ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20230511184836

Preliminary communication
Received: 2023-05-11, Accepted: 2023-05-15

Location of Emergency Treatment Sites after Earthquake using Hybrid Simulation

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Abstract: A mass-casualty natural disaster such as an earthquake is a rare, surprising event that is usually characterized by chaos and a lack of information, resulting in an overload of casualties in hospitals. Thus, it is very important to refer minor and moderately-injured casualties, that are the majority of casualties and whose injuries are usually not life threatening, to ad hoc care facilities such as Emergency Treatment Sites (ETSs). These facilities support the efficient use of health resources and reduce the burden on permanent healthcare facilities. In our study, a hybrid simulation model, based on a combination of discrete events and an agent-based simulation, provides a solution to the uncertainty of positioning temporary treatment sites. The simulation methodology used compares between "rigid" and "flexible" operating concepts of ETSs (main vs. main+minor ETSs) and found the "flexible" concept to be more efficient in terms of the average walking distance and number of casualties treated in the disaster area.

Keywords: earthquake; emergency; temporary emergency facility; hybrid simulation; humanitarian logistics

1 INTRODUCTION

In an earthquake scenario, it is well known that the first hours and days are the most crucial for saving lives [1]; [2]. Following an earthquake, assuming that severe and moderate casualties are evacuated directly to hospitals, one of the main goals of the Israeli government is to prevent overburdening the hospitals during those first hours and days; hence, care of minor injuries elsewhere can leave more resources for severe and moderate casualties. Thus, the Israeli Ministry of Health has decided to establish 120 Emergency Treatment Sites (ETSs) nationwide, covering each city or locality. Their purpose is to handle minor condition casualties and up to 10% of moderate casualties that might arrive. The medical designation of these ad hoc treatment points and their equipment and personnel, which we define conceptually as "rigid" containing only main ETSs, is based on fixed locations throughout the country to treat casualties. The location of an ETS should follow safety guidelines such as being situated in an open space and in a central area. These operational decisions are imposed on Magen David Adom (MADA – the Israeli national emergency medical service) and local authorities, in cooperation with the Israel Police and the Home Front Command as part of preparedness. Unfortunately, the plan to establish and operate ETSs has not yet been implemented. MADA claims that there are disadvantages in preparing these sites ahead of time since the location of future destruction sites cannot be determined in advance.

Our study proposes a "flexible" concept with a new type of ETS that we define as a minor ETS that can be located near a destruction site. The activation of a minor ETS is subject to a specific main ETS, and its uniqueness is its closeness to a destruction site and the ability to set its location after earthquake damage occurs. Assuming that an evacuation procedure will be performed by evacuators (passers-by, volunteers, neighbors, etc.) on foot, under conditions of uncertainty, accompanied by the destruction of infrastructure and poor communications, the constraints considered include the maximum distance between a destruction site and the nearest main or minor ETS for evacuees and evacuators to walk. Early preparation for deployment of the ETS will constitute a basic plan for a tailored response and establishment of minor ETSs in real time. This paper is based on [3].

2 REVIEW OF LITERATURE

The basic plan in Israel for an earthquake event is called "The Preparation Framework" [4]. This framework states a forecast of total casualties that includes approximately 37,000 with minor injuries, 8,600 with moderate or severe injuries, and approximately 7,000 dead. Considering these figures, it is very important to refer minor and moderate-injured casualties, which include most casualties and whose injuries are usually not life threatening, to ad hoc care facilities to support more efficient use of health resources by reducing the overload on the health system.

While extensive research has been devoted to locating permanent healthcare facilities for emergency medical services, the location of temporary facilities in emergency situations has not been sufficiently investigated [5]. Planning the location of permanent facilities is done in a way in which their placement will enable them to respond to a variety of future events for all kinds of casualties and over time. In contrast, the location of temporary facilities that emerge in a case of high and immediate need for medical treatment in a specific location must be done so that their deployment will provide a quick response, with the facility placed near the event site. Patients who receive treatment at these temporary facilities can be discharged home or referred for further treatment to a permanent health facility.

An example of a temporary medical facility is the "Casualty Collection Point" (CCP), which appears in several studies [1, 6, 2]. Such a facility provides a response to various cases and different needs (not only medical) and is usually designed for a longer period (more than three days). Another example of a temporary facility are field hospitals that are established a few days after earthquakes (Armenia, Turkey, India, and Haiti) and provide care for moderate and severe casualties [7]. However, out of 150 articles about medical emergency facilities [5] only 5% of them dealt with temporary facilities – a rate that indicates a significant lack of research in this field.

An important key feature of the temporary medical facility that affects uncertainties in the case of an earthquake is derived from the fact that the location of a planned facility and the facility itself may be damaged during the disaster event. In a survey on the location of medical facilities [8], researchers noted that there is a need to develop a more flexible model and to expand the options of locations and coverage in the solution. The distinction between a temporary facility and a permanent one will enable a suitable and quick response to the needs of the casualties and help decision and policy makers in such circumstances.

A recent study [9] used a two-stage stochastic mathematical model in which recommended locations of temporary medical facilities after an earthquake (a field hospital) were examined. Cohen-Kadosh [10] presented a deterministic mathematical model for locating main and minor ETSs with two objectives: minimizing the overall distance of evacuations from all the destruction sites and maximizing the number of casualties that could receive treatment in the main and minor ETSs.

The knowledge gap we found in the literature regarding using and locating temporary facilities under an assumption of casualty evacuation by relatives or volunteers, while doing so on foot and caring mainly for minor condition casualties needed to be investigated and satisfied.

Our use of simulation aimed to provide an answer to the most known stochastic scenario such as an earthquake. Using simulation methodology allows for the creation of large emergency scenarios with variant damage combinations of random and other characteristics involved in the event.

Fikar at al. [11] presented a study dealing with disaster situations based on multi-agent simulation (agent- based simulation), combined with optimization to determine the location of logistical assistance centers after a disaster (for supplying food, water, medicine, and emergency equipment). Another study [12] examined a robust optimal simulation model to locate aid and supply centers before a disaster such as an earthquake. The study used simulation and established assumptions including known parameters that indicated the extent of the relationship between the various infrastructure types (for example between an electrical system and a gas system or drinking water infrastructure) and the damage following a variety of disaster scenarios.

Brailsford et al. [13] indicated a new trend in combining several types of simulations: discrete event simulation, agent-based simulation, and dynamic simulation, thus, offering a solution for complex situations. About 22% (out of 139) of the articles in that survey dealt with health services. Therefore, in our research, we decided to employ a hybrid simulation combining a discrete-event simulation, which describes the chain of events in the formation of destruction sites as a result of an earthquake and the appearance of evacuees and evacuators, with an agent-based simulation representing what actually happens in the ETSs and the destruction sites, i.e., dealing with the movement and transfer of casualties from destruction sites to the emergency facilities.

3 RESEARCH OBJECTIVE

Considering the above, we examined the ability of positioning ETSs (main and minor) in the case of an earthquake disaster and compared between the two operating concepts – the rigid concept (only main ETSs) versus the flexible concept (main and minor ETSs) – under uncertainty conditions. The hybrid simulation examining different disaster scenarios can support authorities' decisions as to where to position ETSs to result in minimal evacuee transfer distances and a maximal percentage of casualties that could receive medical treatment.

4 HYBRID SIMULATION MODELS FOR AN ETS

4.1 Operating Mode

For a test case, we used a specific city with several destruction sites (7). In the rigid mode, before an earthquake event, candidate main ETSs (3) are pre-determined. In the flexible mode of operation, there are also minor ETSs (5 candidate locations) considered shortly after the earthquake event. The solution for the flexible mode, in Figure 1, shown by arrows the selected ETSs (2 main and 3 minor), those directed by arrows, from the destruction sites as casualties which arrive to the various ETSs. The arrows represent the movement of evacuees carried/accompanied by evacuators from a destruction site to an ETS (main and minor).

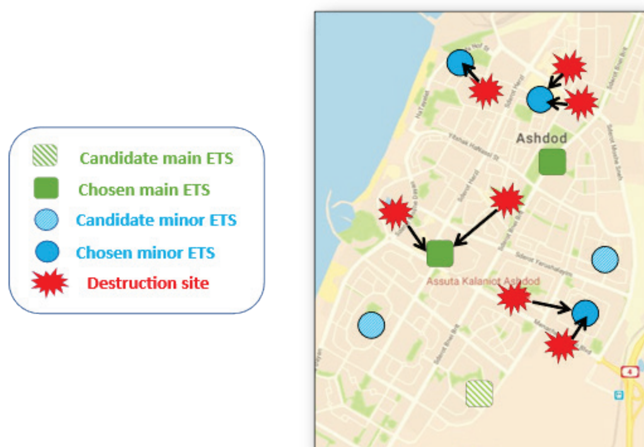

Figure 1 Flexible & Rigid operating concept

4.2 Stochastic Simulations for Casualty Evacuation in an Earthquake

The selected simulation for our study is a hybrid of a discrete simulation, which creates destruction sites, casualties, and evacuators; and an agent-based simulation, which expresses physical evacuation of casualties from destruction sites to ETSs and returning to the evacuation site. In each simulation run, there are entities and resources which have properties that are determined randomly or deterministically.

4.3 Simulation: General Description

We describe here the simulation of evacuation for comparing between two operational modes:

- The rigid concept with one ETS level: only main ETSs – Simulation model A
- The flexible concept with two ETS levels: minor and main ETSs – Simulation model B.

Comparison between the two concepts was done for various levels of each parameter, identifying earthquake scenarios (such as the number of casualties, number of ETSs and their locations) and on the stochastic behavior of the entities or resources (such as the rate of casualty appearances and evacuators, matching between casualties and evacuators, length of walking, road condition and its effect on the length of walking, etc.). For an earthquake event, we determined the locations of the two ETS types: main and minor.

The simulation model was built by using an RStudio interface, combined with a Simmer package [3]. The simulation was defined as a system with no stops, ending either after 48 hours or when no further resources remained. The results were tested by two objective measures:

1) The average distance per casualty from the destruction site to the relevant ETS (as a proxy for evacuation time) was to be minimized.
2) The proportion of casualties who received medical treatment from the total number of casualties was to be maximized.

The chain of events in each simulation run began with an earthquake event, followed by a random number of destruction sites scattered in a pre-defined area. At each destruction site, the simulation randomly created casualties and evacuators. The connection between destruction sites and the various ETSs were limited by the maximal distance allowed between them, and the capacity limitation (number of casualties) in the ETS. The movement of casualties and the ETSs' operation was performed according to the specific concept (rigid or flexible) and ended at the specified time defined for the simulation, either when all casualties from the sites received medical treatment or when the ETS capacity was reached – whichever occurred first.

4.4 System Description

We describe here the system components, model assumptions, and main connections between the entities and resources.

4.4.1 System Components

- A main ETS is a resource providing medical treatment for a given capacity of casualties (most often 250). Its location was taken from several possible given locations.
- A minor ETS is as above, but with a much smaller capacity (most often 50). It is connected to a specific main ETS, as it receives its medical supply only from one main ETS which is connected to it as its source. There was a minimal distance limitation between the minor ETS and the main ETS connected to it, given that the main ETS had enough capacity for the minor ETS.
- An evacuator is a resource representing those persons who establish the minor ETS (in the flexible case) and evacuate the casualties to it. Such a resource is created by the main ETS connected to it. A main ETS served each minor ETS connected to it directly.
- An evacuee is an entity representing a casualty from the disaster site who is waiting to be taken by evacuators to the ETS associated to it (minor or main ETS). These entities were created at each disaster site separately. Each evacuee had a property determining the number of evacuators needed for their evacuation (1–4).

4.4.2 Basic Assumptions of the Simulation Model

- The simulation was modeled without stops, ending at most after 48 hours.
- The time units were in minutes.
- The main ETS was created at the beginning of the simulation.
- The simulation will be repeated under various sets of parameters as shown later.
- A case is a container with medical supplies (for one evacuee/the capacity of a minor ETS usually is 50 casualties) brought from the main ETS connected to the minor ETS.
- The time duration for loading cases in the main ETS and unloading them in the minor ETS was negligible.

4.4.3 Main Stochastic Parameters in Simulation A and B

Some of our assumptions are based on the literature, whereas others are based on interviews with experts during the study or on orders and procedures of the relevant authorities. The parameters related to the walking time are based on experiments performed by the authors.

- The number of destruction sites was selected randomly between 4–10 uniformly. Similarly, the coordinates of their locations were drawn randomly.
- A destruction site was considered randomly from a set of unconnected sites, and the closest available ETS which met the capacity and distance requirements was selected. If no minor ETS was found, then the simulation identified main possible ETSs within the distance limitations, and with sufficient available capacity in relation to the number of evacuees predicted from the site. A minor ETS was connected to the closest main ETS with available capacity.
- The number of casualties at each destruction site was determined randomly according to the number of destruction sites drawn. The sum of all casualties at all destruction sites was determined in advance as the TC (total casualties) given by forecast.
- The arrival time between consecutive evacuees was distributed exponentially, where TC_K was the number of evacuees at destruction site.

- The number of evacuators had a Poison distribution with a rate of 10 per minute.
- Evacuator rests-The evacuators rested every 3 hours [3].
- Evacuee properties – Every evacuee had a property defining the number of evacuators needed, so that 10% of the evacuees needed one evacuator (the evacuees could walk unassisted), evacuees under the age of 14 (evacuees who needed to be carried) who needed two evacuators, and the remainder (older evacuees who needed to be carried) who needed four evacuators (based on information from evacuation authorities).
- Waiting for evacuees in line – The evacuees waited for the number of evacuators they needed. Priority was given to those who needed four evacuators, then two evacuators, and last one evacuator.
- Walking time – The duration of evacuators' walking was based on an experiment that we performed [3] for one evacuee carrying weight as the basic walking time, whereas walking back without weight was adjusted by factor of 0.95.
- Accounting for various terrains (easy, medium, or difficult) – The type of terrain affects the evacuation time. The factor used had the same probability for each type of terrain (1/3). The easy terrain factor was 1, the medium terrain factor was 1.2, and difficult terrain factor was 1.4, based on the method used by the Israeli army.
- The number of evacuators affects the walking duration – The need for team synchronization among the evacuators increases the evacuation time; thus, the larger the team, the longer the evacuation time of the evacuee. Therefore, a single evacuator had a factor 1, two evacuators had a factor of 1.2, and four evacuators had a factor of 1.3.
- The walking duration between the destruction site to ETS – was determined by multiplying the above factors:
- The walking speed from our experiment [3]
- The distance between the destruction site and the ETS
- The terrain factor (easy, medium, difficult)
- Evacuator team size (single, two, or four evacuators).

The goal was to minimize the average distance of casualties, and to maximize the proportion of treated casualties.

4.5 Key Parameters Characterizing an Earthquake Event

For the typical example area in Fig. 1, we examined the sensitivity of the simulation models for five defined key parameters that characterize an earthquake event as follows:

- *TC* – The total number of casualties, which received the following values: 500, 600, 750, 900.
- *RS* – The maximum possible distance from the destruction site to the main ETS ranging from 1,000 to 4,000 meters.
- *RM* – Possible distance from the destruction site to the minor ETS, which received the values: 500, 1,000, 1,500 meters.
- *MS* – Maximal patient capacity in the main ETS, which received the values: 250, 300, 450.
- *MM* – Maximal patient capacity in the minor ETS, 50 or 100.

In addition, there was a sample set of possible locations for three main ETSs and five minor ETSs.

The simulation models were tested according to different combinations of the above sensitivity parameters, where 100 different earthquake scenarios were simulated for each combination of parameters, in which each created a variable number and layout of destruction sites; namely, 4,800 row results were calculated for the rigid perception, and 10,800 row results were calculated for the flexible perception.

To determine which layout performed better and which model we recommend, the results were examined by comparing the findings of the two measures we defined in Section 4.3:

1) The average distance per casualty, which represents the distance that a patient/team would walk from the destruction site to the relevant ETS, as an estimate (proxy) of the evacuation duration; and
2) The proportion of treated casualties in the ETS compared to total casualties in the area.

5 RESULTS

Comparing the simulation of the rigid concept to the flexible concept, we found that for the average walking distance per casualty index, the flexible concept (Model B) was better than the rigid concept (Model A). However, for the average percentage of treated casualty measure, we found that Model A outperformed Model B. Since the simulation was run 100 times for each combination of parameters (as listed in Section 4.6), we were able to test the statistical significance of the results via t-tests and found that most of the results had a 95% significance.

Fig. 2 summarizes the results of the two measures for all the combinations of parameters multi-dimensionally. The left column (*RM* = 0) represents the rigid concept (Model A), and the rest of the *RM* columns represent the flexible concept (Model B). The four dots in each rectangle in each *RM* column provide the results of the two measures as a function of *TC* (in the same order as they appear on the right side of the figure).

In our sensitivity analysis of the parameters, we found that for a possible maximum distance *RS* of 2,000 meters from a main ETS to the destruction site and maximum distance RM 1,000 from a minor ETS to the destruction site, an improvement of the two measures was obtained. Increasing to an *RS* of 3,000, we observed a stabilization in the index values. Along with an improvement in the average distance index, we observed a decrease in the proportion of treated patients. The relative improvement in the distance index (in percent) was usually higher than the relative improvement in the index of treated casualties.

In testing the effect of the ETS's capacity (*TC*) on the results, in comparing the two concepts, we found that as the capacity of the main ETS increased alongside that of the minor ETS, there was an improvement in the average distance measure per evacuee (shorter average distance) compared to a slight decrease in the proportion of treated patients (deterioration in the index) based on the range capacity between the main ETS and the minor ETS. Examining the effect of the total number of casualties on the indicators based on the layout of the ETSs, it can be said that in the rigid concept, as the number of casualties increases, the location of the main ETS has a negative effect. Thus, the main ETS was located, the casualties walked more, while on the other hand, fewer casualties were treated. Checking the flexible concept, we found that as the number of total casualties increased, adding the minor ETSs resulted in smaller average walking distance (improvement of the index), while again decreasing the ratio of treated casualties.

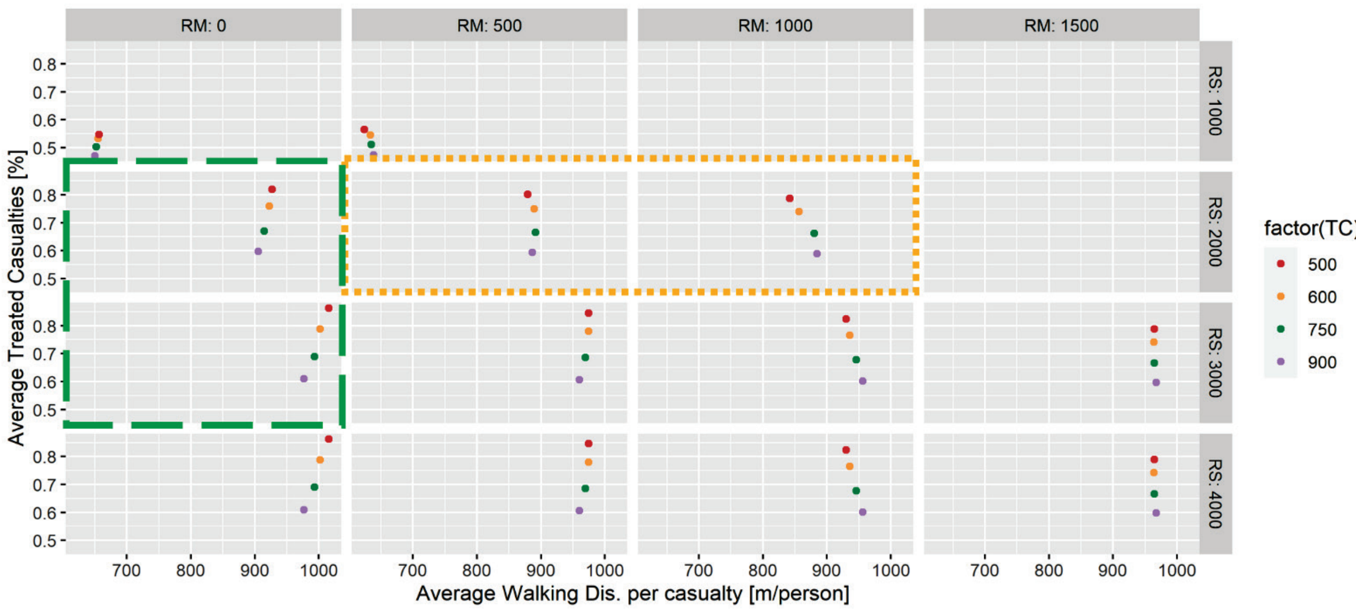

Figure 2 Average walking distance and percentage of treated casualties by various parameters (*RM* from 0-1500, *RS* from 1000-4000 and *TC* from 500-900)

To sum up, it is evident that, for the most part, for the patient proportion index, Simulation model A according to the rigid concept is clearly the preferred one, whereas for the average distance index, the preferred alternative is Simulation model B, according to the flexible concept. It can be said that there is interchangeability between the two indices.

We see, for example, that the capacity of the ETS of both types, and their relative location to the destruction site, affects the ability to determine the preferred alternative. Therefore, a decision must be made on the weight of each index, and this decision remains an open question for policy makers.

6 CONCLUSIONS

This simulation was formulated as a hybrid simulation, incorporating many stochastic parameters that characterize an earthquake event. By averaging multiple cases of earthquake scenarios, we conclude that the flexible concept yields better results regarding the average walking distance index. The analysis in the study shows that there is substitutability between the two indices – the average distance and the proportion of treated casualties – and, therefore, a decision must be made on the weight of each index, and this remains an open question for policy makers. We emphasize that the proposed flexible model should be adapted, and it can be utilized both as part of the preparation phase before an earthquake, and as an autonomous decision support system that supports local authority real-time response to a disaster. The proposal to develop an applicable decision support tool was recently approved by the Israeli Ministry of Science and Technology, and a grant was awarded.

Future research should analyze larger areas of destruction with more main and minor ETSs. Another direction is to consider better rules to improve the percentage of treated casualties using the flexible concept, such as by sending untreated casualties from a minor ETS (due to lack of capacity) to the closest main ETS. Moreover, when a minor ETS finishes treating all its casualties and has leftover supplies, these should be sent to the closest main ETS. Such policies have the potential to reduce the percentage of untreated casualties.

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