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A LOCATION MODEL FOR STORAGE OF EMERGENCY SUPPLIES TO RESPOND TO TECHNOLOGICAL ACCIDENTS IN BOGOTÁ

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ABSTRACT

The Prevention and Attention of Emergencies Fund (FOPAE) of Bogotá currently counts with one warehouse where physical equipment and supplies are stored to respond to different types of emergencies, including technological incidents. The transfer time of these items from the only existing warehouse to an emergency location is a critical factor to reduce the human causalities. To this end and in collaboration with FOPAE, we propose a linear optimization model to determine the optimal location of these warehouses in order to minimize the total costs and subject to covering at least a certain percentage of the affected people and considering the feasible locations for this purpose. Then, using a Monte Carlo simulation method we compare the performance of relief logistics with our proposed solution to that of the existing conditions. This study shows an improvement of over 27% in the average travel times with our proposed solution.

1 INTRODUCTION

In the first decade of the 21st century the frequency of natural disasters and their impact on human and monetary losses have increased about twice in comparison with previous decades, according to EM-DAT (2012). For example, during hurricane Katrina on August 23, 2005, one of the deadliest hurricanes in the United states, at least 1100 people died (Jonkman et al. 2009) and the monetary loss was estimated over 100 billion USD (NOAA 2005). In Colombia the rainy season between July and September of 2010 caused severe flooding in different areas of the country, to the extent that the government declared the "Economic, Social and Ecological State of Emergency" to deal with the emergency that was classified as the worst in the last 40 years in Colombia (IDEAM 2010).

Another large-scale example is the 2011 Tohoku earthquake, also known as the Great East Japan Earthquake occurred on Friday March 11 of 2011 with a magnitude 8.9 in the Richter scale. State of emergency was declared in the Fukushima Nuclear Power Plant and an estimated more than 200,000 people were evacuated inside a 20 km radius from the nuclear power plant (Ian 2011).

In the context of technological disasters there is a close relation between the technological development of the industries and the growth of cities. In many urban areas of the world the limited space to build causes residential zones to be in proximity of industrial facilities, and hence being exposed to high risk. This motivates entire fields of study such as Disaster Operations Management to respond to questions such as how to reduce the consequences of natural and technological disasters on human life and property loss.

A technological disaster is defined as the potential damage to the environment, population and the infrastructure of the city, and is caused by a task or work associated with hazardous material handling and industrial processes (DPAE 1998).

To mitigate the damage caused by a disaster, studies before, during and after the disaster have been widely conducted. Logistics planning in response to emergency situations faces a critical challenge. This involves

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the transportation of sufficient essential supplies such as water, shelter, food, medicine and specialized equipment to the affected areas in order to support basic living needs for the victims.

Bogotá the Colombian capital, is the most populated city in the country with over eight million residents and is divided into 19 urban districts, as shown in Figure 1. The city is framed by a mountain system mainly in the east and is crossed by important rivers such as the "Tunjuelito" and "Fucha" located in the south and is affected by extreme rainy periods and some zones are overpopulated. Bogotá's development plan does not contain adequate planning and management of territory. This causes a problem because in many parts of the city residential and industrial zones are adjacent or share territory. Table 1 shows the distribution of industrial facilities and population per district. The most critical districts are Engativá, Kennedy and Suba that are highly populated and also have a high number of industrial facilities.

Table 1: Percentage of population and industrial facilities per districts.

Districts	% **industrial facilities**	% **Population**
Puente Aranda	26.22%	3.80%
Fontibón	13.87%	4.40%
Kennedy	**8.97%**	**13.85%**
Mártires	8.69%	1.42%
Engativá	**8.64%**	**11.75%**
Barrios Unidos	7.16%	3.32%
Usaquen	4.10%	6.24%
Suba	**3.66%**	**13.47%**
Teusaquillo	3.62%	2.03%
Antonio Nariño	3.34%	1.70%
Chapinero	3.02%	1.82%
Santa fe	1.65%	1.53%
Rafael Uribe	1.53%	5.55%
Tunjuelito	1.45%	2.72%
Bosa	1.33%	7.40%
San Cristobal	1.05%	5.98%
Ciudad Bolivar	1.01%	8.32%
Usme	0.36%	4.35%
Candelaria	0.36%	0.35%

FOPAE (The Prevention and Attention of Emergencies Fund) is a governmental entity dedicated to developing emergency plans such as Emergency Prevention and Attention Plan for the City of Bogotá to respond to different kinds of disasters (FOPAE 2010). In a previous research project (Noreña et al. 2011; Ríos Hurtado and Akhavan-tabatabaei 2011), the case of a 6.2 magnitude earthquake in Bogotá and the future logistics plan of providing auxiliary medical facilities to respond to this emergency during the first four days of relief operations are considered. In this project operations research techniques including discrete event simulation and linear optimization are applied in order to determine the capacity and location of auxiliary medical resources, such as the expanded capacity of permanent hospitals, increase in the number of ambulances and the location and capacity of field hospitals. With the results of the model, the resource gap between the current situation and an optimal situation in which zero people with severe injuries would die due to lack of medical resources is estimated. The results of this study are currently used by FOPAE in the planning and preparation for disasters.

As a second phase of this project, FOPAE is now planning to distribute the emergency supplies that are located in one big warehouse to various warehouses to be located in different parts of the city. They have requested the help of operations researchers to determine the optimal location of these new warehouses to be built in Bogotá, such that the total cost is minimized and at least a certain percentage of the affected people by technological emergencies are covered by each warehouse. For this new project we propose a linear optimization model and use the software ArcGIS (ESRI 2011) in order to calculate some of the parameters. This software is based on Geographic Information Systems (GIS) which Huxhold and Levinsohn (1995) defined as "a collection of information technology, data and procedures for collecting, storing, manipulating, analyzing, and presenting maps and descriptive information about features that can be represented on maps.", then we evaluate the performance of our solution with a Monte Carlo simulation method.

Figure 1: Map of Bogotá's 19 Districts (DANE 2005).

The rest of this paper is organized as follows. In Section 2, we review the relevant literature. In Section 3 we show the proposed optimization model, provide the notation and present the problem formulation. In Section 4 we present a numerical example with randomly generated parameters. In Section 5 we present the sensitivity analysis of the most important parameters of our model. In Section 6 we present the Monte Carlo simulation method to evaluate the effectiveness of our proposed solution. Section 7 concludes the paper and gives suggestions for future work.

2 LITERATURE REVIEW

Waugh and Ronald (1990) and Waugh (2000) classify the emergency management operations 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 of 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.

Our study is focused on the stage of preparedness that includes activities such as emergency planning and budgeting for acquiring vehicles and equipment, maintaining emergency supplies and construction of emergency operation centers, among others (Altay and G. Green III 2006).

The differences between disaster relief and enterprise inventories are significant but are not well understood (Whybark 2007). The physical location of the inventory must take into account the need to have the inventory accessible for monitoring to ensure that they are still useful for their purpose when the need arises. Also these inventories must be accessible as removals are scheduled. It must incorporate considerations of security, corruption in the government or other factors that are not usually contemplated in the management of inventories for enterprises.

Mete and Zabinsky (2010) propose a stochastic optimization approach for the storage and distribution problems of medical supplies to be used during an emergency in two stages. The first stage recommends the best storage locations from possible warehouses and determines their inventory levels and the second, determines the amount of medical supplies to be delivered to hospitals. Then with a mixed integer programming (MIP) model they determine the emergency transportation plan with the number of vehicles available at each warehouse. Other models that are not stochastic like Lin et al. (2011) consider multiple items, vehicles and periods, with soft time windows and a split delivery strategy where a vehicle can partially deliver the items. The model is formulated as a multi-objective integer program, but it is converted to a single objective model by a weight sum method and limiting the number of available routes. Finally they propose two methodologies for solving it, one is a genetic algorithm and the second is through decomposing the original problem. A similar problem is proposed by Han et al. (2011), but with strict time windows. The problem is extremely difficult to solve. To obtain a scalable solution, a new method based on successive sub-problem solving, using Lagrangian Relaxation (LR) is proposed, where the route capacity and location selection constraints are relaxed by Lagrange multipliers. The stochastic models address the issue of randomness which is more consistent with reality, however this approach for larger instances will take more time than the non-stochastic models to be solved. For this reason we select the non-stochastic approach and address the uncertainty of the parameters by testing our results with a Monte Carlo simulation method.

The next three models deal with the problem of reallocation. Takamura and Tone (2003) propose a method based on a combination of the analytic hierarchy process (AHP) and data envelopment analysis (DEA) to solve the problem of the reallocation of several government agencies out of Tokyo. The model proposed by Sefair et al. (2012) is a multi objective optimization model linked to a Geographic Information System that interacts with decision makers to determine which candidate should be transformed into a new park, taking into account different criteria such as geographical coverage and accessibility cost, among others. Finally, Iakovou et al. (1996) propose a model that focuses on technological emergencies such as oil spills using a linear integer programming model and a relaxed model to determine the optimal location and capacity of cleanup equipment, taking into account their post event implications.

In the next section we discuss the optimization model proposed to determine the location of new warehouses with a fixed radius of coverage in order to minimize the total costs and cover at least a certain percentage of the affected people by a technological emergency.

3 OPTIMIZATION MODEL

In the mixed integer linear program presented below, we determine which of a set of pre-specified warehouses need to be opened and decide the allocation of affected zones after the occurrence of a technological disaster. The model formulation includes a set of candidate locations for the Warehouses (I) that are distributed around the city, so each has a geographic coordinate for the latitude and longitude. Also we define three parameters for each warehouse: the capacity c_i, radius of coverage r_i (5 km), and g_i that is the cost of opening a warehouse. An example of the feasible location and the coverage radius is shown in Figure 2 (FOPAE 2010). Also for each warehouse there is a binary decision variable x_i that takes the value 1, if warehouse i is selected to be operating and 0 otherwise. We include a variable z_i which indicates by how much the capacity of each warehouse should be increased, but increasing the capacity also raises the cost $\hat{g}_i$ and it cannot get higher than an upper limit zu_i that we arbitrarily define to be 50% of the total capacity for each warehouse, in the numerical example at the end of this section.

The model also includes a set of demand points (M) which like the warehouses also have geographic coordinates and each one can be classified in a set (K) divided in three types of emergency impact levels: High, Medium and Low. The higher the emergency impact level the bigger the amount of damage to the community.

In Figure 3 (FOPAE 2010) all the potential locations for technological emergencies registered in the city of Bogotá in 2010 are shown. In this figure red dots represent high impact emergency levels, yellow dots are for medium and green are for low. Each of these points is assumed to have a radius of impact (1 km for the sake of our numerical example), so when an emergency happens the people around the location of the emergency are affected, creating a new set of zones (J). For these new objects the set of levels of emergency (K) are also defined. An example of these areas is shown in Figure 5 for high impact technological emergencies. To estimate the average number of affected people for each level k of emergency d_{jk} we take into account that different parts of the city are not equally populated. Figure 6 (DANE 2005) shows how the population is distributed in the 19 districts of the city. We use ArcGIS to calculate the value of the variable v_{ijk} which is 1 if a part of an emergency zone j of the level k is in the radius coverage of a warehouse i, otherwise this value is set to 0. An example is shown in Figure 4 where blue zones are covered by one warehouse. The other decision variable y_{ijk} is also binary and takes the value 1 if the warehouse i supplies the emergency zone j for each level k, and 0 otherwise. So when v_{ijk} takes the value of 1 the variable y_{ijk} can be 1 or 0 but when v_{ijk} is 0 the only value y_{ijk} can take is 0.

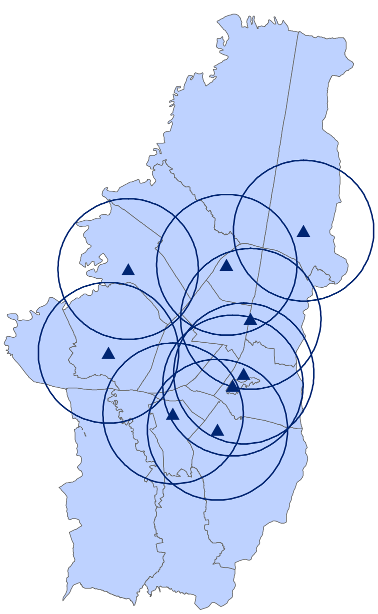


Figure 2: Feasible warehouse locations.

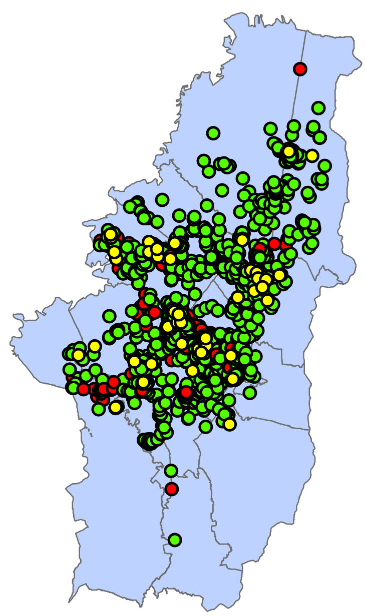


Figure 3: Technological emergencies.

In order to estimate the volume needed in each warehouse, with the help of FOPAE we defined an average emergency supply kit for each level of technological emergency per each affected person. These kits occupy a space w_{jk} in the warehouse. For instance a kit for a high level emergency is assumed to be twice as big as a kit for a low impact level emergency in terms of the volume that it occupies.

Next we present the mathematical formulation of the linear integer program that attempts to find the optimum subset of warehouses to be opened and the optimal allocation policy of affected populations to each warehouse after the occurrence of a technological emergency.

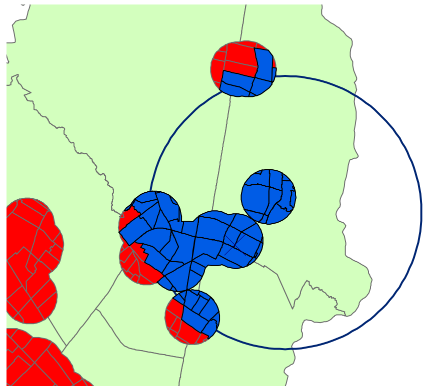


Figure 4: Example of the covered high risk zones by a warehouse.

3.1 Objective Function

$$\min \sum_{i \in I} (x_i g_i + z_i \hat{g}_i) \tag{1}$$

3.2 Constraints

$$c_i + z_i \geq \sum_{k \in K} \sum_{j \in J} y_{ijk} w_{jk} d_{jk} \qquad \forall i \in I \tag{2}$$

$$\frac{\sum_{i \in I} \sum_{j \in J} y_{ijk} d_{ij}}{\sum_{j \in J} d_{jk}} \qquad \forall k \in K \tag{3}$$

$$z_i \leq x_i z u_i \qquad \forall i \in I \tag{4}$$

$$y_{ijk} \leq v_{ijk} \qquad \forall i \in I \forall j \in J \forall k \in K \tag{5}$$

$$\sum_{i \in I} y_{ijk} \leq 1 \qquad \forall i \in I \forall j \in J \tag{6}$$

$$x_i \geq y_{ijk} \qquad \forall i \in I \forall j \in J \forall k \in K \tag{7}$$

$$x_i, y_{ijk} \in \{0,1\}, z_i \in R^+ \cup \{0\} \qquad \forall i \in I \forall j \in J \forall k \in K \tag{8}$$

The Objective Function (1) incorporates the total costs of operating a warehouse and the cost of having extra capacity in order to provide a solution with the lowest cost possible. The current and extra capacity of the warehouses is taken into account by constraint (2). Constraint (3) assures that all warehouses cover at least a percentage of the demand for each type of emergency. Constraint (4) assures that extra capacity is only considered for opened warehouses. Constraint (5) assures that a zone can be served by a particular warehouse if it is inside its coverage radius r_i. Only a zone j can be covered by at most one warehouse (6), only opened warehouses can be assigned a to zone j (7) and finally we can see in the constraint (8) that the variable z_i is continuous and the other two variables x_i and y_{ijk} are integer. For this reason was necessary to use a MIP model.

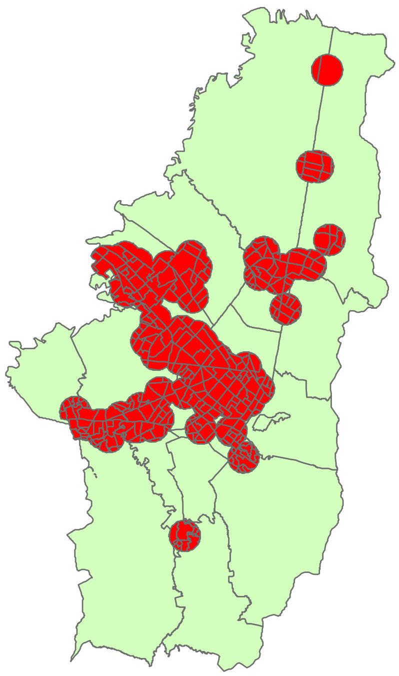


Figure 5: High risk technological emergency.

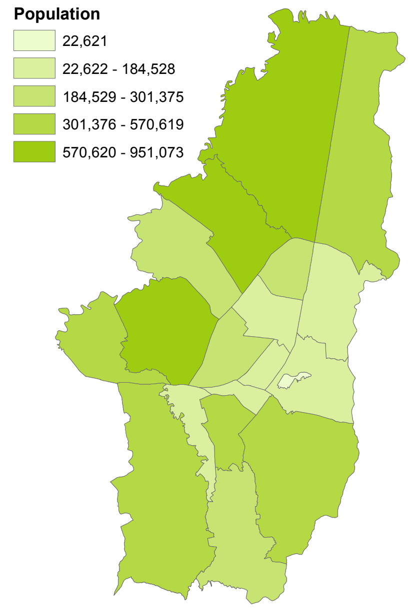


Figure 6: Distribution of population.

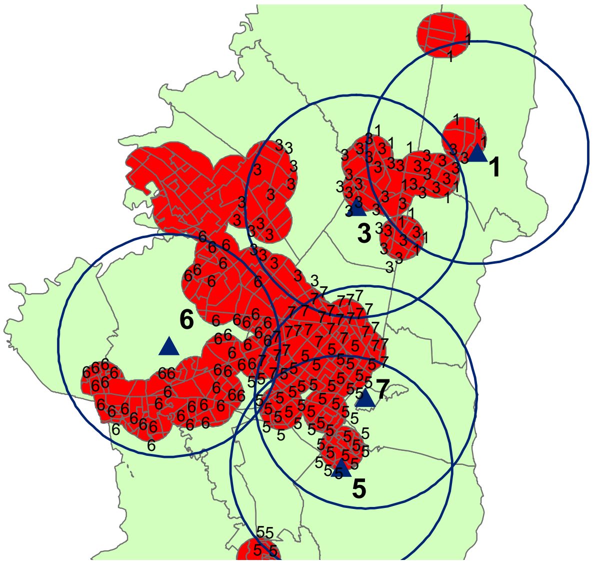
4 RESULTS

To demonstrate the performance of the proposed model we examine an example case in which we consider 9 feasible locations to open warehouses and 2108 affected zones from all levels of the emergency. We solve the optimization model using Xpress-MP (FICO 2011) on a Dell Precision T7400 with Windows Vista Ultimate x64, two processor Intel Xeon X5450 of 3.0GHz and 8GB RAM. Table 2 includes in order from left to right an identification code for all the 9 feasible locations, the operating cost, extra capacity cost and capacity for each warehouse, each of which randomly generated to showcase the performance of our proposed model. Also there is a minimum required service level as the percentage of affected population to be serviced by the assigned warehouse. This service level for high impact emergency points is assumed 50%, for medium impact 30% and for low impact 20% . The last three columns show the percentage of covered demand in each type of emergency impact level, by each selected warehouse. With these parameters defined, we can run the model which takes no more than 30 seconds. The results are shown in the last four columns of Table 2.

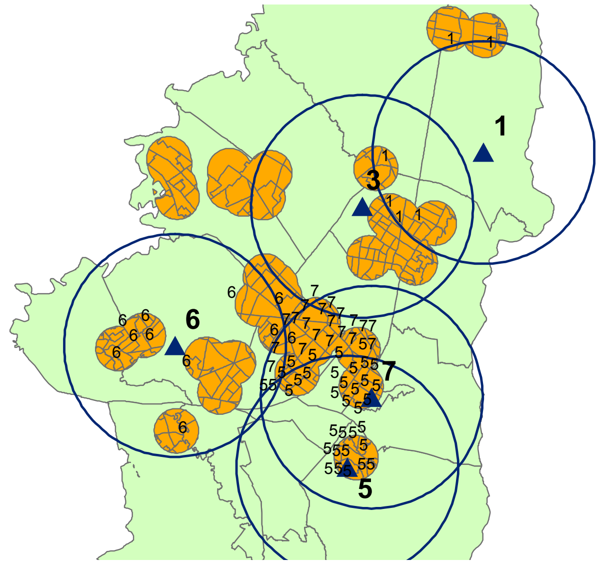
The total cost of the policy is 5,996 monetary units which requires to open warehouses in locations 1, 3, 5, 6 and 7. These five warehouses only cover the 19.14% of the total demand and the service level requirement is barely fulfilled. Also the results show that all warehouses are almost full and warehouse 3 is only filled with items for high level emergency. The location of warehouses that are required to be opened and the zones that are assigned to each are shown in Figure 7a for high impact emergency, Figure 7b for medium and Figure 7c for low impact.

5 SENSITIVITY ANALYSIS

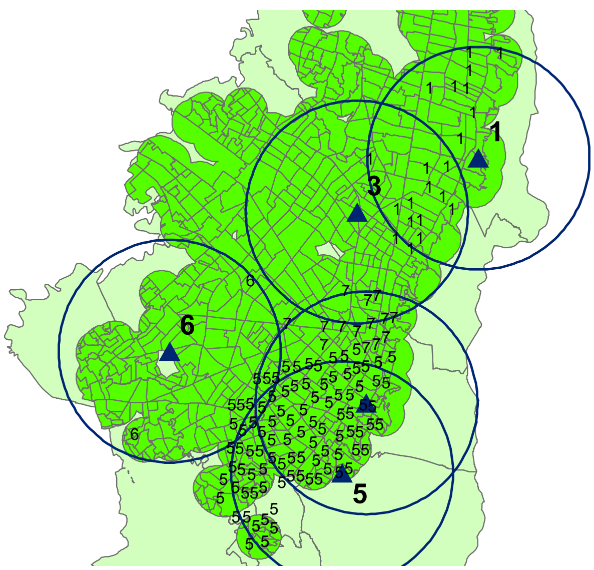
In this part of the study we examine the behavior of the output of the optimization model with different parameters. For this reason we change two parameters in our model, one at a time. First we change the capacity of the warehouses, so we decrease and increase the initial capacity and then we change the minimum service coverage required from 30% to 100% for each type of impact level.



(a) High impact zones.



(b) Medium impact zones.



(c) Low impact zones.

Figure 7: Covered impacts zones.

Table 2: Summary of parameters and results.

WH	Operating Cost ($)	Extra capacity cost ($/$m^3$)	Capacity (m^3)	% Usage	Emergency Level		
					High	**Medium**	**Low**
1	383	75	236,767	71.46%	0.46%	1.61%	1.29%
2	939	291	587,906				
3	517	81	742,235	98.24%	11.29%	0.00%	0.00%
4	2,806	1,070	1,251,729				
5	3,812	558	2,679,384	96.77%	16.61%	9.25%	17.81%
6	672	285	1,325,134	93.89%	14.33%	9.47%	0.26%
7	612	127	831,416	99.85%	7.32%	9.86%	0.65%
8	8,244	954	3,640,993				
9	7,651	1,602	3,454,010				

5.1 Capacity

To illustrate this analysis we change the capacity from -%70 to 50% where 0% is the capacity used in the optimization model of the numerical example in Section 3. In Table 3 the first column (% Change of Capaciy) indicates the increase or decrease in the capacity of the warehouses. Opened warehouses are shown in the second column and for those that need extra capacity the number of the warehouse appears in bold. Finally, the last column shows the percentual difference between the total cost of the initial situation (0%) and the one which is being analyzing.

Table 3: Summary of capacity sensitivity results.

% Change of Capaciy	Open Warehouses	% Change
-70%	**1,2,3,4,5,6,7,8,9**	328%
-60%	3,4,5,6,7,8,**9**	306%
-50%	1,2,3,4,5,6,7,8	200%
-40%	1,3,5,6,7,9	128%
-30%	3,5,6,9	111%
-20%	1,3,4,5,6,7	47%
-10%	1,2,3,5,6,7	16%
0%	1,3,5,6,7	0%
10%	**3**,5,6,7	-6%
20%	2,3,4,6,7	-8%
30%	1,3,4,6,7	-17%
40%	3,4,6,7	-23%
50%	1,2,3,6,7	-48%

As we can observe in the last column when the "% Change of capacity" increases, less warehouses need to be opened therefore the "% Change" is reduced in 48%. On the other hand when the "% Change of capacity" is reduced, the number of warehouses that need extra capacity increases. For instance, when the capacity is reduced to 70% all warehouses are used and all of them need extra capacity. These results show that the model is consistent.

5.2 Service Level

For this part we will analyze the total cost of the optimal policy changing the service level of one impact level and leave the other two constant. In Figure 8 the y-axis shows the total cost and the x-axis, the minimum service level required. At each value of the x-axis there are three bars, each indicating the service level that was changed. For example the first red bar from left is the instance where the minimum service level required for high impact is 30% and the other two service levels remain constant.

We can see that as the service level increases the total cost of opening warehouses increases as well. Also when we try to find a solution to cover all the demand (100% service level) for a low impact level the model cannot find a feasible solution, this is due to the fact that low impact emergencies can cause less damage to the community than the other two levels, but they are expected to happen more often and the required available space of the warehouses is not big enough to respond to them.

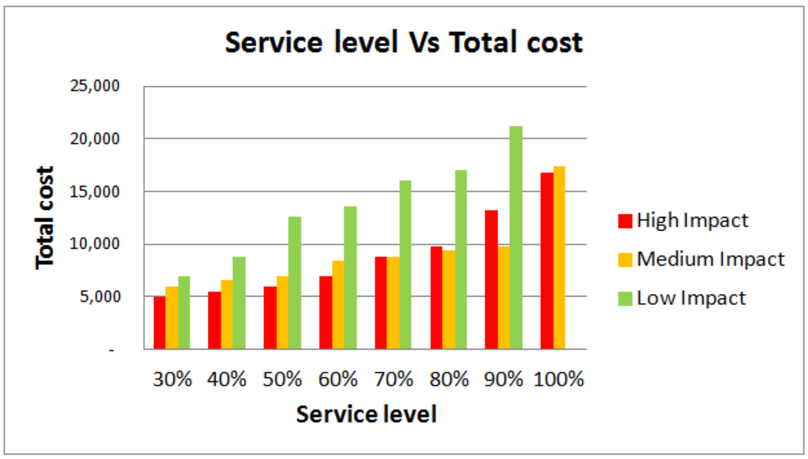


Figure 8: Sensitivity analysis of service levels.

6 PERFORMANCE EVALUATION OF THE OPTIMAL SOLUTION VIA MONTE CARLO SIMULATION

In this section we compare the logistics performance of FOPAE operations under the current situation (i.e., one warehouse only) and the proposed solution we discussed in Section 5. This solution suggests opening of 5 warehouses as shown in Table 2. To compare these two cases we assume that in total FOPAE has access to 5 emergency vehicles to transport the supplies from the warehouses to the emergency points. In the current situation all vehicles are assumed to be concentrated at the only existing warehouse. In the optimal situation we assign one vehicle to each warehouse. All vehicles are assumed to have a fixed capacity which for this example are considered large enough to only serve one emergency at a time. Therefore, the vehicles that travel to a demand point need to come back immediately to the warehouse and recharge the supplies necessary to respond to another emergency.

We employ Monte Carlo simulation method and assign a binomial probability distribution to each point of potential emergency. To illustrate we made an example with 5% chance for each point of becoming active on a given day, but of course this value can be adjusted when real data is available. Therefore, in each replication of the simulation the vehicles are faced with a random number (with the average of 5% of the total number of points) of activated demand points to be visited in random locations.

In order to plan the routes of these vehicles we apply a nearest neighborhood search heuristic in each replication. We use ArcGIS to get the shortest path matrix which has the entire values of minimum distance between the warehouses and the demand points. Finally, running different instances for each scenario will let us find the alternative that reduces the total traveled distance the most.

After running the simulation for 200 replications and randomly activating the demand points, we have found that with a 5% chance of activation for each point it takes the vehicles in the current scenario an average of 127.283 ± 6.076 Km to visit all the demand points and for our optimal solution this distance is 93.191 ± 3.976 Km. This indicates a 27% reduction in the average total traveled distance.

7 CONCLUSIONS AND FUTURE WORK

We developed and presented a mixed-integer programming model for disaster preparedness to plan the optimal storage location for distribution of emergency kits, in order to respond to different levels of technological emergency, taking into account a minimum required service level and the capacity for feasible warehouses to be opened. We showed our approach on an example with randomly generated data and found that from nine feasible warehouses to be opened only five of them were required, minimizing the total cost of opening and covering at least 50%, 30% and 20% of the demand. However, with the outcomes of the sensitivity analysis, we demonstrated that our model produces consistent results and can be applicable to real-life cases in Bogotá and any other city with the necessary data provided by different disaster management decision makers. With the Monte Carlo simulation method we found out that our optimal solution compared to the current situation reduces the total average traveled distance from the warehouse and the potential emergency points by 27%. Further work needs to be done to collect the missing data, in order to demonstrate the performance of the proposed model for the case of Bogotá. To make a complete decision making tool, other types of emergency should also be included in the model, such as flooding and landslides. Also experiments can be carried out by varying the radius of coverage of each warehouse and observing the effect on total costs. Finally, an optimal solution can be derived by balancing the costs and radius of coverage.

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