Optimization of Fire Stations Services in Minna Metropolis using Maximum Covering Location Model (MCLM)

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Research Article

Optimization of Fire Stations Services in Minna Metropolis using Maximum Covering Location Model (MCLM)

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A b s t r a c t

The study is aimed at determining the optimal locations for the present geographical location of fire stations service in Minna Metropolis considering the distance and benefits of the users to the facility or if there is needs for an additional fire stations service to be added using Maximum Covering Location Model (MCLM). The existing fire stations service in the study area were three (3) which served as facilities (Supply) while 2012 and 2014 number of fire incidences and the population were used as the centroid points for the wards and also utilized as demand points which are twenty-five (25) in the study area. The impedance time was set to be 5-minutes and 2000 meter radius was used as a distance factor. After the assessment of the coverage of the existing fire stations service using (MCLM), It was discovered that two wards were uncovered (based on the imposed time constraint) while nineteen (19) wards were uncovered based on the distance factor. Thus, the three fire stations service could not guarantee total coverage in the study area. Therefore, recommendations was made for the location of five (5) new fires stands to serve the uncovered wards in the study areas in case of emergency.

1. Introduction

Locations of the best facilities of emergency services, such as fire stations service and ambulances are the major concerns of the Local and the State Government everywhere in the orb. Determining where to site the

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spare facilities and what figures of these facilities are needed to be sited are very teething troubles that course of action (policy) makers are uneasy with in the present day urban area (Algharib, 2011). Catay et al. (2010) dealing with emergency activity such as sickness, accident, disaster, and fire etc. the arrival time of the fire services or ambulance to the region where the incidence occurred is very paramount in other to safe guard lives and properties. The emergency activity services reduces the death rate and infirmity, as well as assists to anticipate economic losses if it well planned. siting of new stations (fire stations) in a best location as to do with three factors (i.e. time, distance and population) of such area intend to locate the facilities for the benefit of the potential users (demands) to have an ease assess to the facilities (Supply) in other to reduce the hazard that might have caused due to sickness, accident, disaster, and fire etc. to prevent loss of lives and properties if peradventure there is an emergency of call case of any incidence (Challands et al. 2010). Minna fire service is not different from other fire stations service in the entire world. It's meant to serve the entire populace by reducing loss of lives and properties in case if there are emergency cases such as fire, oil spillage etc. considering the major factors (i.e. The distance among the stations should be different however with respect to population density and the land uses and so the response area should be different, but the maximum accessibility and a time interval of 3 to 5 minutes should be the determinant factors, the response time of each station should depend on its area of action, so the stations should cover at most 2000m radius to guarantee quick response with respect to the 40km speed per hour) during the siting of this facility in question (fire station) in other to determine the number of stations that would be enough to occupy the entire service area is of a great concern of the policy maker and the planners (Habibi et al., 2008). This study was carried out in other to solve the problem of inequality distributions of fire stations services in some part of Minna metropolis by determining the optimal locations for the present geographical location of these facilities considering the distance from the potential users (Demands) to where these facilities were sited and also to see if all the potential users (Demands) are benefiting from these facilities or there is needs for an additional fire stations to be added in the study area using Maximum Covering Location Model (MCLM). Also, to determine the best location of additional services of facilities in the city and to assess the maximum coverage of the people the facilities will serve.

2. The concept of Maximum Covering Location Model (MCLM)

Maximum Covering Location Model (MCM); locates a facility called m and the m which is the facility use to increase (maximize) the total figure (number) of the demands to be covered by the facility m. In addition, location-allocation model (MCLM) also handle both high/small demand points in a real sense whereby allow some demand points to be uncovered if the figure (number) needed to covered the total demand points of that particular area as gone beyond the limit range of the m (Authors Research, 2016).

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Thus, based on the defined parameters above; pq is a new variable introduced to be equal to 1 when the demand points (nodes) q is covered and otherwise to be zero. As a result, the new parameters added can be expressed (MCLM) as:

$$Max \sum_{q \in Q} hq\, pq \tag{1}$$

$$\sum_{k \in K} Xk = m \tag{2}$$

$$pq - \sum_{K \in Nq} Xk \leq 0 \; \forall q \; \in Q \tag{3}$$

Where

$$Xk \; \in \; \{0,1\} \, \forall q \; \in K$$

$$pq \; \in \; \{0,1\} \, \forall q \; \in Q$$

From inference drawn from the objectives it locates the actual number of facilities that can be served conveniently in any demand points at any particular region within a specified distance range. Also, that all the demand points (Nodes) within a specific range (distance) would be covered and benefited from the facility in all of set covering location. Therefore, Equation (1) wants facilities m to be sited. Equations (2) links the facility m sited with the number of the demand points meant to be covered and finally, Equation (3) is integral constraints. Thus, two factors were involved in the formulation of location-allocation problems which are maximum distance and time constraints. As a result, set covering model was formulated in other to reduce the cost of siting a facility for the coverage level to be achieved. However, from the literature it was also reviewed that there two (2) main sections of covering models in which coverage is to be optimized when dealing with pull objectives in respect to covering models in the network models they are: Location Set Covering Model (LSCM) and the Maximum Covering Location Model (MCLM). According to Klose and Drexl (2005), Location Set Covering Model (LSCM) was formulated as follows:

$$min \sum_{x \in X} zx$$

$$\sum_{x \in X} akxzx \geq 1 \;\; \forall k \in K,$$

$$zx \in \{0,1\} \, \forall x \; \in X$$

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Where $akx = \begin{cases} 1 \; for \; wkdkx \prec r \\ 0 \; for \; wkdkx \geq r \end{cases}$ computes a set of at most q centers with a range lesser than r or no exit sets. On the contrary, from the design of location – allocation problems, the MCLM is the main location covering problems used to locate the actual number of demand points that the facility will serve conveniently at any particular region within a specified distance range (i.e. determining the circular balls with minimum radius for Euclidean distance within a particular region). Owen and Daskin (1998) and Plastria (2001) provide complete information on this location-allocation problem (MLCM). The Pull objectives are: MCLM locates the actual number of demand points that the facility can serve at any particular region within a specified distance range conveniently. The demand points (Nodes) within a specific range (distance) would be concealed and benefited (served) from the facility in all of set covering location problems.

3. Materials and methods or Study area description

3.1 Materials

Both the primary and secondary data were used in the cost of this study; the primary data used was the spatial data of the existing fire stations (i.e. x and y coordinates) using hand held GPS in the study area which was depicted in Table1and the secondary data includes a LANDSAT ETM 15m resolutions imagery of the study area acquired from Department of Geography, FUT Minna, the total number of recorded fire occurrences and the population.

Table 1: Location of the existing fire Stations and there coordinates within study area

S/N	FIRE STATION NAME	LOCATION	EASTINGS (mE)	NORTHINGS (mN)
1	Fire Service Headquarters	Bosso	230632.000	1064701.000
2	Tudun Wada Fire Service Station	Tunga	231433.000	1061223.000
3	Bosso Fire Service Station	Bosso	229944.000	1064973.000

Prior to the census conducted in 2006; an estimated population of 3.4% annual growth rate was estimated and used in this study. However, in 2012 a total number of fifty (50) fire incidences were recorded while in 2014 a total number of seventy (70) fire incidences were also recorded in Minna Metropolis. The estimated population for 2012 is 426,269 while for 2014 is 455,749 were also used during the course of this study.

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3.2 Methods

The spatial distribution of the fire stations within the study area (i.e. the x and y coordinates) were used to determine the coverage limit between demand points and the facility (fire station) whereby using two constraints (time and distance) alongside with the demand points (i.e. the centroid). The impedance time was set to be 5-minutes and 2000 meter radius was used as a distance. Thus, to evaluate, equate and ascertain the coverage of the facility that would be covered by the demand points based on the two imposed constraints (time and distance); Maximum Coverage Location Model (MCLM) was used alongside with Arc GIS software. Then, with the integration of Maximum Covering Location Model with the Geographical Information System (GIS); 2012 and 2014 populations and previous recorded occurrences of fires was used to produce various coverage results (i.e. the uncovered and covered regions in the study area). Figure 1 shows the pull objectives of MCLM Model used in this study.

3.3 Algorithms of Pull Objectives MCLM

Let F = (x' and y') = Facility (Fire Station) (4)

D = Demand points/Centroid points (5)

IT/DF = Impedance Time (5minutes) and Distance Factor (2000meters) (6)

CA = Covered Area

UA = Uncovered Area

Thus, equate Equations (5) into Equation (4) and impose Constraint Equations (6) as a buffer range to determine the covered and uncovered areas by (MCLM) (7)

Let CA = If Equations (7) fall within the range/ radius of specified buffer range of distance factor (2000m) or impedance time (5 minutes) of Equation (4)

Let UA = If Equations (7) fall beyond the limit of specified buffer range of distance factor (2000m) or impedance time (5minutes) of Equation (4)

Therefore,

FD = CA (i.e. If IT/DF < FD) (8)

If Equation (8) cannot hold (i.e. to cater for the all demand points at a particular region), let additional facilities to be sited for the people in the region be Equation (6) (i.e. facility to cater for the uncovered area)

FD = UA (i.e. If IT/DF > FD) (9)

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However, siting a fire station service, there are two questions to have in mind: (i) Is the siting of the facility will be enough to serve the people intend to serve? (ii) What is the distance of the facility to the potential users (i.e. demand points) to serve? Thus, in siting a fire service station not all the node (demand points) would be served using (MCLM) but if the demand points (i.e. the potential users) to use the facility is within the service region they would also be benefited from the service (facility) even though its more than ten minutes away from the close facility but if it beyond the limit of the imposed time and distance constraints some areas will be uncovered (i.e. They will not be benefited) from the services of the facility in intend to render.

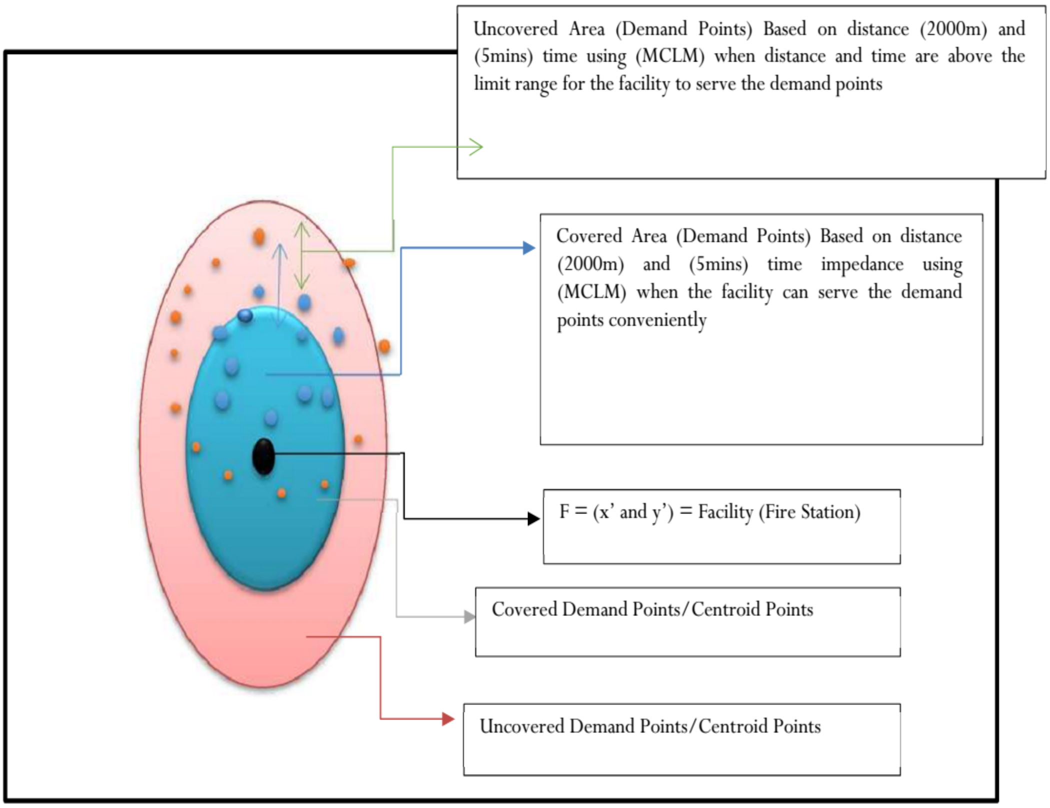

Figure 1: The Pull objectives of MCLM

3.4 Study Area description

Minna the capital city of Niger State has its center co-ordinates on 600 33' 00''E and 90 37' 00'' N and it covered an area approximately 884 hectares. Minna consists of two local Government Areas (i.e. Bosso and Chanchanga Local Government Area). It consists of various neighborhoods as depicted in Figure 2. Minna populations in 2006 census was 348, 788.

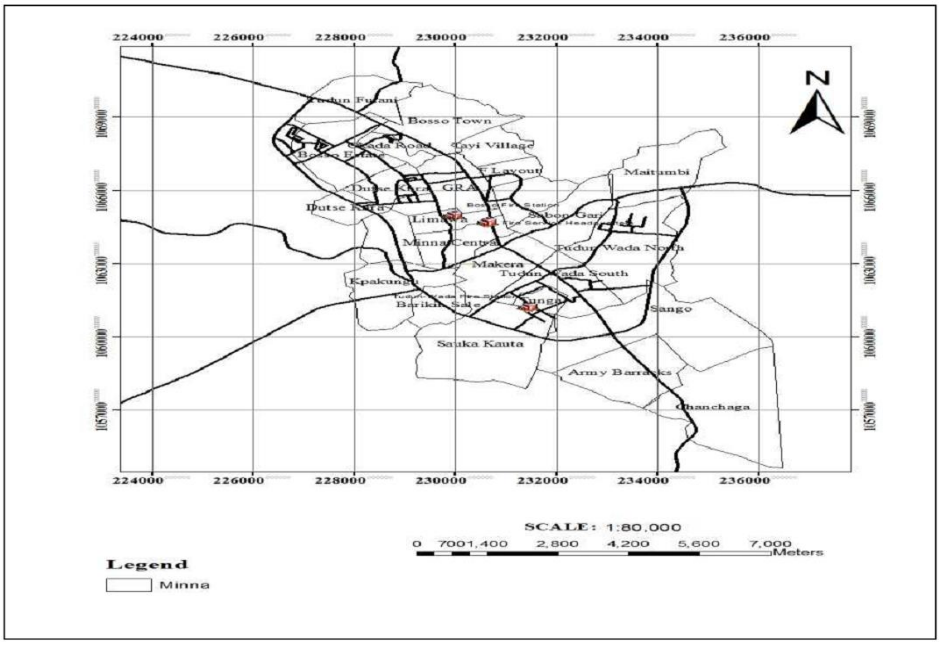

Figure 2: Map of the Study Area (Department of Geography, FUT Minna, 2016)

3.5 Experiment/ tests conducted

Geo-referencing and digitizing a LANDSAT image (i.e. 15m resolutions) of Minna in a layer under the geo-database file format was the first process. Thereafter, the addition of shape files for 2012 and 2014 fire occurrences record and the population of the study area. Thus, additional shape files was also made for the three fire stations found in the study area. The process is depicted in figure 3. The steps used to evaluate the x and y coordinates of the fire stations in the study area using Maximum Covering Location Model was depicted in figure 4. Hence, a dataset is required whenever any analysis wanted to be carried out using Network Analyst Tool in Arc Map. In view of that, in the Network Analyst Toolbar a New Location-Allocation was chosen at the end of the data preparation. On the other hand, for the “new location-allocation”, a layer was produced; and the layer was presented alongside with its six network analysis classes. Originally, by default Network Analysis Class were unfilled. Network analysis classes are: Demand points, Line Barriers, Facilities, Polygon Barriers, Lines and Point Barriers. Finally, all the three fire stations service found in the study area are the facilities in the Network Analysis Class. As demand points (i.e. the potential users), the following data were added for the year 2012 and 2014 respectively (Population and fire incident data). A set-up of location-allocation properties was set and twenty-five (25) demand points were considered for the analysis. Conversely, all the necessary setting was carried out in the location-allocation model software used in running the analysis. Travel from was set to Facility to Demand

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and other default settings of U-turns at junctions and restrictions were maintained. In the 'Analysis Setting' tab, Impedance was set to minutes, In the 'Advanced Setting" tab, Facilities to choose was set to three (3), Problem Type was set to Maximize Coverage, Impedance transformation was set to linear, Impedance cutoff was set to five (5) and other default settings were maintained. The "Solve" button on the Network Analyst Toolbar was then used to run the location-allocation analysis. The analysis was run thrice selecting one fire station at a time until all the three existing fire stations were included in the analysis. Also, impedance cut off was set to 2000 to determine how the models will perform with distance.

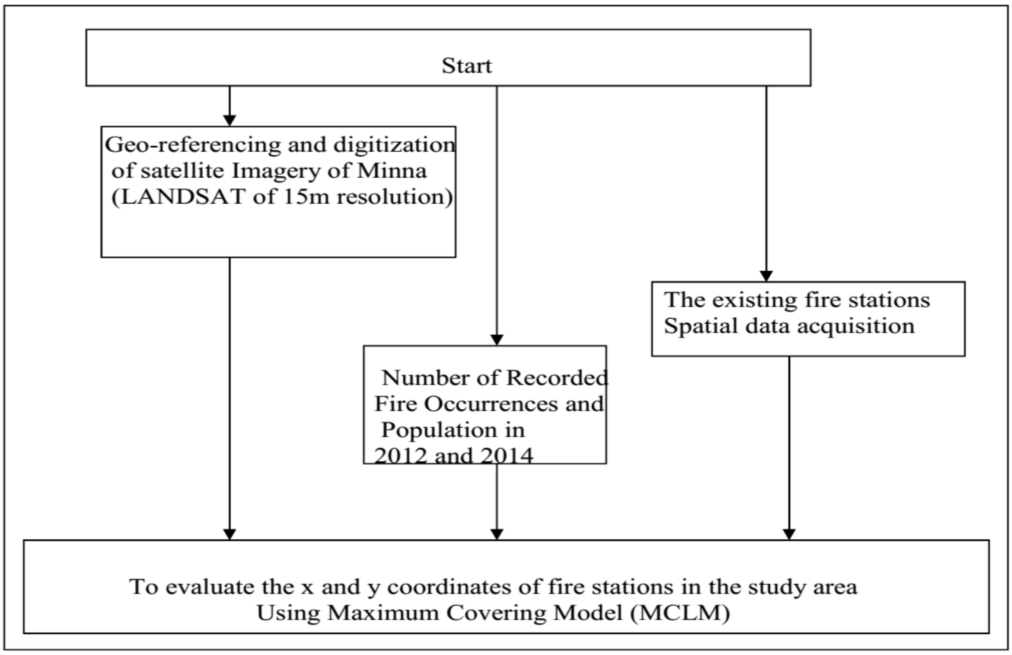

Figure 3: Maximum Covering Model for Data Preparation Analysis (Authors Research, 2016)

4. Results and Discussion

4.1 Results

The outcome of using the Maximum Covering Location Model (MCLM) using one fire station was shown in figure 5, twenty (20) areas were covered out of twenty-five (25). In Figure 6, the result from applying the model using two fire stations is shown and the analysis showed that twenty-three (23) were covered out of the twenty-five (25) areas. However, adding the third fire stations to the analysis doesn't have any effect on the uncovered area earlier from analysis when two fire stations were used. Figures 7 - 9 show the result from applying the Maximum Covering Location Model using the 2000m distance threshold with one, two and three fire stations respectively. Figure 10 shows the locations for siting new fire stations to correct the problem of under-coverage and attain maximum coverage.

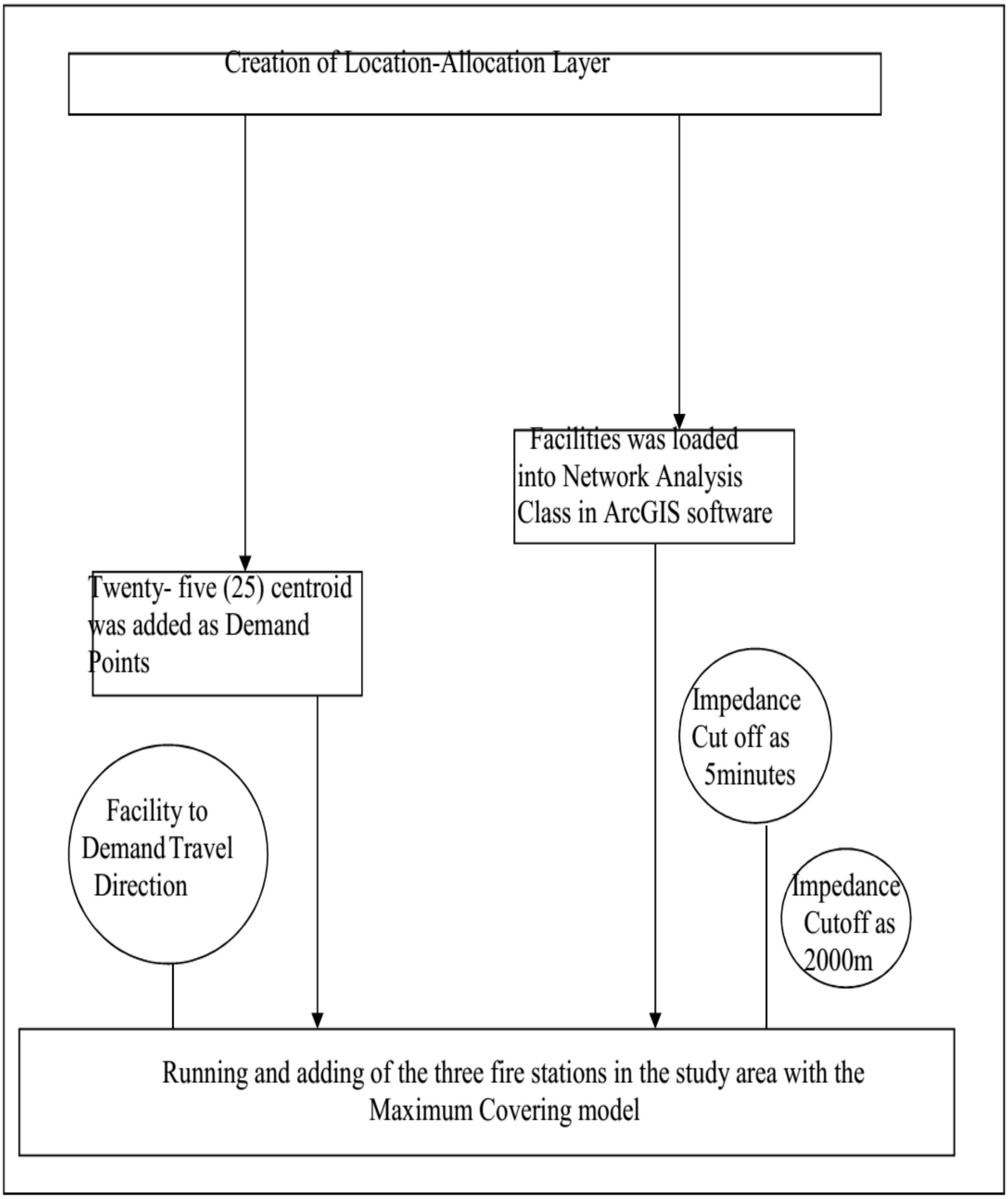

Figure 4: Method of generating location-allocation layer and running of MCLM

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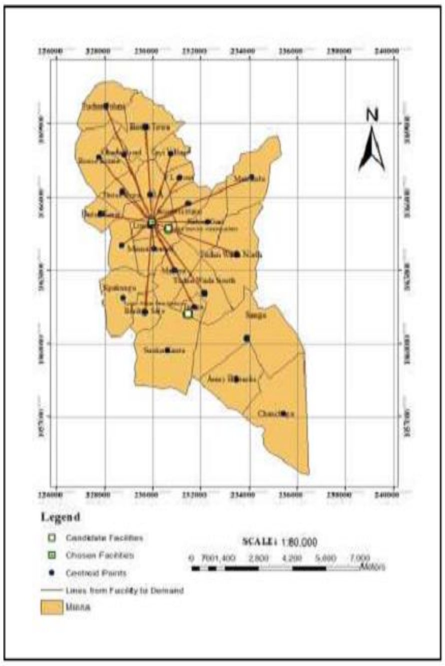

Figure 5: Maximum Covering Model using one fire station

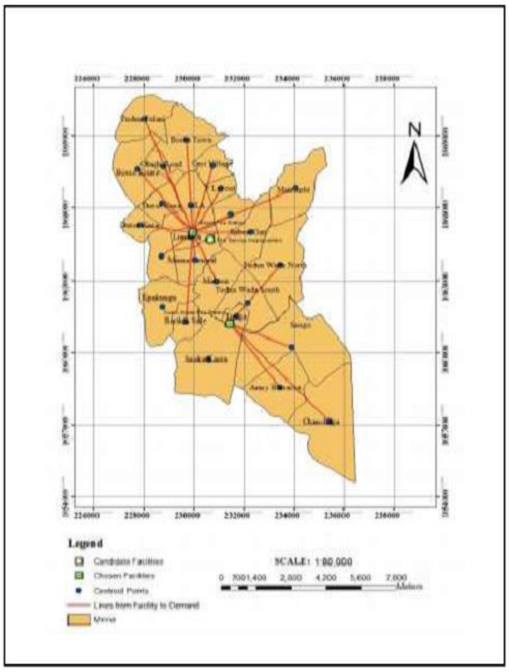

Figure 6: Maximum Covering Model using 5 minutes response time

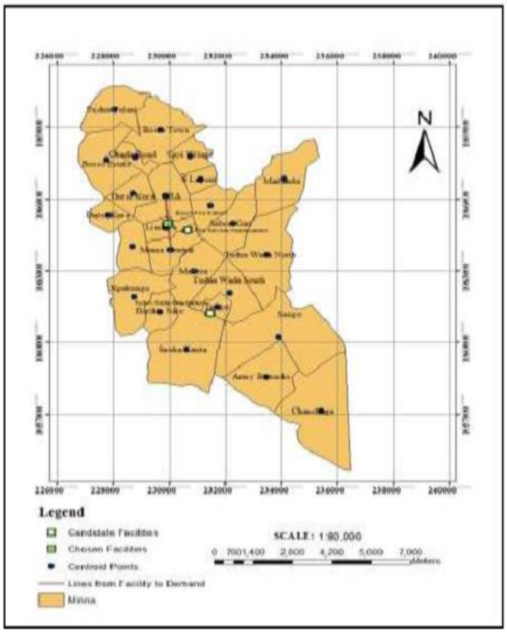

Figure 7: Maximum Covering Model with one Fire station using 2000m distance threshold

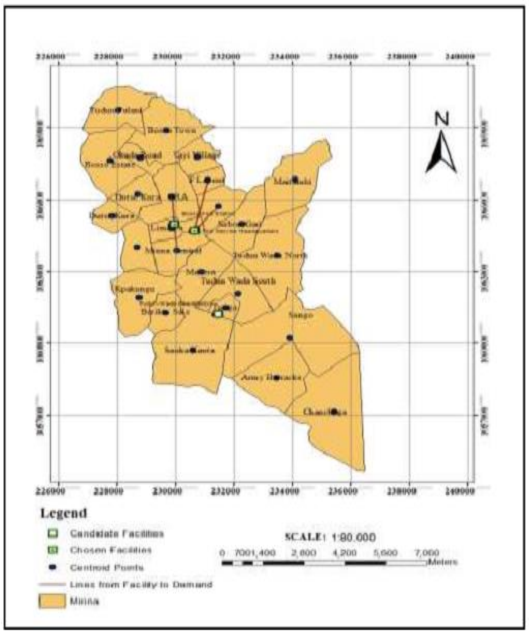

Figure 8: Maximum Covering Model with two fire stations using 2000m distance threshold

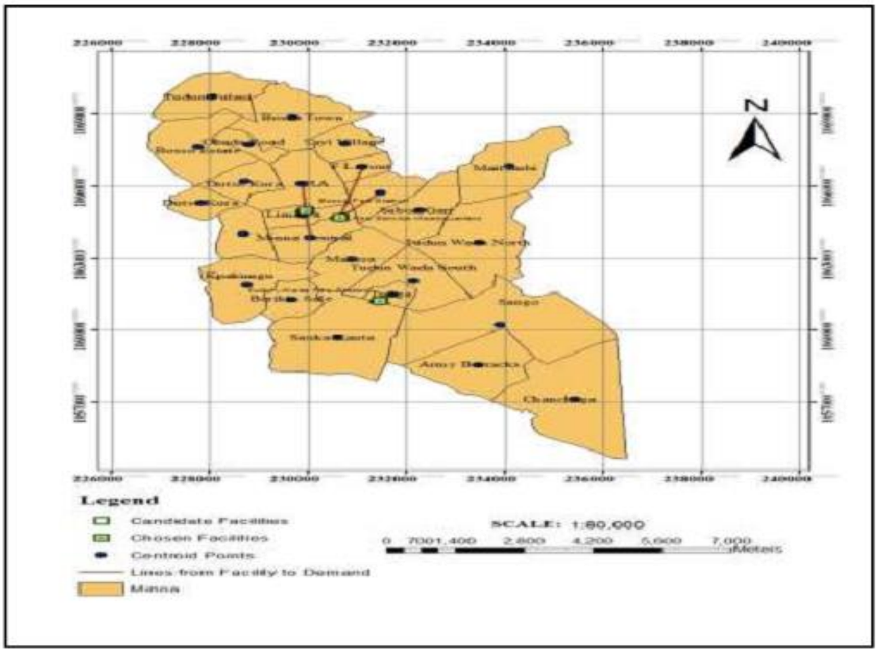

Figure 9: Maximum Coverage Model with three Fire stations using 2000m distance threshold

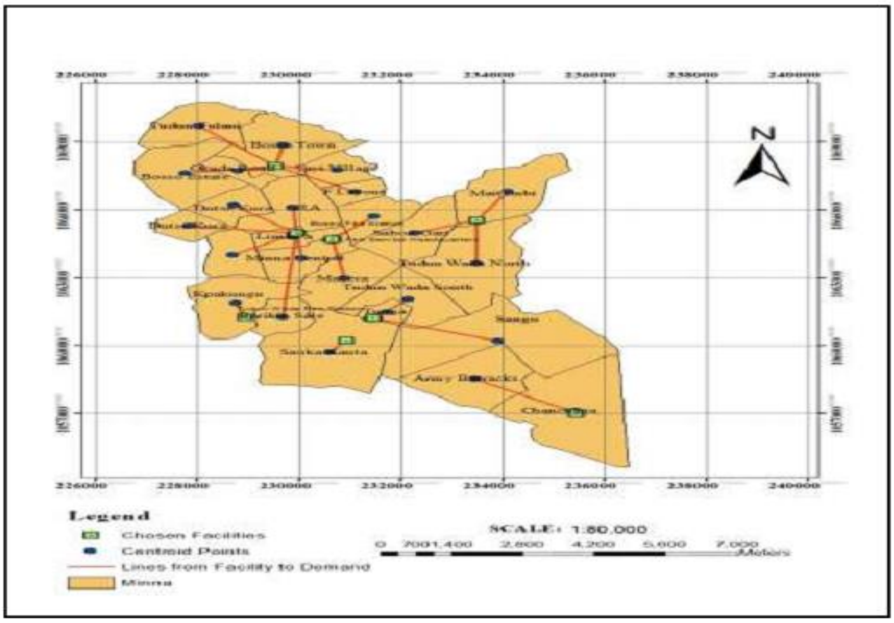

Figure 10: Maximum Coverage range for Siting New fire stands location

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Table 2 and 3 shows the covered and uncovered areas using the 5minute response time and 2000m distance threshold respectively.

Table 2: The figures of fire incidences and population of concealed and unconcealed areas using 5-minutes response time

S/N	Concealed Areas	Population 2012	Affected Area by Fires_2012	Population (2014)	Affected Area by Fires (2014)
1	Bosso Town	22310	6	23850	3
2	GRA	16730	2	9250	2
3	Sabon – Gari	16250	1	17400	1
4	Chanchaga	41270	2	44130	4
5	Limawa	6220	3	6650	3
6	Okada Road	4360	0	4660	0
7	Tunga	3920	7	4190	10
8	Tudun Fulani	16660	0	17810	3
9	Tudun Wada North	30970	2	33110	3
10	SabonGari	10410	1	11130	1
11	Tudun Wada South	15960	4	17100	5
12	Army Barracks	23630	2	24290	1
13	Dutse Kura II	6750	3	9250	2
14	Bosso Estate	20700	2	22130	2
15	Sango	45730	0	48920	3
16	Minna Central I	11420	1	12210	3
17	F-Layout	5032	2	5380	2
18	Dutse Kura I	8650	3	9250	3
19	Maitumbi	21370	3	22850	3
20	Tayi Village	8230	0	8790	0
S/N	Concealed Areas	Population 2012	Affected Area by Fires_2012	Population (2014)	Affected Area by Fires (2014)
21	Makera	15370	2	16440	5
22	Minna Central II	10590	1	11320	3
23	Barikin Sale	7970	1	8520	3

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S/N	Unconcealed Area	Population 2012	Affected Area by Fires_2012	Population 2014	Affected Area by Fires _2014
1	SaukaKauta	37020	0	39580	2
2	Kpagungu	19930	4	21310	

Table 3: 2000m radius as threshold for Concealed and Unconcealed Areas in the study area (Authors' Analysis, 2016)

S/N	Concealed Areas	Unconcealed Areas
1	F-Layout	Okada Road
2	SabonGari I	Dutse Kura I
3	GRA	Bosso Town
4	Limawa	Tudun Fulani
5	Tunga	Dutse Kura II
6	Minna Central I	Bosso Estate
7		Tayi Village
8		SaukaKauta
9		Tudun Wada South
10		Barikin Sale
11		Chanchaga
12		Tudun Wada North
13		Minna Central II
14		Makera
15		Kpakungu
16		Army Barracks
17		Maitumbi
18		Sango
19		SabonGari II

4.2 Discussion of Results

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Twenty-three (23) out of the twenty five (25) areas were hid by just two of the fire stations in the study area shown in figure 6. Sauka-Kauta and Kpakungu are the areas that were uncovered and the two areas covered 56,950 people out of the total number of people in the whole twenty-five (25) areas which was 374,182. However, the addition of the third fire stations to the analysis did not give a result for the additional coverage of the study areas for the uncovered areas earlier mentioned in (section 5.0) from analysis when two fire stations were used; by implication the specified five minutes time impedance used as an effect on the distance to the facility in question (i.e. > Fire Station). Figures 7 to 9 show the result obtained from applying the model using one, two, and three fire stations respectively with the 2000m distance threshold. In figure 8 the three (3) fire stations were added in the analysis and result showed that a total of six (6) areas were covered by the existing three (3) fire stations and nineteen (19) areas were uncovered. The need for siting more new fire stations in the study area is of great concerned based on the fact that the population of the uncovered area in the future will proliferation and it will have an adverse effect on how fire incidences to be attempted to and this will prevent loss of lives and properties if the State Government can site more new fire stations.

Similarly, among the three fire stations found in the study area; two of these existing fire stations are too close to each other (i.e. in term of distance) which are extremely increases the maximum coverage of one and dipping the maximum coverage of other (Bosso Fire Service and Fire Service Headquarters). The analysis of the spatial distribution of the three (3) fire stations located within the study area; the criteria used in siting them and the results of covered and uncovered areas in terms of map were able to ascertain. Based on this, the number of existing fire stations in the study area cannot accommodate the whole city thus more fire stations is needed to be sited. The locations for the new suggested fire stands together with their coordinates to spot-on uncovered area are shown in table 4. The locations of the area for the new proposed fire stands are: Maitumbi, Sauka-Kauta, Kpakungu, Bosso, and Chanchaga area.

Table 4: Location for New Fire Stands Coordinates

S/N	Location	Eastings (mE)	Northings (mN)
1	Maitumbi	233523.267	1065514.298
2	Kpakungu	230898.878	1060241.211
3	Sauka-Kauta	228906.278	1061213.208
4	Chanchaga	235467.262	1056985.019
5	Bosso	229538.077	1067919.992

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5. Conclusion/ Suggestion

5.1 Conclusion

This model (i.e. Maximum Covering Location Model) as proved the efficacy of locating the best location of fire station within a specified areas whereby used to determine the relationship between the facility (fire station) and potential users (demands) that can be concealed in term of distance and a predefined response time. This method of location-allocation problem when integrated with Geographical Information System (GIS) provides an optimal location of facilities. Based on capacity and demand information and queries generated in this work, the expansion and intensification in population there was quite proliferation in the record of the fire incidences between 2012 and 2014. Thus, the incidence of the disaster in the amount of fire in the future will be intensification. As shown in Figure 10 and Table 4.

5.2 Suggestion

It is suggested that the location for siting new fire stands to correct under-coverage problem should be considered. Finally, the optimal fire station centers are visually detected by employing an improved Maximum Covering Location Model, which considers both geographic accessibility and service quality in the research area.

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