# MULTI-COVERAGE DYNAMIC MAXIMAL COVERING LOCATION PROBLEM

Cynthia Porras [*], Jenny Fajardo [*], Alejandro Rosete [*]
*Facultad de Ingeniería Informática, Universidad Tecnológica de la Habana "JoséAntonio Echeverría" (CUJAE), Cuba.

**ABSTRACT**
In the field of service management plays a decisive role the location of the facilities to improve the quality of services. The maximal covering location problem allows locating a known number of facilities in order to maximize the demand covered. An important aspect to take into account is the varying of demand of the nodes with respect to the time (multi-period model). In addition, each facility could be of different types. A model that takes into account the existence of different types of facilities in order to cover the demand in multi-period environments has not been found in the literature. In this paper we propose a new generalization of the dynamic maximal covering location problem where different types of facilities (with different radius of coverage) could be open in each location. In this work we used the model on case study with the objective to locate the police patrol.

**KEYWORDS:** multi-coverage dynamic maximal covering location problem, police patrol.

**MSC:** 90B80

**RESUMEN**
En el campo de la distribución de servicios juega un papel decisivo la localización de las instalaciones con el objetivo de maximizar la cobertura sobre la demanda. El problema de localización de máxima cobertura pretende localizar un número conocido de instalaciones con el objetivo de maximizar la demanda cubierta. Un aspecto importante a tomar en cuenta es la variación de la demanda de los nodos en el tiempo (optimización dinámica). Además, las instalaciones pueden ser de diferentes tipos. En la literatura no se ha encontrado un modelo que tome en cuenta la existencia de diferentes tipos de instalaciones para cubrir la demanda de los nodos en entornos multi-periodos. En este trabajo se propone una extensión del problema de localización de máxima cobertura dinámico donde se tienen diferentes tipos de instalaciones (diferenciadas por el radio de cobertura), las cuales pueden ser habilitadas en cada localización. En este trabajo aplicamos el modelo sobre un caso de estudio con el objetivo de localizar el patrullaje policial.

**PALABRAS CLAVES:** problema de máxima cobertura dinámico multi-cobertura, patrullaje policial

## 1. INTRODUCTION

The locations models are very important in the field of science, industry and real-life. A classic location problem is the Maximal Covering Location Problem (MCLP) [12]. The MCLP was introduced by ReVelle and Church in 1974 [2] and the objective is to locate a known number of facilities in order to maximize the coverage over the demand nodes. The MCLP has been studied in many works and since its first publication until 2015 it has had more than 1550 citations in the academic literature [19] and currently has more than 2000 citations, which represents an increase in research about the problem. Several applications of this problem are: police patrol location [13, 16], ambulances distribution [1, 20], mobile network location [7], mobile sensor location [4], fire stations location [28] and intersection safety camera location [5]. From the MCLP a set of extensions have been made incorporating dynamism, taking into account the fluctuation of the demand nodes in certain periods. In this case, the scenarios can be modelled having periods of time, interpreting the periods as times of day, months and years, where the demand of the clients can be different in each period. The first dynamic MCLP proposal was published in [14], where it was known the number of facilities to be located in each period of time. In this paper we will focus on the variant proposed in [12] (DMCLP), which allows to locate the facilities in long periods of time without preference of number of facilities by period.
The variety of services and resources that exists has led to analyse as to combine the different types of resources to improve the satisfaction of customers. For example: there could be scenarios where it is necessary to locate a set of wifi antennas, but there are different models, which differ in the quality of the

signal that they emit. Having the number of antennas for each model, it is necessary to obtain a combination that allows to locate all the antennas in order to maximize the demand. An extension of the MCLP in order to locate ambulances of different types to maximize coverage of emergencies (MCLP-P) was presented in [20]. In [24] a generalized variant of the MCLP has been proposed, which includes different types of facilities and demand nodes: the multi-type maximal covering location problem (MTMCLP). Recently, in [23] a static robust cooperative maximal covering location problem was proposed, where different types of facilities are differentiated by their capacity and was applied to the location of Tele-taxi stations.
The existence of different types of facilities, where is known the number of facilities that must exist of each type, has not been used in multi-period scenarios. A scenario where it is necessary to take into account both aspects would be: the location of different types of police officers, which have resources that allow them to monitor at different distances. Also, they must monitor areas at different times of the day, where the behaviour of the incidents is different in each schedule. Therefore, a combination of the types of police officers must be obtained in order to maximize the vigilance of the incidents at different times of the day.
A model that can solve the previous situation has not been found in the consulted literature. Then, this paper proposes new a generalization of the DMCLP, which take into account the locations with different types of facilities, where all provided the same service and the difference of one type with respect to another is the coverage radius of the facility. This proposal could be applied in various scenarios such as: the cameras location with different reach levels, the police officer's location depending on the type of vehicle used, where they would change their radius, and the location of different types of wifi antennas, where the types of antennas are differentiated by the level of signal reach, among others.
The paper is organized as follows: Section 0 presents a literature review about variants of MCLP that include dynamism and/or different types of facilities. Section 0 describes the mathematical model of DMCLP. Section 0 describe the mathematical model of the proposal: Multi-coverage dynamic maximal covering location problem (MC-DMCLP). Section 0 presents the application of new model in a case study: Police Patrol Location. Finally, Section 0 provides the conclusions.

**2. LITERATURE REVIEW**

## Dynamic models

The first dynamic maximal covering location problem was proposed by Gunawardare in 1982 [14], where the number of facilities to be located per period of time is known. In 2011 Tanaka [25] proposed a dynamic MCLP where the coverage on the flow is maximized (MFCLSTP), taking into account that the facilities have a start time. Two models are analysed: MFCLSTP1 where the start times are independent for each facility and MFCLSTP2 where all the facilities begin at the same time. Başar et al. [1] applied the dynamic MCLP with double backup coverage (MPBDCM) for the location of ambulances (EMS), and used GIS to represent the solution. Only two periods were analysed, where the number of ambulances assigned to the first period must be less than those of the second period. In 2013 Zarandi et al. [12] proposed a large scale dynamic MCLP (DMCLP), where the number of facilities to be located in each period is unknown. In 2013, Tanaka and Furuta [26] proposed an extension of its proposed model in [25], adding different levels of coverage to the metro stations and to flow of the station. The objective function of this model is defined as the sum of the demand covered by all levels of coverage, so the nodes will be covered by the highest level. In 2015 Forghani y Sahraeian [27] proposed a multi-objective DMCLP where the initial and backup coverage is maximized and the cost of transporting the facilities to the demands nodes is minimized. In 2016 Fajardo et al. [9] propose a hybrid algorithm to solve the DMCLP, the algorithm portfolio, obtaining better results than Simulated Annealing (Linear, Exponential and Hyperbolic) and the Evolutionary Strategy with large-scale instances. Also, Fajardo et al. [10] proposed an extension of the DMCLP where the cost of relocating the facilities from one period to another is taken into account, in addition to the demand covered. Recently, Mišković [17] modelled the robust DMCLP, where the demand of the nodes was unknown in the periods of time, in addition, it was proposed a method to solve the problem based on the Variable Neighbourhood Search (VNS).

## Multi-coverage models

In 1982 ReVelle et al. [18] proposed one of the first static models that take into account the different types of facilities differentiated by their coverage. Two facilities types were established, clinics (level 1) and hospitals (level 2), which had different radios. It was necessary to define the number of facilities per type. In 2009 Ratick et al. [22] proposed a static extension of HMCLP [18] where the uncovered demand (MRHMC) was minimized. It was applied to the location of hospitals and clinics, where the facilities had only two levels of coverage, depending of type: hospital (high level) and clinic (low level). They also had the number of clinics and hospitals separately. Oran et al. [20], in 2012, proposed an extension of the MCLP in order to locate ambulances of different types to maximize coverage of emergencies (MCLP-P). This model was combined with the routing model (VRPTW-P) [6] in order to minimize the distance travelled by ambulances. In 2016 Leigh et al. [16] applied the MCLP for the police patrol location in order to give an adequate response to incidents in a specific area of the United Kingdom. A static model is proposed where the coverage radius of the police officers vary according to the place where they must patrol (City or Rural Area).

In 2017, Paul et al. [21] proposed a multi-objective conditional MCLP applied to the hierarchical location of emergency in United States. In this model, the demand covered is maximized and the cost of modifying the current structure is minimized. There are different types of facility and it has a minimum and maximum coverage radius. The set of new facilities of different types is located from those already existing in the territory. Stanimirović et al [24] proposed a static generalization of MCLP, which includes different types of facilities and demand nodes: the multi-type maximal covering location problem (MTMCLP). The facilities are located by type, but the coverage radius for each facility was the same. Recently, Rezazadeh et al. [23] proposed a static robust cooperative maximal covering location problem, where different types of facilities are differentiated by their capacity and was applied to the location of Tele-taxi stations.

Table **1** shows a summary about the literature review.

In general, dynamic and multi-types proposals have been made, but in the consulted literature a model that takes into account the combination of both aspects was not found.

Table **1** shows a summary of the literature review. It can be seen that the models found do not take into account all the elements that need to be modelled. This paper proposed a generalization of DMCLP proposed in [12], where all the aspects of

Table **1** are taken into account.

## 3. DYNAMIC MAXIMAL COVERING LOCATION PROBLEM (DMCLP)

As the proposal extends the variant proposed in [12], it first present the DMCLP, which allows to locate the facilities in long periods of time without preference of number of facilities in each period. Next, the mathematical formulation of DMCLP is shown:

**Table 1: Summary of literature review.**

| Article | Multi-period | Types of Facilities | Infinite number of types of facilities | Location of facilities per type | Different coverage radius per type |
|---|---|---|---|---|---|
| Tanaka [25] | ✓ | X | X | X | X |
| Başar et al. [1] | | | | | |
| Zarandi et al. [12] | | | | | |
| Tanaka et al. [26] | | | | | |
| Forghani et al. [27] | | | | | |
| Mišković [17] | | | | | |
| ReVelle et al. [18] | X | ✓ | X | ✓ | ✓ |
| Ratick et al. [22] | | | | | |
| Leigh et al. [16] | | | | | |
| Paul et al. [21] | | | | | |
| Oran et al. [20] | X | ✓ | ✓ | ✓ | X |
| Stanimirović et al [24] | | | | | |
| Rezazadeh et al. [23] | | | | | |

Parameters and variables:

- $i, I$: index and set of demand nodes.
- $j, J$: index and set of facility sites.
- $t, T$: index and set of times periods.
- $a_{it}$: demand at node $i$ in period $t$.
- $p$: number of facilities to be located.
- $d_{ij}$: shortest distance (or time) from demand node $i$ to facility at $j$.
- $S$: The distance (or time) standard within which coverage is desired.
- $N_i$: $\{j|d_{ij} \leq S\}$, the set of nodes that are within a distance less than $S$ from node $i$.
- $X_{jt} \in \{0;1\}$: A binary variable which equals 1 if a facility is sited at node $j$ in period $t$.
- $Y_{it} \in \{0;1\}$: A binary variable which equals 1 if node $i$ in period $t$ is covered by one or more facilities stationed within a distance of $S$.

The objective function is:

$$Max\ Z = \sum_{t=1}^{T}\sum_{i=1}^{I} a_{it}Y_{it} \quad (1)$$

Subject to:

$$\sum_{t=1}^{T}\sum_{j=1}^{J} X_{jt} = p \quad (2)$$

$$Y_{it} \leq \sum_{j\in N_i} X_{jt} \quad (3)$$

The objective function (1) maximize the overall covered demand. Constraint (2) shows that the number of open facilities in $T$ periods must be equal to the value $p$ and constraint (3) shows that a demand node can only be covered if it is located at a distance $d_{ij} \leq S$ of open facility and $Y_{it} = 0$.

**4. MULTI-COVERAGE DYNAMIC MAXIMAL COVERING LOCATION PROBLEM (MC-DMCLP)**

Below is present a generalization of DMCLP that allows to have facilities types, where each type have a different coverage (MC-DMCLP). Facilities of $K$-types can be located, defining a $k \in K$ type by the coverage/time $S_k$ that each facility can have. Next, the mathematical formulation of the new proposal is shown:

Parameters and variables:

- $i, I$: the index and set of demand nodes.
- $j, J$: the index and set of facilities.
- $t, T$: the index and set of times periods.
- $a_{it}$: demand for the node $i$ in period $t$.
- $k, K$: index and number de types of facilities.
- $S_k$: coverage distance of $k$-type. It is the minimum distance (or time) between a demand node and facility to be considered as covered.
- $p_k$: number of facilities of $k$-type to be located.
- $d_{ij}$: the shortest distance (or time) from demand node $i$ to the facility $j$.
- $W_{jk} \in \{0; 1\}$: a binary variable, 1 if the facility $j$ can be of type $k$, 0 otherwise.
- $N_{ik} \in \left\{j | d_{ij} \leq S_k \text{ and } W_{jk} = 1\right\}$: set of potential facility locations that can cover the demand generated in $i$ if a $k$-type facility is placed in the facility $j$.
- $X_{jtk} \in \{0; 1\}$: a binary variable, 1 if a facility of $k$-type is placed at node $j$ in period $t$, 0 otherwise.
- $Y_{it} \in \{0; 1\}$: a binary variable, 1 if the demand node $i$ in $t$-period is covered by one or more facilities, 0 otherwise.

The objective function is:

$$Max\ Z = \sum_{t\in T}\sum_{i\in I} a_{it}Y_{it} \quad (4)$$

Subject to:

$$Y_{it} \leq \sum_{k\in K}\sum_{j\in N_{ik}} X_{jtk} \qquad \forall i \in I, \forall t \in T \quad (5)$$

$$\sum_{t\in T}\sum_{j\in J} X_{jtk} = p_k \qquad \forall k \in K \tag{6}$$

$$\sum_{k\in K} p_k \leq J \tag{7}$$

$$\sum_{j\in J} W_{jk} > p_k \qquad \forall k \in K \tag{8}$$

$$\sum_{k\in K} W_{jk} \geq 1 \qquad \forall j \in J \tag{9}$$

$$\sum_{k\in K} X_{jtk} \leq 1 \qquad \forall j \in J, \forall t \in T \tag{10}$$

The objective function remains the same as the DMCLP. Constraint (5) shows that a demand node can be covered if an open facility of $k$-type belong to set $N_{ik}$. Constraint (6) shows that the number of open facilities of $k$-type in $T$ periods must equal the $p_k$ value. Constraint (7) shows that the sum of facilities of $k$-type that will open must be less than total of the available facilities. Constraint (8) shows that the total of facilities of $k$-type must be greater than the number of facilities of $k$-type that will open. Constraint (9) shows that a facility must be at least of one type. Finally, (10) shows that a facility $j$ can only be opened for one type. The proposed is a generalization, because for $K = 1$ the model is equal to DMCLP, for $T = 1$, the model is static with types of facilities, and for $T = 1$ and $K = 1$ the model is equal to MCLP.

## 5. CASE STUDY: POLICE PATROL LOCATION.

This section shows the application of MC-DMCLP for the police patrol location. This case study consists: to locate different types of police officers in order to maximize the vigilance over a group of criminal interest areas.

The MCLP has been used to solve cases studies similar to the presented in this paper. In [3] the MCLP was applied to determine the optimal areas for police patrolling. A comparison of their results obtained with the model vs. real patrol used in the area was made, and the results showed substantial improvements when applying the MCLP. Also, in [13] an applied study is carried out to maximize coverage of the areas where homicides occurred in Medellin. The MCLP was used to model the situation, adding budget constraints. In [15, 16] the MCLP was applied to distribute the police with the objective of giving a rapid response to criminal incidents. The model was part of an application for decision making that allowed the selection of the most appropriate police to handle an incident, according to the area where it occurred (rural and city). Finally, in [11] the MCLP-Tools software, for the visualization of the MCLP, was proposed and a case study was analysed where the police patrol was located in places of Havana. In previous papers, the use of MCLP models and their variants have helped to the decision making in these scenarios, demonstrating that automating the process of locating police officers can improve the results.

This case study has different characteristics: there are four schedules for patrolling ($|T| = 4$, $t = 1$: morning, $t = 2$: afternoon, $t = 3$: night and $t = 4$: early morning). The criminal behaviour of each schedule is different. There are several types of police officers and, in each location there may be a police type $k = 1$ (walk), type $k = 2$ (by motorcycle) or type $k = 3$ (patrol car), i.e. $|K| = 3$. It was generated a random instance on a Havana area, that contains 300 criminal acts ($|I| = 300$), and 547 possible police officer locations ($|J| = 547$) that coincide with the intersections of the streets. The crime level of the events (demand $a_{it}, \forall t \in T, \forall i \in I$) was generated randomly with values from 0 to 100. Each type of police officer has different coverage: walk (0.0015 degrees), motorcycle (0.002 degrees) and patrol car (0.0025 degrees). The difference in the coverage radius was caused by the physical characteristics (walk) and the type of transportation used (motorcycle and patrol car). The distance between police officers and criminal zones is computed by using Euclidean distance. Two experiments with two scenarios were carried out, varying the total of police officers to be located (30 or 50).

Table **2** describes the $p_k$ in each experiments.

**Table 2: Experiment's description.**

| Experiments | Scenario30 | | | | Scenario50 | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | Type 1 | Type 2 | Type 3 | Total | Type 1 | Type 2 | Type 3 |
| 1 | 30 | 15 | 9 | 6 | 50 | 25 | 15 | 10 |
| 2 | 30 | 6 | 9 | 15 | 50 | 10 | 15 | 25 |

The problem proposed was modelled as an optimization problem, and it was defined: representation of problem, which consist of positives number list, where $k$ means the type of police officer that is located, and 0 means that no police officers are located. The mutation operator used is a combination of NSS1 and NSS2 operators proposed in [12]. The model was solved by the algorithm portfolio, proposed in [9], with 10000 iterations. The problem was implemented by using the BiCIAM library [8], which contains the algorithms portfolio used to solve the problem.

Table **3** shows the coverage percent over the areas obtained by the algorithm.

**Table 3: Coverage percent over areas.**

| Experiments | Scenario30 | Scenario50 |
|---|---|---|
| 1 | 53.07 | 72.28 |
| 2 | 61.18 | 83.78 |

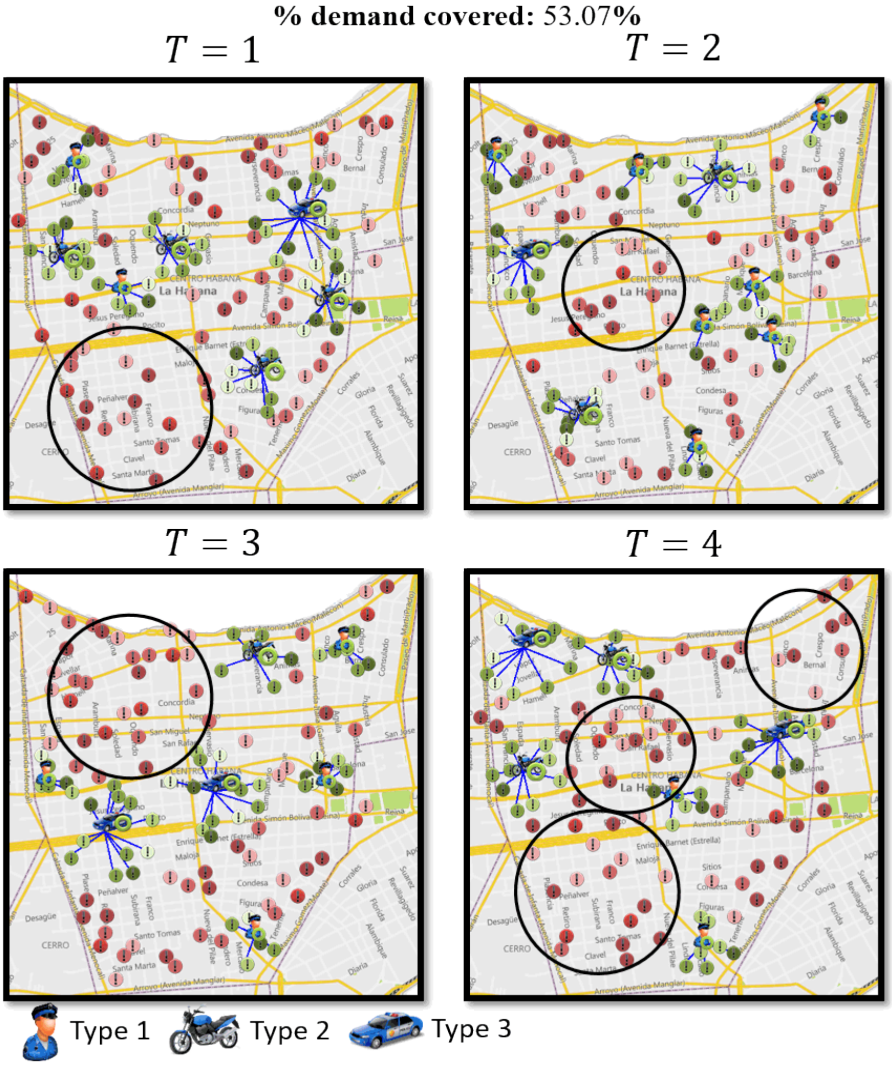


**Figure 1: Case study results (Experiment 1, Scenario30).**

Table **3** shows that with a greater number of police officers in Scenario50 compared to Scenario30, the percent of the crime level covered was increased by an average of 20%, approximately. In addition, with the same numbers of police officers, but exchanging the amounts of type 3 with type 1 (patrol car by police officers walk, in Experiment 2), it is possible to obtain a greater percentage of coverage. This result was expected because police officers of type 3 have a greater radio (best resource, patrol car). In this case, it is necessary to take into account the cost that the police officers of type 3 could represent with respect to type 1, that patrol walk.

Now, the visualization of the experiments on a map will be analysed. For this, the MCLP-Tools software proposed in [11] was extended, including the MC-DMCLP model. This software allows to model and solve variants of the MCLP. Figure 1 shows the results of Experiment 1 for Scenario30.

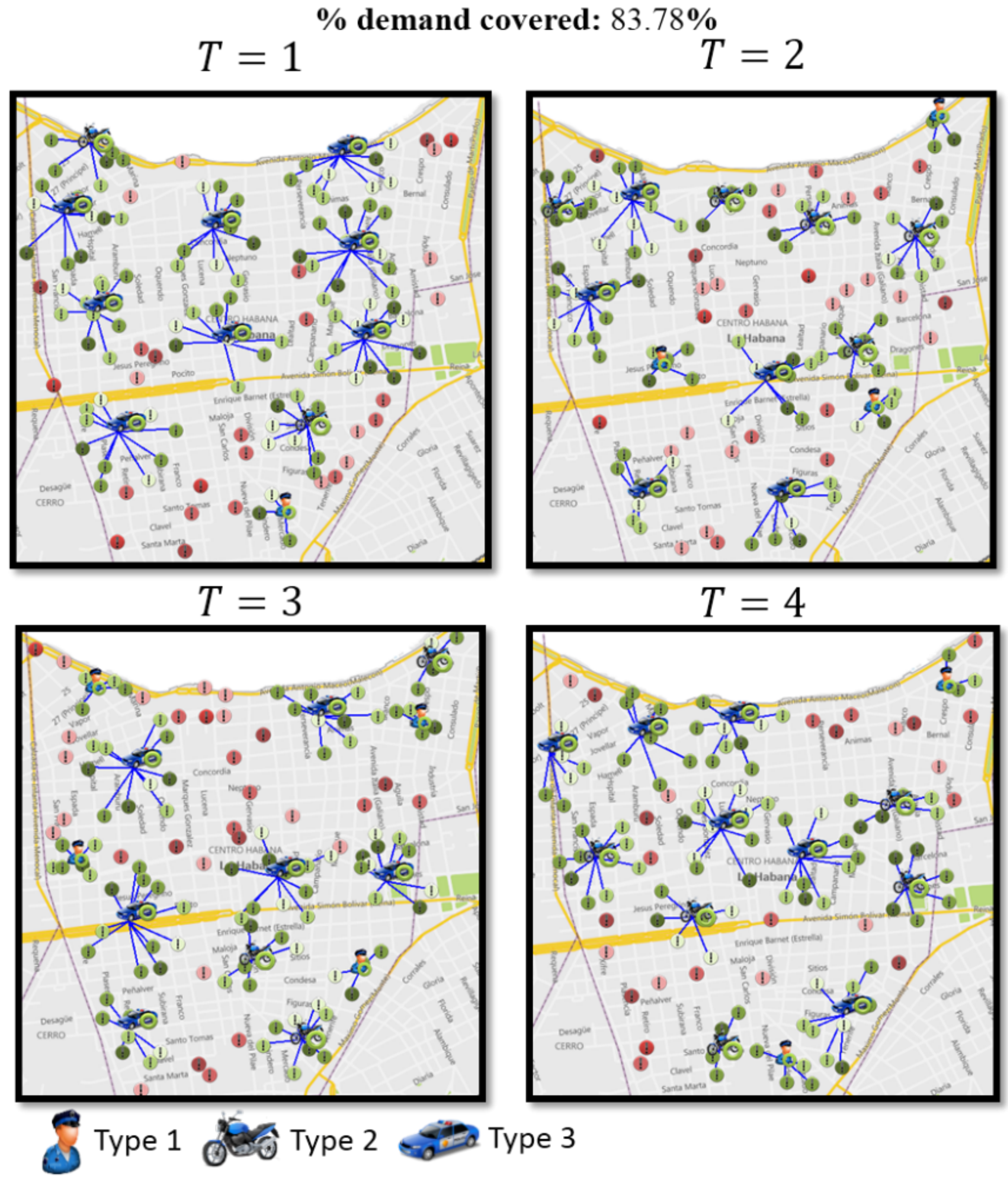


**Figure 2: Case study results (Experiment 2, Scenario50).**

From this experiment, we can perform the following analysis:

- In the regions indicated in Figure 1 (circles), it can be observed the absence of police officers, while in other areas there are police officers watching over a small distance. Therefore, it is important to take into account the distance among the police officers in order to reach a balance among the covered areas.

- With 9 policemen of type 2 (motorcycle) to be located, 4 were located in schedule 1 (morning). With 15 police officers of type 1 (walk), 7 were located in period 2 (afternoon). It can be observed that among the periods of time there is not balance in the number of police officers located. Only the demand of the nodes has influence on the decision of selecting the locations of the police officers.

Figure 2 shows the results of Experiment 2 for Scenario50, in order to analyse the influence of locating more police officers for patrolling.

From this experiment, we can perform the following analysis:

- With a greater number of police officers, a greater level of dispersion over the area is obtained, leaving few areas where police officers were not located.
- With respect to Experiment 1, Scenario30, the solution has more balance in terms of the number of police officers per schedule, with 11 police officers in the morning ($t = 1$) and 13 in the remaining schedules.
- It can be seen that in the morning ($t = 1$) it was located a greater number of police officers of type 3 (patrol car). It was the schedule where the least amount of police officers was located (11 police officers). This happens because in this schedule more police officers of type 3 were located (amount 8) with respect to the others (number 6), then it was not necessary to locate more police officers because the police officers of type 3 have the largest coverage radius.
- In both experiments is worth noting that the proposal assumes an infinite capacity to cover the criminal zones. For example, in several occasions, a police officer with patrol car must monitor an area with many criminal acts, so the real capacity of a police officer is an important element to be consider for this type of scenario.

## 5. CONCLUSIONS

The model proposed is a Dynamic MCLP (DMCLP) generalization that allow to model situations where facilities can be of different types thus implying different radius of coverage in multi-period scenarios. Based on the research carried out, the following conclusions are taken:

- The models proposed in the literature do not allow to combine multi-period approaches with the existence of different types of facilities, where it is necessary to locate a number of facilities per type.
- The model proposed can be applied in different cases, e.g. where there are several types of antennas with different coverage radius, location of different types of cameras, among others.
- The case study analysed demonstrated the application of the proposed model for police patrolling with different types of polices officers in several schedules, which could not be solved with the current models in the literature.
- The use of the model proposed in the case study allowed to make analyses that may be important for this case, for example: the capacity of the police officers and the balance in terms of the number of police officers by types located in the schedules.
- The new model can be improved and adjusted more to reality, but as it is, it can be used in real cases.

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