Hospital Evacuation: A System Dynamics Approach

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Abstract

Purpose – We seek to explore and understand hospital evacuation in the event of a natural disaster that prompts patient evacuation, aiming to understand systemic processes that apply to hospital evacuation and patient relocation.

Design/methodology/approach – We use system dynamics to simulate hospital evacuation in the event of a disaster that prompts patient transfer. System dynamics is a well established simulation method for analyzing complex social systems, which are difficult to predict and often include feedback.

Findings – The key to efficient hospital evacuation lies less in management of patient transportation, i.e., ambulance allocation and evacuation route management, and more in the ability of the receiving hospital to manage the influx of patients. The decision makers on the receiving end (the hospital receiving patients) hold the most leverage in determining the rate of the evacuation.

Practical implications – Based on simulation results, we develop recommendations for hospital evacuation and patient relocation. Planners and policy makers can use the recommendations to facilitate efficient hospital evacuations.

Originality/value – By simulating numerous evacuation scenarios, we provide decision makers with recommendations related to the preparation for and implementation of hospital evacuation in the event of a disaster. The original contribution lies in the discovery of system feedbacks that show better where the leverage exists in the hospital evacuation process.

Keywords: Evacuation, Hospital, System Dynamics, Modeling, Feedback, Disaster Response, Disaster Preparedness, Surge Capacity

1. Introduction

1.1 Disaster Preparedness

Throughout the history of disaster response, governments at federal, state, and local levels have attempted to prevent disasters or reduce their effects through policy controls. Policy and decision makers working in disaster preparedness and response benefit from learning from disasters about the processes involved to make decisions that will return better outcomes.

During any type of disaster, transportation and medical resources will be in high demand. Resources will be stressed and tested during and after the event, as those whom the event affects move to safety and seek medical attention. The history of disaster events around the globe demonstrates that lack of resources has repeatedly been a major obstacle in disaster preparedness (Hoard et al., 2005). Understanding key resources and the management of processes related to maintaining and supporting those resources is crucial in disaster preparedness and response.

1.2 Hospital Evacuation

Hospitals are a key resource related to disaster preparedness. Studying and simulating scenarios and related processes that will potentially unfold during disaster events will assist planners in making informed decisions related to key resources, rather than acting on impulse or wrong information. Hospital evacuation is one important disaster preparedness and response process to consider and understand.

The Agency for Healthcare Research and Quality (AHRQ) classifies hospital evacuation into two categories in the Hospital Evacuation Decision Guide. "Pre-event evacuations are undertaken in advance of an impending disaster, when the hospital structure and surrounding environment are not yet significantly compromised. Post-event evacuations are carried out after a disaster has caused substantial damage to a hospital or the surrounding community." (AHRQ, 2010) This study focuses on pre-event evacuation prompted by natural disasters such as a hurricane.

The process of evacuation, when viewed in the most basic form, is a problem of moving patients safely from a place of potential danger, which we term the Danger Zone Hospital (DZH), to a place of safety, the Safe Zone Hospital, (SZH). Two of the principal factors for decision makers to consider when weighing the risks and benefits of evacuation are

1. In what way will disaster responders transport patients as safely and as efficiently as possible from the DZH to the SZH?
2. What space is available to receive patients in the SZH? In other words, what is the availability of hospital beds and the resources required to support the patients?

By focusing on these principal factors and related variables, this study aims to understand processes for increasing efficiency and effectiveness in the evacuation of a DZH.

1.3 Study Overview

We present the literature review in Section 2, which introduces past research related to hospital evacuation. In Section 3, we provide the objective and approach used in this study, including an overview of the system dynamics modeling approach. In Section 4, we define and discuss modeling assumptions and inputs. In Section 5, we present the system dynamics model used in this study. We present the modeling scenarios and simulation results in Section 6. In Section 7, we discuss our conclusions and recommendations.

2. Literature Review

2.1 Evacuation Planning and Decision Making

The AHRQ explains the term “hospital evacuation decision team” as the persons in charge of planning for an evacuation well in advance of an incident, as well as the persons who ultimately decide whether to evacuate a hospital during an incident. (AHRQ, 2010) The decision to evacuate a hospital in preparation for an event will require input from all members of the decision team. The number of people involved in an evacuation coupled with the complexities involved put the decision team in a position where they must have all available information, on the ready to make their decision quickly.

Several recent studies have commented on the complexities, number of stakeholders, and sheer weight that decisions related to disaster planning can have. “Disaster situations present complex moral and ethical challenges at the patient, caregiver, and societal levels” (Geale, 2012). “Stakeholders in disaster ethics include not only patients and their care providers, but public health officials, policy makers, insurance bodies, non-government organizations, the press, and the general public.” (Geale, S.K. 2012) For more on the ethical approach towards disaster management for various stakeholders, see Dean and Payne (2013). One purpose of our study is to allow decision teams to “rehearse” various disaster evacuation scenarios through simulation, allowing for faster and better decisions during an actual disaster (Senge, 1990).

2.2 Computer Based Support for Decision Making

In preparation for a pre-event hospital evacuation, the decision team will benefit from gathering and understanding as much information about the situation as possible. Lack of adequate information at the time of the decision may hinder the abilities of the decision makers.

Silva (2001) notes that technical support, such as computer-based modeling, can be of great assistance for the hospital evacuation decision team and other planners. “In crisis situations appropriate decision making holds the key to alleviating the intensity of the harmful impacts of the disaster, thus ensuring a successful emergency management process. Often the decisions made under time pressure and limited information, as is the case in a disaster management process, are prone to misjudgment of the evolving and prevailing situation due to errors from inattention to detail, inadequate skills, misinterpretation of available information and inadequate mental stamina…. It is, therefore, crucial that the planning and preparation processes for potential emergencies are carried out in detail, and wherever possible valid and reliable tools and support systems are provided to the planners and decision makers to alleviate the burden of the decisions made during emergencies and crisis situations." (Silva, 2001)

2.3 Receiving Hospital Capacity

A recent study surveyed 34 hospitals from seven major cities across the U.S. to assess the hospitals' ability to accept a large influx of patients during a mass casualty or evacuation event. The communication notes that, "The results of the survey show that none of the hospitals surveyed in the seven cities had sufficient emergency care capacity… centers surveyed had no room in their emergency rooms to treat a sudden influx of victims (patients)." (Waxman, H.A. 2008; DeLia, 2007) The consistent and growing limitations on available space in hospitals suggest that planners must carefully consider the receiving end, SZH, when making decisions about evacuation.

2.4 Past Evacuation Modeling and Research

The AHRQ has developed a computer-based model, the Mass Evacuation Transportation Model (METM), to aid in determination of total hospital evacuation time. Using the METM, the AHRQ simulated mass evacuation scenarios in two major metropolitan cities incorporating many hospitals. We used a systems based modeling approach in this study to understand better the transport of patients with the aim of reducing overall hospital evacuation times and optimizing the number of patients evacuated.

The METM model estimates total time required to evacuate patients from healthcare facilities. The METM study used representative scenarios in Los Angeles and New York City as case studies. We incorporated several of the assumptions outlined as part of the METM modeling study in this study. For example, the METM model ignores preferred receiving facilities lists for each evacuating facility. In other words, disaster responders will not match an evacuated cardiac patient from a cardiac center with a cardiac specialized hospital. The assumption is that this level of detail is not possible or practical in the event of an emergency evacuation.

Excluding the AHRQ METM model there is a lack of information related to the process of hospital evacuation and the decisions related to maintaining and supporting hospitals as a key resource in a disaster situation. The majority of information and studies related to hospital capacity and hospital evacuation are descriptive studies that list statistical information. We use system dynamics to simulate hospital evacuation, aiming to fill information gaps in areas pertinent to decision makers and planners.

2.5 System Dynamics in Disaster Planning

A small number of studies have used system dynamics to answer complex questions related to hospital management and disaster planning. Hoard et al. (2005) introduced the notion of using system dynamics for disaster planning. Their study proposed using system dynamics to create simulation models as “what-if” tools for disaster preparedness planners.

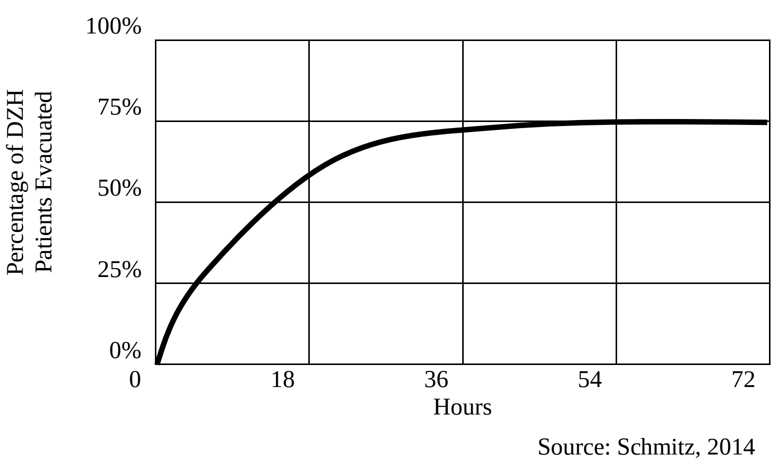
Manley et al. (2005) indicated why system dynamics is well suited for analyzing problems related to hospital capacity and evacuation planning, especially for testing alternative implementation strategies in the dynamically complex and constantly shifting settings that characterize disaster preparedness. System dynamics modeling has the ability to consider self-correcting and reinforcing feedback loops that may become important in a disaster evacuation situation.

3. Objective and Approach

3.1 Application of System Dynamics

Scholars and consultants have applied the system dynamics approach to a number of public policy problems with great success; two examples include municipal planning (Forrester, 1969) and public health resource coordination (Homer et al., 2004). Many disaster preparedness issues are well suited to system dynamics analysis. We used it to simulate hospital evacuation in the event of a hurricane, flood, or some other natural disaster that prompts patient evacuation, simulating a number of different scenarios. The resulting modeling responses will assist in developing principles that apply to hospital evacuation and patient relocation.

Although all models have faults and some level of uncertainty, the results from a modeling study can provide useful information. A well-constructed computer model can provide a unique perspective into the unknown and improve understanding of the cause and effect relationships that are at the heart of a complex issue (Gunning-Schepers, 1999)



Source: Schmitz, 2014

Figure1 Reference Mode for Hospital Disaster Evacuation

3.1.1 Reference Mode

System dynamics modeling typically uses reference modes from actual events as checks on model outputs. The reference modes demonstrate behavior of a model input over time. We have found that, because of the high variability in evacuation scenarios, and the lack of data collection during emergencies, no adequate reference modes for hospital evacuation are publicly available. However, we did get a reference mode from an interviewee, an experienced physician who is director of an Emergency Medicine Department. We show the reference mode in Figure 1; it shows a smooth exponential curve up to the limit of the SZH's capacity.

3.2.2 Dynamic Hypothesis

We have also developed a dynamic hypothesis, represented in a causal loop diagram shown below in Figure 2, which demonstrates our hypothesized understanding of the evacuation process we discuss in this study. The diagram shows variables that are intrinsic to or givens in the situation, such as number of Patients in the DZH. It also shows variables over which policy or decision makers have control, such as the number of Ambulances and even the Capacity of the SZH (which they can increase in the short run by converting non-medical spaces to temporary medical spaces).

The causal loop diagram shows one balancing loop. The number of Ambulances and the Patients in the DZH drive the growth portion of the loop, while the Capacity of the SZH, Rapid Patient Discharge and the Desired Open Beds in the Safe Zone Hospital are the limiting factors that put the brakes on the loop and make it a balancing one. This dynamic hypothesis should produce the kind of curve we showed in the reference mode (Figure 1).

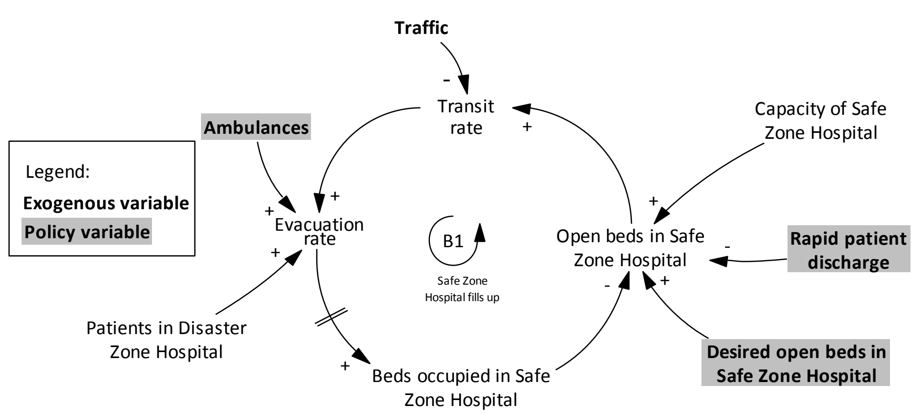


Figure 2 Disaster Evacuation Causal Loop Diagram

3.2 Evacuation Policy Variables

In the event of an evacuation, the decision team will have several options within their control that may influence the success of the evacuation process. Policy variables represent the options that are available to the decision team to set or control prior to the event in the form of a policy to help improve the likelihood of a successful outcome. We list below the three main policy variables identified and used as inputs for the modeling in this study.

3.3.1 Patient Transport

Patient transport is broken into two elements: the number of ambulances and the transit rate of patients. The ambulances refer to those with the required resources needed to move the required patients safely. This includes the driver, supplies for patients, and medical support staff at the DZH, at the SZH, and during transit.

Transit Rate refers to the flow, as patients per hour, of moving patients from the DZH to the SZH. This variable mainly includes traffic management, which disaster mangers can influence in various ways. If they use traffic barriers and traffic guards to block off a designated ambulance travel route, for example, the ambulances would be able to make more trips more quickly between the DZH and SZH than if evacuation traffic jams reduced the flow.

3.3.2 Surge Capacity

Surge capacity is the ability of the SZH to increase the total number of patients it can admit at any given time. In general, hospitals will increase capacity in two ways: rapid patient discharge (RPD), patient boarding and bed management (PBBM). The present study includes surge capacity through PBBM and RPD.

PBBM refers to increasing capacity by methods such as closing cafeterias and utilizing temporary beds. RPD refers to the discharge of patients who are not in immediate need of care and can leave safely in their current state. Managers will likely make use of both methods to increase capacity during an event.

3.3.3 Evacuee Admissions Policy

The admissions policy refers to the willingness of the SZH to admit patients being evacuated from the DZH. We have identified three types of admissions as part of this study: a neutral admissions policy, a liberal admissions policy, and a conservative admissions policy. We explain the admissions policies in Section 4.4.

3.3 Modeling Evacuation

Our aim in modeling a hospital evacuation with focus on ambulance transport is to discover approaches to improve its efficiency during evacuation and reduce overall hospital evacuation time. The approach is to make use of a simplified model that incorporates the major components of ambulance transport.

3.4 Representative Hospitals

We developed a stylized system dynamics model that can account for all the major components of ambulance transport, and, therefore, can apply to any number of scenarios or hospitals. The issue of transit time between hospitals is something that must be calculated and provided as one of the model inputs (discussed in more detail in Section 4).

With the recent evacuation events in New York City prompted by Hurricane Sandy, we decided to base our modeling on two representative hospitals from that area.

The New York Office of Emergency Management has developed a five-stage evacuation plan for the five boroughs that make up New York City. The representative hospitals we suggest include one hospital from within the evacuation zone, designated as the DZH, and one hospital outside the evacuation zone, designated as the SZH. Coney Island Hospital, Brooklyn NY is the DZH within the evacuation zone and Maimonides Medical Center, Brooklyn NY is the SZH. These two hospitals are 5.4 miles apart.

4. Model Assumptions and Inputs

Hospitals of all sizes are now required to have disaster plans. Foremost in these plans is a hospital's ability effectively to address surge capacity. If the hospital cannot do this within its own system, then it must take steps to get external support, either as permanent or temporary resources, or perhaps through flow-control methods such as triage, transfer, and early discharge. (Manley et al., 2005)

Although we have based our study on the representative hospitals listed in section 3.5, the present paper does not represent a case study. We can simulate different levels of the number of patients, transit rate, number of ambulances, and hospital capacities to match any number of evacuation scenarios.

We adopted many of the assumptions used in this modeling study from the METM modeling approach. The METM model assumes that emergency personnel take 70 percent of patients to distant locations, and that the highest acuity patients go to closest facilities while low acuity patients will go to the furthest facilities. The facilities close to the evacuation zone receive largest number of patients.

4.1 Evacuation Assumptions

Most hospital evacuations will include many SZHs for each DZH; in other words, the SZH is typically a group of hospitals prepared to receive evacuating patients. A single hospital will not typically receive all the patients evacuated from a hospital in the danger zone. Our stylized model, however, does assume that there is a single receiving hospital. This approach greatly simplifies the model and still captures the primary components of evacuation. Additionally, we can adjust the model inputs, such as number of patients and number of ambulances, to make the modeling scenarios more realistic.

4.2 Patient Transport

Transit rate governs patient transport. We compute the transit rate in the model based on the number of vehicles and the number of patients transported per vehicle per hour. To make this calculation the distance between the DZH and SZH is required. We have used the distances between the two representative hospitals from New York mentioned in Section 3.5. The METM model assumes that ambulances travel at 20 MPH on average. We have assumed transit rates based on the distance between the DZH and SZH and account for round trips with one patient per vehicle traveling at the posted speed limit (generally about 20 MPH).

4.3 Surge Capacity

In a disaster, it is likely that every hospital will implement some aspect of a surge capacity plan; the question is when the hospital will make the extra capacity available and how much space the surge efforts will gain. In general, regulators expect hospitals throughout the US to produce 15-20% surge capacity within three to four hours (Weiss, 2013). The METM model assumes that receiving hospitals produce 15 percent surge capacity. Our model assumes a 15 percent capacity increase eight hours before the disaster event and represents the PBBM portion of surge capacity.

A study to determine hospital bed surge capacity using physician and nurse manager assessments for the disposition of all inpatients at multiple facilities made 1,741 assessments from four institutions. Managers assessed approximately one-third of all patients as dischargeable at 24 hours (Davis et. al. 2005). Our model assumes that the SZH will discharge approximately thirty percent of its patients within the 24 hours prior to the event to account for the RPD portion of surge capacity.

4.4 Evacuee Admissions

We have identified three types of admissions policies as part of this study: a neutral admissions policy, a liberal admissions policy, and a conservative admissions policy. We show the admissions policies in Figure 3 as variations in how decision-makers "cut off" the admissions inflow. This captures the willingness of the receiving hospitals to admit patients from the DZH and represents the admissions policy of the SZH. The neutral decision policy indicates that managers will accept patients consistently throughout the evacuation. The liberal decision policy indicates that managers will accept patients at a high rate for as long as possible and will stop admissions only just prior to reaching capacity. The conservative decision policy indicates that managers will slow or stop admissions long before reaching capacity. In our interview with a director of emergency medicine (Schmitz, 2014), we learned that hospitals are biased toward a conservative admissions policy.

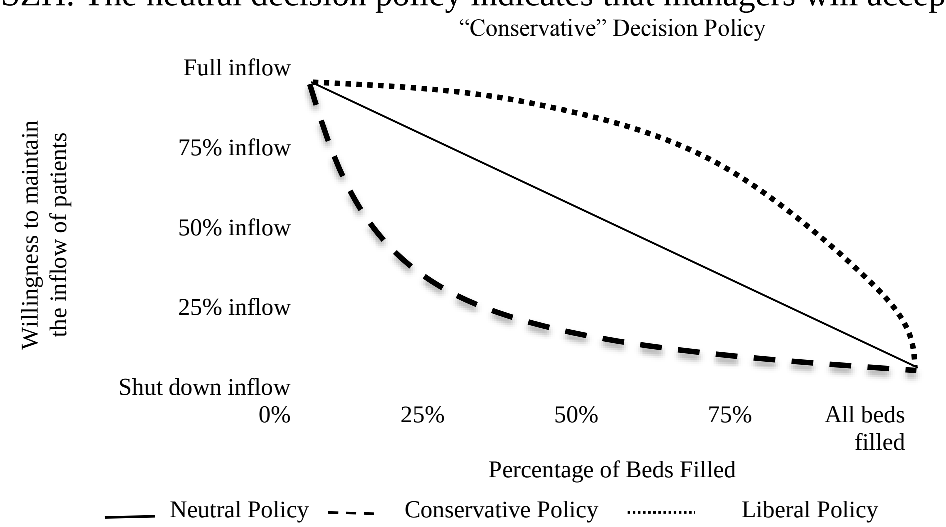


Figure 3 Admissions Decision Policies

4.5 Additional Model Considerations

An additional model consideration is the decision start time. The decision start time refers to when the different policy variables will be set into action relative to the event. Decision makers can trigger the implementation of a surge capacity plan, for example, before an event, during an event, or after an event, depending on the hospital policy and preparedness of the decision makers. We can adjust the model to accommodate any number of scenarios regarding the decision start time; however, we have used only one combination in this study. We envision future work to further study and include this variable in our research, as discussed in Section 7.

5. Modeling Evacuation

Figure 4 shows the major components of the system dynamics model created as part of this study. Our model includes three major stocks: Patients in DZH, DZH patients in SZH, and SZH Patients in SZH. The model also includes two major flows for patients. Patients move from the DZH to the SZH either by way of the evacuation rate flow, or out of the SZH by way of the RPD outflow. Note that only SZH patients can be discharged from the SZH. Patients who are discharged from the DZH will not need to be transported by ambulance, and are not included in the model. The last noteworthy feature of the model is that the decision policies shown in Figure 3 control the flow from the DZH to the SZH; our model formulates this as a negative-sloping function, Effect of Relative DZH patients in the SZH.

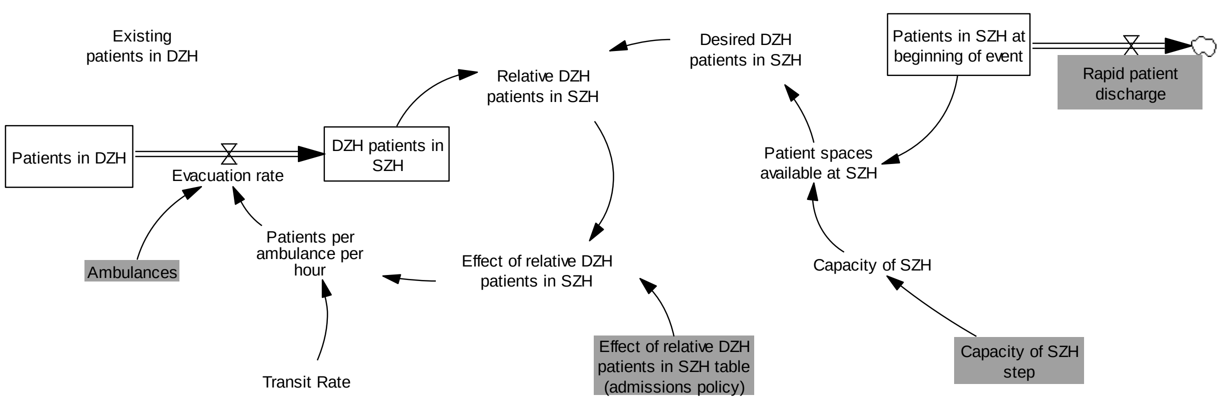


Figure 4 Disaster Evacuation Stock and Flow Model

5.1 Patient Transport

We formulated the evacuation rate by incorporating the number of ambulances, and the rate of patients per ambulance per hour. We formulate this rate using the transit rate, how fast the ambulances can make a round trip between DZH and SZH, and the effect of DZH patients filling up the SZH. We modeled this latter effect, which is in the balancing loop in Figure 2, as a downward sloping (i.e. negative) function similar to those we showed in Figure 3. In this case, this function restricts the flow of patients from the DZH to the SZH based on the intake decision policy, as we show in Figure 3.

5.2 Surge Capacity

We capture surge capacity of the SZH in the model in two ways. An outflow from the SZH patients in SZH stock, which moves incumbent patients in the SZH out of the hospital, represents the RPD portion of the capacity increase. We also formulated a surge capacity step function that allows an increase in patient capacity of a specified number at a specified time. The capacity step function captures the PBBM aspect of surge capacity.

5.3 Evacuee Admissions

As shown in the causal loop diagram presented in Figure 2 the open beds in the SZH is part of a balancing feedback loop that affects the evacuation rate. Patient capacity, patient discharge, and patient intake are mainly what govern open beds in the SZH. The patient intake policy, therefore, is a critical part of the evacuation process.

6. Modeling Results

6.1 Patient Transport

The number of ambulances and the transit rate govern patient transport. Holding one variable constant while varying the others creates different scenarios of patient transport. For this scenario, we selected a constant transit rate and changed the number of ambulances. A future study could vary the transit rate over the course of the evacuation to capture the effects of traffic, ambulance type (Basic Life Support versus Advanced Life Support) and ambulance travel lanes.

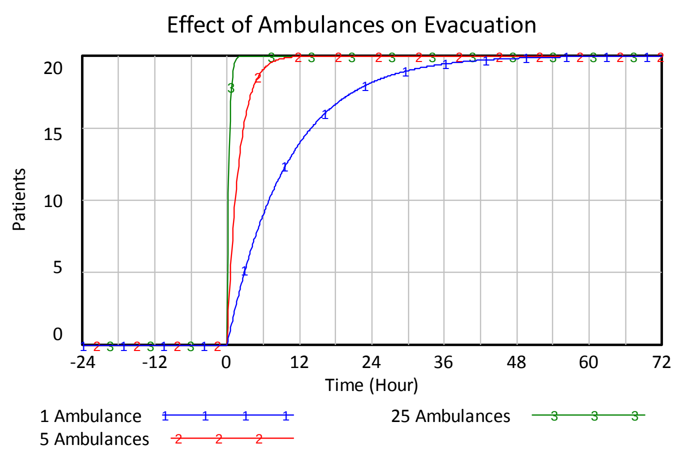


Figure 5 Effect of Ambulances on Evacuation

Figure 5 shows the simulation results for the use of 1, 5, and 25 ambulances for an evacuation. Using one ambulance evacuates the maximum number of patients after 48 hours. Using five ambulances evacuates the maximum number of patients after 12 hours. Using 25 ambulances evacuates the maximum number of patients in fewer than 3 hours.

Notice that in all cases the maximum number of patients evacuated is only 20, which leaves 80 patients in the DZH. This is the result of limited space at the SZH. Although increased ambulances will reduce the overall evacuation time, it is clear that more ambulances will not move all the patients to safety if there is no place for the patients to go. Therefore, the number of ambulances and transit rate are both low-leverage variables if the goal is to evacuate the DZH fully.

Although changes in patient transport policy are low leverage when compared with other policies, providing efficient evacuation requires that disaster managers must still meet certain requirements. Ambulance supply will be different for all hospitals in all situations. Managers would hope that they would always have enough ambulances such that this factor does not slow down the transport of patients. The question is how many ambulances is enough?

Our simulation suggests that little is gained by using more than 25 ambulances for this case. Figure 6 shows the results of doubling the number of ambulances, with full surge capacity and a liberal admissions policy. Evacuation occurs a bit more quickly, but certainly not enough to justify the larger number of ambulances. In general, these results suggest that there is a maximum useful number of ambulances per patient, beyond which an increased number of ambulances provides no benefit for evacuation. A precise determination is beyond the scope of our model, but based on our simulation results we estimate that one ambulance to every four patients being evacuated is sufficient for efficient evacuation. This would take about 12 hours, or roughly one patient every 9 minutes, which is already a very tight logistical task.

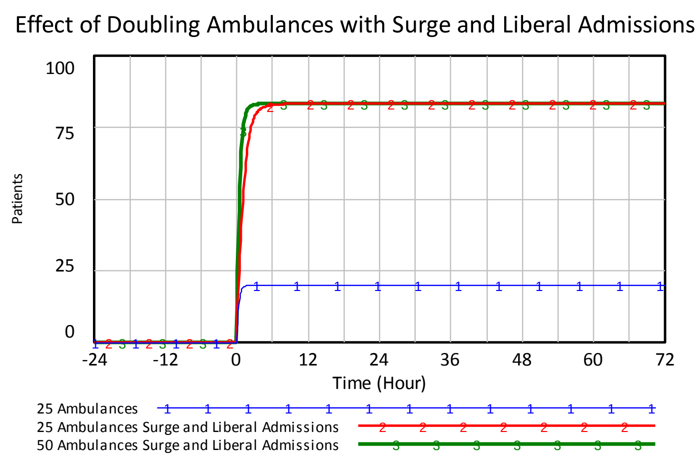


Figure 6 Effect of Doubling Number of Ambulances

6.2 Surge Capacity

When examining the effects of surge capacity on evacuation, we held constant both the number of ambulances and the transit rate. For the results shown in Figure 7, the number of ambulances is 25. The figure shows four model runs:

- no PBBM and no RPD,
- PBBM only,
- RPD only, and
- both PBBM and RPD.

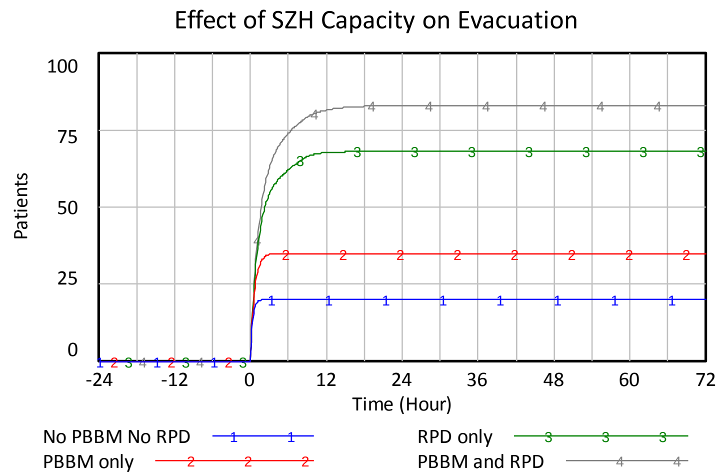


Figure 7 Effect of SZH Capacity on Evacuation

Notice that changing the bed capacity in the SZH increases the number of patients evacuated from the DZH from 20 of 100 to over 80 of 100.

6.3 Evacuee Admissions

The model results shown in Figure 8 show the three different SZH patient intake policies presented in Figure 3. In the model runs presented here, we have assumed 25 ambulances and a constant transit rate. We have also assumed that the SZH will utilize its full surge capacity through RPD and PBBM. Note that we used the neutral decision policy in all previous model runs. The simulation results show that if the SZH receiving patients has a conservative patient intake policy, disaster response personnel will evacuate the maximum number of patients after more than 24 hours. A neutral or liberal policy reduces the evacuation time to 16 and 8 hours, respectively.

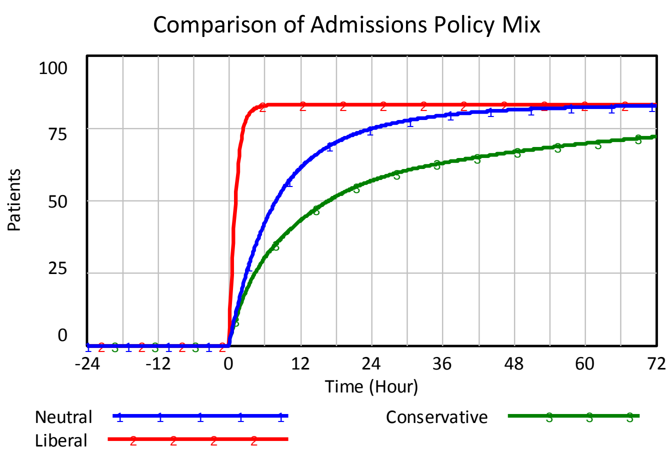


Figure 8 Effect of SZH Intake Policy on Evacuation

7. Discussion and Recommendations

In general, the modeling results indicate that an increase to the number of ambulances or the transit rate has a smaller benefit to evacuation than a change in the capacity of the SZH and the willingness of the SZH to accept new patients. As Senge (1990) says, the leverage in this system is counterintuitive. It is not in the efficient deployment of the ambulances, but in the willingness of the SZH to create room and to adopt a more liberal admissions policy.

7.1 Surge Capacity

Surge capacity (both RPD and PBBM) of the SZH receiving evacuated patients is critical. Timing of implementation of the surge capacity must be as soon as possible to have as much capacity available for evacuees. Surge capacity—Patient Boarding and Bed Management *and* Rapid Patient Discharge—is one of the two major sources of leverage in this system. Creating room downstream is critical for effective evacuation.

7.2 Evacuee Admissions

The SZH evacuation decision policy is the other source of systemic leverage. A "liberal" admissions policy (letting in many patients early and shutting down the inflow as late as possible) results in many more evacuated patients at an earlier time than a "conservative" policy does.

7.3 Optimal Policies

Figure 9 summarizes what the simulation revealed to be the optimal policies:

- One ambulance to every four patients being evacuated. (Base policy uses one ambulance per 20 patients.)
- Maximum surge capacity. (Base policy uses no surge capacity.)
- Liberal admissions policy. (Base policy uses conservative admissions policy.)

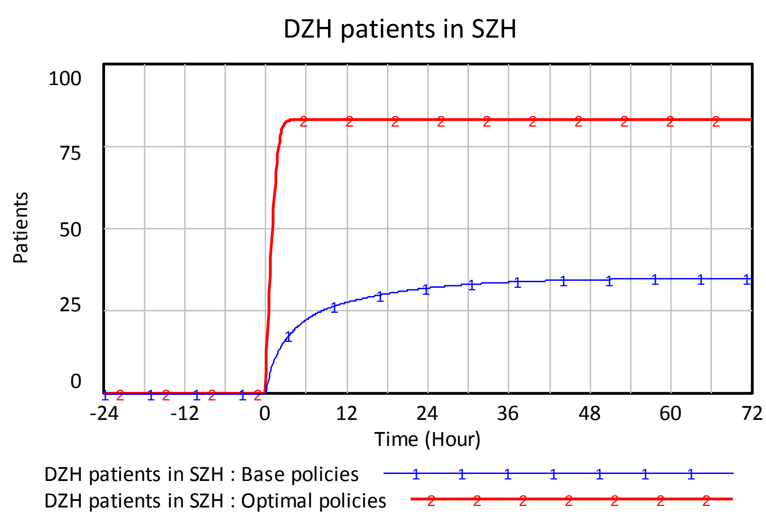


Figure 9 Optimal Policy Summary

Agencies developing policies for evacuation during a disaster should therefor spend their efforts improving their methods for creation of surge capacity and creation of liberal admissions policies.

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