Location of a Temporary Site to Earthquake Waste Separation. Case Study: Mexico City

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Abstract

After the 2017 earthquake in Mexico City, the project "Earthquake Waste Management Proposal in Mexico City" was launched, which includes the removal of waste from the disaster site to a temporary site separation, the last is a temporary storage and waste classification site, that is used before waste being sent to their respective recycling chains or for their proper final disposal. This work presents the optimal location of the temporary site based on the transportation model of Mixed Integer Linear Programming, which evaluates the average distance between the collapsed buildings caused by the earthquake and the sites authorized by the Government of the Mexico City, to select *n* temporary sites whose distance is minimal. The methodology of the present study includes the application of the transportation model, to case study earthquake of September 19th, 2017 in Mexico City, considering next constraints: 14 collapse buildings, 8 possible sites according to official data provided, 1878.63 m^3 (97.83 ton) earthquake waste generation according with previous estimations by the same Project and the location of a single temporary site. The results show that the minimum distance traveled between the points of origin and destination is 51% less than that of the farthest site.

Keywords
Earthquake Solid Waste, Earthquake Waste Management, Temporary Solid Waste Separation Site, Installation Location, Mixed Integer Linear Programming

1. Introduction
Mexico is in an area with high seismic activity because it is located within the area known as the Circumpacific Belt or Ring of Fire, a place that releases between 80 and 90% of the Earth's annual seismic energy, and on the interaction of five tectonic plates (Sistema Geológico Mexicano, 2017). Given the high probability of occurrence of environmental disasters in Mexico, it is necessary to have emergency and response plans that attend the most urgent needs of victims, as well as the subsequent recovery and reconstruction processes in the affected areas. An important part in the elaboration of these plans involves the definition of strategies related to the management of waste generated by the disaster. This was motivated by the fact that efficient waste management influences the environmental impact caused by these events, the public health of the population involved and the process of recovering normality (Brown et al.).

After the 2017 earthquake in Mexico City, the project "Earthquake Waste Management Proposal in Mexico City" was launched, which includes the removal of waste from the disaster site to a temporary site separation, which is a temporary storage and waste classification site before being sent to their respective recycling chains or for their proper final disposal. This strategy allows the recovery of the waste generated by the earthquake and reduction of the environmental damages.

In this type of chaotic and complex circumstances the time is a key factor in safeguarding human lives that are in danger therefore the location of temporary sites with a minimum distance to disaster sites contributes to the prompt release of primary routes, the timely care of affected people and the reduction of risks to public health due to the presence of organic waste in collapsed buildings. This work presents the formulation of an Operations Research model to determine the optimal locations of *n* temporary sites with a minimum distance to the disaster points.

2. Literature review

Disaster mitigation, preparedness, response and recovery issues must be at the forefront not only to generate knowledge that is of interest to researchers, but also to provide the basis for decision-making by the planners, emergency managers and other professionals involved. Community recovery is associated with infrastructure and lifelines that are critical to the operations of other systems such as transportation, electricity, water, and waste disposal. Launching business and mobility is also vital to revive economic activities that provide economic resources in the form of salaries, as well as goods and services (Rodríguez et al.). For example, in the 1985 earthquake in Mexico City, the street and highway network faced problems such as the reduction in the capacity of the transportation network mainly due to blockages caused by structures that collapsed on the streets and aggravated by the debris of collapsed buildings stored on the streets while search , rescue, demolition and cleaning-up activities progressed (Hobeika et al.). Efficient waste management, outside affected areas, contributes to the prompt restoration of normality. The quality of logistics activities during the reconstruction phase can greatly impact the success of the entire disaster recovery process, especially in terms of long-term sustainability and effectiveness (Anglica and Hernández).

The waste generated by earthquake has the potential to be recovered and integrated into specialized recycling chains within Mexico City. These materials can be recycled in existing markets or can be used in post-disaster applications. However, due to the high complexity of the composition of the waste, these require specific classification, separation and handling criteria in order to be valued and sent to the city's recycling centers or sanitary landfills (Reyes Ramírez and Rojas Nava). The benefits of recovering materials from earthquake waste include reducing space in landfills, reducing demand for raw materials, reducing waste management costs (this depends on the relative costs of waste management, including transportation) and job creation (Brown and Milke). The temporary separation site takes on importance within waste management as a place of storage and execution of the necessary operations. The location of the temporary site largely determines the distance, time and cost involved in the management of waste by earthquake. The planning and evaluation of alternatives, with the help of facility location tools and mathematical models developed by disciplines like Operations Research, facilitate decision making and improve the performance of management plans.

The location of facilities is widely used both in the private (industrial plants, banks, shops, etc.), and the public sector (hospitals, postal stations, etc.) and influences numerous operational and logistical decisions (Tatjana). Location and allocation problems determine the best configuration of one or more facilities. The usual practical interpretation of this type of problems is the existence of a social or economic system that need to assign a set of flows between a series of facilities or points of origin and a series of geographically dispersed destinations. The problem is, simultaneously, locating the facilities and determining an allocation of flows, so that the total operating costs of the system are as low as possible. In its most general form, the allocation and location problem is divided into two basic paths as explained below. If the locations of all the facilities are known in advance, but the allocation of flows between the set of facilities and some other set of points is unknown, the problem becomes the ordinary linear programming transport problem. If flow allocation is known, but the geographic arrangement of facilities is unknown, then the problem is a pure location problem and will generally be treated as the classic Weber problem of space economics (Scott).

Operations Research is the quantitative study of the operations of a complex organization and the prediction of the effects of changes in conditions for the guidance of executives in obtaining the maximum effectiveness with the available resources (Goodell Brown and Easterfield). Linear programming is a subset of mathematical programming that is part of Operations Research. Mathematical programming problems are models that try to describe a real-life situation. It does this by using variables and parameters represented by numbers. Although the parameters are numbers known to the decision maker and are taken as a fixed data, the variables are numbers whose values will be determined in the decision process. One of the basic assumptions of linear programming is the deterministic property, which means that we assume that the structure of the problem, as well as all the parameters of the problem, are known with certainty (Eiselt and Sandblom).

The transportation model is a type of linear programming that determines the quantity of goods that must be sent from *i* sources (facilities) to *j* destinations (warehouses or distribution centers) with the objective of minimizing transport costs by satisfying supply and demand limits (Taha). The model can be easily visualized through two matrices, one of costs and the other of flows. The characteristics of the transportation problem are summarized as follows: 1) each destination point has a specific demand that must be met, 2) each origin point can only provide a certain number of units that are to be transported, that is, it has a determined offer, 3) the objective is to minimize the total cost of transportation, according to the costs related to the selected route plan, 4) the cost of distribution is directly proportional to the quantity of items that it distributes or transports, 5) the problem has feasible solution only if the total quantity available from all sources is greater than or equal to the total demand of the destinations (Winston and Goldberg).

The transportation model in its most basic form can assign material flows to all destinations considered; however, for this work it is necessary to include a selection criterion that assigns the flows only to a number n of destinations. It is possible with the inclusion of a binary variable whose value determinate the selection of the temporary sites that imply the optimal cost. When only some of the variables need to be integers and the rest are continuous, the model is called a Mixed Integer Linear Programming problem. Within this classification, those models include non-negative integer variables, continuous variables and binary variables (Cornejo Sánchez and Puente).

3. Methodology

The methodology followed includes the problem definition, the identification of the input, decision and response variables involved in the phenomenon to be modeled, obtaining information from previous data within the same project, the construction of an influence diagram to relate all the variables of the model, the formulation of the mathematical relationship of the transportation model and finally the verification and validation of the model for the case study of the earthquake of September 19, 2017 in Mexico City, through a resolution optimization problems software.

3.1 Problem Definition

For the Mexico City case study, the points of origin are known from the collapsed buildings that occurred in the 2017 earthquake and the destination points as the available sites according to the Government of Mexico City. Given the above, the development of a Mixed Integer Linear Programming transport model is necessary. The debris resulting from the earthquake will be transported in trucks, at the end of search and rescue activities, to be sent to temporary storage and separation sites. The objective of the model is to select, from several available sites, n temporary sites that can receive the total amount of household waste by earthquake scenario in Mexico City. In addition, it must allocate the waste flow between each collapsed building and the selected temporary sites with the minimum total cost and distance. The decision of a single or more than one temporary sites is open to the evaluation of the needs that a certain disaster circumstance requires, in other words, the model should give the liberty to choose as many temporary sites as the decision maker needs to install, at the least cost that this decision implies.

3.2 Variables

The management strategy establishes that the waste that is sent to the temporary site includes that classified as household and excludes the waste from construction and demolition (C&D), such as masonry, concrete, drywall, ceramic, etc. C&D are not considered because they are mostly classified *in situ* and sent directly for recycling or final disposal. Similarly, the temporary site is designed to receive only household waste from residential buildings that had collapsed immediately after the earthquake. The waste from buildings scheduled for demolition, after the earthquake, are excluded because there is the possibility of recovering household goods. In the 2017 earthquake, 14 residential buildings were totally and partially collapsed at the time of the earthquake (Comisión para la reconstrucción, recuperación y transformación de la ciudad de México). The parameters or input variables to the model, regarding the amount of household waste that must be transported, are taken from a previous research within the same project, in which the characterization, classification and estimation of the amount of waste by earthquake was carried out. This research was developed according with Mexican standards and based on data from the earthquake of September 19, 2017. Table 1: Estimate of waste generated by collapsed building, shows the estimate of waste generated by each residential building collapsed at the time of the 2017 earthquake.

Table 1. Estimate of waste generated by collapsed building (Reyes Ramírez and Rojas Nava).

No.	Address	Number of individual household	Weight [ton]	Volume [m^3]
1	Temascaltitla No. 4, Col. Santa Rosa Xochiac. Alc. Álvaro Obregón.	1	0.80	15.40
2	Av. Santa Ana esq. Ejido Santa Cruz Atoyac, Col. Ex Ejido de San Francisco Culhuacán. Alc. Coyoacán.	2	1.60	30.80
3	Amsterdam No. 107 esq. Laredo, Col. Hipódromo. Alc. Cuauhtémoc.	16	12.83	246.38
4	Paseo de las galias No. 47, Col. Lomas Estrella 2da sección. Alc. Iztapalapa.	16	12.83	246.38
5	Avenida 323 No. 655 esq. Avenida 314, Col. Nueva Atzacoalco. Alc. Gustavo A. Madero.	1	0.80	15.40
6	Edimburgo No. 4 esq. Escocia, Col. Del Valle. Alc. Benito Juárez.	21	16.84	323.37
7	Prolongación Petén No. 915, Col. Emperadores. Alc. Benito Juárez.	12	9.62	184.78
8	Viaducto Presidente Miguel Alemán No. 106 esq. Torreón, Col. Piedad Narvarte. Alc. Benito Juárez.	4	3.21	61.59
9	Salvador Díaz Mirón No. 151, Col. Santa María la Rivera. Alc. Cuauhtémoc.	1	0.80	15.40
10	Bretaña No. 90, Col. Zacahuitzco. Alc. Benito Juárez.	3	2.41	46.20
11	Insurgentes esq. Vicente Guerrero, Col. San Gregorio Atlapulco. Alc. Xochimilco.	1	0.80	15.40
12	Niños Héroes No. 173 esq. Galicia, Col. Niños Héroes. Alc. Benito Juárez.	8	6.42	123.19
13	Escocia No. 4 esq. Gabriel Mancera, Col. Del Valle Centro. Alc. Benito Juárez.	12	9.62	184.78
14	Rancho de los Arcos No. 32, Col. Los Girasoles. Alc. Coyoacán.	24	19.25	369.57

For these collapsed buildings, the distances between each of them and the available sites within Mexico City were determined with the help of the Google Maps tool. The distances were calculated from an average of up to three existing routes provided by the tool. Table 2: Distances in km between collapsed building *i* and available site *j*, shows the associated distance matrix.

Table 2. Distances in km between collapsed building *i* and available site *j*

i/j	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
1	36.15	29.75	55.95	58.50	65.70	57.63	63.07	57.03
2	47.57	45.47	79.70	38.25	41.85	81.60	48.10	73.33
3	31.50	32.97	73.10	38.20	56.05	74.95	42.10	69.47
4	54.40	55.90	75.70	39.40	34.80	77.60	47.70	81.00
5	42.87	44.37	85.55	19.70	47.25	93.30	27.57	81.23
6	37.17	36.90	73.17	35.45	41.60	75.07	43.97	73.80
7	41.40	41.10	77.67	40.05	44.40	79.57	46.07	78.37
8	35.53	35.27	73.45	34.93	39.70	75.35	41.93	74.15
9	31.37	34.20	73.10	32.60	58.43	75.00	38.63	68.47
10	38.53	38.27	81.15	36.20	40.80	83.05	42.83	80.87

11	58.10	59.60	79.40	51.00	30.87	81.30	69.70	84.70
12	37.97	37.63	75.75	32.00	40.30	77.60	40.60	71.93
13	37.23	36.93	73.20	35.25	41.40	75.10	42.53	65.10
14	50.60	52.10	71.90	42.70	45.05	73.80	55.40	77.20

This research also includes a design proposal for the temporary site that is limited to the layout, organized by storage cells for each type of waste, and the operational characteristics for its proper management. For purposes of this paper, it is assumed that all temporary sites are the same in design, dimensions, and operation. Each temporary site has an associated installation cost and storage capacity that should be considered as input variables for the transportation model.

Based on the operational characteristics of the proposed site and the characterization and estimation of waste made by Reyes and Rojas, the total capacity of the temporary site was calculated. The volumetric capacity of the temporary site was calculated from the available space per storage cell, the dimensions and the number of racks and containers that each cell can accommodate, as well as the characteristic weights and volumes of the type of waste to be stored. For bulky waste, no containers are used therefore to calculate the volumetric capacity, the area of land destined to store this waste was multiplied by an average height of two meters. The storage weight capacity was calculated through a conversion factor for each type of residue. This factor was calculated according to the weight / volume relationship from the previous waste characterization data. Table 3: Temporary site capacity per storage cell, shows the capacity per storage cell of the temporary site for bulky and non-bulky waste.

Table 3. Temporary site capacity per storage cell

Classification	Storage cell	Container volume (m^3)	Number of containers available	Available volume (m^3)	Conversion factor	Weight (ton)
Non-bulky waste	Electrical items	0.057	960	55.450	0.128	7.13054043
	Organic and biodegradable waste	1.2	204	244.8	1	244.8
	Packaged food	1.2	204	244.8	0.496	121.487
	Paper and cardboard	0.057	360	20.793	0.553	11.512
	Plastics	0.057	492	28.418	0.058	1.664
	Glass	0.057	240	13.862	0.321	4.456
	Metals	0.057	360	20.793	0.224	4.664
	Textiles	0.057	480	27.725	0.035	0.986
	Infectious biological waste	1.1	450	495	0.008	4.362
	Personal property	0.057	240	13.862	0.046	0.641
	Non- recyclable solid waste	0.057	60	3.465	0.034	0.120
	Leftover rubble	1.2	80	96	0.115	11.071
	Contaminated waste	1.1	450	495	0.059	29.583
	Hazardous waste	1.1	450	495	0.293	145.465
Bulky waste	Furniture	-	-	31650.273	0.040	1273.997
	White goods (large volumen)		-	4621.72	0.054	250.855

The storage capacity of the temporary site per storage cell cannot be taken individually as a constraint for the transportation model because the wastes within the debris are mixed at the time of removal from the disaster site and the amount of each type of waste will not be known with certainty until they are separated into the temporary site. However, assuming that the design of the temporary site is based on the composition of waste observed in the 2017 earthquake and its proportion in relation to the estimated total, the sum of the available storage volumes per each storage cell provides us a reference of the total storage capacity of the temporary site. Table 4: Temporary site storage capacity, shows the capacity in volume and estimated weight of the temporary separation site.

Table 4. Temporary site storage capacity

Waste type	Area (m^2)	Volume (m^3)	Weight (ton)
Non-bulky	-	2,254.97	587.95
Bulky	18135.9966	36,271.99	1,524.85
Total capacity		38,526.97	2,112.80

The dimensional unit of the storage capacity of the temporary site must be defined based on the units of load of the debris and the unit cost of transport in order to maintain dimensional coherence in the transportation model. The unit cost of transportation will be defined, as is common, in units of Mexican pesos per cubic meter per kilometer traveled. In this way, the amount of waste and the capacity of the site will be managed in cubic meters for the purposes of the model.

The installation cost of the temporary site and the unit cost of transportation are parameters whose variability is high over time, therefore it is recommended to make an initial estimate at the time of the disaster of the installation cost, according to the operational characteristics of the site described in previous works, and an estimate of the unit cost of transportation given by service providers.

Retaking, the transportation model must take as input data; the location and number of collapsed buildings at the time of the earthquake, the estimated initial amount of household waste by each collapsed building, the number and location of sites available for the installation of the temporary site, the storage capacity and the cost installation of the temporary site and the unit cost of transportation.

3.3 Influence diagram

The influence diagram shows the relationships between the variables involved in the model in order to define a mathematical relationship of the transportation model and its restrictions. The highest level of the diagram represents the decision variable which is the total cost. The following levels represent each of the input and decision variables that intervene in the calculation of the response variable and are involved in modeling and solving the problem. The relationships between variables are defined from mathematical operations that must be represented in the objective function and the restrictions of the linear program. For example, the sum of transportation cost and the installation cost is the mathematical operation to calculate the total cost, while these variables depending of others to also be calculated. The influence diagram that shows the relationships between the variables described in section 3.2 is represented in figure 1: Model influence diagram.

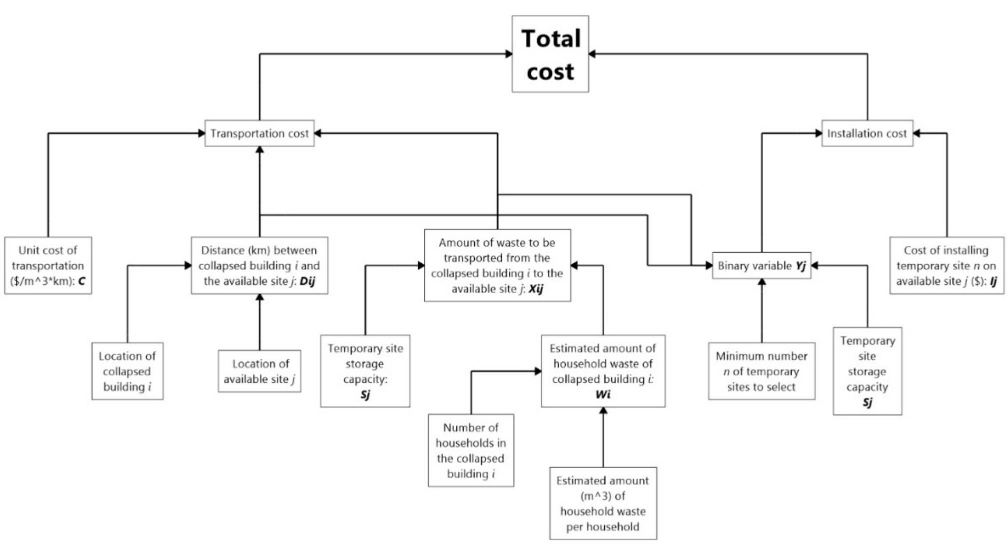

Figure 1. Model influence diagram

3.4 Mathematical relationship

For the application of the transportation model, the collapsed buildings by the earthquake are considered as the points of origin i and the available sites j as the points of destination. For each collapsed building there is a quantity of household waste that needs to be transported to the temporary separation sites, this quantity will take the value of *Xij*. According with the conventional terms of the transportation model, the production capacity will be the amount of household waste generated in each collapsed building, while the demand will be represented by the waste storage capacity of the selected temporary sites. The model must select *n* temporary sites and determine the allocation of the quantities to be transported to each of them, minimizing the total cost of transportation and installation. The development of the general transport model is detailed below, according to the influence diagram shown in figure 1.

1.1.1 Model notations

The transportation model formulation is based on the following notations:

i: *collapsed building*
j: *available site*
l: *total collapsed buildings*
m: *total available sites*
n: *number of selected temporary sites*

1.1.2 Decision variables

X_{ij}: *Amount of waste to be transported from the* $\boldsymbol{i}$ *collapsed building to the* $\boldsymbol{j}$ *available site* $[m^3]$

C: *Unit cost of transportation* $\left[\dfrac{\$}{\boldsymbol{km * m^3}}\right]$

I_j: *Cost to install the* $\boldsymbol{j}$ *temporary site*
D_{ij}: *Distance between collapsed building* $\boldsymbol{i}$ *and available site* $\boldsymbol{j}$
W_i: *Waste generated in the collapsed building* $\boldsymbol{i}$
S_j: *Storage capacity of the* $\boldsymbol{j}$ *available site*

$X_{ij}, C_{ij}, W_i, S_j \in \mathbb{R}^+$

$i = 1,2,3, \dots, l$

$j = 1,2,3, \dots, m$

$Y_j : \begin{cases} 1 & If\ site\ j\ is\ chosen \\ 0 & another\ case \end{cases}$

$Y_j \in \{0,1\},\ j = 1,2, \dots, n$

1.1.3 Objective Function

The function aims to minimize the total cost of transportation, associated with a shorter distance, of the amounts of household waste by earthquake at each collapsed building to the temporary separation sites. The installation cost accompanies the binary variable as a selection criterion for the temporary sites. The optimal solution tends to minimize the cost of installing the sites, in addition to the cost of transporting the waste to each of them.

$$\min Z = \sum_{i=1}^{l} \sum_{j=1}^{m} C D_{ij} X_{ij} + \sum_{j=1}^{m} I_j Y_j$$

1.1.4 Constraints

The number of temporary sites that the model selects is a decision to be made based on each disaster situation. The criteria of minimization of the total cost, which refers to the joint cost of installation and transportation, or solely the minimization of the cost of transportation (possibly associated with a smaller distance, but with a greater number of connected sites) can be used due to prioritization of recovery time over total cost or vice versa. Other influencing factors are the degree of affectation of the earthquake, the total estimated amount of waste, the availability of human, technical and financial resources, the locations and the number of available sites, among other particular aspects given at the time of the earthquake. Thus, it will be necessary to enter the model the number of temporary sites that are required to install through the restriction to select at least *n* temporary sites:

$$\sum_{j=1}^{n} Y_j \geq n$$

For $n \geq 1$

The amount of waste generated at a collapsed building must be removed completely, regardless of whether it is destined for more than one temporary site or not. This restriction is met through:

$$\sum_{j=1}^{m} X_{ij} = W_i$$

For $i = 1, \dots, l$

The storage capacity of a temporary site will only be considered if it is selected by the model. The storage capacity constraint includes the binary variable to ensure that waste will be sent to the site only if it has been selected, such as:

$$\sum_{i=1}^{l} X_{ij} = S_j Y_j$$

Para $j = 1, \dots, m$

3.5 Verification and validation of the model

The verification and validation of the model was performed using the observations and data obtained for the earthquake of September 19, 2017 in Mexico City as is described in section 3.2. The assumptions are the following: the selection of a single temporary waste separation site, an installation cost of the temporary site of 200,000 Mexican pesos, and an average unit cost of transportation (to date) of 24.20 Mexican pesos per cubic meter per kilometer traveled. The optimization problem was solved using the Excel spreadsheet and the specialized software LINGO. The results in both software's were consistent, however, Excel allows a better visualization and manipulation of the data, as well as the input and solution of the model through the Solver complement. Figure 2: Solution of the transportation model through the solver plugin of the Excel software, shows a section of the spreadsheet used to verify the transportation model, it includes the matrix of flows or amounts of waste that are assigned to the selected temporary site. The model solution determines the available site number 4 as the optimal location. The site number 4 is located in Zumpango in the State of Mexico and represents a minimum total cost of 1,735,445.69 Mexican pesos.

Distance Matrix D_{ij} (km)

Collapsed buildings *i*	Temporary site *j*: 1	2	3	4	5	6	7	8
1	36.15	29.75	55.95	58.50	65.70	57.63	63.07	57.03
2	47.57	45.47	79.70	38.25	41.85	81.60	48.10	73.33
3	31.50	32.97	73.10	38.20	56.05	74.95	42.10	69.47
4	54.40	55.90	75.70	39.40	34.80	77.60	47.70	81.00
5	42.87	44.37	85.55	19.70	47.25	93.30	27.57	81.23
6	37.17	36.90	73.17	35.45	41.60	75.07	43.97	73.80
7	41.40	41.10	77.67	40.05	44.40	79.57	46.07	78.37
8	35.53	35.27	73.45	34.93	39.70	75.35	41.93	74.15
9	31.37	34.20	73.10	32.60	58.43	75.00	38.63	68.47
10	38.53	38.27	81.15	36.20	40.80	83.05	42.83	80.87
11	58.10	59.60	79.40	51.00	30.87	81.30	69.70	84.70
12	37.97	37.63	75.75	32.00	40.30	77.60	40.60	71.93
13	37.23	36.93	73.20	35.25	41.40	75.10	42.53	65.10
14	50.60	52.10	71.90	42.70	45.05	73.80	55.40	77.20
Total distance traveled	**580.38**	**580.45**	**1,048.78**	**534.23**	**628.20**	**1,080.92**	**650.20**	**1,036.65**

Unit cost ($/m^3*km)
24.20

Cost Matrix Cij (\$/m^3)

Collapsed buildings *i*	Temporary site *j*: 1	2	3	4	5	6	7	8
1.00	874.83	719.95	1,353.99	1,415.70	1,589.94	1,394.73	1,526.21	1,380.21
2.00	1,151.11	1,100.29	1,928.74	925.65	1,012.77	1,974.72	1,164.02	1,774.67
3.00	762.30	797.79	1,769.02	924.44	1,356.41	1,813.79	1,018.82	1,681.09
4.00	1,316.48	1,352.78	1,831.94	953.48	842.16	1,877.92	1,154.34	1,960.20
5.00	1,037.37	1,073.67	2,070.31	476.74	1,143.45	2,257.86	667.11	1,965.85
6.00	899.43	892.98	1,770.63	857.89	1,006.72	1,816.61	1,063.99	1,785.96
7.00	1,001.88	994.62	1,879.53	969.21	1,074.48	1,925.51	1,114.81	1,896.47
8.00	859.91	853.45	1,777.49	845.39	960.74	1,823.47	1,014.79	1,794.43
9.00	759.07	827.64	1,769.02	788.92	1,414.09	1,815.00	934.93	1,656.89
10.00	932.51	926.05	1,963.83	876.04	987.36	2,009.81	1,036.57	1,956.97
11.00	1,406.02	1,442.32	1,921.48	1,234.20	746.97	1,967.46	1,686.74	2,049.74
12.00	918.79	910.73	1,833.15	774.40	975.26	1,877.92	982.52	1,740.79
13.00	901.05	893.79	1,771.44	853.05	1,001.88	1,817.42	1,029.31	1,575.42
14.00	1,224.52	1,260.82	1,739.98	1,033.34	1,090.21	1,785.96	1,340.68	1,868.24

Flow Matrix X_{ij} (m^3)

Collapsed buildings *i*	Temporary site *j*: 1	2	3	4	5	6	7	8	Constraints of generated waste in m^3 (W*i*)		
1	0.00	0.00	0.00	15.40	0.00	0.00	0.00	0.00	**15.40**	=	**15.40**
2	0.00	0.00	0.00	30.80	0.00	0.00	0.00	0.00	**30.80**	=	**30.80**
3	0.00	0.00	0.00	246.38	0.00	0.00	0.00	0.00	**246.38**	=	**246.38**
4	0.00	0.00	0.00	246.38	0.00	0.00	0.00	0.00	**246.38**	=	**246.38**
5	0.00	0.00	0.00	15.40	0.00	0.00	0.00	0.00	**15.40**	=	**15.40**
6	0.00	0.00	0.00	323.37	0.00	0.00	0.00	0.00	**323.37**	=	**323.37**
7	0.00	0.00	0.00	184.78	0.00	0.00	0.00	0.00	**184.78**	=	**184.78**
8	0.00	0.00	0.00	61.59	0.00	0.00	0.00	0.00	**61.59**	=	**61.59**
9	0.00	0.00	0.00	15.40	0.00	0.00	0.00	0.00	**15.40**	=	**15.40**
10	0.00	0.00	0.00	46.20	0.00	0.00	0.00	0.00	**46.20**	=	**46.20**
11	0.00	0.00	0.00	15.40	0.00	0.00	0.00	0.00	**15.40**	=	**15.40**
12	0.00	0.00	0.00	123.19	0.00	0.00	0.00	0.00	**123.19**	=	**123.19**
13	0.00	0.00	0.00	184.78	0.00	0.00	0.00	0.00	**184.78**	=	**184.78**
14	0.00	0.00	0.00	369.57	0.00	0.00	0.00	0.00	**369.57**	=	**369.57**
Constraints of storage capacity in m^3 (S*j*)	**0.00**	**0.00**	**0.00**	**1,878.63**	**0.00**	**0.00**	**0.00**	**0.00**			
	≤	≤	≤	≤	≤	≤	≤	≤		Objective Function	
	0.00	0.00	0.00	38,526.00	0.00	0.00	0.00	0.00			$ 1,935,445.69

Transportation cost	1,735,445.69
Installation cost	200,000.00

Site	1	2	3	4	5	6	7	8	Number of locations selected		
Sj	38,526.00	38,526.00	38,526.00	38,526.00	38,526.00	38,526.00	38,526.00	38,526.00			
Ij	$ 200,000.00	$ 200,000.00	$ 200,000.00	$ 200,000.00	$ 200,000.00	$ 200,000.00	$ 200,000.00	$ 200,000.00	n		
Yj	0	0	0	1	0	0	0	0	1	≥	1

Figure 2: Solution of the transportation model through the solver plugin of the excel software

4. Results and conclusions

The linear program of the proposed transportation model determines the optimal location of a single temporary site in a place known as Ejido de San Juan Zitlatepec belonging to the municipality of Zumpango in the State of Mexico. The location of this temporary site represents a minimum total cost of 1,735,445.69 Mexican pesos. The amount of household waste sent to the temporary site is equivalent to 71.02% of the non-bulky waste storage capacity while it is only 4.16% of the total capacity. The sum of the distances between each of the 14 collapsed buildings by the 2017 earthquake and the selected temporary site is 534.23 km, which is 51% less than that of the farthest site and 7.95% less than that of the next nearest site.

By running the model with the selection of two temporary sites, the cost of transportation decreased by 2.81% while the total cost increased by 7.82%. For this solution, the model sends only 13.93% of the total waste to the nearest second site. This is due to the fact that, although forcing the model to select two sites, the first one continues to be the closest to most of the disaster points and the decision to locate two temporary sites does not represent, for this case study, a viable alternative. In addition, the design capacity of a single temporary site is expected to be sufficient to meet the requirements for receiving waste in the event of an earthquake. However, due to the level of uncertainty of this type of event, it is a decision that will continue to open the evaluation of alternatives in a given scenario. The use of the model developed here is a useful tool for the evaluation of alternatives mentioned above through the analysis of the response variables provided. The study concludes that the location of temporary waste separation sites through the proposed model contributes to the planning of pre-disaster actions, as well as those of response and decision-making in the post-disaster stage.

Such as the case of earthquake waste management, the location of facilities and / or strategic locations of warehouses, collection centers, medical care, support brigades, among others, is essential for the efficient management of humanitarian supply chains and logistics in emergencies. The opportune actions in these cases procure and save human lives and decrease the affectations and impacts on the society and the environment involved. It is necessary to continue working on this axis of development to increase the resilience of Mexico City to these types of events and in the long term of other vulnerable areas of the country.

Acknowledgements

This research was financed with resources from the Program of Support for Research Projects and Technological Innovation (PAPIIT, by its name in Spanish: Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica) of National Autonomous University of Mexico. Project number TA101119.

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