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An optimization model for the location of disaster refuges

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A B S T R A C T

We developed a flexible planning tool by means of an optimization approach that is able to locate and assign refuge centers through facilitating buildings to provide shelter and medical and psychological assistance to the victims taking into account the quality of service. The article proposes variants within the optimization model that allow the decision maker to evaluate different realities in the plan. The performance of the models inside the red zone of the 2010 earthquake in Chile is illustrated.

1. Introduction

In spite of the economic, social, and scientific progress that has been widely achieved, natural and technological disasters still make visible the vulnerable condition of thousands of people every year. According to the World Disaster Report in 2013, made by the International Federation of Red Cross and Red Crescent Societies, during the period of 2003–2012, 6699 disasters of this sort took place, causing 1.1 million deaths and 2167.4 million injuries. In Chile, during the same period, 890 deaths and 3 070 260 injuries were reported. Two terrible events occurring during this period were the earthquakes and tsunamis in Indonesia and neighboring countries in December of 2004 and in Japan in March of 2011. The earthquake in Asia occurred on December 26, 2004 and had a magnitude 9 "megathrust". It left at least 266 000 dead, including 166 000 in Indonesia, 38 000 in Sri Lanka, 16 000 in India 5300 in Thailand and 5000 foreign tourists. The number of people injured was over 500 000 and the number of people affected was up to 5 million; they lost homes, or access to food and water. The estimated cost of aid and reconstruction following the tsunami was 7.5 billion USD.[1] On March 11, 2011, a magnitude-9 earthquake shook northeastern Japan, unleashing a savage tsunami. The effects of the great earthquake were felt around the world, from Norway's fjords to Antarctica's ice sheet. More than 18.000 people were killed in the disaster, most of whom died by drowning. The tsunami caused a cooling system failure at the Fukushima Daiichi Nuclear Power Plant, which resulted in a level 7 nuclear meltdown and the release of radioactive materials. Two years after the quake, about 300 000 people who lost their homes were still living in temporary housing.[2]

Chile is a country that is susceptible to being stricken by natural disasters due to its geographic, climatic and geologic characteristics. Earthquakes, tsunamis, volcanic eruptions, floods, and wildfires are some of these. Earthquakes and tsunamis, however, are the most worrying of the list because of having the highest death toll, as well as generating major psychological impact and material damage.

Some of the biggest earthquakes that have occurred in Chile are those with epicenters in Chillán (1939; M 7.8), in Valdivia (1960; M 9.5) and in Cobquecura (2010; M 8.8). Of these, the latter two are among the 10 biggest earthquakes ever measured (the first and the ninth, respectively).

Approximately 1655 people have been killed, 3000 injured, 2 000 000 left homeless, and $550 million in damages have been recorded in southern Chile alone; tsunamis have caused 61 deaths, $75 million in damages in Hawaii; 138 deaths and $50 million in

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[1] http://www.newscientist.com/article/dn9931-facts-and-figures-asian-tsunami-disaster.html.

[2] http://www.livescience.com/39110-japan-2011-earthquake-tsunami-facts.html.

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damages in Japan; 32 dead and missing in the Philippines; and $500 000 in damages on the west coast of the United States.[3]

The 2010 Cobquecura earthquake (574 deaths, 46 missing and more than 2 million injured according to a statistical report released by the Legal Medical Service of Chile) exposed the fact that the traditional planning systems aren't capable of providing a suitable organized reaction to the disaster covering all the necessities that arise during a catastrophe. It is necessary to anticipate the facts and make a plan for the location of refuges and the distribution of resources for reducing panic, giving shelter, providing medical care and saving lives in an efficient manner. All the devastating effects that have been mentioned fostered a growing interest in the development of measures to be taken for reducing the impact of a possible disaster, and this interest eventually gave rise to disaster operations management [11].

Disaster Management can be defined as the discipline that tries to figure out how to avoid and face risks [14]. A system of disaster management is a cycle that comprehends four stages (Fig. 1): *mitigation, preparation, response and recovery* [1,25,29]. *Mitigation* consists of the application of measures that prevent the disaster from occurring or reduce its effects if it does occur. *Preparation* enables communities to organize and prepare for appropriate action in case of disaster. Logistical planning for aid operations, establishing communication plans, assignment of responsibilities, coordination of operations and aid staff training are all done at this stage. *Response* involves the use of resources and emergency procedures carried out according to the previous planning requiring the immediate participation of staff and delivery of all equipment to the disaster zone. *Recovery* refers to the activities covering long term effects, such as stabilizing and restoring the damaged area.

Humanitarian Logistics has become a line of research based on concepts from logistics but focused on disaster situations, which can be used both for an immediate response and for long term measures. Thomas and Kopczak [28] defined Humanitarian Logistics as “The process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people”. Within this context, Van Wassenhove [31] states“A successful humanitarian operation mitigates the urgent needs of a population with a sustainable reduction of their vulnerability in the shortest amount of time and with the least amount of resource”. Therefore, it is very important to consider each one of the four phases defined above and to establish a set of work conditions, operations, models and simulations which permit the implementation of a coherent and efficient system to aid in making good decisions in a time of disaster. For a disaster two main problems are related to refuge location and the assignment of people affected. Associated with these problems is the necessity to design plans for the distribution of resources (human and material) and the assistance of these people.

Paper Contribution: In this article we propose four variants of an optimization model to enable the location and assignment of temporary refuges, based on recent contributions from the modeling perspective and from the thresholds for real applications identified by the review literature. They consist of innovative mixed integer programming models that consider two hierarchy levels and allow building flexible plans using demographic and social impact requirement parameters (quality of service, maximum traveling distance per person, and the conditions of the refuge), both in their objective function and in their constraints. The model is applied to an urban micro-zone in a Chilean community, located in the zone most heavily struck by the 2010 earthquake. Census micro-data was gathered using standard software and was subsequently employed for the application of the models.

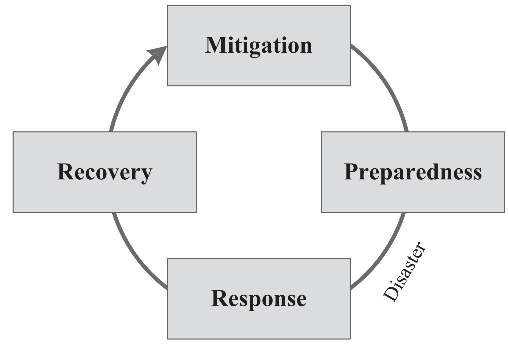


Fig. 1. Phases of a disaster management system.

The article is organized as follows: in Section 2 a bibliographical discussion is presented; Section 3 develops the optimization model and its variants, along with an explanation of its components and the assumptions that support the design of the model; Section 4 gives details about the description of the zone to which the models were applied, explains how the information about homes was gathered, and defines the values of several parameters; in Section 5 the results from the application of the models in the case study are analyzed and guidelines for their utilization are given; Section 6 shows through experimental results that two variants of the model are able to get nearly optimal solutions in a reasonable time when a set of small and medium size instances is tested; finally, in Section 7, conclusions and possible future studies are presented.

2. Literature review

Many papers have been published about Humanitarian Logistics in the last 10 years. Kunz and Reiner [19] presented an overview of the research in this field. They found 5 reviews and 174 papers published in international journals, covering the period from 2006 to 2012. Altay and Green [1] surveyed the literature to identify potential research directions in disaster operations and discussed several relevant issues. Galindo and Batta [11] illustrated the evolution of the application of methods belonging to Operations Research and Operations Management in Disaster Management. They also discussed the studies proposed by Altay and Green [1] and suggested that there are several pending challenges. Based on this discussion, Galindo and Batta [11] proposed new directions for applied research such as incorporating new technologies, using formal statistical information sources and making using efficiency criteria in decision making. Most of these suggestions are incorporated into the present work.

Caunhye et al. [5] commented that few works studying models for the location of emergency facilities exist. In particular, the papers discussed above do not consider some aspects like the non-monetary costs associated and the quality of service at the facilities.

An et al. [2] proposed a location model for emergency facilities which determines the planning for pre-emergency as well as the corresponding evacuation operations. Görmez et al. [13] proposed a location model for relief facility installation in the city of Istanbul, assuming a possible future earthquake. They tried to optimize the location of the facilities given the location of people. Naji-Azimi et al. [22] presented the localization of satellite distribution centers for supplying humanitarian aid by solving a set covering

[3] U.S. Geological Survey (USGS) “Historic World Earthquakes - Sorted by country/Region & Date - Chile”. earthquake.usgs.gov/earthquakes/.

problem, considering a set of previously defined demand points. Lin et al. [21] proposed the localization of temporal (provisional) depots around the area affected by the earthquake and studied their assignment with the demand points. Coutinho-Rodrigues et al. [7] proposed a clustering based approach that assumes there will be enough space to build a shelter area in each cluster. Li et al. [6] proposed a solution method for a multi-objective shelter site location and routing problem. Kilci et al. [20] proposed a bi-level optimization method to select the location of shelter sites after a hurricane and provided a study with data from North Carolina. The recent paper of Kilci et al. [18] proposed a mixed integer linear programming model for selecting the location of temporary shelter sites.

In the field of Optimization the term Hierarchical Optimization could have several interpretations. A traditional one is in the context of Multiobjective Optimization, where several objective functions are jointly optimized, then a hierarchical ranking of the objectives could exist. Some papers discussing this type of problem are Daskin and Stern [8] and Anandalingam and Friesz [3], but our interest is focused on a different type of Hierarchical model discussed below. Narula [23] and Eitan et al. [10] described a classification for these problems including a hierarchy of the facilities according to the relation among the types of facilities, the type of flow on the arcs and the type of flow in the nodes. Two types of hierarchies for the facilities are defined: successively inclusive and successively exclusive. In a successively inclusive hierarchy a facility offers its own level of service as well as the other lower levels of service. Narula and Ogbu [24] have studied cases of this type in a problem of maximum coverage. Galvão et al. [12] used a hierarchical model with 3 successively inclusive levels for the location of perinatal facilities in Rio de Janeiro. They also presented a mixed integer linear programming model used to study relaxations and algorithms using networks from the literature.

The location and assignment of refuges must take into consideration some specific requirements in this situation. On one hand, for a time after the disaster a group of victimized families requiring a physical space that satisfies their basic needs (food, cleanliness and safety) does exist; on the other hand, it is highly probable, depending on the magnitude of the event, that a portion of these families requires medical and psychological aid as well. These needs could appear immediately after the event or after the family has been installed in the refuge. Given the nature of the above conditions, our proposal is that it is possible to model the refuge location problem and the assignment of families to the refuges as an optimization model, using two levels depending on the type of refuge used. One type of refuge provides only a basic service, that is, the use of a physical shelter for the affected families and the other, which also provides basic shelter, but primarily gives medical attention and psychological assistance.

A very important discussion about the differences between commercial and humanitarian logistics is presented in Holguín-Veras et al. [15] and Holguín-Veras et al. [16]. They showed that most optimization models studying facility location problems appearing in the literature on Humanitarian Logistics consider only a traditional objective function minimizing transportation costs (or distances). Holguín-Veras et al. [16] analyzed several papers and compared the structural characteristics of the proposed models; they found that only in two out of 20 papers the study of characteristics of humanitarian logistics appeared. Perez [26] and Jaller [17] included social costs and human suffering in their studies about humanitarian logistics as part of their Ph.D. Thesis. The discussions and findings in these two papers together with the experience lived in several disasters like Katrina, Haiti and Chile, mentioned in the Introduction, motivate our work and therefore, the structure of the proposed optimization model together with the objective function and some constraints, explicitly include elements of social costs and human suffering.

3. An optimization model for refuges location

An optimization model including four variants that emphasize different aspects related to humanitarian logistics is introduced in this section. A relevant discussion on several assumptions made in the formulation of the optimization model is presented below.

3.1. Basic concepts and assumptions

A basic concept for these models is the *household*. According to the United Nations Statistics Division, a *household* is a person or a group of people living in a dwelling and that, at least for their food, depend on a common income. A household is normally formed by persons who are blood related but not necessarily; it is also possible, and quite common, to have households with only one person [30].

In a post-disaster scenario, some assumptions for the construction of the optimization model are relevant. First, it is assumed that a disaster provokes a significant degree of material damage to buildings; thus, it is assumed that part of the population is impacted by the disaster. Next, it is also assumed that several homes are psychologically affected by material loss, injuries and potential fatalities. Due to service problems at hospitals and other health facilities provoked by excess demand and/or destruction of those facilities, it is necessary to count on additional places to attend to the basic needs of the affected people.

In the definition of an optimization model for representing the problem, it is clear that this is a complex problem since it must integrate decisions about the localization of the refuges and the assignment of the affected homes to the selected refuges. Typically, this type of problems is modeled by using, either several levels (multilevel optimization) or several stages (multistage optimization). In section 2 we mention one type of multilevel optimization model where the levels are associated with hierarchies, in particular, the model of hierarchical location-allocation problems, Narula [23].

In the context of multistage optimization, a 2-stage model could be also applied to our problem. In the first stage, opening cost data for the refuges and statistical information about the victims are used to decide which refuges to open first. Once the victims arrive to the refuges, it is possible to extend the solution for opening more refuges, which leads to additional costs and the assignment of demands for the new refuges. See Birge and Louveaux [4] and Shmoys [27] for detailed information about multistage optimization. Both models, multilevel and multistage normally lead to difficult optimization problems, at least when the base problem come from Location problems. In our application, we decide to use the multilevel model of Narula [23], based on the successful application of this type of model to health problems Galvão et al. [12].

Considering the above, the model assumes that it is necessary to count on two types of additional health services: Service 1 is the provision of basic resources for shelter and Service 2 is necessary medical and psychological care. To carry out these services, two types of refuges are defined: an A type refuge offers only Service 1 while the B type refuge offers both services 1 and 2. This definition is a special case of a hierarchy between facilities as explained in Section 2 Narula [23] and Galvão et al. [12], that is, there is a successively inclusive hierarchy where the B type refuge includes Service 2 and also the service provided by Service 1 at a lower level of complexity.

In the context of households staying in an A type refuge providing Service 1 and other households living in a B type refuge providing Service 1 and 2, it is possible to consider that, after a time, some disaster victims at type A refuge could need medical or psychological attention due to the post-disaster effects related to the injury or death of family and friends. In hierarchical location-allocation models, Narula [23], this operation is named *interservice referral* which is a typical movement in public health networks. Consequently, a parameter (θ) is defined that estimates the proportion of households moving from an A type refuge to a B type due to needing Service 2.

With respect to the objective function defined in the optimization models, the basic model essentially tries to minimize the total distance from homes to the refuges. This is an important criterion given the difficulty of such movement after a disaster versus a normal situation. Additionally, the proximity of the affected housing to the refuge contributes to the ease of arrival of relatives and friends living near the family. This basic *HMCA* model assumes that each potential refuge could be A type or B type and it is the model that decides the type of refuge selected. In contrast to the basic model, one of its extensions, $HMCA_s$, assumes that at the moment of decision-making there is more information about the refuges so it is possible to a priori differentiate the potential refuges as A type or B type. The second extension of the basic model, $HMCA_sD_t$, strengthens the criterion of minimizing the total distances in the objective function by limiting the maximum distance that a victim should travel to a refuge and then diminishing the risks associated with that relocation.

The last extension of the basic model, $HMCA_sD_tQ$, includes one term in the objective function associated with the quality of service in the potential refuges, so its application depends on the available information about the refuges. In any real situation, the potential refuges must meet some basic requirements like location, cleanliness, safety, number of bathrooms, and other infrastructure features. Along with these characteristics, differences certainly exist in the way these requirements are met within each refuge. In an ideal situation, an updated evaluation of the quality of the potential refuges could eventually exist; otherwise, it would be necessary to quickly evaluate, immediately after the disaster, the real state of the potential refuges. In devastation provoking disasters, the second alternative is mandatory. Therefore, it can be expected that any refuge possessing a better evaluation than another would be preferred in this context. This indicator is called the quality of service of the refuge j and it is denoted by c_j. Considering that the magnitude of the disasters for which these models are designed provokes many injures and based on the analysis in the above paragraphs, all the variants of the model assume that some victims initially located in an A type refuge would go to a B type refuge since after a time some health problems may present themselves. The problem contains several components which are structured in Fig. 2.

As mentioned in Section 2, our optimization model is based on the use of levels as defined by Galvão et al. [12] so a hierarchical model that considers the selection of refuges at two levels is proposed, the type A refuge provides basic assistance (food, clothing and shelter) and the B type refuge provides medical and psychological assistance (inclusive hierarchy) in addition to basic assistance. The initial model tries to minimize the total distance traveled by households considering four types of movements. In the next section a hierarchical optimization model is presented which is structured according to this strategy of using several levels.

Some basic assumptions for the appropriate formulation of the models are:

- Householders affected by the disaster who cannot live in their dwellings must go to an A type or B type refuge.

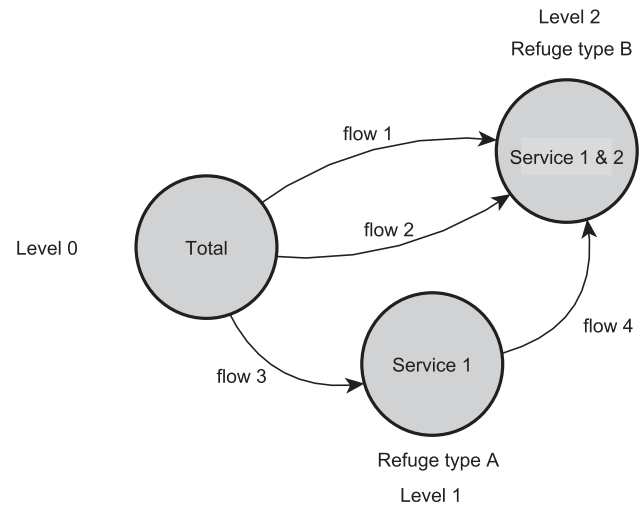


Fig. 2. Flow of disaster victims.

- Householders needing medical or psychological assistance must go to a B type refuge.
- Some householders at an A type refuge could go to a B type refuge since after a time some health or psychological may present themselves.
- All the persons forming a particular household must move together.

The flow dynamics of the proposed model can be seen in Fig. 2, where Level 0 represents the initial state of the victims, Level 1 is the service providing basic assistance and Level 2 includes medical and psychological assistance. Flow 1 and Flow 3 represent the flow of victims requiring basic service who may go to a nearby A type or B type refuge; Flow 2 is the flow of victims immediately requiring medical and psychological service who must go to B type refuges; and Flow 4 is the flow of victims relocating from an A type refuge to any B type refuge when they require medical or psychological assistance.

Considering the official statistical information available in the country being studied, this model considers demographic parameters related to each square within the studied area, such as: the percentage of households needing shelter, structure of the flows and population size. It is assumed that the movement is done by households since under disaster conditions it is considered important to maintain the families together, otherwise, the economic and medical problems caused by the disasters are augmented by the psychological component. Additionally, one variant of the model includes an alternative objective function considering the particularities of the humanitarian logistic.

The model considers the following sets: I is the set of squares; J is the set of potential refuges.

S is the set of services delivered by the refuge, $s = 1$ basic service of shelter and $s = 2$ medical and psychological attention.

T is the set of refuge types, $t = \mathrm{A}$ offers only service 1 and $\mathrm{t} = \mathrm{B}$ offers both services 1 and 2. The mathematical model also considers the following parameters:

W_i: Total number of households in square $i \in I$.
β_{is}: Proportion of households in square $i \in I$ requiring service $s \in S$.
d_{ij}: Rectangular distance between demand point $i \in I$ and $j \in J$.
d_{jk}: Rectangular distance between the refuge $j \in J$ and the refuge $k \in J$.

α: Factor adjusting the importance of the two types of distance from a refuge of A type to a refuge of B type.
θ: Proportion of households moved from an A type to a B type refuge due to needing service 2.
N_t: Maximum number of refuges of type $t \in T$.
Q_{js}: Capacity of the refuge $j \in J$ for providing the service $s \in S$.
ρ_t: Level of minimum utilization of the refuge of type $t \in T$.
σ: Percentage of the capacity of B type refuges available for sheltering victims that do not require medical and psychological services.

The decision variables are:

x_{ij}^s: Number of victims going from square $i \in I$ to the refuge $j \in J$ requiring service $s \in S$.
z_{jk}: Number of victims going from a refuge $j \in J$ providing service 1 to a refuge $k \in J$ providing service 2.
y_j^t: 1 if the refuge $j \in J$ is selected as type $t \in T$ and 0 otherwise.

Below a basic optimization formulation (a mixed-integer linear programming model) is presented. This model is named *HMCA*. Then, some additional constraints are detailed generating new variants of the basic model. The last model presented considers an objective function measuring the quality of service given by the combination of the distance traveled by victims and the quality of the assistance provided in the refuges. The practical use of these variants will depend on the particularities of the specific disaster in the city analyzed.

$$\text{Min } Z = \sum_{i \in I} \sum_{j \in J} \sum_{s \in S} d_{ij} \left(x_{ij}^s \right) + \alpha \sum_{j \in J} \sum_{k \in J} d_{jk} z_{jk} \tag{1}$$

Subject to

$$\sum_{j \in J} x_{ij}^s = \beta_{is} W_i, \quad \forall i \in I, \ \forall s \in S \tag{2}$$

$$\sum_{k \in J} z_{jk} \geq \theta \sum_{i \in I} x_{ij}^1, \quad \forall j \in J \tag{3}$$

$$\sum_{i \in I} x_{ij}^1 \leq Q_{j1} y_j^1 + \sigma Q_{j2} y_j^2, \quad \forall j \in J \tag{4}$$

$$\sum_{i \in I} x_{ij}^2 + \sum_{k \in J} z_{kj} \leq (1 - \sigma) Q_{j2} y_j^2, \quad \forall j \in J \tag{5}$$

$$\sum_{t \in T} y_j^t \leq 1, \quad \forall j \in J \tag{6}$$

$$\sum_{j \in J} y_j^t \leq N_t, \quad \forall t \in T \tag{7}$$

$$\sum_{i \in I} x_{ij}^1 \geq \rho_1 Q_{j1} y_j^1, \quad \forall j \in J \tag{8}$$

$$\sum_{i \in I} x_{ij}^2 + \sum_{k \in J} z_{kj} \geq (1 - \sigma) \rho_2 Q_{j2} y_j^2, \quad \forall j \in J \tag{9}$$

$$x_{ij}^s, \quad z_{jk} \in Z^+, \quad \forall i \in I, \forall j \in J, \forall k \in J, \forall s \in S \tag{10}$$

$$y_j^t \in \{0, 1\}, \quad \forall j \in J, \forall t \in T \tag{11}$$

In the objective function (1) the total distance traveled by victims is minimized; the first part is the distance traveled by households to their refuges and the second part is the distance from an A type refuge to a B type for the need of Service 2. Constraints (2) ensure that households in need of refuge receive it. Constraints (3) ensure that victims needing to move from an A type refuge to a B type refuge be a proportion of those staying in an A type refuge. Constraints (4) and (5) consider the capacity of each type of refuge; in a disaster of high impact with many injured people every B type refuge should assign a high percentage of its space to medical and psychological attention and then the parameter sigma should takes on small value. Constraint (6) ensures that each refuge is associated with only to one type, A or B, but not both. Constraint (7) ensures that the number of located refuges of each type is lower than or equal to the number of possible refuges. Since each refuge, either A type or B type, has operation costs, constraints (8) and (9) ensure that the located refuges satisfy some utilization level which is managed by the parameter ρ. Constraints (10) and (11) define the decision variables used.

3.1.1. Capacitated hierarchical model with refuge attribute selection ($HMCA_S$)

Since two types of refuges exist, A type and B type, it is possible to state that the selected refuges must have differently defined characteristics such as a basic refuge (A type), or a refuge with medical and psychological assistance (B type). It would be possible to define a priori which refuge has the conditions for each type of service and then the group of constraints (7) are changed by (7.a) and (7.b):

$$\sum_{j \in J_t} y_j^t \leq N_t, \quad \forall t \in T \tag{7.a}$$

$$\sum_{j \in J \setminus J_t} y_j^t = 0, \quad \forall t \in T \tag{7.b}$$

where $J_t \subseteq J$ is the set of refuges type t (t = A basic refuge, t = B refuge with medical and psychological assistance), $J_1 \cap J_2$ is the set of refuges satisfying the requirements of both types.

Then, the resulting model is:
Min: (1), subject to: (2)–(6), (7.a), (7.b), (8)–(11)

3.1.2. Capacitated hierarchical model with refuge attribute selection and threshold of maximum distance ($HMCA_S D_T$)

It is also desired that victims in a household go a short distance to a refuge, and one way to model this situation is to constrain the maximum distance from a home to a refuge (d_{max}^s) and between refuges (dz_{max}). Constraints (12) and (13) consider this property which helps to provide a better service for victims.

$$x_{ij}^s \left(d_{ij} - d_{max}^s \right) \leq 0, \forall i \in I, \forall j \in J, \forall s \in S \tag{12}$$

$$z_{jk} \left(d_{jk} - dz_{max} \right) \leq 0, \forall j \in J, \forall k \in J \tag{13}$$

Then the new model can be formulated as follows:
Min: (1), subject to: (2)–(6), (7.a), (7.b), (8)–(13)

3.1.3. Capacitated hierarchical model with refuge attribute selection, threshold of maximum distance, and quality of service ($HMCA_S D_T Q$)

Optimization models for the location of refuges and the assignment of victims to them could be enhanced through the definition of a function measuring the quality of service in the refuges. This function incorporates two parts. The first part (F_1)

related to the distances from homes to the refuges and the second (F_2) is based on a previous evaluation of the different refuges. Some elements considered in the evaluation would be: quality of the different services, quality of the infrastructure, bathrooms, parking, and kitchen. The objective function includes a parameter ω defining the relative importance of F_1 and F_2, so the decision maker will assign the specific values.

$$\max F = F_1 - F_2 \tag{14}$$

$$F_1 = \frac{\omega}{H}\left(\sum_{i\in I}\sum_{j\in J}\sum_{s\in S} d'_{ij}x^s_{ij} + \alpha\sum_{j\in J}\sum_{k\in J} d'_{jk}z_{jk}\right) \tag{F.a}$$

$$F_2 = \frac{(1-\omega)}{|J|}\sum_{j\in J}\sum_{t\in T} c_j y^t_j \tag{F.b}$$

Therefore, the model can be formulated as follows:

Max: (14), subject to: (2)–(6), (7.a)–(7.b), (8)–(13)where $H = \sum_{i\in I}\sum_{s\in S}\beta_{is}W_i + \alpha\frac{\sum_{j\in J}\theta_j}{|J|}\sum_{i\in I}\beta_{i1}W_i$ is the total travel of households needing refuge (see Fig. 2, number of families in flows 1, 2, 3 and 4); c_j is the index that represents a penalization of the quality of refuge j, varying between 0 and 1. $c_j = 0$ represents the lowest penalization (facility of maximum quality) and $c_j = 1$ represents the highest penalization (facility of minimum quality), ω assumes a value between 0 and 1, corresponding to the importance of the first component in the objective function, d'_{ij} is a normalization of the distance d_{ij}, $d'_{ij} = 1$ when d_{ij} is minimum and $d_{ij} = 0$ when d_{ij} is maximum. Formally defined as: $d'_{ij} = \frac{d_{max}-d_{ij}}{d_{max}-d_{min}}$, $\forall i\in I,\ j\in J$, where d_{max} and d_{min}, are the maximum and minimum distance in the d_{ij} matrix.

4. Case study: earthquake and tsunami in Chile

This section first presents a motivation for the models proposed in the paper, providing a short review of the earthquake and tsunami that occurred in Chile in 2010. Afterwards, the characteristics of the studied area and the obtaining of model parameters are presented.

4.1. The earthquake-tsunami of February 2010 in Chile

As already mentioned in section 1, this paper is strongly motivated by the terrible earthquake and tsunami that occurred in Chile on February 28, 2010. As a result of the disaster, several thousands of families completely lost their houses and other thousands had to abandon their homes due to insecurity and partial destruction. Additionally, many families were psychologically affected by the disaster, mainly children and the elderly; many of whom also had minor or serious injuries. The main cities of the VII region, like Talca (capital of the region) and Curicó, had their hospitals seriously damaged. Many families didn't have medical assistance after the disasters and also had to wait several days for medical attention. Other hospitals in smaller cities were also affected provoking a massive transfer of households to the hospitals in distant regions. The difficult situation experienced by thousands of Chilean families had such an impact that the Chilean government took some initiatives for the planning of critical infrastructure and services with a systemic strategy before future disruptive disasters.

Next, Section 4.2 discusses detailed information from Curicó, the studied city, explaining how information was collected about the affected homes, the characteristics of the different refuges and the distances between the homes and the refuges.

4.2. Characteristics of the geographic zone and parameter defining

The models defined in Section 4 are illustrated in Chile, specifically for a neighborhood of Curicó (Fig. 3), a city located 207 *km* south of Santiago, the capital of Chile. The database of the Instituto Nacional de Estadística (INE) has been used for information about households within the studied area in Curicó. Information like the building material of houses or some characteristics of the population are extracted from the database by the software Redatam+SP.[4] Given the rectangular street design in the studied city, Google Maps was used for calculating the Manhattan distance between two points. It is assumed that the homes and refuges are located in the center of each square and also the direction of each street is not considered when households move to the refuges.

In the case of potential refuges, these must be equipped to shelter victims for several days. A temporal refuge can be understood as a house or a safe physical space used for sheltering as well as providing basic needs and health services to victims affected by a disaster or an unexpected event. Most cities do not have special refuges for disaster events, and normally schools, gyms or other physical spaces with the appropriate characteristics are used.

According to the Department of National Emergencies of the Pan-American Health Organization (OPS/OMS), the necessary conditions to be satisfied by a facility to be considered a refuge are: operative bathrooms, space for walking, gyms or sport facilities, a closed and safe space, parking for the management of vehicles (ambulances, food transport and security transport), and special spaces for storage of different goods as typical examples.

The proportion of households requiring shelter is determined depending on the type of damage suffered by the dwelling, consisting of three levels: Acceptable, Recoverable and Unrecoverable. These levels are calculated according to the Materiality Index of the Dwelling [9] which is an index that measures the quality of the material attributes of the dwellings. The proportion is considered as the sum of the dwellings in recoverable or unrecoverable state with respect to the total dwellings in the studied area.

The victims requiring medical and psychological assistance can request this service immediately after the disaster or after a time living in a basic refuge. In the first case the group of households is defined depending on the proportion of disabled people at each square, with respect to the total households. The second group is based on the number of children under 9 years of age and individuals over 70. The total available capacity for households in each facility considered as a refuge is estimated in relation to the total physical space considering services and transit spaces. Since there are two different services, the capacity of the facilities attending to medical and psychological needs is defined as lower than the capacity of the facilities attending to basic needs, as the service including medical and psychological assistance requires more space for medical resources and utensils.

In the study, the following values for the parameters were considered. Given the possible impact of the parameter alpha in the model, different values were used trying to reflect the real impact in the solutions obtained; three values of α, $\alpha = 0.1$, $\alpha = 0.5$ and

[4] Acronym for REtrieval of DATa for small Areas by Microcomputer. Versions of Redatam are used in the majority of the Latin American and Caribbean countries, in many of Africa and Asia, as well as in many developed countries. All generations of Redatam have been developed and maintained by the Latin American and Caribbean Demographic Centre (CELADE), which is the Population Division of ECLAC. Available at http://www.eclac.org.

Fig. 3. Studied area, a neighborhood of the community of Curicó, Chile.

$\alpha = 0.9$. Also, 135 squares and 15 refuge facilities have been included in the studied area. Considering the high costs associated with the operation and maintenance of the refuges a high value of the parameter ρ was fixed; a minimum level of utilization of $\rho = 0.9$ for both services, A type and B type was defined, and a value of 10% for the capacity of the B type refuge available for victims requiring only basic services was also defined. That is, it is assumed that the disaster was one of high impact.

5. Results and analysis

Implementation: The Mixed Integer Linear Programming model has been implemented in CPLEX 12.5 through the platform IBM ILOG OPL IDE 6.3 (all the parameters by default). The experiments were done in an Intel Core i7-3610QM computer.

5.1. Results for the case study

To carry out the analysis of results, several scenarios were considered. For the *HMCA* model different values of the parameter N_t were taken (see Table 1). The minimum quantity of refuges to be installed so that all households needing a refuge have one is 8 (Scenario 4), and for each type of refuge the number to install is 4. The inverse relation between the number of installed refuges and the average distance traveled by victims is clear. When the number of installed refuges is minimum, the average distance traveled is maximum, and reverse (see Table 1). The preferred refuges of A type are refuges 8, 9 and 14 (in at least 8 out 12 scenarios) and of the B type are refuges 1, 4 and 13 (in at least 8 out 12 scenarios).

For scenarios 4, 8 and 12 the different values of α maintain the selection of refuges fixed but in the rest of the cases where the model has more flexibility (a greater value of N_t) different selections were found.

For the model $HMCA_S$ it is considered a priori that the refuges must satisfy some conditions to be defined as a determined type of refuge. The sets of refuges are specified in Table 2. In Fig. 4 it is possible to note the changes in the selection and assignment of the refuges to Scenario 1 in the model *HMCA* (4a) compared to the model $HMCA_S$(4b). There are 4 possible cases:

- The refuges selected as A type in model *HMCA* are also selected as B type in model $HMCA_S$. This happens for refuges 2,3,5,6, and 11.
- The refuges selected as B type in *HMCA* are selected as A type in $HMCA_S$. It is true for refuges 1 and 9.
- The refuges selected in *HMCA* are not selected in $HMCA_S$. This is observed for refuge 13.
- The unselected refuges in *HMCA* are selected in $HMCA_S$. This is observed for refuge 7.

Note the increase in the assignment of refuges with medical and psychological assistance. Fig. 4a represents the best possible scenario noting that the model *HMCA* assigns the type of selected refuge, and Fig. 4b represents the best possible scenario noting that the model $HMCA_S$ considers that the refuges have a priori defined their type.

Table 1
HMCA Results. *SC*: Scenario, α: Factor considering different travel costs, N_1: Maximum number of refuges A type, N_2: Maximum number of refuges B type, *TSR* (*TC*): Total selected refuges (Total capacity), *NRS1* (*C*): Number of refuges A type selected (Capacity), *NRS2* (*C*): Number of refuges type 2 selected (Capacity), *ADT*: Average distance traveled (m), *SR*: Selected refuges (A type), (B type).

SC	α	N_1	N_2	TSR (TC)	$NRS1$ (C)	$NRS2$ (C)	ADT	$SR(Atype, Btype)$
1	0.1	15	15	13 (1.191)	7 (804)	6 (387)	396.310	(2,3,5,6,8,11,14), (1,4,9,10,13,15)
2		6	6	11 (1.164)	5 (832)	6 (332)	418.672	(1,8,9,11,15), (3,4,5,7,13,14)
3		5	5	10 (1.149)	5 (832)	5 (317)	423.846	(1,8,9,11,15), (3,4,7,13,14)
4		4	4	8 (1.134)	4 (791)	4 (343)	625.146	(7,9,10,14), (1,4,12,13)
5	0.5	15	15	13 (1.160)	7 (825)	6 (335)	448.183	(2,3,5,6,8,9,14), (1,4,7,10,11,15)
6		6	6	12 (1.172)	6 (827)	6 (345)	481.188	(3,5,7,8,11,14), (1,2,4,6,13,15)
7		5	5	10 (1.149)	5 (832)	5 (317)	518.442	(1,8,9,11,15), (3,4,7,13,14)
8		4	4	8 (1.134)	4 (791)	4 (343)	693.650	(7,9,10,14), (1,4,12,13)
9	0.9	15	15	13 (1.160)	7 (825)	6 (335)	489.751	(2,3,5,6,8,9,14), (1,4,7,10,11,15)
10		6	6	12 (1.172)	6 (827)	6 (345)	530.771	(3,5,7,8,11,14), (1,2,4,6,13,15)
11		5	5	10 (1.183)	5 (823)	5 (360)	588.942	(3,5,7,10,14), (1,2,4,12,13)
12		4	4	8 (1.134)	4 (791)	4 (343)	759.022	(7,9,10,14), (1,4,12,13)

Table 2
Sets of refuges according to their type.

Type of refuge	Refuge N°
A Type	1, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
B Type	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 15

The impact of the model $HMCA_SD_T$ can be seen in Fig. 5, where the frequency of the travel of victims under different conditions is analyzed. The histograms 5a and 5b represent the model $HMCA_S$ for which distance constraints do not exist. In this case the travel of victims from their homes to the refuges is frequently between 100 and 150 m, considering 160 households (5a). Also, the travel between refuges is more frequently between 700 and 750 m, considering 60 homes. The histograms 5c and 5d show the travel of victims in the model $HMCA_SD_T$ including a constraint of maximum distance of 1000 m in both cases. In the histogram 5c the constraint does not alter the maximum distance of 650 m, but it is possible to note a redistribution of the assignments.

Additionally, when the maximum distance traveled between refuges is set at 600 m, a clear difference with the former case is noted since there is an effect when the distance is constrained and also the distribution of frequencies is changed as can be seen in the histogram 5e. In this case the distance traveled between homes and refuges is constrained to 1500 m, and the frequency of the traveled distances are redistributed as shown in the histogram 5f.

With respect to the analysis of the last model, $HMCA_SD_TQ$, it is necessary to examine (14), corresponding to an objective function weighting distances (F1) and quality of service (F2). The results are shown in Table 4 where it is seen that when the relative importance of quality of the refuges is increased (a lower value of ω) the average quality penalization index (AQPI) of the installed refuges is decreased from 0.333 to 0.256 meaning the average quality is increased. An important input for $HMCA_SD_TQ$ is c_j which represents the quality of potential refuges, and uses a particular scenario that is presented in Table 3. Remember that if the quality of a refuge is low, its score will be close to 1. On the other hand, if the quality is high the score will be close to 0. From Tables 3 and 4 it is clear that the worst refuges, that is, those with maximum value of c_j ($SC = 5$ and $SC = 8$) are unselected by the model when the value of the parameter ω is high and thus the quality of the refuges is not emphasized. Additionally, refuges 4, 9 and 12 have high quality and the model selected them in all scenarios.

5.2. Some guidelines for the use of optimization models

The models proposed in this paper are intended to solve two important post-disaster problems, namely, the evacuation of victims to refuges and the attention to victims at the refuges. The use of the different models depends on the information available to the planners and the specific characteristics of the region where the disaster occurs.

A first peculiarity of the decision making process is related to the knowledge of the planners about the refuges. If the refuges satisfy some basic requirements and there is no additional information about them, then using the first model *HMCA* would be appropriate. In this case the model decides which of the refuges is A type or B type. On the other hand, if the planners have more information about the refuges they can decide a priori the type of every refuge by using the second model $HMCA_S$.

Another fact is related to the characteristics of the region where the disaster occurs. If the disaster occurs in a small region, the distance traveled by victims would consequently be small and the basic model *HMCA* should be chosen. On the contrary, in a big city these average distances will be larger and it is important to emphasize the control over the maximum distance to be traveled by victims to get to a refuge. The third model, $HMCA_SD_T$, incorporates this constraint.

The last model, $HMCA_SD_TQ$, considers a situation where detailed information exists about the refuges so that the planners can decide each refuge type and they can also include the quality of the refuges in the objective function. This variant of the basic model could be particularly useful in the case where the severity of the disaster is high. Note that in the presentation of the models each new variant incorporates the previous modifications of the basic model.

Regarding recommendations before running the model it is important to mention having the most possible information about key aspects like the description of the potential refuges, the best evacuation roads for victims and the communication with other agents in the city, like police, firefighters, rescue units and others. In the context of severe disasters, the collapse of telephones and internet is common so that special means of communication are necessary.

6. Computational performance of the optimization model

For analyzing the computational performance of the proposed optimization model, in Section 5 it was shown that the model was implemented using data from part of a city in Chile. An instance consisting in 135 squares and 15 refuge facilities was considered in the case study and the solver was able to solve all the variants of the model for this instance in 900 s, at most.

With the aim of having a better appreciation of the solver performance when applied to a broad range of instances, a set of 4 groups of instances were created. The sizes of the instances for the

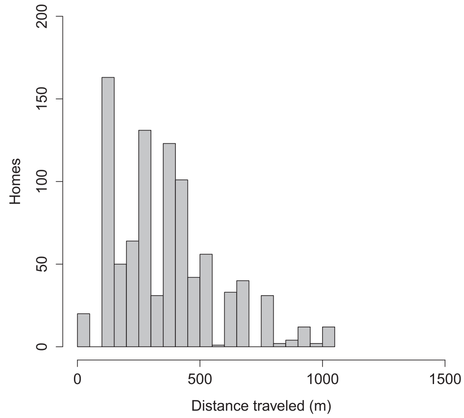
Fig. 4. Comparison of selection of refuges.

different groups are 15 potential refuges and 100 blocks (very small size), 30 potential refuges and 400 blocks (small size), 90 potential refuges and 900 blocks (medium size) and 160 potential refuges and 1600 blocks (large size). For each group 10 instances of type $p-q$ having the same number p of potential refuges, and the same number q of blocks for households in the studied area. Two variants of the optimization model were selected for the experiments, the simplest model HMCA and the more sophisticated model $HMCA_sD_tQ$. Table 5 shows the results of experimentation and illustrates the optimality gap considering the maximum time of 900 s for each run of CPLEX.

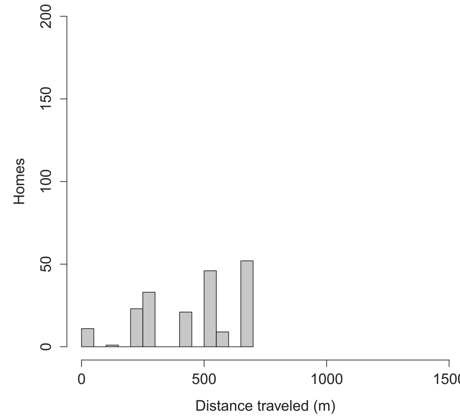
The experiments show that the hardness of the problem increases with the size of the instances when the value of the optimality gap is used for this measure, and the same occurs for both variants of the model. More specifically, this is true for the three indicators of the gap, namely, the minimum, average and maximum gap. Also, it can be noted that there is no significant difference in the performance of the solver between the two variants. Altogether, as expected, the optimality gap increases with the size of the instance and for the largest instances (fourth group) the maximum gap achieved (67,14%) shows that the solver is not able to get a good solution in 900 s. These experiments make evident that it is possible to get very good solutions in reasonable time for small and medium size instances. On the contrary, for the largest instances is desired the future design of a heuristic method.

7. Conclusions and future work

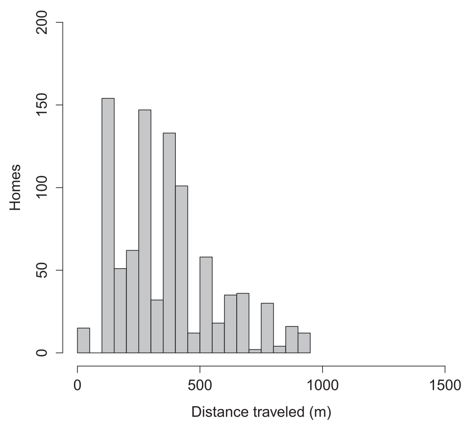
In this paper we use an optimization model for solving the problem of refuge location and victim assignment after a disaster. With the objective of designing optimization models able to capture the complex environment, the models include (in a hierarchical scheme) transportation of victims to the refuges, medical and psychological assistance, and quality of service offered by the refuges. One model in the approach is formulated in terms of maximizing the quality of service.



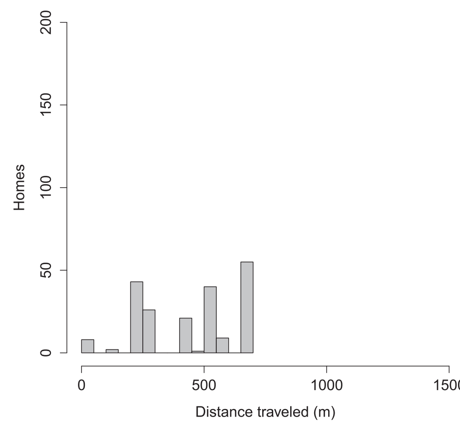
(a) $HMCA_S,\ x$



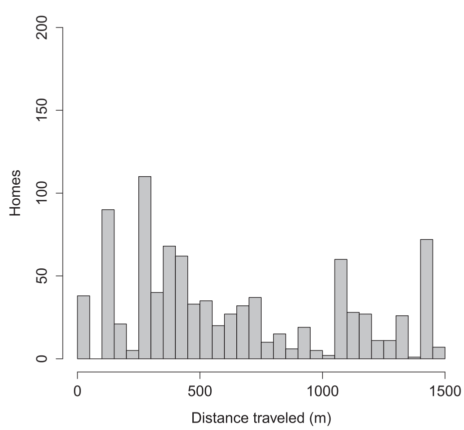
(b) $HMCA_S,\ z$



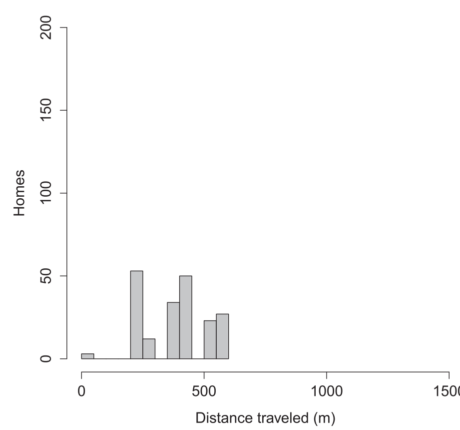
(c) $HMCA_SD_T,\ x \leq 1,000\ m.$



(d) $HMCA_SD_T,\ z \leq 1,000\ m.$



(e) $HMCA_SD_T,\ x \leq 1,500\ m.$



(f) $HMCA_SD_T,\ z \leq 600\ m.$

Fig. 5. Histograms of distances traveled by homes.

Table 3
Penalization of the quality of the refuges.

Refuges	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
c_j	0.5	0.5	0.5	0.15	0.6	0.5	0.3	0.7	0.1	0.15	0.4	0.1	0.2	0.2	0.3

Table 4
$HMCA_SD_TQ$ Results. *SC*: Scenario, *TSR* (*TC*): Total selected refuges (Total capacity), *NRS*1 (*C*): Number of refuges A type selected (Capacity), *NRS*2 (*C*): Number of refuges B type selected (Capacity), *ADT*: Average distance traveled (m), *AQI*: Average quality penalty index of selected refuges, *OF*: Objective function value, *SR*: Selected refuges (A type), (B type).

SC	ω	*TSR* (*TC*)	*NRS*1 (*C*)	*NRS*2 (*C*)	*ADT*	*AQPI*	*OF*	*SR*
1	0.9	12 (1227)	4 (886)	8 (341)	429.582	0.333	0.55036	(1,7,8,14), (3,4,5,9,10,11,12,15)
2	0.8	11 (1212)	4 (886)	7 (326)	434.558	0.309	0.46378	(1,7,8,14), (3,4,9,10,11,12,15)
3	0.7	11 (1182)	4 (834)	7 (348)	441.302	0.291	0.37797	(1,6,11,14), (3,4,7,9,10,12,15)
4	0.6	10 (1176)	4 (855)	6 (321)	452.113	0.290	0.29482	(1,6,9,14), (3,4,7,10,11,12)
5	0.5	10 (1176)	4 (855)	6 (321)	452.113	0.290	0.21346	(1,6,9,14), (3,4,7,10,11,12)
6	0.4	10 (1134)	4 (813)	6 (321)	472.678	0.270	0.13280	(1,9,14,15), (3,4,7,10,11,12)
7	0.3	10 (1134)	4 (813)	6 (321)	472.678	0.270	0.05460	(1,9,14,15), (3,4,7,10,11,12)
8	0.2	9 (1194)	3 (868)	6 (326)	554.988	0.256	−0.01677	(1,13,15), (3,4,7,9,10,12)
9	0.1	9 (1194)	3 (868)	6 (326)	554.128	0.256	−0.08505	(1,13,15), (3,4,7,9,10,12)

Table 5
Statistics of the running times and gap MILP on CPLEX 12.5. Each group is composed of 10 instances $p-q$. p represents the number of potential refuges and q represents the number of blocks.

Model	Instance p-q	Gap [%]			Time [s]		
		min	av	max	min	av	max
HMCA	15−100	0,00	0,00	0,02	5,00	309,60	901,00
	30−400	0,02	0,19	0,67	900,00	900,00	900,00
	90−900	1,70	3,40	4,80	900,00	900,00	900,00
	160−1600	1,66	38,33	67,14	900,00	900,00	900,00
$HMCA_SD_TQ$	15−100	0,00	0,03	0,09	0,65	630,34	900,00
	30−400	0,00	0,56	5,00	3,98	373,25	900,00
	90−900	0,00	1,54	6,68	91,97	810,22	900,00
	160−1600	0,13	6,58	55,70	900,00	900,00	900,00

The models require different assumptions about the characteristics of the concrete infrastructure and the desired objectives in real situations. The performance of the different variants of the basic mathematical model is illustrated with data from a neighborhood in the city of Curicó, Chile, one of the most affected cities in the earthquake that occurred in Chile in 2010. The computational experiments in the case study show that the models are flexible and capable of making good decisions.

The optimization models are able to find near optimal solutions in reasonable times using a commercial optimization solver. In the future the design of heuristics for solving the problem could be necessary in the context of applications using larger sized instances as was observed in the computational experiments with the model.

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