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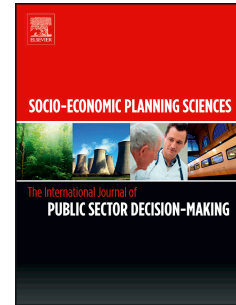
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Multi-period location of flow intercepting portable facilities of an intelligent transportation system

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ABSTRACT

Intelligent transportation systems are of great importance in urban traffic management. In this context variable message signs (VMS) play a major role in providing drivers with useful information during their trips.

In this paper we consider the problem of finding the optimal location of a set of portable VMS on an urban network where flow patterns change during a time horizon.

We propose two original solving approaches based on flow intercepting facility location ILP models.

The paper presents an application of the proposed approaches to real-like test networks and discusses the results obtained providing some indications on their practical applications.

In recent years intelligent transportation systems (ITS) based on innovative information and communication technologies have been increasingly used in traffic management and control, environmental protection, city logistics and urban security. In this context advanced traveler information systems play a major role and a significant contribution to this role is made by variable message signs (VMS) which constitute one of the most important components of an ITS ([35], [28], ERTICO – ITS Europe: www.ertico.com).

Different classifications of VMS have been proposed, depending on their technology, activation mechanism and kind of information displayed. Generally speaking they are devices able to display real-time messages for network users with the aim of providing drivers with useful information and instructions during their trips. Most VMS consist of two elements, a graphic image (pictogram) and an alphanumeric text to be displayed. They can be managed both remotely and on field. The messages must be intelligible, incisive and concise so that they can be easily understood without being a source of distraction. They may be either pre-recorded or created in real time, if necessary.

VMS messages convey different kinds of information to road users related to: driving suggestions and speed recommendation; advisable paths and time needed to reach a certain destination; congestion levels at nodes that are critical during rush hours; timing and location of special events; services available on the network (i.e. refueling stations, parking areas and number of available lots); state of the network (road closures and road construction/maintenance activity or work-in-progress); unusual or unexpected events (i.e. incidents, accidents, disruptions or public demonstrations); modal choices (recommended park and ride areas and/or public transport in the vicinity); urban area protection (restricted zones, pedestrian areas, limited traffic zones or limited parking zones); route diversion (whether voluntary or mandatory) with instructions about alternative routes which allow the flow equilibrium on the network to be re-established; weather conditions; law enforcement; incident management; public safety and security.

Over the years, VMS have been explored in several areas of interest and from different viewpoints. Here we have cited only a few of the most recent contributions. The important issue of route guidance and route choice is discussed in [9] and [11]. Readability and comprehension of displayed messages are treated in [8] and [32] [32]. Contributions about evaluation of VMS benefits and economic impact on travel times and other cost categories may be found in [23] and [26]. The issue of driver response is dealt with in [24], [19], [36] and [31]. Finally lane use balancing is examined in [30].

From the list of potential applications and theoretical/empirical contributions, the usefulness of VMS is evident: they are conceived to impact on the behavior of drivers in order to improve traffic dynamics. For this reason they constitute a remarkable tool for collective route guidance, providing drivers with instructions and suggestions aimed at reducing the traffic congestion level and preserving user safety and awareness; for example in the case of unexpected events that alter the normal state of the network, with evident social and economic benefits. Indeed, the main impact of the VMS is on traffic efficiency, achieved as a result of speed recommendations and congestion reduction, and environmental benefits, achieved as a result of reduced fuel consumption and emissions.

Until now they have been widely used on highways and have recently also found many applications on urban networks. This is confirmed by many real-life applications. For example, during the Winter Olympics in Turin 2006, VMS were a key element in the traffic management strategy. In Barcelona VMS are used for lane multi-usage over different time periods of the day, with the aim of reducing the congestion in the commercial city center, leading to a travel time reduction of 12% to 15%. In Paris, SIRIUS (Information System for an Understandable Network for the User) uses more than 150 VMS, located before highway junctions or road network exits.

ITS technologies play a remarkable role in local government, for both technicians and policy decision makers, as witnessed by the specific actions undertaken by many road traffic authorities. Here we have provided just a few examples. The New York State Thruway Authority defines the guidelines for effective VMS usage, with the purpose of providing directions to assist Authority personnel, contractors, concessionaires and regional traffic management centers, who are responsible for VMS operation and message design. In the UK, in response to the European Union Directive 2010/40/EU, the Department for Transport published a report on “Intelligent Transport Systems in the UK”, describing the current situation in the country: a large number of VMS are placed across the road network (about 2,800 VMS on the Strategic Road Network in England) and a plan for future installations across the UK is outlined. In 2009 the

Conference of European Directors of Roads (CEDR) published a report entitled “VMS harmonization in Europe”, aimed at monitoring the main developments across Europe as well as understanding the issues arising from and the obstacles to VMS harmonization and interoperability.

Taking into account what has been said so far in terms of advantages provided by the VMS for the traffic network management, great attention has to be paid to effective VMS location on a road network.

This problem has been widely dealt with in literature. The approaches used are generally based on empirical evidence and/or experimental tests, but there are also many methodological contributions to the problem modeling and algorithmic solutions. We have cited the most recent among them here. In [22] the authors use a method, based on driving simulation experiments, to determine VMS locations for safe exiting at freeway off-ramp; in [12] a natural algorithm for VMS location is proposed; in [37] the authors develop a study on the optimization of VMS location, based on drivers’ guidance compliance behaviors; in [16] the evaluation of a VMS location scheme effectiveness, in parking guidance system, is discussed; in [21] the authors present an incremental assignment model for VMS parking location problems; and finally, in [17] an algorithm for VMS location on an urban network, considering road attributions, is proposed.

For an effective VMS location it is also important to take into account flow pattern changes that may occur on urban networks during the day, in terms of flow values (peak or off-peak periods) and/or in terms of origin/destination travel demands, for trips towards and away from the city center. In other words the VMS location must be adapted to the flow variation in the areas that are candidate sites for their placement.

To this end it is necessary to take into account the differences between fixed and mobile VMS. Fixed VMS are huge gantries installed on network links that require a considerable economic investment. Once deployed they cannot be moved to other points of the network. They may not be in keeping with a city's image, especially in areas with historic buildings and monuments. They are therefore generally installed along highways or at the entrance to urban areas, or at least outside city centers. By contrast, portable VMS, which are the focus of this paper, are relatively small, designed to be moved from one location to another, and are used for a certain period of time. This makes them environmental-friendly, easy to handle and very flexible. For the above reasons they can be located on a highway or on the main roads of an urban area.

Due to their characteristics, fixed VMS have to be placed in points of the network where the flow level and the need to inform users do not change during the day. Portable VMS seem to be more suitable in all those cases where the flow pattern may vary during the day. Thanks to their features, they can be used in all situations caused by unusual traffic variations or by accidents and other special events, adapting their placement to the flow pattern variation induced by these events.

Their placement can therefore be performed as a multi-period operation or, if necessary in the case of unusual and significant events that change the network conditions, in a strictly dynamic way.

An intuitive and effective criterion for the portable VMS location is their capability to intercept drivers who have to be informed. For this reason the formulation of the flow intercepting facility location problem (*FIFLP*) can be used, aimed at either maximizing the intercepted flow with a pre-fixed number of VMS or minimizing the number of VMS required to intercept a pre-fixed amount of flow. As the reader will see in the following section, the literature about *FIFLP* is well established, but, to the best of authors’ knowledge, all the contributions concern the single-period case (referred to in the following as *SP-FIFLP*), whereas the multi-period case (*MP-FIFLP*) has never been dealt with in literature. This work is aimed at filling this gap.

Indeed in the following we will define a tactical and operational decision problem, which could be expressed as multi-period flow intercepting facility location problem (*MP-FIFLP*). We will tackle it by two different integer linear programming (*ILP*) based approaches, a *sequential* and an *integrated* one.

Being k the number of periods taken into account, the sequential approach is based on the decomposition of the *MP-FIFLP* in k single-period *FIFLP* and $k - 1$ assignment problems of *facilities* to *places*, devoted to minimizing the facility re-location cost.

Original *ILP* formulations are presented for the integrated approach, where the previous two problems are solved at the same time, with several kind of objective functions, taking into account all the information about path flows in the different periods of the time horizon under investigation.

The paper is structured as follows: in *Section 2* we recall the *FIFLP*, its basic assumptions and related *ILP* models; in *Section 3* we focus on the *MP-FIFLP* and on the two proposed approaches; and finally, in *Section 4* we test the proposed formulations on real-like test networks and discuss the results obtained providing indications about their practical applications.

2. Flow intercepting facility location problems (FIFLP)

As discussed above, in this work the problem of dynamically locating portable VMS on a network is approached as a *MP-FIFLP*. In order to clearly frame and explain the *MP-FIFLP* and related approaches, in the following sub-sections we will recall the *SP-FIFLP*, related main literature and basic ILP models.

2.1. Problem definition and literature review

There is a broad range of literature on facility location problems (*FLP*) and related variants, with different application fields and solution approaches ([25], [20]).

A classification present in *FLP* literature is based on the kind of demands to be satisfied. In *point based demand FLP*, the facilities are located in order to satisfy the demand expressed at the nodes of the network, whereas in *flow based demand FLP* (also referred to as *flow intercepting facility location problem, FIFLP*), the facilities to be located do not generate/attract flows, but intercept them along their pre-planned paths from origins to destinations.

Another classification of the *FLP* can be made in terms of number of periods to be taken into account. In the single-period *FLP* the facilities have to be opportunely located, in the node or on the links of the network, on the basis of aggregated information about average demands or user flows over a single time period. In multi-period *FLP* at each period composing a time horizon, portable facilities have to be opportunely positioned and repositioned in the nodes or on the links of a network on the basis of the current demands or user flow information.

Single and multi-period *point based demand* facility location problems (p-median, simple plant and related variants), starting with the seminal papers by Hakimi [13], Ballou [2] and Schilling [27], respectively, have been widely studied. Concerning the multi-period variant, in its more general form, it consists in determining the number and the positions of the facilities to be activated and/or relocated at each period of the time horizon, in order to minimize single or multiple criteria related to location and service costs. For a complete review of the main literature on multi-period point based demand *FLP*, readers interested should refer to [17] and [1].

By contrast, research activity on single-period *flow interception facility location problem (SP-FIFLP)*, introduced in the seminal papers by Hodgson [14], Hodgson [15] and Berman et al.[3], is consolidated but more limited. As discussed in *Section 1*, in *SP-FIFLP* one of the following two objectives has to be achieved:

- **O1**: maximizing a performance criterion related to the flow traversing the network (with a constraint on the number of intercepting facilities to be located in the nodes or on the links of the network);
- **O2**: minimizing the number of intercepting facilities to be located or the total installation/usage cost (with a lower bound constraint on the total amount of flow to be intercepted).

In [5] *SP-FIFLP* is classified in two main categories: flow oriented and gain oriented problems, also referred to in [10], as punitive and preventive *SP-FIFLP* respectively. In the flow oriented *SP-FIFLP* the performance criterion is the total amount of flow intercepted by the facilities, regardless of the position where the interception occurs. In the gain oriented *SP-FIFLP* the performance criterion is the total amount of intercepted flow, weighted according to the specific position of the node/link along the path, where the interception occurs. *SP-FIFLP* has been used in literature to solve several real facility location problems in different fields [7]. For a review of the main contributions in the field, readers interested should refer to [4], [34] and [33].

However, to the best of the authors' knowledge, the multi-period *flow interception FLP (MP-FIFLP)*, has never been dealt with in literature and no contribution explicitly takes into account the facility relocation cost issues. In *Section 3* this problem will be defined and formulated in terms of ILP models.

2.2. Basic assumptions and ILP models for the *SP-FIFLP*

The formulation of the *SP-FIFLP* with both objectives (**O1** and **O2**), requires the following five assumptions:

1. Knowledge of the origin-destination paths and related non-zero flows.

2. No link failure occurs and so flow deviation from predefined paths is not possible.
3. Multiple counting of intercepted flow is not allowed in the objective function.
4. Each flow is entirely intercepted by a single facility.
5. Facilities are located either in the nodes or on the links.

It is important to underline that even if these assumptions seem to be very constraining, most of them can be easily relaxed without changing the general structure of the *SP-FIFLP*. These issues are discussed in [5] and [34].

On this basis two different ILP models have been proposed in literature to formulate the *SP-FIFLP*. The first formulation (*F1*), aimed at maximizing the intercepted flow, given a prefixed number of facilities (objective **O1**), can be interpreted as a variant of the maximal covering location problem [6]. The second formulation (*F2*), aimed at minimizing the total location or usage cost of the facilities, given a lower bound on the minimum amount of flow to be intercepted (objective **O2**), can be interpreted as a variant of the set covering problem [29].

We will refer to a network $G(N,A)$, where N is the set of nodes and A is the set of links. Moreover we define the following sets and parameters:

- P set of paths, with non-zero flows, traversing the network;
- N_p subset of nodes ($N_p \subseteq N$) belonging to a path $p, p \in P$;
- f_p flow value associated to a path $p, p \in P$;
- h_i fixed location or usage cost of a facility at node $i, i \in N$;
- m number of facilities to be located;
- C_ε^* amount of flow to be intercepted: $C_\varepsilon^* = \varepsilon \cdot \sum_{p \in P} f_p, \varepsilon \in [0; 1]$.

For both formulations we will use the following decision variables:

- $x_{pi} = \{0,1\}$ equal to 1 if a facility is located at node $i, i \in N_p$, on the path $p, p \in P$, 0 otherwise;
- $y_i = \{0,1\}$ equal to 1 if a facility is located at node $i, i \in N$, 0 otherwise.

(Formulation *F1*)

$$\text{Max } z = \sum_{p \in P} \sum_{i \in N_p} f_p x_{pi} \quad (1)$$

s.t

$$\sum_{i \in N} y_i = m \quad (2)$$

$$y_i \geq x_{pi} \quad \forall p \in P, i \in N_p \quad (3)$$

$$\sum_{i \in N_p} x_{pi} \leq 1 \quad \forall p \in P \quad (4)$$

$$x_{pi} = \{0,1\} \quad \forall p \in P, i \in N_p \quad (5)$$

$$y_i = \{0,1\} \quad \forall i \in N \quad (6)$$

The objective function (1) maximizes the intercepted flow (objective **O1**). Constraint (2) imposes that the number of facilities to be located has to be equal to m . Constraints (3) are consistency constraints, imposing that a path $p, p \in P$, can be intercepted at a node $i, i \in N_p$, i.e. $x_{pi} = 1$, only if a facility is located at node $i, i \in N$, i.e. $y_i = 1$. Constraints (4) are single counting constraints. Constraints (5) and (6) impose that all the variables are binary.

(Formulation *F2*)

$$\text{Min } z = \sum_{i \in N} h_i y_i \quad (7)$$

s.t

$$y_i \geq x_{pi} \quad \forall p \in P, i \in N_p \quad (3)$$

$$\sum_{i \in N_p} x_{pi} \leq 1 \quad \forall p \in P \quad (4)$$

$$\sum_{p \in P} \sum_{i \in N_p} f_p x_{pi} \geq C_\varepsilon^* \quad (8)$$

$$x_{pi} = \{0,1\} \quad \forall p \in P, i \in N_p \quad (5)$$

$$y_i = \{0,1\} \quad \forall i \in N \quad (6)$$

The objective function (7) minimizes the total fixed facility location/usage cost (objective **O2**). As regards the constraints, the difference compared to formulation *F1* is the substitution of constraint (2) with

3. Multi-period flow intercepting facility location problem and solving approaches

In tactical and operational *FLP*, we can assume that, at certain time intervals, the network passes from a period to another one and we have to consider its evolution in terms of network parameters, over the whole time horizon. With particular reference to urban traffic management and portable VMS location, each period corresponds to different flow patterns, i.e. flow values associated to the O/D pairs. Hence, for an effective usage of the VMS, they have to be located and dynamically relocated according to the network parameter values at each period of the time horizon.

On this basis, as discussed above, it is easy to see that the location of these facilities requires a multi-period location approach, where we have to combine the flow intercepting facility location problem with the facility relocation problem from one period to the next one, in order to obtain the optimal sequence of facility positions on a network within a time horizon (*MP-FIFLP*).

Given these two problems that make up the *MP-FIFLP*, two different kinds of objectives can be optimized:

- *intra-period objectives*: with reference to each period of the time horizon, optimizing the same objectives defined for the *SP-FIFLP*, i.e. **O1** or **O2**;
- *inter-period objectives*: with reference to the transition between two consecutive periods, minimizing the facility relocation cost (in the following referred to as objective **O3**).

The two *intra-period* objectives and the *inter-period* objective can be combined in order to obtain two different variants of the *MP-FIFLP*:

- **Problem P1**, whose objective is a combination of **O1** and **O3**;
- **Problem P2**, whose objective is a combination of **O2** and **O3**.

For each problem, we propose a *sequential* and an *integrated approach*, described in further detail in the following subsections. In the VMS location problem, the two approaches should not be considered as alternative. The choice between them must be made by taking into account the specific features of the problem under investigation. This issue will be discussed more fully in *Section 4*.

3.1. Sequential Approach

The *sequential approach* is composed of two ILP models, sequentially and iteratively solved. The first model can be either *F1* or *F2*. The choice between them depends on the specific problem, **P1** or **P2** respectively, under investigation. The second model is an assignment model (*AM*) of facilities to potential locations, devoted to managing the facility relocation during the transition from the period t to the period $t+1$, minimizing the facility relocation cost. More precisely, being N_t^* and N_{t+1}^* the sets of nodes chosen as optimal facility locations at periods t and $t+1$ respectively, the assignment of the facilities from the nodes of N_t^* to the nodes of N_{t+1}^* has to be determined.

Being T the set of periods composing the time horizon, the first model is solved $|T|$ times while the latter is solved $|T|-1$ times.

When solving the first model, the evolution of the network parameters, previously defined for *F1* and *F2*, is taken into account specifying the values of f_p , h_i and C_ε^* for each period. These values will be indicated in the following as f_{pt} , h_{it} and $C_\varepsilon^*(t)$, $t \in T$.

Moreover, in order to formulate the assignment model *AM*, we have to consider the additional parameter c_{ij} , $i \in N_t^*$ and $j \in N_{t+1}^*$, i.e. the relocation cost of a facility from node i to node j . This cost can be constant throughout the time horizon or can vary at each period that is part of it. Then the following decisional variable is defined:

- $r_{ij} = \{0,1\}$ equal to 1 if a facility located at node i , $i \in N_t^*$, is moved to node j , $j \in N_{t+1}^*$,
0 otherwise.

(Formulation *AM*)

$$\text{Min } z = \sum_{i \in N_t^*} \sum_{j \in N_{t+1}^*} c_{ij} r_{ij} \quad \text{ACCEPTED MANUSCRIPT} \quad (9)$$

s.t.

$$\sum_{j \in N_{t+1}^*} r_{ij} = 1 \quad \forall i \in N_t^* \quad (10)$$

$$\sum_{i \in N_t^*} r_{ij} = 1 \quad \forall j \in N_{t+1}^* \quad (11)$$

$$r_{ij} = \{0,1\} \quad \forall i \in N_t^*, j \in N_{t+1}^* \quad (12)$$

The objective function (9) minimizes the total relocation cost (objective **O3**). Constraints (10), (11) and (12) are the typical constraints of the assignment model.

The model *AM* can be used straightway for problem **P1**, whereas it is necessary to slightly modify its structure when it is used for problem **P2**. Indeed with reference to problem **P1**, given the fixed number of facilities to be located (m), the sets N_t^* and N_{t+1}^* obtained by solving model *F1* at period t and $t+1$ respectively, have always the same cardinality. Hence the number of facilities to be relocated at each transition is the same. This does not apply to model *F2*, since the number of facilities located on the network to intercept the prefixed amount of flow at each period ($C_\varepsilon^*(t)$), may vary from t to $t+1$. Hence the sets N_t^* and N_{t+1}^* can have different cardinality. In order to manage this situation, model *AM* has to be slightly modified introducing a dummy node, indicated by letter D . This node, added to set N_t^* if $|N_{t+1}^*| > |N_t^*|$ (*case 1*) or to set N_{t+1}^* , if $|N_t^*| > |N_{t+1}^*|$ (*case 2*), can be seen as a “depot” where a number of facilities equal to the difference between the cardinalities of N_t^* and N_{t+1}^* is stored. On this basis, being $\overline{N}_t^* = N_t^* \cup \{D\}$, formulation *AM* is modified as follows for *case 1*:

(Formulation *AM - modified*)

$$\text{Min } z = \sum_{i \in N_t^*} \sum_{j \in N_{t+1}^*} c_{ij} r_{ij} \quad (9)$$

s.t.

$$\sum_{j \in N_{t+1}^*} r_{ij} = 1 \quad \forall i \in N_t^* \quad (10)$$

$$\sum_{i \in \overline{N}_t^*} r_{ij} = 1 \quad \forall j \in N_{t+1}^* \quad (11.b)$$

$$\sum_{j \in N_{t+1}^*} r_{Dj} \leq |N_{t+1}^*| - |N_t^*| \quad (13)$$

$$r_{ij} = \{0,1\} \quad \forall i \in N_t^*, j \in N_{t+1}^* \quad (12)$$

Model *AM-modified* for *case 1* guarantees that all the facilities located at period t are relocated at period $t+1$, and the additional ones are taken from the dummy node with a relocation cost equal to zero. A similar and straightforward modification can be made for *case 2*. For the sake of brevity we will not report it, but we merely highlight that *AM-modified* for *case 2* guarantees that all the facilities located at period t are relocated at period $t+1$, and the exceeding ones are moved into the dummy node with no relocation cost.

3.2. Integrated Approach

The *integrated approach* solves the *MP-FIFLP* providing the optimal solutions for the entire time horizon over which the network evolves. Two *ILP* models have been formulated. The first, referred to as *F3*, is aimed at solving problem **P1**. The second one, referred to as *F4*, is aimed at solving problem **P2**.

Given the problem setting introduced in previous sections, both models *F3* and *F4* use the following decision variables:

- $y_{ijt} = \{0,1\}$ equal to 1 if the facility $j, j = 1, \dots, m$, is located at node $i, i \in N$, at the period $t, t \in S$, equal to 0 otherwise;
- $x_{ipt} = \{0,1\}$ equal to 1 if a facility is located at node $i, i \in N_p$, belonging to path $p, p \in P$, at period $t, t \in S$, equal to 0 otherwise.

With reference to model *F3*, we need to define the following objective function components.

$$A = \sum_{i \in N_p} \sum_{p \in P} \sum_{t \in S} (f_{pt}) x_{ipt}; \quad (14)$$

$$B = \sum_{k,q \in N, k \neq q} \sum_{j=1}^m \sum_{t=1}^{|S|-1} f[d(k,q)] y_{kjt} y_{qjt'}, \text{ such that } t' = t+1. \quad (15)$$

The first component, A , expresses the flow intercepted at each period and has to be maximized. The second component, B , is related to the total facility relocation cost and has to be minimized. In order to

define it, we introduce the relocation cost function, $f[d(k,q)]$, concave and non-decreasing. The argument of this function, $d(k,q)$, indicates the length of the path (or the travelling time/cost) between two nodes k and q of the network. On this basis problem **P1** can be formulated as follows:

(Formulation *F3*)

$$\text{Min } z = -\alpha A + B \quad (16)$$

s.t.

$$\sum_{j=1}^m y_{ijt} \leq 1 \quad \forall i \in N, t \in S \quad (17)$$

$$\sum_{i \in N} y_{ijt} = 1 \quad \forall j = 1, \dots, m, t \in S \quad (18)$$

$$x_{ipt} \leq \sum_{j=1}^m y_{ijt} \quad \forall i \in N_p, p \in P, t \in S \quad (19)$$

$$\sum_{i \in N_p} x_{ipt} \leq 1 \quad \forall p \in P, t \in S \quad (20)$$

$$x_{ipt} = \{0,1\} \quad \forall i \in N_p, p \in P, t \in S \quad (21)$$

$$y_{ijt} = \{0,1\} \quad \forall i \in N, j = 1, \dots, m, t \in S \quad (22)$$

Consistently with objectives **O1** and **O3**, the objective function (16) minimizes a linear combination of the two previously described components, i.e. (14) and (15), opportunely weighted by the tuning factor α , $\alpha \in [0; 1]$. The negative sign for the component A is required since it should be maximized but it is within an objective function to be minimized. Constraints (17) and (18) impose that each facility can be located in no more than one node in each period and that each facility has to be necessarily located in a node at each period respectively. Constraints (19) are consistency constraints and guarantee that if there is at least one facility on a path at a given period, then the path can be intercepted. Constraints (17) are single counting constraints at each period. Finally, constraints (21) and (22) impose that all the variables are binary.

As regards model *F4*, in order to formulate it, we have to define another objective function component, referred to as A' , which substitutes the component A of *F3* and expresses the facility location or fixed usage cost at each period:

$$A' = \sum_{i \in N} \sum_{j=1}^m \sum_{t \in S} h_{it} y_{ijt}; \quad (23)$$

On this basis problem **P2** can be formulated as follows:

(Formulation *F4*)

$$\text{Min } z = \beta A' + B \quad (24)$$

s.t.

$$\sum_{j=1}^m y_{ijt} \leq 1 \quad \forall i \in N, t \in S \quad (17)$$

$$x_{ipt} \leq \sum_{j=1}^m y_{ijt} \quad \forall i \in N_p, p \in P, t \in S \quad (19)$$

$$\sum_{i \in N_p} x_{ipt} \leq 1 \quad \forall p \in P, t \in S \quad (20)$$

$$\sum_{i \in N} y_{ijt} \leq 1 \quad \forall j = 1, \dots, m, t \in S \quad (25)$$

$$\sum_{p \in P} \sum_{i \in N_p} f_{pt} x_{ipt} \geq C_{\varepsilon}^*(t) \quad \forall t \in S \quad (26)$$

$$\sum_{i \in N} y_{ijt} - \sum_{i \in N} y_{ijt+1} = 0 \quad \forall j = 1, \dots, m, t = 1, \dots, |S| - 1 \quad (27)$$

$$x_{ipt} = \{0,1\} \quad \forall i \in N_p, p \in P, t \in S \quad (21)$$

$$y_{ijt} = \{0,1\} \quad \forall i \in N, j = 1, \dots, m, t \in S \quad (22)$$

Consistently with objectives **O2** and **O3**, the objective function (24) minimizes a linear combination of the two previously defined cost components, i.e. (23) and (15), where the location (usage) cost is opportunely weighted by the tuning factor β , $\beta \in [0; 1]$. The constraints of the model are the same as model *F4*, with the only exception of constraints (26) and (27). In particular constraints (26) impose a lower bound on the minimum amount of flow to be intercepted at each period and constraints (27) impose that the number of located facilities has to be the same over the whole time horizon under investigation. It is important to note that in model *F4* the value of m is overestimated, since the optimal number is then returned by the model solution.

The objective functions of both models, (16) and (24), are non linear objective functions because of the quadratic term B . However, we can easily linearize them by introducing the following variable:

- $w_{kq}^{jt} = \{0,1\}$ equal to 1 if a facility $j, j = 1, \dots, m$, is located in node $k, k \in N$, at period $t, t = 1, \dots, |S|-1$, and in node $q, q \in N$, at period $t+1$, equal to 0 otherwise.

On this basis, (15) can be modified as follows:

$$\sum_{k,q \in N} \sum_{j=1}^m \sum_{t=1}^{|S|-1} f[d(k,q)] w_{kq}^{jt} \quad (15.b)$$

Moreover, being variable w_{kq}^{jt} the product of binary variables, then the following constraints have to be added to both formulations:

$$w_{kq}^{jt} \leq y_{kjt} \quad \forall j = 1, \dots, m, t = 1, \dots, |S| - 1, k, q \in N \quad (23)$$

$$w_{kq}^{jt} \leq y_{qjt'} \quad \forall j = 1, \dots, m, t = 1, \dots, |S| - 1, k, q \in N \quad (24)$$

$$w_{kq}^{jt} + 1 \geq y_{kjt} + y_{qjt'} \quad \forall j = 1, \dots, m, t = 1, \dots, |S| - 1, k, q \in N, \text{ such that } t' = t + 1 \quad (25)$$

As an alternative to constraints (23), (24) and (25), we could also use the following couple of constraints in order to linearize the term B :

$$y_{kjt} + y_{qjt'} \geq 2w_{kq}^{jt} \quad \forall j = 1, \dots, m, t = 1, \dots, |S| - 1, k, q \in N, \text{ such that } t' = t + 1 \quad (26)$$

$$y_{kjt} + y_{qjt'} - 1 \leq w_{kq}^{jt} \quad \forall j = 1, \dots, m, t = 1, \dots, |S| - 1, k, q \in N, \text{ such that } t' = t + 1 \quad (27)$$

In this way $F3$ and $F4$ are transformed from non-linear to linear integer programming models.

4. Test and results

In this section we report the results obtained for problem $P1$ and $P2$ through the two proposed approaches (sequential and integrated), on a test network, with a semi-circular topology made up of 5 layers, which can be considered as representative of a typical coastal urban area.

The experimentation aims to show that the proposed approaches can be a valuable tool for local authorities in charge of traffic management, in order to make decisions about the effective usage of the VMS already available or the number of VMS needed for an effective traveler information system for the area of interest.

The test network $G(N,A)$ has 46 nodes and 115 undirected links. We defined 36 o-d paths on the network. Figure 1 shows the network and some sample paths (with different dotted lines). The origin nodes are represented by dark grey circles on the outermost layer, i.e. at the outskirts of an urban area. The destination nodes are represented by light grey circles on the innermost layer, i.e. in the city center. VMS have to be located and relocated only in the intermediate nodes, represented by white circles, belonging to the three intermediate network layers.

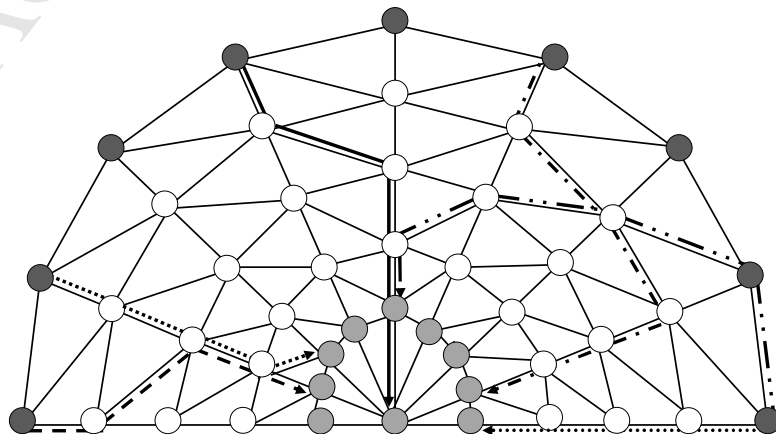


Figure 1. Test network

In the following we will provide details about the parameter setting used for the experimentation.

When dealing with urban traffic management, the different periods of the time horizon usually correspond to the parts of the day (i.e. morning, afternoon and evening) where traffic dynamics, as well as congestion levels, are supposed to be steady. Hence, traffic dynamics and congestion levels vary from one period to another, but not during the period itself.

Each path defined on the network may be characterized by a high/medium/low flow value according to the period under consideration. It therefore follows that, in an urban area, we can have a peak period (high path flow values) or an off-peak period (low path flow values).

In our experimentation we consider a daily time horizon divided into four periods of the same duration. For each time period and for each path we defined realistic flow values (measured as vehicles/hour), derived from an estimated O-D matrix related to the urban area of Naples.

In Table 1, for each period, we report the minimum, the average, the maximum and the total flow value over all the available 36 paths. The total flow traversing the network during the four time periods is equal to 162543 vehicles.

	<i>Periods</i>			
	<i>t = 1</i>	<i>t = 2</i>	<i>t = 3</i>	<i>t = 4</i>
<i>Min Value</i>	481	476	226	476
<i>Avg Value</i>	1285	1049	1183	999
<i>Max Val</i>	2024	2047	2046	2045
<i>Total flow (TF)</i>	46256	37761	42575	35951

Table 1. Flow values defined on the test network

As regards the cost parameters (expressed in euro), the VMS fixed location cost is the same for all the possible facility locations at each period of the time horizon ($h_{it} = 500$). The cost of each link is equal to the Euclidean distance between its vertices and the relocation cost is proportional to the cost of shortest path between the nodes. The minimum, the average and the maximum relocation cost values are respectively 0, 220.5 and 598.6. The minimum cost corresponds to the case where no relocation occurs, i.e. when the relocation occurs from a node to itself.

Finally, different values of the parameters m and C_{ε}^* and of the tuning parameters α and β , have been considered in order to experience different scenarios and to perform a sensitivity analysis of the solutions obtained. In particular:

- six values of m , from 3 to 8. The maximum value is $m = 8$, since by using 9 VMS we would intercept all the flows traversing the network at each period of the time horizon with no relocation of the facilities;
- three values of C_{ε}^* : 50%, 75% and 90% of the total flow;
- five values of α : 0.01; 0.05; 0.1; 0.25; 1. These values take into account that, given the different order of magnitude of the parameters involved in the objective function of $F3$, values of α lower than 0.25 allows solutions with a better trade-off between the two objective function components;
- seven values of β : 0.1; 0.2; 0.3; 0.4; 0.5; 0.75; 1. These values are motivated by the fact that the cost parameters used in the objective function components of $F4$, unlike $F3$, have comparable order of magnitude. Moreover these values of β generate instances of the problem $P2$ with VMS characterized by increasing fixed location costs.

Given this parameter setting, the following 59 instances have been generated and solved:

- 5 instances for the sequential approach $F1 + AM$;
- 3 instances for the sequential approach $F2 + AM$;
- 30 instances for the integrated approach $F3$;
- 21 instances for the integrated approach $F4$.

All the tests have been run on a computer with an Intel(R) Core(TM) i7-4600M CPU @ 2.90 Ghz Processor and 8.00 GB RAM and have been solved by Xpress 7.9 imposing a computation time limit of 7200 seconds.

For the sake of the brevity, in the following, we will present only the results obtained for the whole time horizon under investigation, without reporting the ones obtained at each time period of which it is made up.

Before focusing on the analysis of the results, we briefly discuss the quality of the solutions obtained and related computation time. Most of the instances have been solved to optimality. In particular, all the sequential approach instances have been optimally solved with very low or negligible computation time. This is important since the solution of the sequential approach, as will be explained later, can be used to compute an upper bound for the integrated approach. As regards $F3$ instances, most of them (about 90%) have been solved to optimality with a computation time not higher than 300 seconds. For a few of them the optimal solution has not been determined within the imposed time limit, but the optimality gap is always lower than 3%. Finally $F4$ is the most difficult to be solved. However, most of the instances (80% of them) have been solved to optimality with a computation time near the imposed time limit. The few unsolved instances present an optimality gap that in the worst case is 7%. The most difficult $F4$ instances are the ones characterized by low values of β .

The experimental results related to models $F1+AM$ and $F3$ for problem PI are summarized in Table 2. The table reports the following information for each value of m (on the rows):

- $O1 + O3$: objective function value;
- αIF : intercepted flow (IF) weighted by parameter α , i.e. the component A of (16);
- $IF/TF(\%)$: percentage of the intercepted flow (IF) compared to the total flow (TF);
- $Rcost$: relocation cost, i.e. the component B of (24).

As regards the columns of the Table 2, we report the results of the sequential approach ($F1+AM$) in the first one and the results of the integrated approach ($F3$) with the chosen α values in the other columns.

It is important to recall that, since we are not comparing the two approaches, the results of the sequential approach have been added in order to give an evaluation of the best and worst case (bounds) in terms of intercepted flow and relocation cost respectively. Indeed, when $\alpha > 0$, then the solution of model $F3$ will never overcome the solution of $F1 + AM$ in terms of intercepted flow, but will be lower than or equal to it in terms of relocation cost. Given the order of magnitude of the parameters, it is easy to note that the sequential approach is very close to the integrated one only if $\alpha = 1$.

Let us now analyze the solution of model $F3$ with reference to its two parameters.

It is easy to note that for a given value of m , the higher the value of α , the higher the ratio between intercepted flow and total flow. This can be easily explained since the component A of $F3$ objective function, given also the order of magnitude of the flows and of the relocation cost values, becomes much more important than component B . Coherently, the higher the value of α , the higher the relocation cost. This is due to the fact that, given the limited number of available VMS, if the weight of component A is high, then the model will try to relocate the available facilities in order to intercept as much flow as possible at each period of the time horizon. Only with $m = 8$, the effect on the relocation cost is very limited, regardless of the value chosen for α .

Increasing the value of m , instead, obviously increases the intercepted flow, but the relocation cost does not follow a similar trend. Indeed, the highest relocation cost is obtained with $m = 5$ or $m = 6$ and $\alpha = 1$, and not with the lowest number of facilities, i.e. $m = 3$. This can be explained by the fact that, if the number of facilities is low, the gain achieved by relocating the facilities may be not large enough to balance the relocation costs.

These results for problem PI , even if obtained on a sample case, allows us to draw some conclusions about the decisions that the local authorities can take using the proposed approaches.

Firstly they allow us to determine the sequence of positions of the available portable VMS, within a given time horizon, guaranteeing on one hand the widest possible diffusion of the information and on the other low relocation costs and, consequently, a reduced number of facility movements within an urban area.

Secondly, with specific reference to the integrated approach, if messages with different priority have to be displayed, then assigning high α values to the paths interested by the highest priority messages and low α values to the ones interested by the lowest priority messages, a local authority can use model $F3$ to better manage the limited number of VMS, relocating them where the situation is more critical.

VMS	Objectives	F1 + AM	F3 ($\alpha=0.01$)	F3 ($\alpha=0.05$)	F3 ($\alpha=0.1$)	F3 ($\alpha=0.25$)	F3 ($\alpha=1$)
$m = 3$	$O1 + O3$	94823.62	-794.33	-4090.99	-8614.46	-22473.63	-92711.02
	αIF		794.33	4242.35	9142	23223.25	93711
	IF/TF (%)	57.68	48.87	52.20	56.24	57.15	57.65
	$Rcost$	1069.62	0	151.36	527.54	749.62	999.98
$m = 4$	$O1 + O3$	114252.74	-1038.74	-5193.70	-10570.02	-27426.21	-112426.26
	αIF	-	1038.74	5193.70	11229.70	28329.25	113342
	IF/TF (%)	69.73	63901	63.91	69.09	69.72	69.73
	$Rcost$	915.74	0	0	659.68	903.04	915.74
$m = 5$	$O1 + O3$	132970.22	-1197.88	-5989.40	-12240.88	-31820.47	-130299.60
	αIF	-	1197.88	5989.40	12945.20	32730.75	131443.00
	IF/TF (%)	80.87	73.70	73.70	79.64	80.55	80.87
	$Rcost$	1515.22	0	0	704.32	910.28	1143.4
$m = 6$	$O1 + O3$	146348.60	-1329.67	-6692.73	-13668.72	-35164.62	-142886.42
	αIF	-	1329.67	6798.05	14330.60	35826.50	144143.00
	IF/TF (%)	88.90	81.80	83.65	88.16	88.16	88.68
	$Rcost$	1842.60	0	105.32	661.88	661.88	1256.58
$m = 7$	$O1 + O3$	155000.30	-1453.75	-7268.75	-14679.62	-37579.52	-152443.52
	αIF	-	1453.75	7268.75	14953.90	38288.00	153152.00
	IF/TF (%)	94.43	89.44	89.44	92.00	94.22	94.22
	$Rcost$	1507.30	0	0	274.28	708.48	708.48
$m = 8$	$O1 + O3$	161015.96	-1571.77	-7858.85	-15766.82	-39581.12	-158788.94
	αIF	-	1571.77	7858.85	15876.20	39690.50	159006.00
	IF/TF (%)	98.12	96.70	96.70	97.67	97.67	97.82
	$Rcost$	1534.96	0	0	109.38	109.38	217.06

Table 2. Results of $F1 + AM$ and $F3$ for problem $P1$.

The experimental results related to models $F2+AM$ and $F4$ are summarised in Table 3. The table reports the following information for each value of the percentage of C_ε^* (on the rows):

- $O2 + O3$: objective function value;
- $Lcost$: fixed location cost weighted by parameter β , i.e. component A' of (24);
- # VMS: number of VMS located on the network;
- $IF/TF(\%)$: percentage of the intercepted flow (IF) with respect to the total flow (TF);
- $Rcost$: relocation cost, i.e. the component B of (24);

As regards the columns of the Table 3, we report the results of the sequential approach ($F2 + AM$) in the first one and the results of the integrated approach ($F4$) with the chosen β values in the other columns.

Also in this case, it is important to recall that, since we are not comparing the two approaches, the results of the sequential approach have been added in order to give an evaluation of the best and worst case in terms of location cost and relocation cost respectively. Indeed, if $\beta > 0$, then the solution of model $F4$ will never overcome the solution of $F2 + AM$ in terms of intercepted flow, but will be lower than or equal to it in terms of relocation cost. Given the order of magnitude of the parameters, it is easy to note that the sequential approach is close near to the integrated one only in case of high values of β .

Let us now consider the solution of model $F4$ with reference to its parameters. It is easy to note that for $C_\varepsilon^* = 0.50 \cdot TF$ imposing $\beta \geq 0.2$ we always obtain the same solution, in terms of chosen facility locations, using the minimum number of VMS. The same occurs for $C_\varepsilon^* = 0.75 \cdot TF$ and $C_\varepsilon^* = 0.90 \cdot TF$ with $\beta \geq 0.3$. Therefore, given the configuration of the paths on the network, no reduction in the number of VMS used is achieved by imposing high values of β , i.e. giving more importance to the component A' .

On this basis local authorities, given a specific type of VMS characterized by its fixed cost, can use model $F4$ to infer information about the size of the VMS fleet and the savings achievable in terms of relocation costs.

Moreover, with specific reference to the integrated approach, if different kinds of VMS are available, the local authorities, opportunely choosing different β values for each of them, can use model $F4$ to decide the composition and/or the usage of their VMS fleet and to define their relocation on the network. Indeed assigning low values of β to the cheapest VMS and high values of β to the most expensive ones, the model $F4$ will return solutions where the ITS system will use a high number of cheap VMS, which will be frequently relocated, and a low number of expensive VMS, which will rarely change their positions during the time horizon.

C_{ε}^*	Objectives	F2 + AM	F4 ($\beta=0.1$)	F4 ($\beta=0.2$)	F4 ($\beta=0.3$)	F4 ($\beta=0.4$)	F4 ($\beta=0.5$)	F4 ($\beta=0.75$)	F4 ($\beta=1$)
$0.50 \times TF$	$O2 + O3$	7223.68	800	1481.96	2081.96	2681.96	3281.96	4781.96	6281.96
	$\beta \cdot Lcost$	6000	800	1200	1800	2400	3000	4500	6000
	# VMS	3	4	3	3	3	3	3	3
	IF/TF (%)	52.32	57.74	51.61	51.64	51	51.64	51.64	51.64
	Rcost	1223.68	0	281.96	281.96	281.96	281.96	281.96	281.96
$0.75 \times TF$	$O2 + O3$	11526.38	1200	2400	3398.54	4398.54	5398.54	7898.54	10398.5
	$\beta \cdot Lcost$	10000	1200	2400	3000	4000	5000	7500	10000
	# VMS	5	6	6	5	5	5	5	5
	IF/TF (%)	78.06	81.32	78.78	398.54	398.54	398.54	398.54	398.54
	Rcost	1526.38	0	0	76.63	76.63	76.63	76.63	76.63
$0.90 \times TF$	$O2 + O3$	15311.56	1600	3200	4518.54	5918.54	7318.54	10818.5	14318.5
	$\beta \cdot Lcost$	14000	1600	3200	4200	5600	7000	10500	14000
	# VMS	7	8	8	7	7	7	7	7
	IF/TF (%)	91.73	92.91	96.69	92.62	92.62	92.62	92.62	92.62
	Rcost	1311.56	0	0	318.54	318.54	318.54	318.54	318.54

Table 3. Results of $F2 + AM$ and $F4$ for problem $P2$.

To conclude this section, on the basis of the results presented, we will briefly discuss the practical application of the two different approaches.

As already stated above the two approaches are not alternative, but their usage depends on the specific problem under investigation. Indeed, when the problem is characterized by a great deal of uncertainty, we need real time on-line data and facility locations have to be determined taking into account the current network state, described by the available data. In this case, if the need to lower the relocation cost is not particularly important, the sequential approach is suggested. In particular, if relevance is given to flow maximization, the $F1+AM$ sequential approach has to be used. If relevance is given to the minimization of the number of facilities to use, the $F2+AM$ approach will be used.

When the problem is not characterized by a great deal of uncertainty and/or real time on-line data are not available, we need good and trustworthy off-line data (based on available historical series) about the network parameter values. In this case the usage of the integrated approach is advisable in order to lower the relocation cost to optimize the system performance. In particular, if relevance is given to the maximization of the intercepted flow, the model $F3$ will be used. If priority is given to the minimization of the facility location and/or usage cost, the model $F4$ will be used.

5. Conclusions

In this paper we tackled the portable variable message signs location problem as a multi-period flow intercepting facility location problem ($MP-FIFLP$). This tactical and operational decision problem arises when portable facilities have to be dynamically located and relocated in the nodes or on the links of a network according to varying conditions, expressed in terms of flow parameter values, in order to both maximize the flow intercepted by the facilities (or to minimize the number of used facilities) and minimize the relocation cost associated with them.

The *MP-FIFLP* arises not only in urban traffic management, but also in many other fields of application, such as network monitoring and control, city logistics and urban security, where it is fundamental to take into account the uncertain nature of the phenomena under investigation and its evolution over a given time horizon.

We proposed a sequential and an integrated approach for the solution of the *MP-FIFLP*, both based on *ILP* formulations and we experienced them on a real-like test network. The results obtained confirm the possibility of local authorities using them as a valuable decision support tool in several flow intercepting facility location problems arising in real applications.

Future work perspectives should address the improvement and the integration of the proposed formulations with additional constraints, modeling other specific features of the *MP-FIFLP*. Moreover, with reference to the integrated approach, the development of ad-hoc (exact and/or heuristic) algorithms should be further investigated in order to effectively tackle *MP-FIFLP* large size instances arising in real world applications.

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Highlights

- The role of the variable message signs (VMS) for urban traffic management is discussed.
- The portable VMS dynamic location problem is studied.
- We formulate the VMS location problem as a multi-period facility location problem (MP-FIFLP).
- We propose two different approaches (sequential and integrated) for the MP-FIFLP.
- Several hints about the applicability of the proposed approach are given.

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