients at this safe location to continue to provide their healthcare needs. Other staff members will return to the original floor to evacuate additional patients. Two staff members are assigned to each critical patient, and one staff assists each less critical patient. Elevators are assigned for less critical and critical patients while the walking wounded patients are guided to stairways. Fig. 1 provides a flowchart illustrating the evacuation process that has been applied in the model.

The purpose of the diagram or model detail is to present the concept. The model can be easily programmed to support managers using "what-if" type of scenarios to evaluate their system under different conditions. Managers can use the proposed model as user-friendly and simple software which basically requests

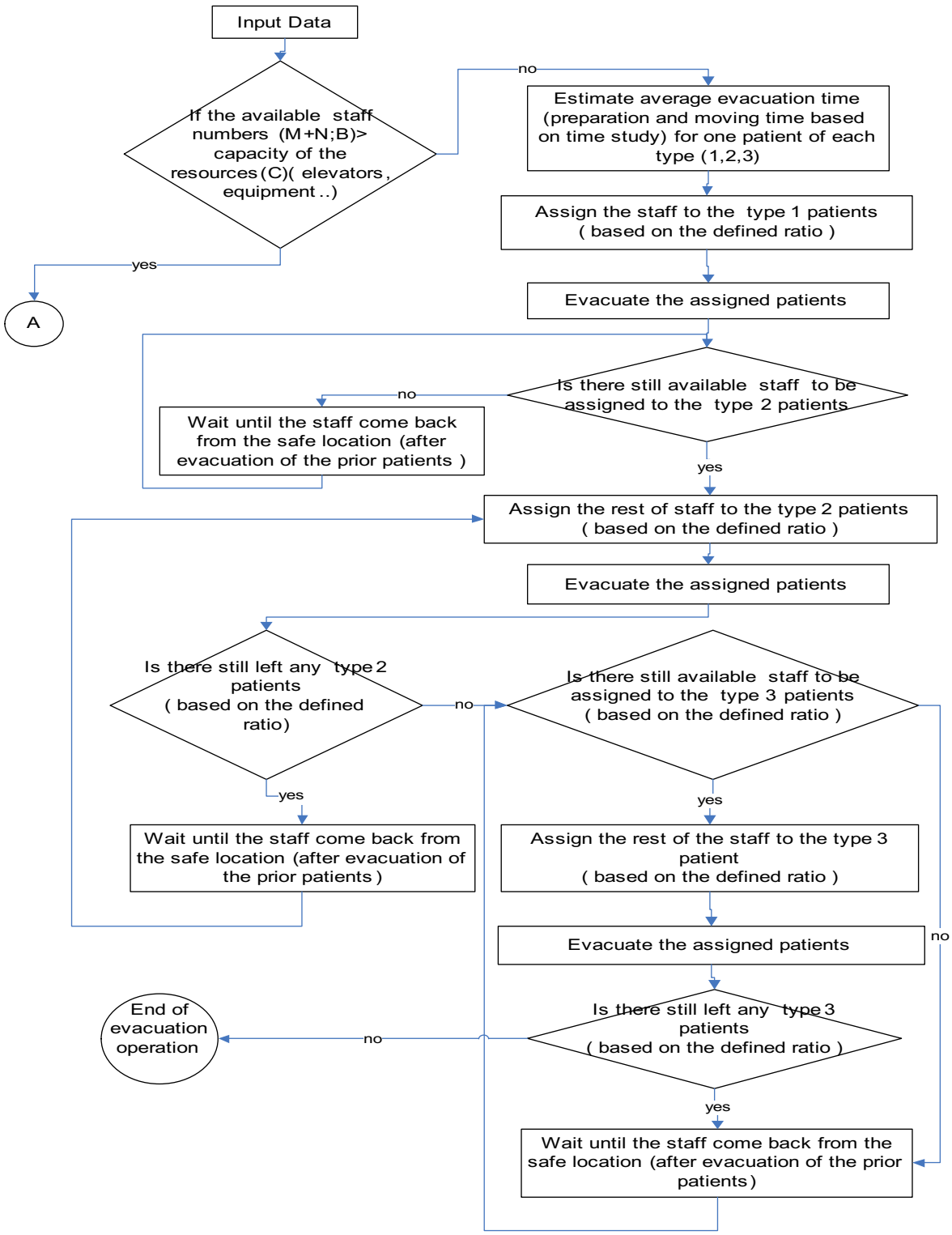

Fig. 1. Overall view of evacuation process for estimation of evacuation time.

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input data (such as number of patients, resources, etc.) and immediately estimates the evacuation time.

Different hospitals have different resources which greatly impact the evacuation time; however the parameters in the model are variables. For instance, even at the same hospital, when 20 staff and 5 elevators are available, estimation of the evacuation time is different than with 18 staff with 3 elevators. Layout restrictions or even evacuation time for each patient type can be adjusted by time studies as part of the input preparation of the model.

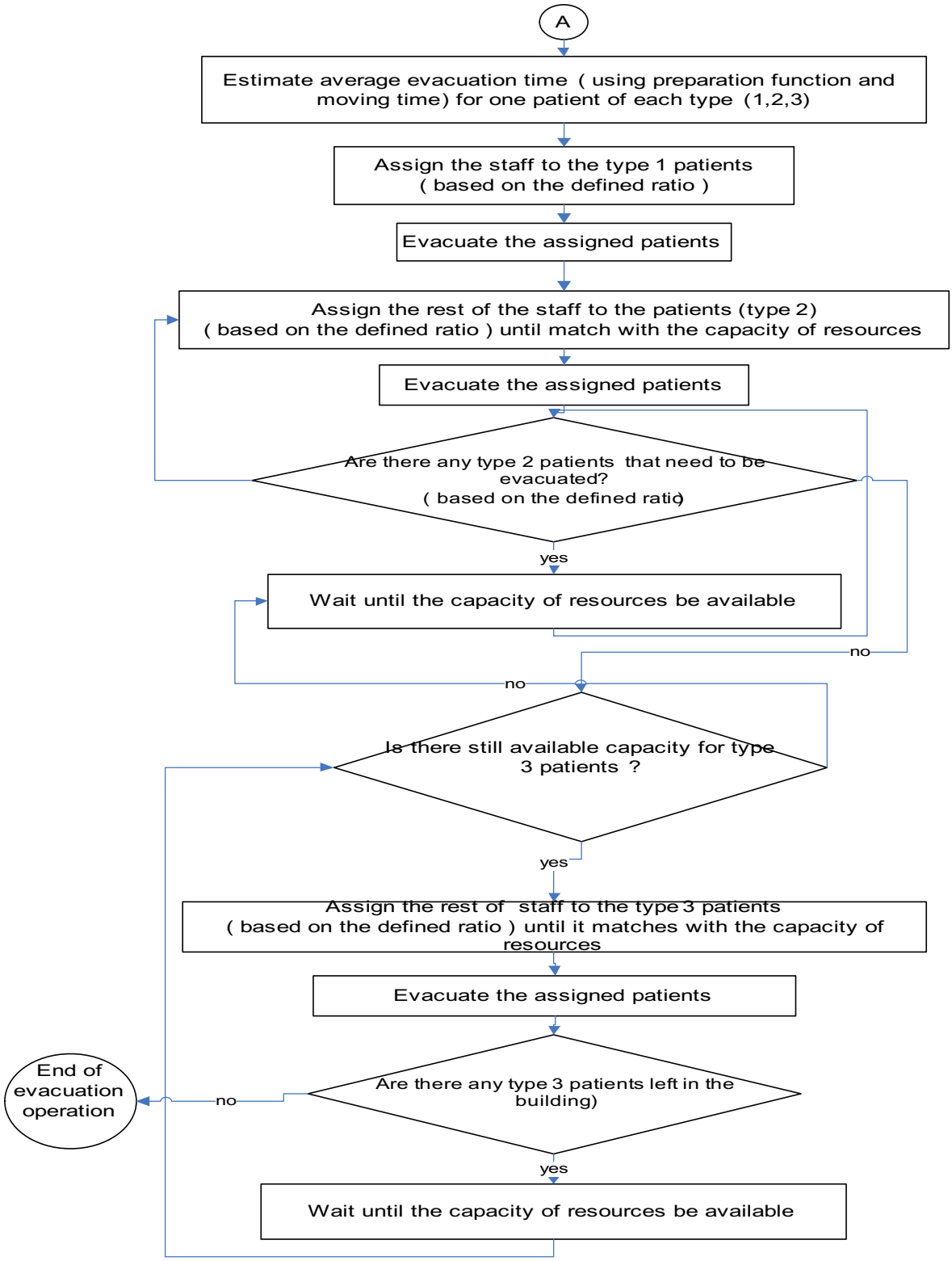

Fig. 1 (*continued*)

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According to our experience with hospital evacuation modeling and in consultation with a disaster preparedness group of a major hospital in our original case study, the main resource bottleneck in a hospital may be the staff or elevators rather than other resources such as bedsore oxygen tanks. However, by considering the role of other types of resources, the model can become much more comprehensive. This would add great complexity to the prediction model. While all types of resources for the entire building are vital, it can be seen that incorporating resource allocation can be a challenge. Since the walking wounded patients are guided to stairways and there are typically not many walking wounded patients on higher floors in a hospital, the number of stairways need not be considered as a constraint. However, the number of available elevators can be a real bottleneck if the entire building needs to be evacuated.

In this model, the role of elevators is evaluated to determine whether they may play a bottleneck role or not. Theoretically speaking, if the number of available staff and the capacity of other resources are greater than the elevators, then elevators can have an impact on the operation as a constraint or bottleneck. This is true unless the number of patients is low or if there are not many floors involved in the evacuation process. Our model is based on one individual floor. Evacuating several floors simultaneously along with the scheduling of elevators creates complexities in the evacuation process that is certainly worthy of future study.

The evacuation process used in this model has two parts. The first part is to make patients ready for moving to the safe location (preparation time) such as preparing wheelchairs, disconnecting the patients from equipment, or connecting them to portable equipment. The second part is to move to the safe location (running time). The running time can be measured by time study methods; however the preparation time can be affected by the following two situations.

2.1. Situation 1

If facilities or resources such as elevators are not playing bottleneck roles, i.e. number of staff is less than the capacity of these resources, then a portion of the staff is assigned to Type 1 patients and family members immediately. The number of staff assigned depends on the number of people in this group, the physical layout conditions and the emergency situation. Since the objective is to evacuate as many people as possible, the priority in the evacuation process is first Type 1 patients, then Type 2 and then Type 3. The logic here is that Type 1 patients are the fastest to evacuate, while Type 2 patients are faster than Type 3 patients. Assigning the available staff based on this priority can save more lives. The next group of staff is assigned to Type 2 patients. After evacuating this type of patients, the staff is assigned to Type 3 patients.

Although the resource allocation priority is based on the patients' type, Type 1 patients need many less resources in comparison with Type 2 and Type 3 patients. For instance, one staff may help all Type 1 patients in a waiting room of a clinic toward an exit. The ratio of resource allocation may mitigate the concern of following the priority rule of resource assignment in a real evacuation event. Moreover, the assigned staff for Type 1 patients can easily rejoin the rest of staff after helping the Type 1 patients to be evacuated.

Recently, a number of articles consider the issue of determining patient prioritization strategies for the evacuation of hospitals and other healthcare facilities (Childers, Visagamurthy, & Taaffe, 2009; Klein & Nagel, 2007). Opinions differ about how to prioritize patients to be moved. One study by Childers and Taaffe (2010) demonstrates a modeling approach involving dynamic programming and simulation. Prioritization schemes may vary for different objectives and scenarios leading to generalized evacuation guidelines.

The applied concept in the proposed model is basically similar to the shortest processing time in scheduling theory. To have more throughputs, the shortest processing time method is used. This method is generally the best technique for minimizing job flow (patient flow) and minimizing the average number of jobs (patients) in the system. Its main disadvantage is that long duration jobs (Type 3 patients) may be continuously pushed back in priority in favor of short duration jobs (Type 1 or Type 2 patients). However, this disadvantage does not affect our goal in this research which is to evacuate the most people in a short period of time.

In addition to the shortest processing time rule, other scheduling rules may be employed for evacuation, such as rush scheduling where emergency patients are evacuated first or first come, first served scheduling where patients are evacuated in the order in which they arrive at an elevator or staircase. Certainly in a hospital evacuation, management may choose to focus on specific objectives leading to the use of other than the shortest processing time rule.

Note that preparation time in this situation can be measured by time study methods. For example, the time to prepare a Type 2 patient is 5 min. This time is added to the running time for a Type 2 patient, presented in the proposed model as P22 for Type 2 patients (preparation time + running time). Table 1 demonstrates the concept of the evacuation process when the number of staff is less than the elevators' capacity. In this example, the assumptions are as follows: 13 patients (Type 2), 8 elevators available, 5 staff, and one staff stay with the patient after first round of evacuation in the safe location.

The total evacuation time is 24 min to evacuate all patients. This is a very simple example; however in reality we might face different types of patients.

Table 1
An example of evacuation process for situation 1.

Room	Patient (Type 2)	Assigned Staff to patients and elevators	Using elevators (from 8 available elevators)	Evacuation time in each round trip (min)	Round trip	Cumulative evacuation time
1	One Patient	← 1 →	1	5 (preparation) + 3 (running) = 8	↓1↑	8
2	One Patient	← 2 →	2	5 (preparation) + 3 (running) = 8		
3	One Patient	← 3 →	3	5 (preparation) + 3 (running) = 8		
4	One Patient	← 4 →	4	5 (preparation) + 3 (running) = 8		
5	One Patient	← 5 →	5	5 (preparation) + 3 (running) = 8		
6	One Patient	← 1 →	1	5 (preparation) + 3 (running) = 8	↓2↑	16
7	One Patient	← 2 →	2	5 (preparation) + 3 (running) = 8		
8	One Patient	← 3 →	3	5 (preparation) + 3 (running) = 8		
9	One Patient	← 4 →	4	5 (preparation) + 3 (running) = 8		
10	One Patient	← 1 →	1	5 (preparation) + 3 (running) = 8	↓3↑	24
11	One Patient	← 2 →	2	5 (preparation) + 3 (running) = 8		
12	One Patient	← 3 →	3	5 (preparation) + 3 (running) = 8		
13	One Patient	← 4 →	4	5 (preparation) + 3 (running) = 8		

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Table 2
An example of evacuation process for situation 2.

Room	Patient	Assigned Staff to patients and elevators	Using elevators (from 2 available elevators)	Evacuation time in each round trip (min)	Round trip
1	One Patient (type2)	← 1 →	1	AP (preparation) + 3 (running)	↓1↑
2	One Patient (type2)	← 2 →	2	AP (preparation) + 3 (running)	
3	One Patient (type2)	← 3 →	1	AP (preparation) + 3 (running)	↓2↑
4	One Patient (type2)	← 4 →	2	AP (preparation) + 3 (running)	
5	One Patient (type2)	← 5 →	1	AP (preparation) + 3 (running)	↓3↑
6	One Patient (type3)	← 6 and 7 →	2	AP (preparation) + 3 (running)	
7	One Patient (type 3)	← 4 and 5 →	1	AP (preparation) + 3 (running)	↓4↑

Although the resource utilization needs of Type 1 patients may not be significant in comparison with the other types of patients, the number of Type 1 patients must still be considered as part of the model. The care and evacuation of Type 1 patients who are part of the unit are still concerns of the hospital manager. In the case of a unit with many Type 1 patients, since they utilize staff they will impact the estimate of the evacuation response time.

2.2. Situation 2

If the facilities or resources such as elevators are playing bottleneck roles, i.e. number of staff is greater than the capacity of these resources, then staff can save time in the evacuation process by preparing the patients for the evacuation. In other words, the available capacity of resources is not adequate to assign a patient to each staff (or a group of 2 staff people for Type 3 patients), and evacuate the patients. Staff prepares Type 2 patients followed by Type 3 patients and moves them toward the safe location as soon as elevators are available. Here the preparation time, referred to as AP in the model, is calculated based upon the number of patients (Type 2 and Type 3) and staff. The rest of the process is similar to situation 1. Table 2 demonstrates the concept of the evacuation process in this situation using the following assumptions: 5 patients (Type 2), 2 patients (Type 3), 2 elevators available and 7 staff.

The calculation of the preparation time (AP) in the second situation will be illustrated shortly. The algorithm estimates the evacuation time for each floor. Therefore, the value of parameters such as the evacuation times for each type of patient (P11, P22, and P33) and number of patients (P1, P2, and P3) may vary among individual floors.

There are 14 different sets of conditions, the most possible in a hospital setting, that were modeled and shown in Appendix A. The most possible setting means that we did not consider rare cases for modeling, for example: having 14 patients in a floor and 1 staff available to evacuate them or having 2 patients in a floor with 15 available staff. Appendix A contains Table A1 showing the differences among the 14 conditions for which the estimated evacuation times have been calculated.

The notation for the parameters of the model which allows for multiple scenarios is as follows:

P1 = Number of walking wounded patients-Type 1.
P2 = Number of less critical patients (in wheelchair)-Type 2.
P3 = Number of critical patients (on bed)-Type 3.
P11 = Evacuation time for one Type 1 patient from a floor to the safe location.
P22 = Evacuation time for one Type 2 patient from a floor to the safe location.
P33 = Evacuation time for one Type 3 patient from a floor to the safe location.
M = Number of Medical staff.
N = Number of Non medical staff.
B = Number of staff who stay with their patients in the safe location.
R = Number of assigned to the walking wounded patients.
C = Number of available elevators.
Et = Estimated evacuation time.

We restate that the objective of evacuation is to minimize the evacuation time and maximize the number of evacuees. Therefore, the priority is to evacuate the patients from Type 1 to Type 3 respectively. Obviously patients need less help in this order and this is a realistic reaction of a system in an event.

Part of the model is applicable in a situation in which elevators play a bottleneck role. In such case, we expect to have the following conditions:

$$M + N - R > C$$
$$M + N - B > C$$

The evacuation time for a Type 2 or Type 3 patient consists of two times: the preparation time and the running time. The following functions are used for P22 & P33 in this situation:

Pt2 is preparation time for a Type 2 patient.
P2m is running time from the floor to the safe location for a Type 2 patient.
Pt3 is the preparation time for a Type 3 patient.
P3m is running time from the floor to the safe location for a Type 3 patient.

AP is average preparation time for a patient per staff as follows:

$$\mathrm{AP} = \frac{\mathrm{P2} \times \mathrm{Pt2} + \mathrm{P3} \times \mathrm{Pt3}}{M + N - B}$$
$$\mathrm{P22} = \mathrm{AP} + \mathrm{P2m}$$
$$\mathrm{P33} = \mathrm{AP} + \mathrm{P3m}$$

As an example of one of the functions, the expected evacuation time based upon the following condition is:

$$\text{If } \mathrm{P1} \geqslant 1, \quad \mathrm{P2} < (M+N) - R, \quad \mathrm{P2} > C, \quad \mathrm{P3} < (M+N),$$
$$\mathrm{P3} > (M+N-B)/2, \quad 1 \leq R \leq (M+N), \quad M+N-R \geqslant C,$$

$$M+N-B \geqslant C, \quad (M+N-R)/2 \geqslant C \text{ and } G$$
$$= C - \left(\mathrm{P2} - \left(C + \left[\frac{\mathrm{P2} - C}{C}\right] \times C\right)\right)$$

$$\text{Then} \quad \mathrm{Et} = \mathrm{P22} + \left[\frac{\mathrm{P2} - C}{C}\right] \times \mathrm{P22} + \mathrm{P33} + \left[\frac{\mathrm{P3} - G}{C}\right] \times \mathrm{P33}$$

Note: The function of [ ] creates a lower value of integer number. Also for a lower value less than 1, the value is considered 1. For example [5.6] = 5 and [0.3] = 1.

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Table 3
Estimated evacuation time based on the functions & simulation.

Scenario	Floor	Staff	Patients Type 3	Patients Type 2	Patients Type 1 (or family member)	*R*	*B*	Number of available elevators	Evacuation time (min)		Difference
									Prediction model	Simulation result	
1	4	27	13	7	6	1	2	2	64.2	71.3	−7.1
2	4	20	10	5	5	1	2	2	44.2	51.5	−7.3
3	4	12	8	10	6	1	2	3	63	69.9	−6.9
4	4	27	15	15	4	1	3	7	32.5	42.4	−9.9
5	4	10	8	5	3	1	2	1	106.8	99.4	7.4
6	4	15	11	10	4	1	2	4	49.5	60.7	−11.2
7	4	9	10	10	5	1	2	3	88.3	95.8	−7.5
8	5	28	15	7	6	1	2	2	73.5	84.2	−10.7
9	5	10	9	11	4	1	2	4	96.7	112.2	−15.5
10	5	12	10	13	5	1	3	6	98.1	93.7	4.4
11	5	8	7	9	4	1	2	2	104.2	115.3	−11.1
12	5	15	10	9	7	1	3	7	39.1	45.2	−6.1
13	5	8	9	12	3	1	2	5	109	119.9	−10.9
14	5	10	6	9	4	1	2	2	74.75	87.2	−12.45
15	6	23	11	12	5	1	2	2	80.3	94.6	−14.3
16	6	7	11	10	3	1	2	7	79	92.2	−13.2
17	6	12	8	9	5	1	2	2	80.8	86.6	−5.8
18	6	13	12	16	4	1	3	4	127	121.9	5.1
19	6	6	7	8	2	1	2	2	111	121.7	−10.7

To demonstrate the aforementioned function, consider the second scenario shown in Table 3 that has the following conditions:

$$M + N = 20 \quad \mathrm{P3} = 10 \quad \mathrm{P2} = 5 \quad \mathrm{P1} = 5 \quad C = 2 \quad B = 2 \quad R = 1$$

To find P22 and P33, AP need to be calculated. Assume that Pt2, the preparation time for Type 2 patient, is 2 min and Pt3, the preparation time for a Type 3 patient, is 3 min.

$$\mathrm{AP} = \frac{\mathrm{P2} \times \mathrm{Pt2} + \mathrm{P3} \times \mathrm{Pt3}}{M + N - B} = \frac{5 \times 2 + 10 \times 3}{18} = 1.6$$

so

$$\mathrm{P22} = \mathrm{AP} + \mathrm{P2m} = 1.6 + 4 = 5.6$$

$$\mathrm{P33} = \mathrm{AP} + \mathrm{P3m} = 1.6 + 5 = 6.6$$

$$G = C - \left(\mathrm{P2} - \left(C + \left[\frac{\mathrm{P2} - C}{C}\right] \times C\right)\right)$$
$$= 2 - \left(5 - \left(2 + \left[\frac{5-2}{2}\right] \times 2\right)\right) = 1$$

$$\mathrm{Et} = \mathrm{P22} + \left[\frac{\mathrm{P2} - C}{C}\right] \times \mathrm{P22} + \mathrm{P33} + \left[\frac{\mathrm{P3} - G}{C}\right] \times \mathrm{P33}$$
$$= 5.6 + \left[\frac{5-2}{2}\right] \times 5.6 + 6.6 + \left[\frac{10-1}{2}\right] \times 6.6 = 44.2$$

The necessity of knowing the amount of evacuation time is when Type 2 and Type 3 patients are in the system. In this case, the amount of evacuation time for walking wounded patients (Type 1) does not affect the entire evacuation time, and so it is not part of the model. However, we don't really ignore the impact of walking wounded patients in the evacuation process. Since two parallel evacuation operations (walking wounded and Type 2 and Type 3 patients) are performed simultaneously, and the time that is needed to evacuate patients of Type 2 and Type 3 is more than the walking wounded, therefore the evacuation of Type 1 patients has no impact on the overall estimation of evacuation time in our model. One obvious situation in which this is not true is when there are no Type 2 or Type 3 patients. Also, in the rare case that there is a large number of walking wounded patients (Type 1), and there is no lack of required resources to evacuate Type 2 and Type 3 patients at the onset of evacuation process; i.e. there is one staff available for each Type 2 patient and two staff available for each Type 3 patient, then Type 1 patients may have an impact on the evacuation processing time.

The evacuation issues are often revealed when managers must deal with limited resources and different types of patients. As mentioned in the paper, rare cases are not the subject of our study. For more clarification, although we considered patients in three different categories (Types 1, 2 and 3), that does not mean, for instance, that Type 2 patients in two different departments or floors have the same evacuation time (P22). Even the preparation time based on the illness for the same type patients can be different. As explained in the model, the time can be studied by time study techniques in the data gathering step as model input.

Another factor that can have an impact on the evacuation time is the effect of panic and/or anxiety on the part of the staff which would likely vary widely with the type of emergency that is occurring. It is not really easy to have a precise measure of the panic impact; however managers or expert people can adjust the time that the staff needs to evacuate the patients based on the type of emergency.

The designed model can predict the time needed for the evacuation of a single floor. Considering the entire building for evacuation makes the prediction more complex. Sharing resources, congestion in the hallways, etc. which are part of the dynamic of the evacuation process, might need to be considered in a stochastic model. This would all be a part of future research. However, the model presented in this paper can still provide valuable information in order to consider the evacuation of the entire building.

3. Data implementation and result analysis

Appendix A contains the prediction model showing the calculation of the hospital evacuation times. The model requires 14 different equations. The prediction model was applied by using data from a local hospital. The model considered 19 different scenarios which involved combinations of the following variables: hospital floor, number of staff, number of patients of each type, number of assigned staff to walking wounded patients (Type 1 patients), number of staff who stay with their patients in the safe location,

and number of available elevators. The hospital floors considered in these scenarios were primarily occupied with patients in wheelchairs (Type 2 patients) and patients on beds (Type 3 patients), both of whom have difficulty being evacuated. Evacuating the Type 1 patients, the walking wounded, was not considered to be a major concern. It is common to assign one staff member for each floor ($R = 1$) to the walking wounded patients and their family members to facilitate their evacuation. The variables used in each of the scenarios, along with the estimated evacuation time for the specific floor found by using the prediction model and the simulation model are shown in Table 3.

To evaluate the accuracy of the prediction model, the evacuation times, in minutes, for the prediction model were compared with the results from a simulation model. This simulation model had been designed previously for use in this local hospital using Arena Software Version 9.

Once the data collection was complete, the next step was to analyze the accumulated information to be used in the simulation model. More detailed analysis and distribution fitting was carried out using the Arena Software input analyzer. Arena Software allowed for graphic model verification, statistical analysis, multiple scenarios and varying input parameters.

Fig. 2 shows a comparison of the evacuation time results between the prediction model and simulation model.

The mean absolute difference between the evacuation times of the prediction and simulation models is 9.34 min, or a percentage difference of 11.47%. For hospital managers who attempt to estimate the evacuation times in their facilities in case of an emergency, this difference between the two models would be considered acceptable. Evacuation operations for one individual floor may not expose the complexities or all of the difficulties of the evacuation for an entire multi-storied building. On a single floor, we often have less staff than the number of patients. Patients' preparations can create delays and all patients may not simultaneously be ready for evacuation and resource utilization. Despite these conditions, queuing problems may not arise while using elevators or exit doors since the evacuation process is not competing with the evacuation from other floors.

Nevertheless, queuing concerns may arise in a single unit operation evacuation when patients are available with adequate number of staff for their preparation but only a limited number of elevators or exit doors are available concurrently. However, these conditions may not be a common occurrence.

According to Table 3, in most scenarios, the predication model results are smaller than the simulation results. These differences, however, are not significant. The effect of the dynamic behavior of evacuation course and congestion may be the main reason of this difference. To tackle this issue and reduce this effect, the evacuation time per patient (P33, P22, and P11) can be determined by time study techniques and adjusted by a fraction of the time based on the system and floors condition for any hospital by expert analysis.

4. Conclusion

In this paper, we presented a prediction model that estimates the evacuation time in each floor of a hospital building based upon different sets of conditions. Incident managers at hospitals aim at evaluating the current performance of operations and executive plans for potential disaster events. We believe that this model can provide incident managers with estimates of the evacuation times of different types of patients and can offer support to the managers with their resource allocation decisions in emergency situations.

In summary, the evacuation process used in this model consisted of two steps. The first step was to make patients ready for moving to the safe location (preparation time) and the second step was to move to the safe location (running time). All type of patients (i.e. "walking wounded" (Type 1 patients), "less critical", (Type 2 patients), and "critical", (Type 3 patients)) were considered to enhance the applicability of the model. Since elevators or number of staff may play a critical role as main bottlenecks during the evacuation process, they were also considered. All main drivers in evacuation operations and modeling were defined as variables to provide a wide variety of analysis and evaluation for managers. The model was applied to different scenarios involving combinations of hospital variables. The evacuation time results were shown to be within an acceptable range of the times generated by an existing simulation model at a local hospital. However, unlike various forms of simulation models, this prediction model performs without layout restrictions. Thus, as a generic model, it can be used in various hospital settings.

The major advantage of the prediction model is that the computation time is short and the model does not need a lengthy and costly design and validation period as required with simulation models. Getting an estimate quickly and in an acceptable estimate range is desirable and more beneficial than the time and cost involved in developing simulation models. Also, simulation models are generally based on the layout of a given facility. However, lack of adherence to the layout specification in the prediction model enhances its capability to be used for any hospital.

Based on our knowledge, there is no such model in the literature, and the aim of this research is to work on the development of prediction models that may initiate new avenues of research for scholars and practitioners. We believe this is the beginning of

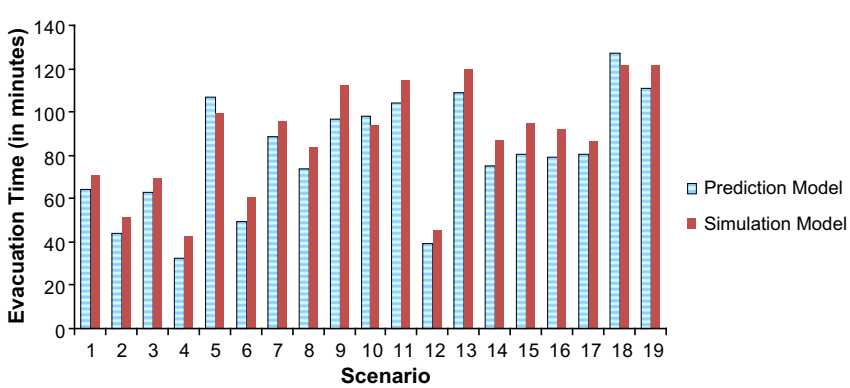

Fig. 2. Comparison of evacuation times for prediction and simulation models.

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a journey. In the more complex evacuation cases, such as several floors simultaneously, elements of the model may be competing with one another for resources (elevators or staff being demanded on multiple floors) or elements may become free due to resource capacity changes (extra elevators or staff will be available when some of the floors are evacuated and extra help can change the dynamic of the operations). One way of envisioning this problem is as a queuing network with stochastic arrival and service processes. Although these characteristics make the modeling difficult, part of our future work is to explore these more advanced situations for the entire building. Future research would involve analysis of the dynamic behavior of the evacuation course in greater detail, with a focus on the congestion in the hallways and/or stairways. Incorporating this type of future work into the prediction model would certainly yield greater accuracy of the evacuation time estimates.

Appendix A. Estimation the evacuation time

The following expressions illustrate the set of functions for estimating the evacuation time for a given floor of the hospital.

P1 = Number of walking wounded patients-Type 1.
P2 = Number of less critical patients (in wheelchair)-Type 2.
P3 = Number of critical patients (on bed)-Type 3.
P11 = Evacuation time for one Type 1 patient from the floor to the safe location.
P22 = Evacuation time for one Type 2 patient from the floor to the safe location.
P33 = Evacuation time for one Type 3 patient from the floor to the safe location.
M = Number of Medical staff.
N = Number of Non medical staff.
B = Number of staff stay with patients in the safe location.
R = Number of assigned staff to the walking wounded patients.
C = Number of available elevators.
Et = Estimated evacuation time.

Note: In the following equations, the function of [ ] creates a lower value of integer number. Also for a lower value than 1, the value is considered 1. For example [5.6] = 5 and [0.3] = 1 (see Table A1).

Based on the following conditions, the estimated evacuation time is:

A.1. Equation No. 1

If $\mathrm{P1} \geqslant 1, \quad \mathrm{P2} > (M+N), \quad \mathrm{P3} > (M+N), \quad 1 \leqslant R \leqslant (M+N),$

$\dfrac{\mathrm{P2}-(M+N-R)}{(M+N-B)}$ is not integer number,

$\left[\dfrac{2(M+N)-B-\mathrm{P2}-R}{2}\right] \geqslant 1,$

$M+N-R \leqslant C$ and $M+N-B \leqslant C$ then

$$\mathrm{Et} = \left\{\mathrm{P22} + \left[\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}\right] \times \mathrm{P22} + \left[\frac{2(M+N)-B-\mathrm{P2}-R}{2}\right] \times \mathrm{P33} + \left[\left(\mathrm{P3} - \frac{(M+N-B)-((M+N-R)-\left[\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}\right] \times (M+N-B))}{2}\right) \times \frac{2}{(M+N-B)}\right] \times \mathrm{P33} + F \times \mathrm{P33}\right\}$$

If $\left(\left(\mathrm{P3} - \dfrac{(M+N-B)-((M+N-R)-\left[\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}\right] \times (M+N-B))}{2}\right) \times \dfrac{2}{(M+N-B)}\right) > 1$ and non-integer, then $F = 1$ otherwise $F = 0$

A.2. Equation No. 2

If $\mathrm{P1} \geqslant 1, \quad \mathrm{P2} > (M+N), \quad \mathrm{P3} > (M+N), \quad 1 \leqslant R \leqslant (M+N),$

$\dfrac{\mathrm{P2}-(M+N-R)}{(M+N-B)}$ is not integer number,

$\left[\dfrac{2(M+N)-B-\mathrm{P2}-R}{2}\right] < 1,$

$M+N-R \leqslant C$ and $M+N-B \leqslant C$ then

$$\mathrm{Et} = \mathrm{P22} + \left[\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}\right] \times \mathrm{P22} + \left[\frac{2(M+N)-B-\mathrm{P2}-R}{2}\right] \times \mathrm{P22} + \left[\left(\mathrm{P3} - \frac{(M+N-B)-((M+N-R)-\left[\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}\right] \times (M+N-B))}{2}\right) \times \frac{2}{(M+N-B)}\right] \times \mathrm{P33} + F \times \mathrm{P33}$$

If $\left(\left(\mathrm{P3} - \dfrac{(M+N-B)-((M+N-R)-\left[\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}\right] \times (M+N-B))}{2}\right) \times \dfrac{2}{(M+N-B)}\right) > 1$ and non-integer, then $F = 1$ otherwise $F = 0$

Table A1
Summary of the set of conditions.

Equation	P1	P2	P3	R	$M+N-R$	$M+N-B$	Some of the conditions (more details are in each equation)
1	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} > (M+N)$	$1 \leqslant R \leqslant (M+N)$	$M+N-R \leqslant C$	$M+N-B \leqslant C$	$\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}$ not an integer $\left[\frac{2(M+N)-B-\mathrm{P2}-R}{2}\right] \geqslant 1$
2	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} > (M+N)$	$1 \leqslant R \leqslant (M+N)$	$M+N-R \leqslant C$	$M+N-B \leqslant C$	$\frac{\mathrm{P2}-(M+N-R)}{(M+N-B)}$ not an integer number $\left[\frac{2(M+N)-B-\mathrm{P2}-R}{2}\right] < 1$
3	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} > (M+N)$	$1 \leqslant R \leqslant (M+N)$	$M+N-R \leqslant C$	$M+N-B \leqslant C$	
4	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} \leqslant (M+N-R)$	$\mathrm{P3} < (M+N)$	$1 \leqslant R \leqslant (M+N)$	$M+N-R \leqslant C$	$M+N-B \leqslant C$	
5	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} < (M+N)$ and $> (M+N-R)$	$\mathrm{P3} < (M+N)$	$1 \leqslant R \leqslant (M+N)$	$M+N-R \leqslant C$	$M+N-B \leqslant C$	
6	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} > (M+N)$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 \geqslant C$	$M+N-B \geqslant C$	$\frac{\mathrm{P2}-C}{C} > 1$ or $\frac{\mathrm{P2}-C}{C} < 1$
7	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} > (M+N)$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 < C$	$M+N-B \geqslant C$	
8	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} \leqslant (M+N-B)/2$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 \geqslant C$	$M+N-B \geqslant C$	$\frac{\mathrm{P2}-C}{C} > 1$ or $\frac{\mathrm{P2}-C}{C} < 1$
9	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} \leqslant (M+N-B)/2$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 < C$	$M+N-B \geqslant C$	
10	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} < (M+N)$ and $> (M+N-\mathrm{E})/2$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 \geqslant C$	$M+N-B \geqslant C$	
11	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} > (M+N)$	$\mathrm{P3} < (M+N)$ and $> (M+N-B)/2$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 < C$	$M+N-B \geqslant C$	
12	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} < (M+N)-R$	$\mathrm{P3} \leqslant (M+N-B)/2$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 \geqslant C$	$M+N-B \geqslant C$	
13	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} < (M+N)-R$	$\mathrm{P3} \leqslant (M+N-B)/2$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 < C$	$M+N-B \geqslant C$	
14	$\mathrm{P1} \geqslant 1$	$\mathrm{P2} < (M+N)-R$	$\mathrm{P3} < (M+N)$ and $> (M+N-B)/2$	$1 \leqslant R \leqslant (M+N)$	$(M+N-R)/2 \geqslant C$	$M+N-B \geqslant C$	

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A.3. Equation No. 3

If $P1 \geqslant 1, \quad P2 > (M+N), \quad P3 > (M+N), \quad 1 \leqslant R \leqslant (M+N),$

$\dfrac{P2-(M+N-R)}{(M+N-B)}$ is integer number,

$M+N-R \leqslant C$ and $M+N-B \leqslant C$ then

$$Et = P22 + \left[\frac{P2-(M+N-R)}{(M+N-B)}\right] \times P22 + \left[\frac{2P3}{(M+N-B)}\right] \times P33$$

$$+ F \times P33 \text{ If } \frac{2P3}{(M+N-B)} > 1 \text{ and non-integer,}$$

then $F = 1$ otherwise $F = 0$

A.4. Equation No. 4

If $P1 \geqslant 1, \quad P2 \leqslant (M+N-R), \quad P3 < (M+N), \quad 1 \leqslant R \leqslant (M+N),$

$M+N-R \leqslant C$ and $M+N-B \leqslant C$ Then

$$Et = P22 + \left[\frac{2P3}{(M+N-B)}\right] \times P33 + F \times P33$$

If $\dfrac{2P3}{(M+N-B)} > 1$ and non-integer,

then $F = 1$ otherwise $F = 0$

A.5. Equation No. 5

If $P1 \geqslant 1, \quad P2 < (M+N), \quad P2 > (M+N-R), \quad P3 < (M+N),$

$1 \leqslant R \leqslant (M+N), \quad M+N-R \leqslant C$ and $M+N-B \leqslant C$

The same as Equation Nos. 1 or 2

A.6. Elevator capacity constraints

In the following equations, the elevators can play a bottleneck role:

$$M+N-R > C$$
$$M+N-B > C$$

If the above constraints are not satisfied, then previous equations are used. The evacuation time for a Type 2 or Type 3 patient consists of two times: the preparation time and the running time. The following functions are used for P22 & P33 in this situation:

Pt2 is preparation time for a Type 2 patient.
P2m is running time from the floor to the safe location for a Type 2 patient.
Pt3 is the preparation time for a Type 3 patient.
P3m is running time from the floor to the safe location for a Type 3 patient.

AP is average preparation time for a patient per staff as follows:

$$AP = \frac{P2 \times Pt2 + P3 \times Pt3}{M+N-B}$$
$$P22 = AP + P2m$$
$$P33 = AP + P3m$$

The estimate of the evacuation time can be calculated in different conditions as follows.

A.7. Equation No. 6

If $P1 \geqslant 1, \quad P2 > (M+N), \quad P3 > (M+N),$
$1 \leqslant R \leqslant (M+N), M+N-B \geqslant C,$
$(M+N-R)/2 \geqslant C$ If $\dfrac{P2-C}{C} > 1$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + P33 + \left[\frac{P3}{C}\right] P33$$

If $\dfrac{P2-C}{C} < 1$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + \left[\frac{P3}{C}\right] P33 + P33$$

If $\dfrac{P3}{C}$ is integer or < 1, the last P33 will be considered 0

A.8. Equation No. 7

If $P1 \geqslant 1, \quad P2 > (M+N), \quad P3 > (M+N), 1 \leqslant R \leqslant (M+N),$
$M+N-R \geqslant C, M+N-B \geqslant C,$
$(M+N-R)/2 < C$ then

$$F = \frac{(M+N-B) - P2 - (C + [(P2-C)/C]C)}{2}$$

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + \left[\frac{2(M+N)-B-P2-R}{2}\right] \times P33$$
$$+ \left[\frac{P3-F}{(M+N-B)/2}\right] \times P33 + P33$$

If $\dfrac{2(M+N)-B-P2-R}{2} < 1,$

then P22 should be considered instead of P33

If $\dfrac{P3-F}{(M+N-B)/2} < 1$or integer, the last P33 is 0

A.9. Equation No. 8

If $P1 \geqslant 1, \quad P2 > (M+N), \quad P3 \leqslant (M+N-B)/2,$
$1 \leqslant R \leqslant (M+N), M+N-R \geqslant C,$
$M+N-B \geqslant C, (M+N-R)/2 \geqslant C$

If $\dfrac{P2-C}{C} > 1$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + P33 + \left[\frac{P3}{C}\right] P33$$

If $\dfrac{P2-C}{C} < 1$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + \left[\frac{P3}{C}\right] P33 + P33$$

If $\dfrac{P3}{C}$ is integer or < 1, the last P33 is considered 0

A.10. Equation No. 9

If $P1 \geqslant 1, \quad P2 > (M+N), \quad P3 \leqslant (M+N-B)/2,$
$1 \leqslant R \leqslant (M+N), \quad M+N-R \geqslant C,$
$M+N-B \geqslant C$ and $(M+N-R)/2 < C$

If $\dfrac{P2-C}{C}$ is integer then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + P33$$

If $\dfrac{P2-C}{C}$ is not integer then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + 2 \times P33$$

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A.11. Equation No. 10

If $P1 \geqslant 1$, $P2 > (M+N)$, $P3 < (M+N)$,
$P3 > (M+N-B)/2$, $1 \leqslant R \leqslant (M+N)$,
$M+N-R \geqslant C$, $M+N-B \geqslant C$,
$(M+N-R)/2 \geqslant C$ and

$$F = \frac{(M+N-B) - P2 - (C + [(P2-C)/C]C)}{2} \text{ then}$$

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + \left[\frac{2(M+N)-B-P2-R}{2}\right] \times P33 + \left[\frac{P3-F}{C}\right] \times P33 + P33$$

If $\frac{P3-F}{C}$ is integer then the last P33 is equal to 0

A.12. Equation No. 11

If $P1 \geqslant 1$, $P2 > (M+N)$, $P3 < (M+N)$,
$P3 > (M+N-B)/2$, $1 \leqslant R \leqslant (M+N)$,
$M+N-R \geqslant C$, $M+N-B \geqslant C$,

$$(M+N-R)/2 < CF = \frac{(M+N-B) - P2 - (C + [(P2-C)/C]C)}{2} \text{ then}$$

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + \left[\frac{2(M+N)-B-P2-R}{2}\right] \times P33 + \left[\frac{P3-F}{(M+N-B)/2}\right] \times P33 + P33$$

If $\frac{2(M+N)-B-P2-R}{2} < 1$,
then P22 should be considered instead of the first P33

If $\frac{P3-F}{(M+N-B)/2} < 1$or integer, the last P33 is 0

A.13. Equation No. 12

If $P1 \geqslant 1$, $P2 < (M+N)-R$, $P3 \leqslant (M+N-B)/2$,
$1 \leqslant R \leqslant (M+N)$, $M+N-R \geqslant C$, $M+N-B \geqslant C$,
$(M+N-R)/2 \geqslant C$ and

$$G = C - \left(P2 - \left(C + \left[\frac{P2-C}{C}\right] \times C\right)\right)$$

If $P2 > C$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + P33 + \left[\frac{P3-G}{C}\right] \times P33,$$

If $P2 < C$ then $Et = \left[\frac{P3}{C}\right] \times P33 + P33$

If $\frac{P3}{C} < 1$ or integer, then the last P33, is 0

A.14. Equation No. 13

If $P1 \geqslant 1$, $P2 < (M+N)-R$, $P3 \leqslant (M+N-B)/2$,
$1 \leqslant R \leqslant (M+N)$, $M+N-R \geqslant C$,
$M+N-B \geqslant C$, and $(M+N-R)/2 < C$
If $P2 > C$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + P33$$

If $P2 < C$ then $Et = P22 + P33$

A.15. Equation No. 14

If $P1 \geqslant 1$, $P2 < (M+N)-R$, $P3 < (M+N)$,
$P3 > (M+N-B)/2$, $1 \leqslant R \leqslant (M+N)$, $M+N-R \geqslant C$,
$M+N-B \geqslant C$, $(M+N-R)/2 \geqslant C$ and

$$G = C - \left(P2 - \left(C + \left[\frac{P2-C}{C}\right] \times C\right)\right)$$

If $P2 > C$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + P33 + \left[\frac{P3-G}{C}\right] \times P33$$

If $P2 < C$ then

$$Et = \left[\frac{P3}{C}\right] \times P33 + P33$$

If $\frac{P3}{C} < 1$ or integer then the last P33 is 0

If $(M+N-R)/2 < C$ and $P2 > C$ then

$$Et = P22 + \left[\frac{P2-C}{C}\right] \times P22 + \left[\frac{P3}{(M+N-B)/2}\right] \times P33 + P33$$

If $P2 < C$ then $Et = P22 + \left[\frac{2P3}{(M+N-B)}\right] \times P33 + P33$

References

Agency for Healthcare Research and Quality, US Department of Health & Human Services (2009). Mass evacuation transportation model. <http://massevacmodel.ahrq.gov/(X(1)S(2rp4lf55pbtftr55zk0ktm21))/Home.aspx>.

Augustine, J., & Schoettmer, J. (2005). Evacuation of a rural community hospital: Lessons learned from an unplanned event. *Disaster Management & Response, 3*(3), 68–72.

Bakuli, D. L., & MacGregor Smith, J. (1996). Resource allocation in state-dependent emergency evacuation networks. *European Journal of Operational Research, 89*(3), 543–555.

Barnett, J., Dennis-Rouse, M., & Martinez, V. (2009). Wildfire disaster leads to facilities evacuation. *Orthopaedic Nursing, 28*(1), 17–20.

Castro, C., Persson, D., Bergstrom, N., & Cron, S. (2008). Surviving the storms: Emergency preparedness in Texas nursing facilities and assisted living facilities. *Journal of Gerontological Nursing, 34*(8), 9–16.

Chalmet, L. G., Francis, R. L., & Saunders, P. B. (1982). Network models for building evacuation. *Management Science, 28*(1), 86–105.

Childers, A. K., & Taaffe, K. M. (2010). Healthcare facility evacuations: Lessons learned, research activity, and the need for engineering contributions. *Journal of Healthcare Engineering, 1*(1), 125–140.

Childers, A. K., Visagamurthy, G., & Taaffe, K. (2009). Prioritizing patients for evacuation from a healthcare facility. *Transportation Research Record: Journal of the Transportation Research Board, 2137*, 38–45.

Choi, W. (1991). A simulation model for emergency building evacuation. In *Simulation in emergency management and engineering, conference proceedings*.

Cova, T. J., & Johnson, J. P. (2003). A network flow model for lane-based evacuation routing. *Transportation Research Part A, 37*(7), 579–604.

Drager, K. H., Lovas, G., Wiklund, J., Soma, H., Duong, D., Violas, A., et al. (1992). EVACSIM – A comprehensive evacuation simulation tool. In J. D. Sullivan (Ed.), *International emergency management and engineering conference – Managing risk with computer simulation* (pp. 101–108).

Franzese, O., & Joshi, S. (2002). Traffic simulation application to plan real-time distribution routes. In *Proceedings of the 2002 winter simulation conference* (pp. 1214–1218).

Gray, B., & Hebert, K. (2007). Hospitals in Hurricane Katrina: Challenges facing custodial institutions in a disaster. *Journal of Healthcare for the Poor and Underserved, 18*(2), 283–298.

Gwynne, S., Galea, E. R., Owen, M., Lawrence, P. J., & Filippidis, L. (1999). A review of the methodologies used in the computer simulation of evacuation from the built environment. *Building and Environment, 34*(6), 741–749.

Hobeika, A. G., & Jamei, B. (1985). MASSVAC: A model for calculating evacuation times under natural disaster. *Proceedings of the conference on computer simulation in emergency planning* (Vol. 15, pp. 23–28). Society of Computer Simulation.

Hyer, K., Brown, L., Christensen, J., & Thomas, K. (2009). Weathering the storm: Challenges to nurses providing care to nursing home residents during hurricanes. *Applied Nursing Research, 22*, e9–e14.

Jafari, M. A., Golmohammadi, D., & Seyed, K. (2008). Management of medical staff in case of emergency evacuation. *Journal of Homeland Security and Emergency Management, 5*(1), 1–18 (Article 4).

Klein, K., & Nagel, N. (2007). Mass medical evacuation: Hurricane Katrina and nursing experiences at the New Orleans airport. *Journal of Emergency Nursing, 5*(2), 56–61.

Lewis, S. (2007). Georgia hospital hit by f3 tornado – All patients evacuated through the ED. *ED Management Tornado, 19*(4), 37–39.

Lo, S. M., Fang, Z., & Chen, D. H. (2001). Use of a modified network model for analyzing evacuation patterns in high-rise buildings. *Journal of Architectural Engineering, 7*(2), 21–29.

Pidd, M., de Silva, F. N., & Eglese, R. W. (1996). A simulation model for emergency evacuation. *European Journal of Operational Research, 90*(3), 413–419.

Schultz, C., Koerig, K., & Lewis, R. (2003). Implications of hospital evacuation after the Northridge, California earthquake. *The New England journal of Medicine, 348*(14), 1349–1355.

Sheffi, Y., Mahmassani, H., & Powell, W. B. (1982). A transportation network evacuation model. *Transportation Research Part A, 16*(3), 209–218.

Taaffe, K. M., Kohl, R., & Kimbler, D. L. (2005). Hospital evacuation: Issues and complexities. In *Proceedings of the 2005 winter simulation conference* (pp. 943–950).

Tayfur, E., & Taaffe, K. (2009). A model for allocating resources during hospital evacuations. *Computers & Industrial Engineering, 57*(4), 1313–1323.

Weinroth, J. (1989). An adaptable microcomputer model for evacuation management. *Fire Technology, 25*, 291–307.

Wolshon, B. (2001). One-way-out: Contra flow freeway operation for hurricane evacuation. *Natural Hazards Review, 2*(3), 105–112.

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