Capacity and location planning of auxiliary medical facilities in earthquake relief operations

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Abstract

In this paper, we apply operations research techniques including Discrete Event Simulation and Mixed Integer Programming to determine the required resource capacity to treat severely injured people and the location of temporary hospitals during the first days of relief operations after a disaster strikes.

We estimate the resource gap between the resource capacity in a city and an optimal situation, in which zero people with severe injuries would die due to lack of medical resources. This optimal policy is found through successive scenario evaluations with the simulation model in which the transfer and accommodation of injured people to medical facilities in disaster conditions is represented.

For people with minor injuries, we formulate a location-allocation problem to find the optimal locations for field hospitals that meet all the demands of this category of patients in a predetermined radius. This model minimizes the total cost of establishing temporary facilities subject to maintaining a predefined service level. The results of this study are currently used by the city officials in planning and preparation for disasters. We apply our approach to a case study in the city of Bogotá in two cases of a 6.2 and 7.0 magnitude earthquakes in Bogotá (Colombia).

Keywords: Mixed Integer Programming, Discrete Event simulation, Disaster Operations Management

1. Introduction

The Centre for Research on the Epidemiology of Disasters (CRED), defines a disaster as a situation or event which overwhelms local capacity, requiring external help on the national or international level; an unforeseen and often sudden event that causes great damage, destruction and human suffering.Theses disasters can be classified in five groups: geophysical, meteorological, hydrological, climatological and biological. Historical data found in [1] shows that in 2011 natural disasters have killed a total of 30,773 people, caused 244,7 million victims worldwide and the economics damages were the highest ever registered, with an estimated US$ 366.1 billion.

In particular, geophysical disasters have caused 69,098 deaths on average per year from 2001 to 2010 and the economic losses continue increasing. Examples can be found around the world, for instance the Tohoku earthquake and tsunami in Japan (2011) was the most expensive natural disaster ever recorded or the Haiti earthquake (2010) alone caused the death of more than 222,500

Country	Date	No. Killed
China P Rep	27-Jul-1976	242,000
Haiti	12-Jan-2010	222,570
China P Rep	22-May-1927	200,000
China P Rep	16-Dec-1920	180,000
Indonesia (Tsunami)	26-Dec-2004	165,708
Japan	1-Sep-1923	143,000
Soviet Union	5-Oct-1948	110,000
China P Rep	12-May-2008	87,476
Italy	28-Dec-1908	75,000
Pakistan	8-Oct-2005	73,338

Table 1: Top 10 most important Earthquake disasters from 1900 to 2012 sorted by number of deaths

people [1]. The deadliest earthquakes since the beginning of the twentieth century sorted by the number of killed victims [2, 3] are shown in Table 1.

Large scale disasters such as earthquakes can strike our societies leaving much devastation and many casualties behind, partially as the consequence of an ineffective emergency response [4]. To reduce the severity of damage caused by a disaster, communities get prepared by stockpiling inventory, building adequate structures and training medical assistance, among others. Each of these decisions and actions could make a community more resilient to natural disasters, if done properly [5][6]. Nevertheless, the decision-making process to support emergency response is not an easy process because of unpredictability in the magnitude, timing and location of the event and the inevitable need for collaboration and coordination of response agencies at the city, state, and national levels [7]. Operations Research (OR) tools such as math programming, probability and statistics, simulation and queuing theory, among others show tremendous potential to support this decision-making process [8].

In this paper we propose two models for capacity and location planning of medical facilities in response to a disaster in an urban area. We first divide the live victims of the event into two categories of critical and non-critical patients assuming that the critical patients have a limited survival time, until they reach medical attention. They are treated in permanent and fully equipped facilities, not damaged by the disaster, and are transferred to such facilities via ambulances and possibly wait to seize a bed to be treated. If the total time from the moment when the disaster strikes, until the treatment procedure is over is longer than the survival time of these patients, they are considered deceased. We depict this process via a discrete event simulation model with the current available resources of the city (hospital beds and ambulances) as input, and find the number of deceased patients as the output. Then by successively increasing the resource capacities we find the optimal combination of the number of ambulances and hospital beds that reduces the number of deceased to zero. The gap between this capacity level and that of the current situation in the city is then identified to help the decision makers seek resources in order to fill it. For the case of non-critical patients with non-life threatening injuries, we assume that the city puts up medical tent or converts existing public facilities such as schools, churches or hotels to temporary clinics. For this situation we propose a location-allocation model to find the optimal placement of such facilities to cover a certain percentage of demand as the minimum service level, under budget constraints.

We consider the case of Bogotá, the capital of Colombia with approximately 8.5 million inhabitants and inadequate infrastructure. The city is located on a fault line and is predicted to experience a massive earthquake in the near future. Our goal for this case study is to find the gap between the available medical resources (hospital beds and ambulances) and the quantity required for an optimal situation in which no life is lost due to the lack of such resources. Also, through the proposed optimization model we find the optimal location and capacity of temporary facilities in order to minimize the waiting time of non-critical patients.

The rest of this paper is organized as follows. In Section 2 we will explain how simulation and optimization can support disaster operation management. In Section 3 we show our proposed methodology, in Section 3.1 we discuss in details the proposed discrete-event simulation approach to balance the resource allocation between hospital beds and ambulances and in Section 3.2 we show the proposed optimization model to locate the temporary hospitals throughout the city, given a set of constraints. The case study on the city of Bogotá is presented in Section 4 and in Section 4.1 we show the results of applying our proposed methodology to the data from Bogotá. Finally Section 5 concludes the paper and gives suggestions for future work.

2. OR and Disaster Operations Management

A survey of literature on Disaster Operations Management (DOM) is done by Altay et al. [8]. In this article the emergency management operations are divided into four phases: mitigation, preparedness, response, and recovery. Mitigation is the application of measures that will either prevent or reduce the impacts when the disaster occurs. Preparedness activities prepare the community to respond to the disaster. Response phase comprises the employment of resources and emergency procedures as guided by plans to preserve life, property, the environment, and the social, economic, and political structure of the community. Recovery involves the actions taken in the long term after the immediate impact of the disaster has passed, in order to stabilize the community and to restore some semblance of normalcy. This classification shows that 24% of the articles reviewed here belong to natural disasters, 65% are related to the decisions made before a disaster strikes (mitigation and preparedness) and 12% use simulation as an OR technique to solve the problem. However, simulation requires a large amount of effort in time, cost, and data. Therefore, operational researchers have attempted to combine simulation with other operational research techniques, such as linear programming, to capitalize on the advantages of using both techniques simultaneously [9].

Jun et al. [9] carried out a survey focusing on articles that analyze single or multi-facility health care clinics (emergency departments, surgical centers, among others). Their work is divided in two main topics, patient flow and allocation of resources. The first is related with problems of patient scheduling, admissions, flow schemes, scheduling and availability of resources. The second topic is more closely related with our work, as it studies the bed, room and staff sizing and planning. Gunal et al. [10] classify papers according to the areas of application evident in the literature: accident and emergency department (AE), inpatient facilities, outpatient clinics, other hospital units (laboratories, operating theatres, surgical suites, pharmacies, and screening units) and whole hospital simulations. At the end they conclude that, just like Fone et al. [11] thre is an increasing trend in the literature on this subject, but a low rate of successful implementations. For instance analysts are expected to generate quick solutions, which they failed to do so due to the time spent in collecting and analysing data. On the other hand when quick solutions are expected, modellers tend to oversimplify the models, which can cause the decision makers lack of confidence.

There have been important developments in the fields of facility location, relief distribution and casualty transportation using DES and mathematical programming methods. According to Caunhye et al. [12] relief distribution refers to bringing relief (medical supplies, shelters, manpower, etc.,) to people; whereas, casualty transportation sends injured people to medical centers. For the facility location field, authors like Rawls et al. [13] and Hung Lin [14] have developed optimization models, minimizing total transportation costs or distance between supply and demand points, using mixed integer programming, two-stage stochastic programming and multiphase heuristic approaches. On the other hand, authors like Van Hentenryck [15], have created models to solve both problems (facility location and relief distribution) by designing multiple algorithms like the multi-stage hybrid-optimization algorithm for the customer allocation, constraint programming for repository routing, and heuristics like the large neighborhood search for the routing part. Some others like Ye et al. [16] and Yi el al. [17] have implemented simulation models and GIS (geographical information systems) in order to solve the first stages of the process and model capacities in facilities like hospitals or warehouses, helping to find a better solution in the next stages, which are commonly optimization formulations. One of the most complete works of research is done by Görmez et al [18] who studied the location of disaster response facilities in Istanbul under a destructive earthquake scenario, with the objective of minimizing the average-weighted distance between casualty locations and facilities, using GIS tools. According to their model (a two stage stochastic solution) opening a small number of facilities will be sufficient to cope with the considered disaster.

The Facility Location Problem (*FLP*) is a central problem in OR [19, 20]. This problem considers a set of customer $\mathcal{I}$ and a set of facilities $\mathcal{J}$. The goal is to locate a subset of facilities and allocate each customer i to at least one facility j. Generally, two types of costs are to be considered : the set-up cost of the facility and the allocation cost of a customer i to a facility j. Both customers and facilities are generally considered as discrete points on a network. The goal is to minimize cost or maximize profit [21].

Many variants of the *FLP* exist and the earliest studied are the Uncapacitated Facility Location Problem (*UFLP*) but, in many cases, it is elementary to consider capacity over the facility in terms of customers connections and/or quantity of goods which can be stored. Good surveys to present both problems are [22, 23, 24]. In [25], a location model to pre-position humanitarian assistance pack-up kits is presented to respond to an earthquake. Particular attention is given to the content of the kits (shelters, infant needs, water, etc.).

The Maximum Covering Location Problem (*MCLP*) attempts to solve location problems when all the demand points cannot be covered without excessive resources. Church and ReVelle [26] and White and Case (1974) developed the MCLP models that do not require full coverage of all demand points. In [27] a model is proposed to solve a facility location for large-scale emergencies. It formulates the problem as *MCLP*. The model is solved by three heuristics in comparison with a CPLEX resolution (a genetic algorithm heuristic, a locate-allocate heuristic, a Lagrangian relaxation heuristic). A flood emergency threat with uncertainty is formulated by two stochastic programming models in [28]; an approach with the sample average approximation (SAA) that joins a scenario development with geographic information system (GIS)[1] to find the best average solutions.

[1] ArcGIS software. The same GIS is used into this study.

3. Methodology

The main objective of this work is to create a tool to facilitate the decision making process for resource allocation in response to an earthquake or similar massive disasters. Our specific objective is to optimize the performance measures of response in the first hours of an earthquake in recovering and attending both critical and non-critical patient and determine the resource gap to reach an optimal performance. We focus on the medical attention to the critical and non-critical injured patient within the first 96 hours after an earthquake scenario. For each of the two categories of patients we define an indicator to measure the performance of the medical attention during the relief operations. For the critical patients the performance measure is defined as the expected number of deaths due to lack of medical resources, including ambulances and hospital beds. For non-critical patients the performance measure is defined as the time until they are attended in a clinic or hospital.

For critical patients we develop a discrete event simulation model (DES) that describes the process of transferring patients to the fully equipped hospitals in ambulances, as well as their assignment to a bed before their life time expires. This model successively evaluates scenarios by incrementing the resources (hospital beds and ambulances). With this tool decision makers can see the consequences of choosing any combination of capacity for hospital beds and the ambulance fleet in terms of the number of deaths; hence empowering them to make better decisions.

For non-critical patients we formulate a location-allocation optimization model to determine the optimal capacity and location of tents (and other temporary facilities) to be set up as medical clinics to treat such patients. The constraints of this model include feasible locations for tents, limited budget to set up and operate the facilities and proximity to points of demand, among others. The results of this model show the optimal configuration of temporary facilities with a given budget, to attend the non-critical patients in minimum time.

3.1. The Discrete Event Simulation Model

In this section we describe our approach of developing a DES model using Arena by Rockwell Software [29] to represent the process of transferring the critical and non-critical injured patients to the designated medical facilities during the first four days of disaster response.

According to the medical classification system of Triage [30] we consider the red and yellow classifications as the critical patients and the green patients as non-critical. Figure 1 depicts the flow diagram of these patients. We assume that the critical patients are transferred to permanently equipped medical facilities in proper ambulances and non-critical patient to temporary facilities in personal vehicles as a strategy to de-congest hospitals.

At the beginning of each replication the injured and trapped people are created as entities in the model. The maximum number of trapped and injured are set according to a general discrete distribution and their inter-arrival times are assumed to be continuous random variables. A proportion of the trapped people are gradually added to the deceased according to a continuous function categories [31] and the rest are assumed to be rescued and added to one of the two injured categories with a certain probability [32]. The critical patients are assumed to be unstable with injuries to their critical organs or heavy bleeding (red and yellow triage tags). Such patients are likely to die from the injury within the first few hours of the disaster. However, the non-critical patients (green triage tag) can survive their injuries for longer than a few hours, although possibly in pain and discomfort, such as people with minor lacerations, sprains or abrasions [33].

To estimate the transfer time of patients from the triage to the medical facilities once they are picked up by a vehicle, we define the speed of the vehicle as a random variable and use

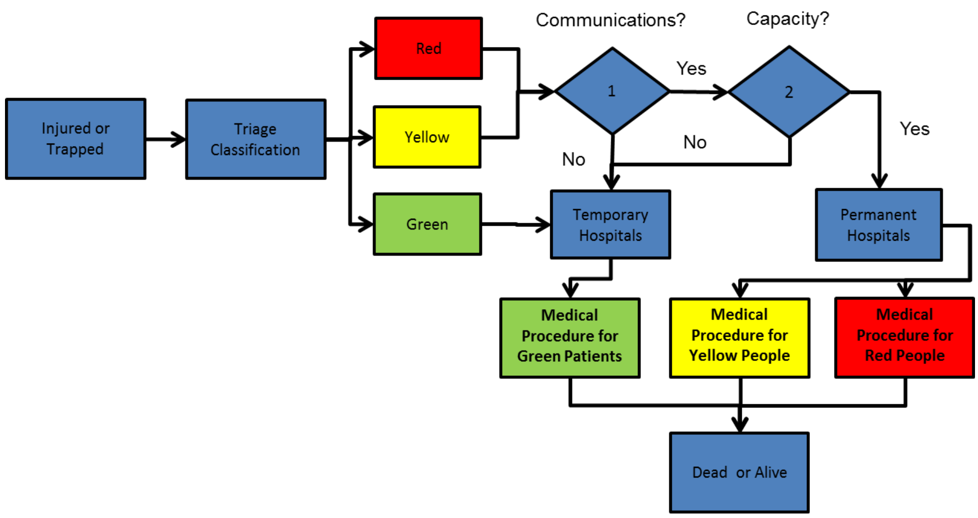

Figure 1: Injured and trapped flow diagram

the distance between the points where the injured victims are located and the destination, where a patient can seize available medical resources. We assume that the critical patients must be transferred to fully equipped hospitals in an ambulance while the non-critical patients can be treated in less specialized, temporary clinics and be transferred in other types of vehicles [34]. For the duration of a medical procedure and for the survival time, we also define probability distributions that depend on the patient's triage tag. If the sum of waiting time to be picked up by an ambulance, transportation time, waiting time to seize the medical resources and the medical procedure takes longer than the patient's survival time the victim is considered deceased.

We also establish some rules for sharing medical resources between facilities. For example when a hospital is full then the ambulances can redirect the patient to another near by hospital. These rules are decided based on the number of injured in each medical facility, the distances between facilities and communication lines are available between the two facilities. We assume that in the first hours of a large-scale disaster the communication will be out.

At the end of the simulation run the number of deceased is stored as the outcomes of a combination of decisions on hospital and ambulance capacities. To obtain a set of solutions we run the model successively, changing the values of the decision combinations in each run.

3.2. The Location-Allocation Model

The non-critical patients are assumed to be taken to temporary clinics in the form of tents or converted public facilities such as schools, churches or hotels. For this category of patients, we propose a Location-Allocation model to determine the optimal capacity and location of such facilities to be used as temporary hospitals.

This model considers a given geographical territory and assumes that the requests are concentrated among finite demand areas. The eligible sites for locating tents or hotels have been identified and a radius of coverage has been defined for each potential facility location. Each demand point has distinct needs according to the number of non-critical patients affected. The selection of facilities must also consider criteria such as costs, capacities and service level.

3.2.1. Mathematical formulation

The following notation is used to formulate the Location/Allocation model:

Set of indices and parameters

To formulate this problem, we considers a set I of demand points, a set J of available sites to set up a tent, a set K of public facilities such as churches or hotels and a set L representing the types of tents (in terms of their capacity). The parameter n_l represents the number of available tents of types l. According to the radius of coverage of tents and hotels, a covering parameter has been calculated using geographical information system (ArcGIS). This parameter has a value of 1 if a demand point i is covered by an eligible site j (cov^T_{ij}) where a tent can be set up or by a public facility k (cov^H_{ik}). A value for the radius of coverage is chosen to represent the coverage of such facilities. Capacities cap^H_k and cap^T_l represent the number of demand points which can be allocated respectively to a public facility k and a tent of type l. The cost of using a public facility is given by f^H_k and the cost of setting up a tent by f^T_l. Each point i has a demand quantity represented by d_i. The service level α represents the attended demand by facilities and tent over the total demand.

Decision Variables:

$$x^T_{ij} = \text{The percentage of coverage of point } i \text{ by tent } j$$

$$x^H_{ik} = \text{The percentage of coverage of point } i \text{ by public facility } j$$

$$y_k = \begin{cases} 1 & \text{if public facility } k \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

$$z_{lj} = \begin{cases} 1 & \text{if tent } l \text{ is assigned to a tent } j \\ 0 & \text{otherwise} \end{cases}$$

Objective Function and Constraints:

In continuation, we present the formulation of our proposed Location-Allocation model with the objective of minimize the costs of covering public facilities or setting up tents.

$$
\begin{aligned}
&\min \sum_{k \in K} f_k^H * y_k + \sum_{l \in L} f_l^T * \sum_{j \in J} z_{lj} && && (1)\\
&s.t. && &&\\
&\quad \sum_{j \in J} z_{lj} \leq n_l && \forall l \in L && (2)\\
&\quad \sum_{k \in K} x_{ik}^H + \sum_{j \in J} x_{ij}^T \leq 1 && \forall i \in I && (3)\\
&\quad \sum_{i \in I} d_i * x_{ik}^H \leq cap_k^H * y_k && \forall k \in K && (4)\\
&\quad \sum_{i \in I} d_i * x_{ij}^T \leq \sum_{l \in L} z_{lj} * cap_l^T && \forall j \in J && (5)\\
&\quad x_{ik}^H \leq cov_{ik}^H * y_k && \forall i \in I, \forall k \in K && (6)\\
&\quad x_{ij}^T \leq cov_{ij}^T * \sum_{l \in L} z_{lj} && \forall i \in I, \forall j \in J && (7)\\
&\quad \sum_{i \in I} d_i * \Big(\sum_{k \in K} x_{ik}^H + \sum_{j \in J} x_{ij}^T \Big) \geq \alpha * \sum_{i \in I} d_i && && (8)\\
&\quad 0 \leq x_{ik}^H \leq 1 && \forall i \in I, \forall k \in K && (9)\\
&\quad 0 \leq x_{ij}^T \leq 1 && \forall i \in I, \forall j \in J && (10)
\end{aligned}
$$

The constraint (2) limits the number of each type of tents available. Constraint (3) expresses the fact that a demand point may be covered by a public facility or a tent. Constraint (4) and constraint (5) restrict the items by the capacity of public facilities and tents. Constraint (6) is a spatial constraint that enables the allocation of a demand point to a public facility. The same goes for a tent in constraint (7). The demand points covered must comply a certain service level by the constraint (8).

3.2.2. Implementation

The problem is to minimize the costs of Location-Allocation model under a service level. In DOM, the service level is important to minimize human loss. We developed an algorithm which finds the maximum service level possible iteratively. This algorithm solves each problem until it finds a feasible (in terms of the service level) and optimal solution. The algorithm is detailed in Algorithm 1. We coded the model in `C++` and used the CPLEX Solver 12.3. The processor is an

Intel Core 2 Duo 2.4GHz with 4 GB of RAM.

Algorithm 1: ALGORITHM OF RESOLUTION

```
input  : step, the iteration's step (0.01 - 0.1)
output: sol*, the optimal solution
begin
    serviceLevel ← 1 ;
    repeat
        serviceLevel ← serviceLevel - step;
    until solvePL(serviceLevel) == TRUE;
    sol* ← getOptimalSolution();
    return sol*;
end
```

4. Case Study - City of Bogotá

In the following section we implement the two models on a real situation in the City of Bogotá and evaluate the performance of our proposed methodology.

Bogotá, the Colombian capital, is the most populated city in Colombia with more than 8 million residents according to the 2005 national census [35]. The city is divided into 19 urban districts and one rural district as shown in Figure 2. This urban layout is situated in a region with high risk for natural disasters including earthquakes, flooding, landslides and wild fires [34]. Over the past few years, the Prevention and Attention of Emergencies Fund (FOPAE) and other government institutions have laid out the general structure and organizational control scheme during a disaster to improve the response efficiency in the city, in a document called the Bogotá Emergency Plan (BEP).

The BEP focuses on the occurrence of an earthquake, a plausible scenario based on the actual seismic risk associated with Bogotá's location on a fault line. The document explains the roles and responsibilities of all governmental agencies that are involved in the emergency management as well as the interaction among them. However, the document lacks detailed provision for the logistics of transporting and accommodating injured people to medical facilities during the disaster response phase. Moreover, the capacity of auxiliary medical resources required to tend the patients in each district and the ideal locations in which to set up temporary medical facilities are yet undecided.

For this reason FOPAE and city's Department of Health consider two options to provide temporary hospitals. The first option, is to set up field hospitals in the form of medical tents in parks close to permanent hospitals and the second option, is to convert some of the existing hotels to temporary hospitals, using their readily available facilities such as beds and utility connections. All the basic tents are equipped with portable medical kits needed to tend minor injuries. On the other hand, they hotels that belong to the major hotels guild in the country (COTELCO) are also committed to help in case of a disaster. However, FOPAE does not know which ones of these hotels should be prepared and equipped and how many tents and in which locations are to be set up to respond to the emergency.

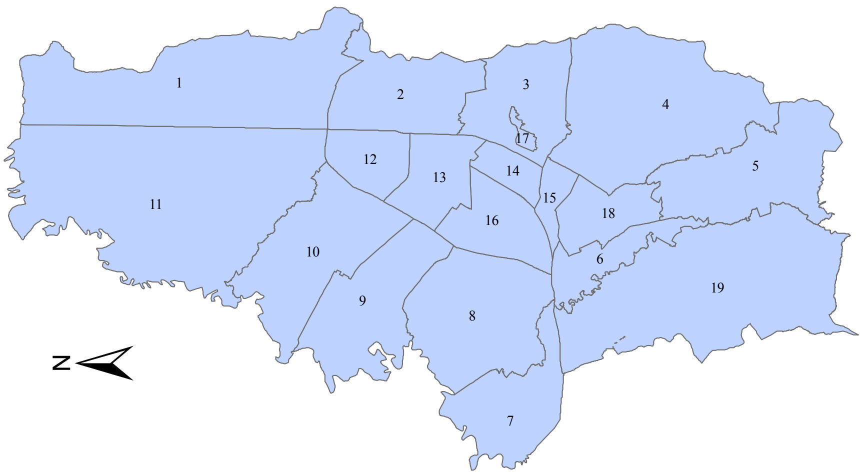

Figure 2: City of Bogotá and its zonal divisions

BEP defines the damage scenario, for which the city prepares itself, as a 6.2 and a 7.0 magnitude earthquake on the Richter scale, return period of 250 years, depth of 23 kilometers and epicenter distance of 39.5 kilometers from the frontal fault on the eastern branch of the Andean Mountain Range. Given this scenario and the structural reliability and vulnerability of the city, the number of injured, trapped and dead people in each district is estimated through a seismic risk assessment model. This model takes into account characteristics of the city's infrastructure, such as antiquity of buildings, construction materials, type of construction and number of floors, in order to calculate the number of victims. It is estimated that in the first scenario (6.2 magnitude) a total of 17,333 individuals will be injured and 27,197 people will be trapped and these numbers are more than double for the second scenario [36].

Currently, the available capacity in the hospitals and the number of ambulances in the city are critical issues for medical attention in a disaster. The city accounts with 142 ambulances in the public health system, and 532 ambulances in total between the private and public systems and the average speed of ambulances and personal vehicles is assumed 20 km/h in disaster conditions [37]. There are also a total of 9000 hospital beds in the public hospitals; however city's Department of Health estimates that under normal conditions and off the flu season, only 5% of this capacity is available. However According to the hospitals' expansion plan, in crisis conditions the total capacity of permanent hospitals can be increased by 20% through organizing stretchers in the hallways and free spaces, and by another 25% through evacuating prior patients who are in stable conditions, at the time of the disaster. In this work, and based on verifications with city officials, we assume that the hospitals do not get damaged during the aforementioned earthquake scenarios.

For the DES model we choose a normal distribution of the maximum number of injured and trapped for each district with the corresponding mean and variance, as shown in Table 2 [34]. Once a critical or non-critical patient seizes a bed we assume a uniform distribution for the duration of the medical procedure in hours of red, yellow and green. We also consider a distribution for the survival time in hours of the critical patients based on expert interviews. The

no	District	Trapped		Injured	
		Mean	Variance	Mean	Variance
1	Usaquén	597	179.1	391	117.3
2	Chapinero	406	121.8	238	71.4
3	Santa fe	1786	535.8	997	299.1
4	San Cristóbal	472	141.6	298	89.4
5	Usme	50	15	30	9
6	Tunjuelito	996	298.8	638	191.4
7	Bosa	390	117	259	77.7
8	Kennedy	1981	594.3	1308	392.4
9	Fontibón	4294	1288.2	2961	888.3
10	Engativá	1770	531	1128	338.4
11	Suba	899	269.7	600	180
12	Barrios Unidos	1190	357	620	186
13	Teusaquillo	1426	427.8	763	228.9
14	Mártires	2197	659.1	1392	417.6
15	Antonio Nariño	1184	355.2	741	222.3
16	Puente Aranda	4632	1389.6	3143	942.9
17	Candelaria	626	187.8	402	120.6
18	Rafael Uribe	803	240.9	485	145.5
19	Ciudad Bolvar	1327	398.1	896	268.8

Table 2: Mean and variance of the number of injured and trapped victims in each district

rules for sharing medical resources between districts are shown in Table 3.

Some additional assumptions about the disaster situation are listed below. These assumptions are in accordance with BEP, FOPAE and Department of Health and are necessary to plan the relief operations.

- The earthquake happens during the day.
- The earthquake does not occur during the flu season.
- Ambulances are assumed to transport only one critical patient at a time.
- Rescue teams are available to support the emergency from the first moment.
- Hospitals do not get damaged during the earthquake.

In order to respond to a 6.2 or 7.0 magnitude earthquake, FOPAE has acquired 13 basic medical tents to address minor injuries. These tents have two different capacities, Type 1 tents with 13 beds and Type 2 beds with 25 beds. FOPAE assumes that medical staff, medications and other medical supplies can be provided through city-wide volunteer plans, national and international aid and hence at this phase of planning these items can be assumed readily available as soon as ambulances and hospital beds are provided for the victims. In this case study, we consider 95 demand points, 95 sites where tents can be located and 71 hotels available to be converted to temporary facilities.

From	To
Santafé	San Cristobal
Chapinero	Usaquén
Ciudad Bolivar	Bosa
Engativá	Fontibó
Tunjuelito	Rafael Uribe
Antonio Nariño	Mártires
Kennedy	Teusaquillo
Puente Aranda	Teusaquillo

Table 3: Rules for sharing medical resources in the city

4.1. Results

We run the DES model with a set of scenarios, varying the number of ambulances and the capacity of hospitals in each district. We start with the current level of resources namely, 532 ambulances, and 5% of extra capacity in the public hospitals. Then we separately increment the number of ambulances one at a time and the hospital capacity by 10% each time, until we reach zero deaths. We consider a total of 96 hours in each replication with 30 replications for each scenario.

Table 4 shows sample results for these runs and the percentage of change in the number of deaths. Figure 3 shows the results for one district, Candelaria in the two dimensional space (hospital capacity and the total number of ambulances), using color coding to represent various surfaces for the death toll.

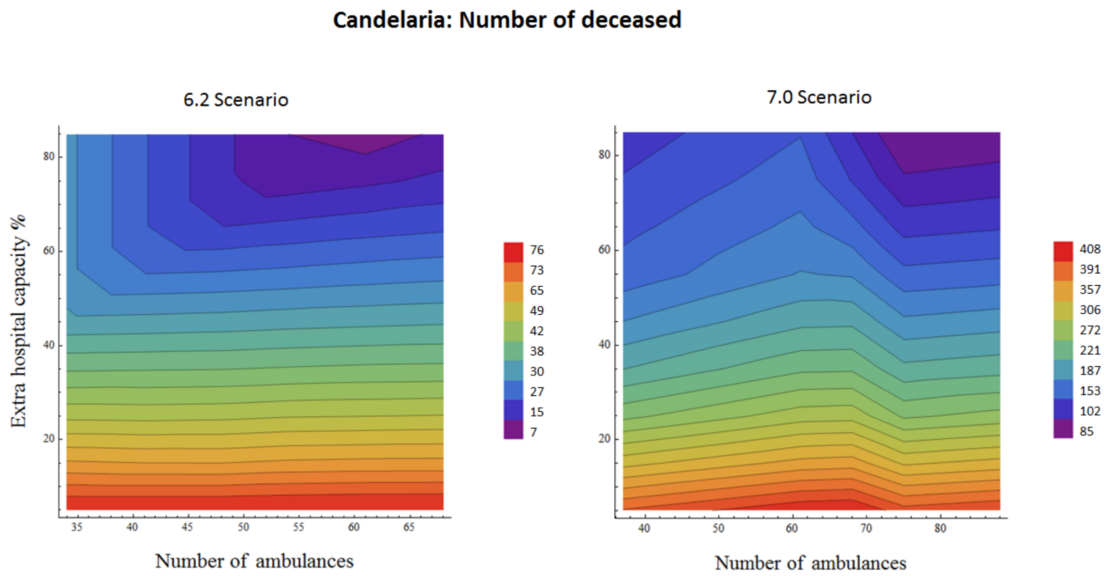

Figure 3: Number of death with various combinations extra ambulances and extra hospital capacity for Candelaria

In Figure 3 the zone with intense purple color represents the lowest number of deceased and the red zone represents the greatest number of dead people. Results show that there are several optimal combinations of ambulance-hospital capacity to reach the minimum number of deaths. Also these graphics provide the opportunity for the decision makers to evaluate various suboptimal but affordable configurations, in case of a limited budget that is below the optimal configuration. Similar analysis is done for all the 19 urban districts in the city. The difference between the 6.2 and 7.0 scenarios is the number of trapped and injured, so as we expect the number will increase in the 7.0 scenario, but this increase it is not scalar hence the shape change in the surface level of the graphics.

No Ambulances	Extra Hospital Capacity	Average # of deaths	Half width	Percent Reduction
142	0.05	3588.56	51.52	—
	0.2	3569.63	43.28	0.0053
	0.5	3482.93	49.28	0.0294
	0.9	3482.8	53.28	0.0295
532	0.05	3483.36	51.78	0.0293
	0.2	3269.9	49.68	0.0888
	0.5	3209.43	54.68	0.1056
	0.9	3189.06	53.12	0.1113
700	0.05	3452.33	55.19	0.038
	0.2	3192.16	53.49	0.1105
	0.5	3112.03	53.5	0.1328
	0.9	3052.23	38.09	0.1495

Table 4: Sample results of simulation runs

For the non-critical patients we run Location-Allocation model assuming the costs of setting up the two types of tents and the conversion of hotels of COTELCO to temporary clinics. This costs are proximate based in interviews with COTELCO and FOPAE officials.

For the 6.2 scenario, the problem is solved in 45 seconds. The cost of the optimal solution is 110,596,952 USD with a service level of 63%. This policy indicates that 22 hotels must be adapted and 1 tent of type 1, 4 tents of type 2 must be set up. For the 7.0 scenario, since the demand increments greatly, the optimal solution is open of all the hotels and all the tents available, which cause a rise in the total costs. The Figure 4 shows the locations of tents and hotels for 6.2 scenario.

5. Conclusion

The models that are developed in this work contribute to the improvement of the preparation phase in disaster response, through finding the gap in medical resources in order to effectively attend the injured victims. Also given limited budget for investment to improve this gap, these models help find the optimal configuration of resources including additional ambulances, hospital capacity and field hospitals.

The simulation model finds the optimal number of additional ambulances and increased capacity of permanent hospitals in order to have zero people die due to lack of resources. The results of this model help to identify the resource gap between current and optimal situations. This gap can be partially filled with ambulances from the private health system and with hospi-

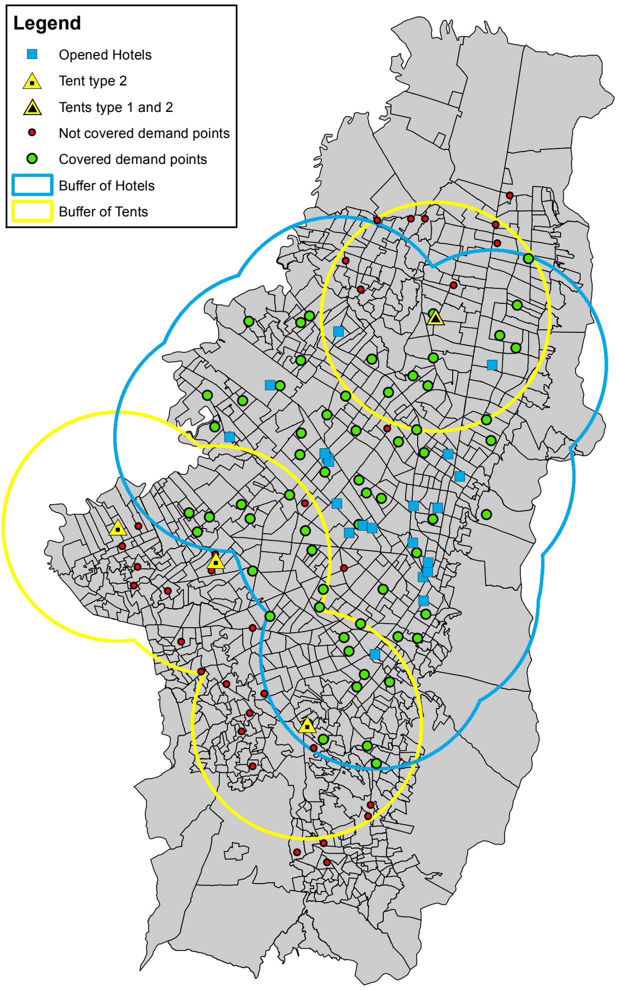

Figure 4: Location-Allocation results of 6.2 scenario

tal expansion plans, but strategies like establishing fully equipped field hospitals and converting vans into ambulances must be taken into account in order to reduce that existing gap.

The optimization model determines the optimal capacity and location of medical tents as well as the selection of hotels that must be converted into temporary hospitals in order to meet all the demands of non-critically injured people with minimum waiting time, within the a given radius of coverage, while minimizing the costs of the policy.

We have examined the performance of our models on a case study in the City of Bogotá. The results show that the current number of ambulances and capacity of hospitals in the city are not enough to reach zero deceased due to lack of resources. To achieve this goal we found that increasing only the number of ambulances or the percentage of extra capacity is not enough. It is necessary to increase both, the number of ambulances need to be twice as large as the current situation and the extra capacity of hospital need to be nearly 70% versus the current 5%.

From the results of the optimization model we found that converting hotels into temporary clinics is a better option for reducing costs due to their available basic infrastructure to accommodate patients with minor injuries. However in certain areas where hotels are not available tents need to be set up and its policy only achieves a service level of 63%.

Further work needs to be done in order to make a complete and precise decision-making tool. First, the assumptions of the DES model need to be improved regarding the creation of injured people (specifically the trapped people) and the possibility of including triage classification times. Second, other types of location alternatives should also be included in the Location-Allocation model and the demand can be assumed to follow a discrete probability function.

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