Optimal Location of Security Devices

Antonio Sforza, Stefano Starita and Claudio Sterle

Abstract The design of a security system, in terms of number and position of the security devices composing it, is one of the main issue tackled in METRIP project (MEthodological Tool for Railway Infrastructure Protection). It is a complex problem where a very large set of configurations has to be explored in order to determine the most efficient one, which guarantees the highest protection level. Indeed a good placement of the devices has to satisfy two main targets. On one side it has to guarantee the highest security level, i.e. it has to be able to control the widest achievable area. On the other side, it has to be economically sustainable, i.e. it has to be realized with acceptable costs. In literature this problem is generally referred to as sensor placement problem, widely treated by integer linear programming models and combinatorial optimization methods. In this chapter we will present the main covering models present in literature and adopted in METRIP project for the placement of devices preventing the malicious intrusions in railway assets, with particular reference to the intrusions in a railway station. The applicability of these models will be proved using two test cases which represent two typical railway asset schemes.

Keywords Security system design · Covering problem · Coverage and visibility analysis · Device location · Directional sensor placement

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1 Introduction

The great amount of incidents occurred worldwide shows that terrorists seek targets that have emotional or symbolic value, such as widely recognizable icons and targets whose destruction would significantly damage or disrupt an economy. The economic impact of such attacks is indirect [1, 2]. Data provided by Mineta Transportation Institute's National Transportation Security Center (MTI/NTSC) show as from 1970 to 2011, 2.927 attacks against public transportation systems were committed. About 48 % were carried out on buses, while the 43 % were perpetrated against railway infrastructure systems (in the following referred to as RIS). Even though attacks against buses are more frequent, RIS attacks are in general more lethal, as witnessed by the attacks in Madrid 2004, in London 2005 and in Mumbai 2008.

Hence it is clear that a RIS has a great appeal on assailants, especially in urban areas, because of its intrinsic value, vulnerability and difficulties in guaranteeing its protection, due to its nature, which precludes the passengers' screening and identification, and to its specific features [3]:

- open infrastructure;
- high levels of passenger density;
- hazardous materials on the lines;
- extent of the infrastructures inside the city;
- economic and social relevance of the railway transportation system.

For all these reasons prevention and preparedness to risks in RIS requires: proper analysis of the vulnerabilities of the system; clear awareness of criticalities and possible countermeasures; adequate methods to design, scale and optimize the protection.

METRIP (Methodological Tools for Railway Infrastructure Protection) is an European Project focalized on these challenging aims. The general objective of the project is the development of a methodological tool aimed at increasing the protection of a RIS asset, by the following process [4]:

- identifying the most critical and vulnerable assets;
- defining the attack scenarios to be detected for each asset;
- designing the security system in terms of type, number and position of the protection devices;
- evaluating the effectiveness of the security system in terms of asset vulnerability to an attack.

The tool is composed by three interacting modules briefly described in Sect. 4, with particular reference to the Optimization Module (*OM*), devoted to determine the optimal location of the protection devices composing the security system. This problem is referred in literature to as the sensor placement problem and in this chapter we will survey some covering optimization models which can be used for its solution to design the security system of a RIS asset. We will also give hints explaining how these models can be used to achieve also some specific monitoring tasks.

This chapter is structured as follows. Section 2 provides a brief description of some protection devices which can be employed in a RIS security system. Section 3 is devoted to the sensor placement problem. Section 4 is focused on the Optimization Module of METRIP tool and on the models used in it for the optimal placement of the security devices. Results obtained by presented models on two sample test cases are shown in Sect. 5. Section 6 is devoted to conclusions.

2 Protection Devices for a RIS

A huge number of protection devices can be employed in a RIS security system, some of them, specifically devoted to the detection of particular attacks, as for example Chemical, Biological, Radiological, Nuclear and Explosive (CBRNe) attacks, are installed just on request. On the other side a *Baseline Security System* (BSS) is usually installed for the protection of an asset, not only a RIS asset, with the aim of preventing malicious intrusions. The BSS system is composed by three main classes of protection devices opportunely integrated:

- *Video Surveillance Devices*: fixed perspective cameras (directional cameras); PTZ (Pan-Tilt-Zoom) cameras; omnidirectional cameras; high resolution cameras (particularly suitable for cameras equipped with video-analysis tool).
- *Access Control Devices*: triple technology volumetric sensors; magnetic contacts; proximity readers; access control systems (ACS2/ACS8); infrared barriers.
- *Audio Surveillance Devices*: microphones; sound cards; sound analyzer server.

The placement of some devices, such as for example magnetic contacts, access control systems or sound cards is determined by their specific usage, whereas the placement of other devices, such as cameras, volumetric sensors and microphones, has to be strategically performed. Indeed many types of these devices, differing in performances and costs, are available. Moreover, generally, the higher is the security level guaranteed by a device, the higher is its cost. Hence a good and strategic placement of these devices has to efficiently solve the trade-off between the achievement of higher security levels and the minimization of the costs. Moreover, for some of these devices, in particular for cameras, several constraints have to be taken into account when specific security tasks have to be achieved. For intrusion detection, the complete coverage of the asset is required; a reliable security system, or a system aimed at performing the tracking of objects/people moving in an area, requires that points of the asset have to be covered by more than one camera; the usage of video-analysis algorithms, as face recognition algorithms or, specifically for RIS, yellow line crossing algorithms, requires that cameras have to be opportunely positioned, with respect to the object, in order to guarantee a good quality of the image.

3 State of the Art of the Sensor Placement Problem

Location problems consist in determining the best locations of one or more facilities/devices on the basis of a predefined performance criteria and operational constraints. More precisely given the distribution of a good/service demand, the aim is to determine the location of a set of facilities/devices, minimizing location and service costs (generally related to distance or time parameter). These problems have been widely approached by mixed integer linear programming models and optimization methods. In [5] they are classified in three main groups: *p*-median models [6, 7], *p*-center models [6, 8] and covering models [9]. The third group concerns location problems which consists in the placement of a set of facilities, in points of a region of interest, with the aim of satisfying a real or virtual service demand. A point can be covered by a facility just in case the adopted covering criteria is met [9, 10]. A complete review of the main works on covering problems is out of the scope of this chapter, but a good review of the most recent contribution can be found in [11, 12].

The optimal location of protection devices, as said above, is referred to in literature as the sensor placement problem. This problem has been widely treated in literature as a set covering problem, where the facilities to be located are the security devices and the satisfaction of the demand corresponds to the coverage of the set of points schematizing the region of interest to be controlled.

The first attempts to tackle the problem consider it as a variant of the art gallery problem (*AGP*), introduced in [13]. This problem is widely explored in [14] and a review of the most recent advances in the field can be found in [15]. The *AGP* problem consists in opportunely distributing the minimum number of guards in an area such that all its points are observed. In the *AGP* the guards are assumed to have an unlimited omnidirectional monitoring capacity, i.e. they can cover a 360° angle with no distance constraints. These assumptions are too strong and unrealistic for the security devices under investigation, since they are generally directional devices with very different performances and costs. For this reason the sensor placement problem is also referred to as the directional sensor placement problem. The interested reader is addressed to the work by [16] for a complete survey on coverage models and methods for directional sensor placement problem.

In the following we will just summarize the main recent contributions where new issues of the problem are examined and solved. In [17] the authors tackle and solve by integer linear programming models the problem of placing omnidirectional devices, differing for coverage ranges and costs, in a region schematized by a grid of point. They also treat the problem of determining the device placement where each grid point is covered by a unique subset of sensors. This work is extended in [18] where the device detection probability is introduced. Indeed the authors assume that the detection probability of a target decreases exponentially with the distance between the sensor and the target. Hence they solve the problem of locating the minimum number of devices which guarantee that every grid point is covered with a minimum confidence level. In [19] real operational constraints and capabilities of the devices are taken into account for the first time. It tackles the problem of determining the optimal positioning and the number of cameras in a region, given a set of task-specific constraints and a set of possible cameras to use in the layout. It considers very realistic regions, i.e. volumes with holes and static or dynamic objects within it. Then it focuses on planar regions and solve the camera layout problem with certain task-specific constraints by binary optimization over a discrete problem space. In [20] the authors, starting from the idea proposed in [17], tackle the problem of locating directional sensors (i.e. cameras which do not possess circular sensing ranges) with the aim of coverage maximization and the achievement of the coverage at a certain resolution. In [21] the problem is treated with reference to a 3D region in an urban environment. The visibility analysis is tackled by a GIS-based approach and the problem is solved by integer linear programming models. The problem of locating directional sensor in a region of interest characterized by the presence of blocks is treated in [22]. This work, moreover, proposes an original integer linear programming model where the points of the region to be controlled are opportunely weighted in function of their importance. The orientation of directional sensors within a 2D plane is explicitly taken into account in [23]. In [24] a new method for determining the best placement for large numbers of cameras within arbitrary building layouts is described. The method takes as input a 3D model of the building, and uses a genetic algorithm to find a placement that optimizes coverage and overlapping between cameras. The positioning error bounds are taken into account in [25], within an integrated maximal covering and backup covering problem solved by a simulated annealing based approach. The error bound concept is also considered in [26] together with aspects related to lack of knowledge regarding the target to control.

4 The Optimization Module

The decisional process developed by the METRIP tool, briefly introduced in Sect. 1, is performed by three main interacting modules:

- **Unified Modeling Language Module (UMLM)**, devoted to develop the UML models of the:
  - RIS assets (geometry, physical structure and main components);
  - attacks against RIS (effects, used mean, main steps of the attack);
  - protection devices (technological features and cost of each device).
- **Optimization Module (OM)**, devoted to find the optimal location of the security system devices within the asset through integer linear programming (ILP) covering models solved by the optimization software Xpress-MP. The location of the devices is optimized with respect to the covered space of the asset and takes into account its specific geometry.

- **Vulnerability Analysis Module (VAM)**, devoted to the vulnerability evaluation of the asset in relation to the kind of attacks and protection devices.

In this chapter we will focus on the Optimization Module (*OM*) and on the mathematical models implemented in it for the optimal location of the protection devices. The *OM* is devoted to manage a library of optimal covering ILP models used in the design of the security system. These models determine the number and the location of most of the control devices which constitute the *BSS*. The *OM* performs the following main activities:

- Asset discretization.
- Coverage analysis.
- Coverage model selection.
- Solution of the model by the Xpress optimization software and generation of the output for the *UMLM*.

In the following sub-sections we will explain in detail the first three phases. In the next section we will present the results obtained solving the model by the Xpress optimization software.

4.1 Asset Discretization

Given the information about the asset geometry (shape, width and length) provided by the *UMLM*, the area of the asset to be protected, referred to as region of interest, has to be made discrete, i.e. we have to pass from the continuous two-dimensional representation to a discrete representation of the region [21, 22]. This operation is performed building a grid with step size k on the plant of the asset to be controlled. The set of points of the grid is referred to as R and we have to cover/protect these points. Obviously the smaller is the step size of the grid, the higher is the cardinality of R and consequently more detailed is the schematization of the area.

In this phase we define also the set of points where the devices could be placed, referred to as L. Generally L is constituted by the points sited on the edges and corners of the asset walls and of the obstacles present in the region of interest.

In some cases these points have to respect particular conditions. For example, if video-analysis algorithms have to be used, possible location points are the ones which have to be used in order to allow that the algorithms effectively work. In particular if we have to locate cameras equipped with video-analysis algorithms for the control of the yellow line crossing, then the camera has to be installed perfectly aligned with the yellow line. This means that the only possible points for placing these cameras are the ones along the yellow line. Similar considerations could be done for the face recognition algorithm equipped cameras, which, to be effective, require to be placed almost orthogonally with respect to the target.

4.2 Coverage Analysis

The activity of a BSS device can be schematized through a ***coverage area***, i.e. the portion of area that can be controlled by it. It is defined by two parameters:

- θ, *coverage angle*, expressed in degrees (0° ÷ 360°), within which the device is active;
- r, *coverage ray*, maximum distance (expressed in metres) to which the device is still effective.

For example, the area covered by a microphone is a "circle" with a coverage angle $\theta = 360°$, and a certain coverage ray r. Instead the area covered by a camera for a Closed Circuit Television (CCTV) is a "circle sector" with $\theta < 360°$ and ray r.

The coverage area of a security device having a coverage angle lower than 360°, as for example a CCTV, is defined by its orientation. For sake of clarity, let us suppose to have a CCTV camera with a 90° coverage angle. Given a potential location, the camera can be installed with 4 different orientations which cover 4 different circle sectors, e.g. 0°–90°, 90°–180°, 180°–270, 270°–360°. This means that in a certain point of the set L we can locate a single device with a certain orientation, or more devices with different orientations. To enlarge the space of the locations, the orientations taken into account for this camera could generate a certain overlapping of the coverage areas. If, for example, the overlap is equal to 45°, we can generate 8 orientations and so 8 different circle sectors: 0°–90°, 45°–135°, 90°–180°, 135°–225°, 180°–270, 225°–315°, 270°–360°, 315°–45°. To enumerate all the possible orientations for a device located in a point of set L we can define a step δ, δ ∈ [0° ÷ θ]. For each potential location a device can be located using $n = \lfloor 360°/\delta \rfloor$ different orientations. In this way, it is possible to define, as extension of the set L of the potential locations, a set L' of potential locations with orientations, $|L'| = n \times |L|$.

Coverage analysis consists in determining which are the points of R that can be controlled by a device positioned in a potential location with a certain orientation. In the following this set of points will be referred to as S, $S \subseteq R$. This operation is made for each potential location of the set L' and it can be performed in two ways:

1. ***Geometrical coverage***: the sub-set S for each potential location of a device is built with reference only to the angle θ and the ray r of the coverage area, without taking into account the presence of obstacles in the region of interest.
2. ***Physical coverage***: the set of points of S is filtered considering the presence of obstacles which can interdict the activity of the device. Hence a set $S' \subseteq S$ is generated. This analysis is based on geometric considerations which take into account the coverage area of the device and the shape and the sizes of the obstacles. In this case the set of points R to be covered has to be reduced to the set R', which is the union of all the sets S', S' = U[S'].

In Fig. 1 we show an example of asset discretization (a grid with 49 points) and 8 potential locations for the devices. Moreover we show the coverage area and the

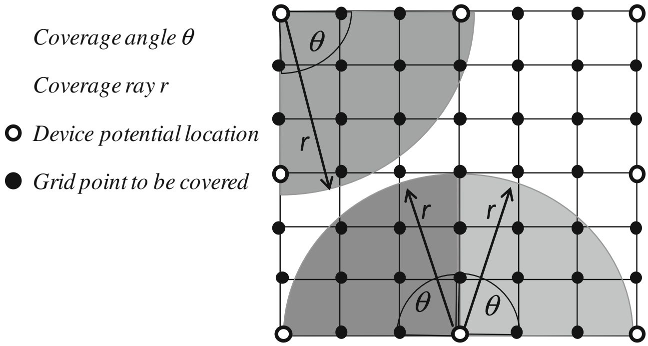

Fig. 1 Asset discretization and coverage area of three devices

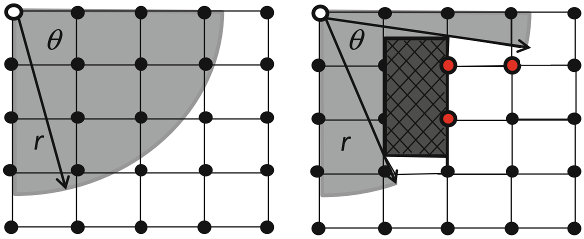

Fig. 2 Geometrical and physical coverage of a device

sub-set S of covered points for three devices with a certain orientation. It is important to note, as explained above, that a single device could be located in a point with a certain orientation and that more devices could be located in the same point with different orientations. In Fig. 2 instead we show the difference between the geometrical coverage (sub-set S) and the physical coverage (sub-set S') in case of presence of an obstacle.

The coverage analysis allows to generate the so-called *Coverage Matrix* (*CM*), a binary matrix where the rows correspond to the elements of the set L', i.e. to all the potential locations with orientations, and the columns correspond to the points of the set R to be covered. Hence its dimensions are $(n \times |L|,|R|)$. Its generic element c_{ij} is equal to 1 if device i, $i \in L'$, can cover the point j, $j \in R$, (i.e., in other words, if the point j belongs to the set S' of the device i), otherwise it is equal to 0. The coverage matrix is the fundamental input for all the covering ILP models used in METRIP.

In case of cameras the coverage area is referred to as Field of View (FoV), i.e. the maximum volume visible from a camera, and we do not speak in terms of coverage analysis, but in terms of visibility analysis [19]. Moreover when cameras have to be placed, then two other parameters can be taken into account for specific requirements:

- Spatial Resolution (SP), i.e. the ratio between the total number of pixels on its imaging element excited by the projection of a real object and the object's size.
- Depth of Field (DoF), i.e. the distance between the nearest and farthest objects that appear in acceptably sharp focus in an image.

4.3 Coverage Model Selection

Covering problems can be classified in function of two main objectives (Fig. 3):

- Minimization of number or total cost of control devices to be located,
- Maximization of the region covered by the devices.

The first class of covering problems arises when we have to determine the number of control devices to be located, minimizing the total installation cost and covering all the points of the region of interest or a sub-set of them. Within the first class we can operate the classification of the points of the region in two groups, *important* and *general* points. A point can be classified as important if it is:

- a potential point used by an attacker for the intrusion (window, doors, fences, etc.);
- a valuable point of the RIS (control room, vault, etc.)
- an important point for safety reasons, for instance entrance/exit from elevators and escalators have to be compulsorily controlled by video-surveillance system because the operator has to intervene in case of malfunctioning.

Important points, contrarily to *general points*, have to be compulsorily controlled. If all the points have the same importance, then the problem is referred to as Set Covering Problem (*SCP*) [9], otherwise it is referred to as Weighted Demand Covering Problem (*WDCP*) [22].

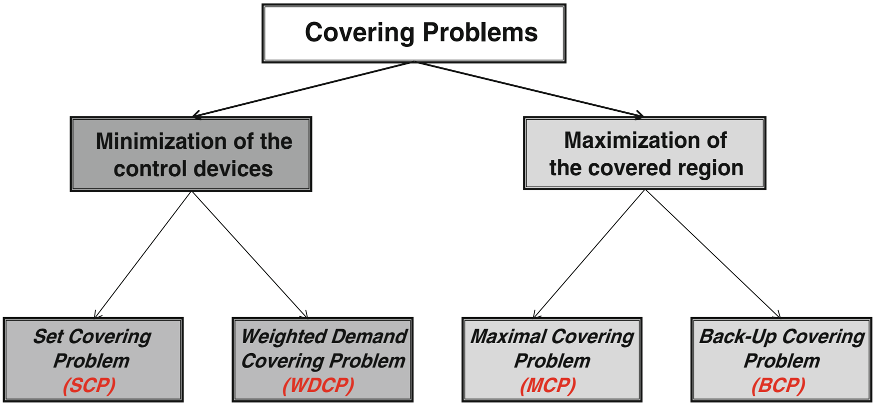

Fig. 3 Classification of the covering problems

Concerning the second class of covering problems, they arise when we have to determine the position of a prefixed number of control devices in order to maximize primary and/or secondary coverage (also referred to as multiple or back-up coverage) of the region of interest. If the aim is determining the solution which maximizes the primary coverage and consequently the number of primary covered points, then the problem is referred to as Maximal Covering Problem (*MCP*) [10]. If the aim is determining the solution which maximizes the multiple coverage and hence the number of multiple covered points, then the problem is referred to as Back-up Covering Problem (BCP) [27]. In these problems the points to be controlled can be weighted or unweighted, depending on the need of assigning them different importance values.

4.3.1 Minimization of the Control Devices Number

In the formulation of the first class of covering models, the following notations will be adopted:

$R = \{1, \ldots, \|R\|\}$	set of points representing the region of interest;
$L' = \{1, \ldots, \|L'\|\}$	set of device potential locations with orientations;
s_j	flag value defined for each j, $j \in R$. It is equal to 1 if the point j has to be compulsorily controlled, 0 otherwise;
h_i	installation cost at a potential device location i, $i \in L'$;
α	parameter between 0 and 1 regulating the placement of a new device in case a "significant" number of general points of the region of interest is controlled

Moreover the following variables will be used:

- $y_i = \{0, 1\}$: binary variable associated to each potential device location i, $i \in L'$, with a specific orientation. It is equal to 1, if a device is installed at the location i, 0 otherwise.
- $x_j = \{0, 1\}$: binary variable associated to each point j to be covered, $j \in R$. It is equal to 1 if the point j is covered, 0 otherwise.

It is important to underline that, due to the fact that a device can be positioned in a potential location using different orientations, as explained in Sect. 3.2, each y_i variable, $i \in L'$, corresponds to a device in a certain point with a certain orientation.

Set Covering Problem (*SCP*)

The ILP model for the set covering problem is:

$$Min\ z = \sum_{i \in L'} h_i y_i \tag{1}$$

s.t.

$$\sum_{i \in L'} c_{ij} y_i \geq 1 \quad \forall j \in R \tag{2}$$

$$y_i = \{0,\ 1\} \qquad \forall i \in L' \tag{3}$$

The objective function (1) minimize the total installation cost of the control system. Constraints (2) impose that each point j, $j \in R$, has to be covered at least by one device. Constraints (3) are binary constraints for variables y_i, $i \in L'$. Note that, if the cost h_i is equal for all the potential locations i, $i \in L'$, then the model returns the position of the minimum number of control devices to be located in order to cover all the points of the region.

Weighted Demand Covering Problem (*WDCP*)

The ILP model for the weighted demand covering problem is:

$$Min\, z = \sum_{i \in L'} y_i - \alpha \sum_{j \in R} \left(1 - s_j\right) x_j \tag{4}$$

s.t.

$$\sum_{i \in L'} c_{ij}\, y_i \geq 1 \quad \forall j \in R | s_j = 1 \tag{5}$$

$$\sum_{i \in L'} c_{ij}\, y_i \geq x_j \quad \forall j \in R | s_j = 0 \tag{6}$$

$$y_i = \{0,\ 1\} \quad \forall i \in L' \tag{7.a}$$

$$x_j = \{0,\ 1\} \quad \forall j \in R \tag{7.b}$$

The objective function (4) is composed by two terms. The first term minimizes the number of control devices to be located in order to cover all the important points of the region. The second term tries to locate an additional control device if its installation increases the number of controlled general points of a minimum threshold value defined by the parameter α. In order to define the value α, we have to consider that if we want to install a new device just if N^* additional general points are covered, then the value of α has to satisfy the following two conditions: $1 - \alpha \times N^* < 0$ and $1 - \alpha \times \left(N^* - 1\right) > 0$. Constraints (5), as constraints (2), impose that each important point j, $j \in R$, has to be covered at least by one device i, $i \in L'$. Constraints (6) impose that a general point is covered just in case a device able to control it has been installed. Constraints (7a) and (7b) are binary constraints for y_i, $i \in L'$, and x_j, $j \in R$.

4.3.2 Maximization of the Covered Region

In the formulation of the second class of covering models we integrate the previous notations with the following parameters:

- d_j weight associated to a point of the region j, $j \in R$;
- p maximum number of devices to be installed;
- β parameter between 0 and 1 weighting secondary coverage with respect to primary one.

Moreover an additional binary variable will be used:

- $u_j = \{0, 1\}$: binary variable associated to each point j to be covered, $j \in R$. It is equal to 1 if the point j is covered by two or more devices, 0 otherwise.

Maximal Covering Problem (*MCP*)
The ILP model for the maximal covering problem is:

$$Max\, z = \sum_{j \in R} d_j x_j \tag{8}$$

s.t.

$$\sum_{i \in L'} c_{ij} y_i \geq x_j \quad \forall j \in R \tag{9}$$

$$\sum_{i \in L'} y_j = p \tag{10}$$

$$y_i = \{0,\ 1\} \quad \forall i \in L' \tag{11.a}$$

$$x_j = \{0,\ 1\} \quad \forall j \in R \tag{11.b}$$

The objective function (8) maximizes the number of covered points of the region, each of them weighted by its importance d_j. If all the points have the same weight, then the model maximizes the number of covered points. Constraints (9) impose that a point j, $j \in R$, is controlled just in case at least one device i, $i \in L'$, among the ones able to control it, is located. Constraint (10) imposes that the number of devices to be located has to be exactly p. Finally constraints (11.a) and (11.b) are binary constraints for variables y_i, $i \in L'$, and $x_j, j \in R$, respectively. Note that using constraint (10) we are implicitly assuming that all the control devices have the same installation cost and moreover this cost does not depend on the position where the device will be located. If we want to take into account different installation costs, this constraint can be generalized using the following budget constraint, where B is the available budget.

$$\sum_{i \in L'} h_i y_i \leq B \tag{12}$$

Back-up Covering Problem (*BCP*)

The ILP model for the back-up covering problem is:

$$Max\, z = (1 - \beta) \sum_{j \in R} d_j x_j + \beta \sum_{j \in J} d_j u_j \tag{13}$$

s.t.

$$\sum_{i \in L'} c_{ij} y_i \geq x_j + u_j \quad \forall j \in R \tag{14}$$

$$\sum_{i \in I} y_i = p \tag{15}$$

$$u_j \leq x_j \quad \forall j \in R \tag{16}$$

$$y_i = \{0,\ 1\} \quad \forall i \in L' \tag{17.a}$$

$$x_j = \{0,\ 1\} \quad \forall j \in R \tag{17.b}$$

$$u_j = \{0,\ 1\} \quad \forall j \in R \tag{17.c}$$

The objective function (13) maximizes the weighted sum of the primary and multiple coverage of the points of the region of interest. The relative weight of these two components is defined by the value of the parameter β. Moreover each point of the region is weighted in function of its importance d_j. Constraints (14) and (15) are the same constraints of the model described for the MCP. Constraints (16) impose that each a point $j, j \in R$, is back-up/multiple covered just in case if it is a primary covered. Finally constraints (17.a), (17.b) and (17.c) are binary constraints for variables y_i, $i \in L'$, x_j and u_j, $j \in R$. Also this model can be generalized by the usage of constraint (12) as done for the *MCP*.

4.4 Framework of the OM

To summarize the main activities performed by the Optimization Module of the METRIP tool can be schematized as reported in Fig. 4.

It is important to note that, as explained in Sect. 1, at first the *OM* receives the input information related to the assets and protections from the *UMLM*, then the *OM* returns the solutions of the covering models to the *UMLM*. This allows to populate the *UMLM* models with additional information which will be used by the *VAM*.

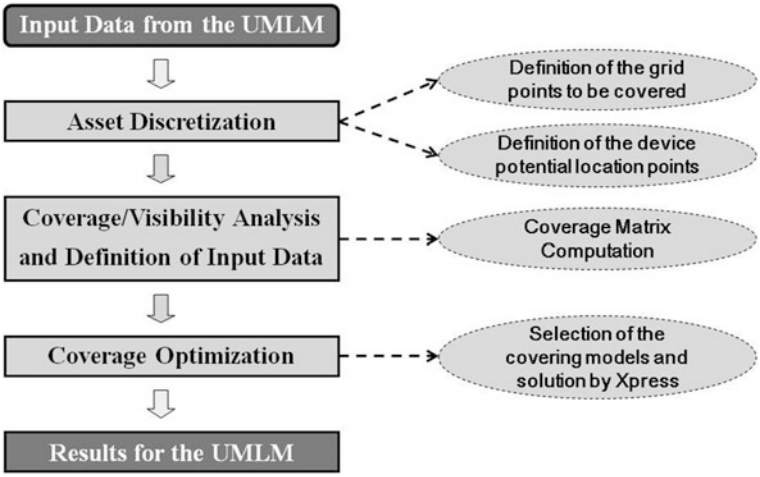

Fig. 4 Optimization module main activities

5 Experimental Results

The four presented covering models have been experienced on two test cases which schematize two typical RIS assets: the first is an open space with several entrances along the boundaries, which recalls the idea of a railway station atrium; the second is a scheme of a railway station. The usage of these two particular test cases is motivated by the fact that we wanted to test the model in two opposite situations, i.e. a first situation where no obstacles are present in the area to be controlled, hence geometrical and physical coverage coincide, and a second situation, where instead the presence of blocks significantly affects the covering capabilities of the devices. In both cases the devices to be located are fixed perspective cameras. The characteristics of the used cameras and their orientations are specified for each test case. The models have been solved by the optimization software FICO™ Xpress-MP 7.3 and run on an Intel® Core™ i7, 870, 2.93 GHz, 4 GB RAM, Windows Vista™ 64 bit.

5.1 Open Space Test Case

The tackled open space case is represented in Fig. 5 where the area to be controlled has been discretized with a grid of 441 points. The white and the black circles indicate the side entrances and the possible locations of the cameras (100 points) respectively. Only one kind of camera has been taken into account, referred to as CCTV1 ($\theta = 90°,\ r = 25$). We solve the four presented models using CCTV1 camera with 4 and 8 orientations in the range $0° \div 360°$. In the first case we have a 400×441 coverage matrix, whereas in the second case, a 800×441 coverage matrix.

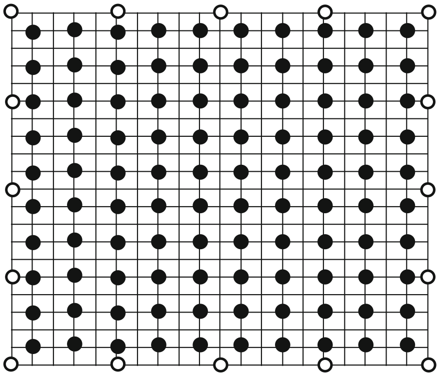

Fig. 5 Open space test case

Results and computation time of the *SCM* and *WDCM* are summarized in Table 1 where: the second column reports the number of cameras to be installed; the third and the forth columns report the number of covered points and the percentage (with respect to the total number of points of the region of interest) respectively; the fifth column reports the computation time in seconds.

In *SCM* the location cost of a camera (h_i, $i \in L'$) has been set to 1, hence it minimizes the number of cameras to be used. In *WDCM*, the parameter α has been set to 0.067. This means (as explained in Sect. 4.3) that the model will locate an additional camera just if it covers at least 10 uncovered general points of the region of interest.

As expected, the *SCM* provides a solution that covers all the points of the region of interest and the introduction of additional camera orientations allows to decrease the number of installed devices from 19 to 18. The *WDCM* provides solution where all the important points are covered and it shows the same reduction, from 15 to 14 cameras when 8 orientations are used. We can also notice that *WDCM*, using 4 cameras less than *SCM*, even if it does not achieve the complete coverage of the region of interest, allows to cover more than 90 % of its points. The highlighted improvement of the solution of the two models using 8 orientations is obvious, even if it is not very consistent. This is basically due to the fact that the region of interest is an open space, free of blocks and hence the usage of more orientations is not very effective.

Table 1 Results of the *SCM* and *WDCM* on the open space scheme

SCM	CCTV	Covered points	COV (%)	CPU time (s)
CCTV1 (4 orient.)	19	441	100	2.4
CCTV1 (8 orient.)	18	441	100	28.3
WDCM (α = 0.067)	CCTV	Covered points	COV (%)	CPU time (s)
CCTV1 (4 orient.)	15	409	92.74	3.3
CCTV1 (8 orient.)	14	414	93.88	13.7

The solutions of the *SCM* and *WDCM* with 4 orientations and 8 orientations are reported in Figs. 6 and 7 respectively, where we indicate the covered, uncovered and important points in light grey, dark grey and white respectively.

Computational results of the *MCM* are summarized in Table 2 where: the second column reports the prefixed value of p, i.e. the number of available cameras; the third and forth columns report the number of covered points and the percentage (with respect to the total number of points of the region of interest) respectively; the fifth and the sixth column report the number of multiple covered points and the related percentage (with respect to the total number of points of the region of interest) respectively; the seventh column reports the computation time. The maximum values of p in the two cases, i.e. 19 and 18, are imposed on the basis of the *SCM* results.

Generally different values of the weight d_j can be chosen for the grid points to be covered in function of their positions within the region of interest. In this experimentation they have been set to 10 for some relevant points and to 1 for the other points. This allows us to compare the *MCM* solutions, where the important points

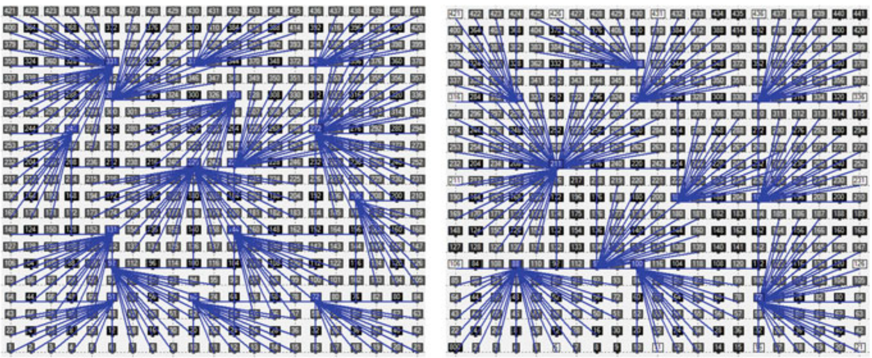

Fig. 6 Solutions of *SCM* and *WDCM* with CCTV1 cameras (4 orientations)

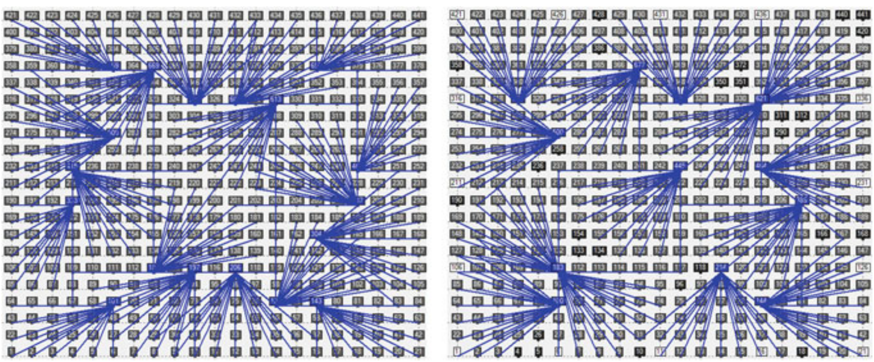

Fig. 7 Solution of *SCM* and *WDCM* with CCTV1 cameras (8 orientations)

Table 2 Results of *MCM* on the open space case

	CCTV	Covered points	COV (%)	M-covered points	M-COV (%)	CPU time (s)
CCTV1 (4 orient.)	8	278	63.04	0	0	3.1
	10	331	75.06	12	2.7	8.3
	13	388	87.98	33	7.5	62.4
	16	426	96.59	57	12.9	85.5
	19	441	100	100	22.7	120.0
CCTV1 (8 orient.)	8	278	63.04	0	0	6.7
	10	334	75.37	5	1.13	41.8
	13	398	90.25	26	5.8	72.6
	16	432	97.96	50	11.3	102.6
	18	441	100	88	19.9	160.9

have higher weight values, and *WDCM* solutions, where the important points have to be compulsorily covered.

It is easy to observe that the computation time increases with the value of p, but in all the cases we find the optimal solution within an acceptable computation time.

In Table 2 we also report the percentage of the multiple-covered points of the region of interest (referred to as M-COV %), since we want to highlight the fact that this coverage model, as the ones presented above, does not provide solution where each point has to be compulsorily covered by just one device.

Also in this case we can notice that using the same number of cameras, the solutions with 8 orientations for each potential location are obviously better than the ones with 4 orientations. Anyway, also in this case the improvement is not so effective because of the structure of the area. This observation can be clearly noticed in Fig. 8 where the percentage of primary and multiple covered points, varying the value of p and using 4 and 8 orientations, are reported. It is easy to see that these two trends are very similar. Finally in Fig. 9, as an instance, we show the solutions obtained with p = 10 and p = 18 using 8 orientations. We can note that in both cases, all the important points are covered by at least one camera and the solution

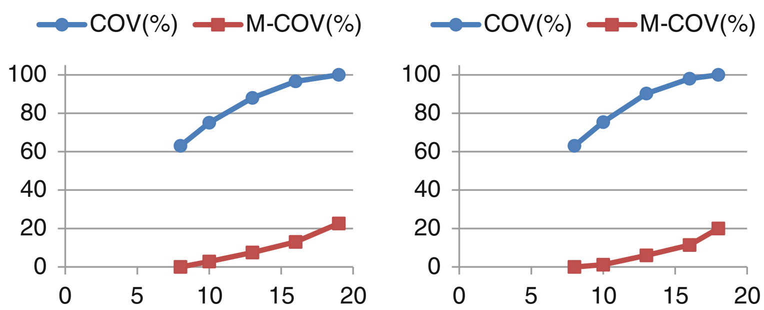

Fig. 8 Primary and multiple coverage solving *MCM* varying p with 4 and 8 orientations

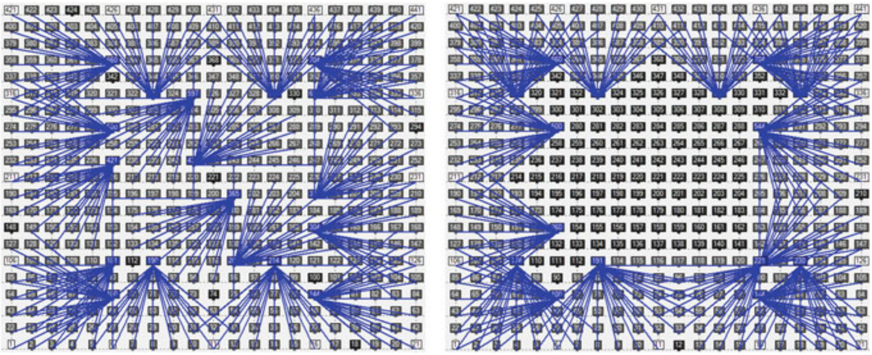

Fig. 9 *MCM* solutions using 10 and 18 cameras (8 orientations)

using 18 cameras is slightly different by the optimal one of the *SCM* because of the different weights of the points.

The results of the *BCM* are summarized in Table 3 The reported information are the same of Table 2, with the addition of the column β, i.e. the weight of the multiple coverage with reference to the primary one. The same d_i values defined for *MCM* have been used. For the sake of brevity, we just present the results with 4 and 8 orientations varying β but fixing the value of p to 19 and 18, i.e. to the number of cameras required for the complete coverage of the area. It is easy to observe that the usage of β values higher than 0 provides an increase of the percentage of multiple-covered points and the usage of β values lower than 0.5 allows to obtain solutions with a good trade-off between primary and multiple coverage of the points. This results is also highlighted in Fig. 10 where the percentage of primary and multiple covered points varying β is reported. Finally, as an instance, in Fig. 11 we show the solutions obtained by *BCM* using 18 cameras with β = 0.2 and β = 0.9 respectively. It is important to observe that the solution with β = 0.2 covers almost all the region

Table 3 Results of *BCM* on the open space case

	β	CCTV	Covered points	COV (%)	M-covered points	M-COV (%)	CPU time (s)
CCTV1 (4 orient.)	0	19	441	100	100	22.70	120.0
	0.2	19	428	97.05	137	31.07	97.7
	0.4	19	404	91.61	174	39.46	11.4
	0.6	19	358	81.17	221	50.11	202.3
	0.9	19	336	76.19	259	58.73	244.0
CCTV1 (8 orient.)	0	18	441	100	88	19.9	160.9
	0.2	18	430	97.5	152	34.47	111.2
	0.4	18	420	95.24	160	36.28	94.4
	0.6	18	325	73.70	225	51.02	289.4
	0.9	18	311	70.52	238	53.97	302.8

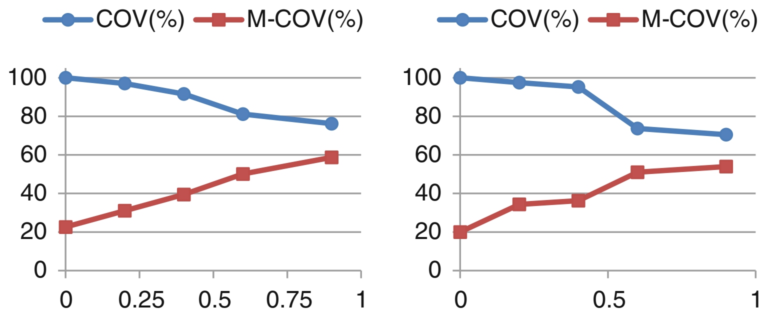

Fig. 10 Primary and multiple coverage solving *BCM* using 19 cameras (4 orientations) and 18 cameras (8 orientations) varying β

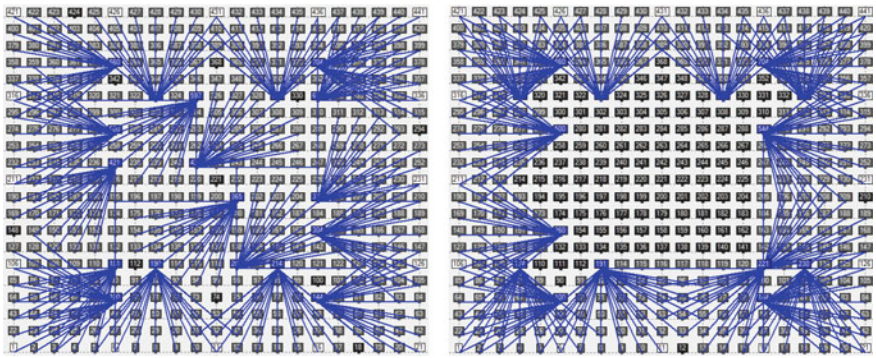

Fig. 11 *BCM* solutions using 18 cameras (8 orientations) with β = 0.2 and β = 0.9

of interest only once, whereas the solutions with β = 0.9 covers the important points of the region of interest (characterized by higher weight values) more than once.

5.2 Railway Station Case

In this section we present the results of the four models on the railway station scheme reported in Fig. 12 The area to be controlled has been discretized by 621 points, which are then reduced to 526 because of the presence of the obstacles (offices, walls and pillars). The potential locations for the cameras are 143, represented by black circles. The important points are represented by white circles and are positioned in correspondence of entrances, elevators, lifts and among the platforms (Fig. 13).

Two kinds of cameras have been taken into account: CCTV1 ($\theta = 90^\circ,\ r = 25$); CCTV2 ($\theta = 30^\circ,\ r = 50$). We solve the models using:

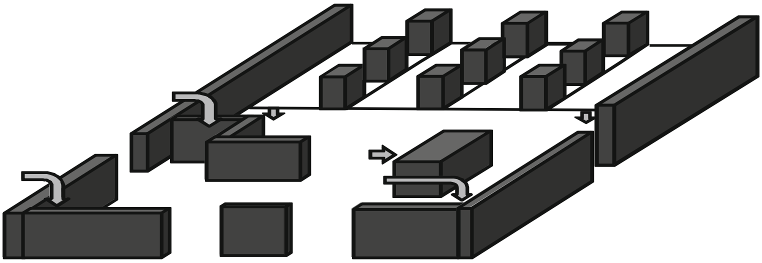

Fig. 12 3D scheme of the station

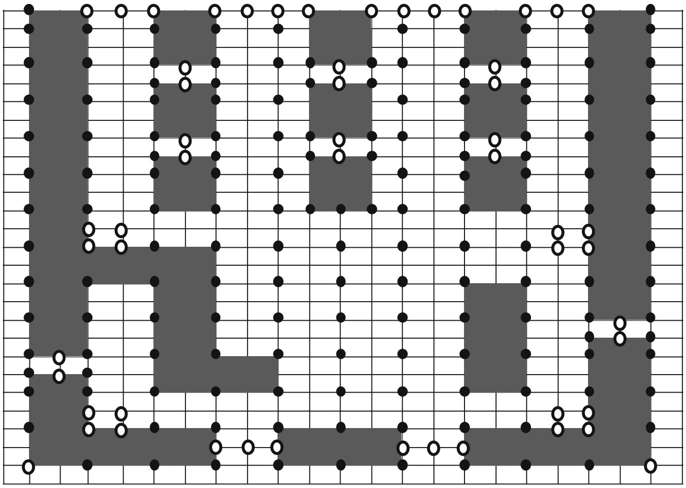

Fig. 13 Discretized scheme of the station with potential camera locations and important points

- CCTV1 with 8 orientations in the range 0° ÷ 360°;
- CCTV1 with 8 orientations in the range 0° ÷ 360° and CCTV2 with 12 orientations in the range 0° ÷ 360°.

In the first case we have a 1,144 × 621 coverage matrix, whereas in the second case we have a 2,860 × 621 coverage matrix.

Computational results of the *SCM* and *WDCM* are summarized in Table 4 where the same information of Table 1 are reported. Also in this case in *SCM* the cost of each camera (h_i, $i \in L'$) has been set to 1, and in *WDCM*, the parameter α has been set to 0.067. As expected the *SCM* provides a solution that covers all the points of the region of interest and the usage of both kind of cameras (i.e. 20 different camera orientations) allows to decrease the number of installed devices from 45 to 39. Hence, contrarily to what occurred for the open space, in this case the reduction of the number of cameras is more consistent. This is due to the fact that geometrical

Table 4 Results of the *SCM* and *WDCM* models on the railway station scheme

SCM	# CCTV	Covered points	COV (%)	CPU time (s)
CCTV1	45	526	100	0.5
CCTV1 + CCTV2	39	526	100	6.3
WDCM (α = 0.067)	# CCTV	Covered points	COV (%)	CPU time (s)
CCTV1	26	366	69.58	1.4
CCTV1 + CCTV2	28	449	85.36	5.5

and physical coverage do not coincide for most of the camera possible positions/ orientations.

Concerning instead *WDCM*, it returns solutions that cover all important points but, contrarily to the open space case, they do not cover almost all the region of interest. Moreover we can note that the usage of both kinds of cameras provides an increase of the located ones, contrarily to what occurs for the *SCM*. This can be explained by the fact that, given the presence of the blocks, no additional 90° camera able to cover at least 10 uncovered points could be found. On the contrary, the usage of a 30° camera, allows to achieve this result with two additional cameras. The solutions of the *SCM* and *WDCM* with a single kind of camera (CCTV1) and with both kinds of cameras (CCTV1 and CCTV2) are reported in Figs. 14 and 15 respectively.

Computational results of *MCM* are summarized in Table 5 which reports the same information of Table 2. Also in this case, as done for the open space case, the maximum values of p, i.e. 45 and 39, are imposed on the basis of the *SCM* results and the weight values (d_i) has been set 1 for the generic points and to 10 for the important ones in order to compare the solution with the one of *WDCM*.

The same considerations provided for the open space case can be repeated for the railway station scheme. Indeed we can notice that using the same number of devices, the solutions with two kinds of cameras are significantly better than the ones with one kind of camera. As explained for the *SCM* and *WDCM*, this result

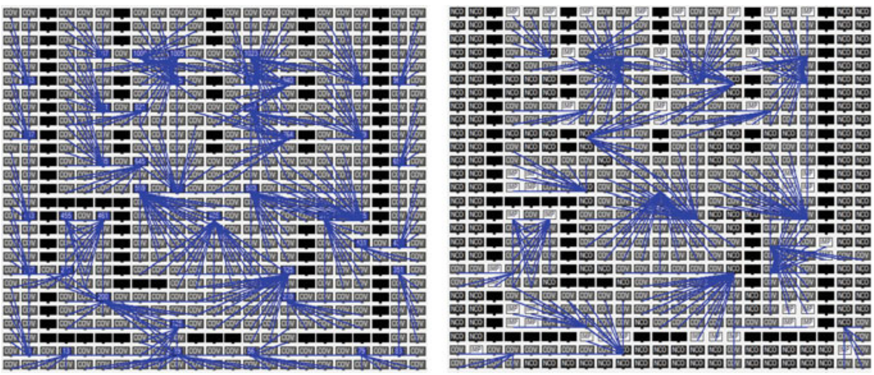

Fig. 14 Solutions of *SCM* and *WDCM* with CCTV1 cameras (8 orientations)

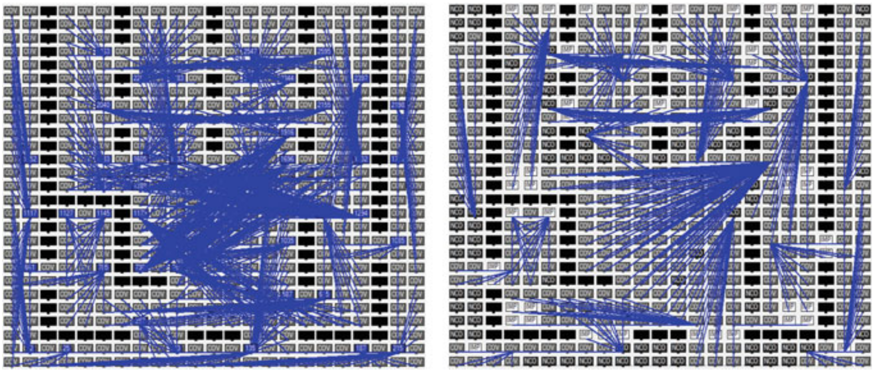

Fig. 15 Solutions of *SCM* and *WDCM* with both cameras (8 + 12 orientations)

Table 5 Results of *MCM* on the railway station scheme

	CCTV	Covered points	COV (%)	M-covered points	M-COV (%)	CPU time (s)
CCTV1	17	347	65.97	22	4.18	2.2
	24	430	81.75	20	3.80	7.9
	31	488	92.78	57	10.84	12
	38	515	97.90	95	18.06	14.48
	45	526	100	171	32.51	11.09
CCTV1 + CCTV2	17	426	80.99	38	7.22	12.5
	24	481	91.45	80	15.21	21.2
	31	509	96.67	161	30.61	43.8
	38	525	99.81	172	32.70	23.7
	39	526	100	174	33.08	50.2

depends on the structure of the station, where many blocks are present. This observation can be also noticed in Fig. 16 where the percentage of primary and multiple covered points varying the value of p, using one kind and two kind of cameras are reported. It is easy to see that these two trends are significantly different for this test case, contrarily to what occurred for the open space case.

Finally, as an instance, in Fig. 17 the solutions obtained using the two kinds of cameras with $p = 31$ and $p = 39$ are shown. Also in this case, as for the open space, we can note that all the important points are covered by at least one camera and that the solution with 39 cameras is different by the *SCM* optimal because of the different weights of the points.

The results of the *BCM* are summarized in Table 6 which reports the same information of Table 3. Also in this case it is easy to observe that the usage of β values higher than 0 provides an increase of the percentage of multiple-covered points and values lower than 0.5 allows to obtain solutions with a good trade-off

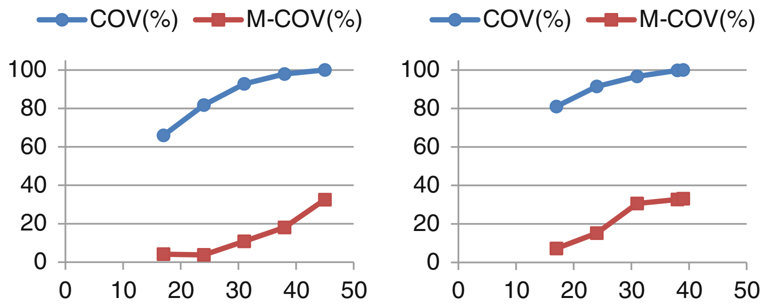

Fig. 16 Primary and multiple coverage solving *MCM* varying *p* with CCTV1 cameras (8 orientations) and with both kind of cameras (8 + 12 orientations)

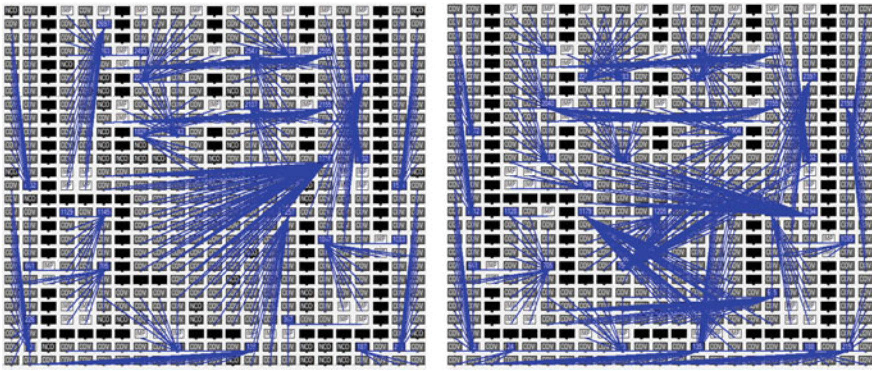

Fig. 17 *MCM* solutions using 31 and 39 cameras (8 + 12 orientations)

Table 6 Results of *BCM* on the railway station case

	β	CCTV	Covered points	COV (%)	M-covered points	M-COV (%)	CPU time (s)
CCTV1	0	45	526	100	171	32.51	11.09
	0.2	45	368	69.97	228	43.35	0.4
	0.4	45	334	63.50	234	44.49	0.2
	0.6	45	328	62.36	241	45.82	0.9
	0.9	45	302	57.41	251	47.72	4.7
CCTV1 + CCTV2	0	39	526	100	174	33.08	50.2
	0.2	39	375	71.29	225	42.78	20.4
	0.4	39	374	71.10	227	43.16	38.4
	0.6	39	361	68.63	239	45.44	43.3
	0.9	39	320	60.84	265	50.38	216.8

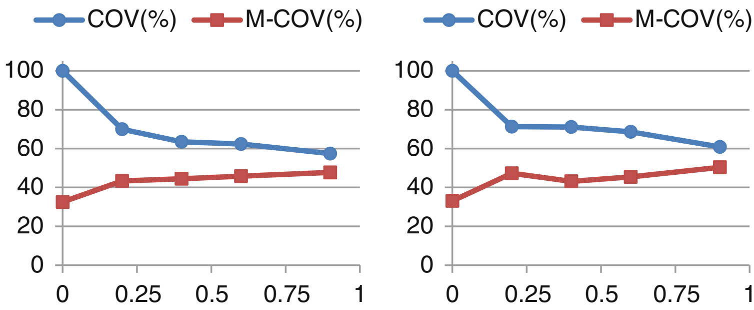

Fig. 18 Primary and multiple coverage solving *BCM* using 45 cameras (8 orientations) and 39 cameras (8 + 12 orientations) varying β

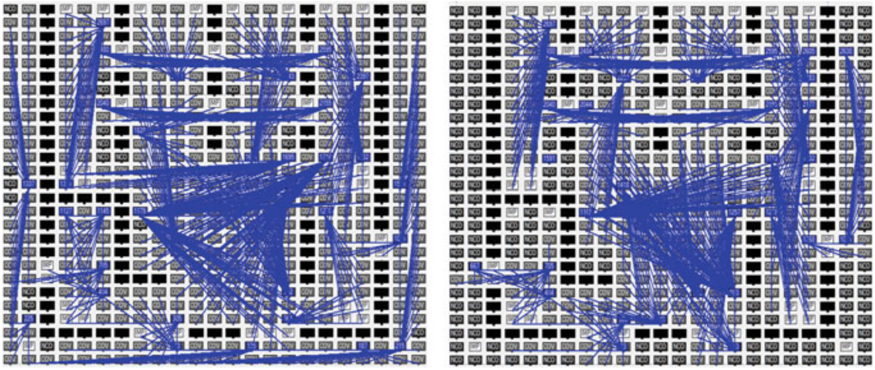

Fig. 19 *BCM* solutions using 39 cameras (8 + 12 orientations) with β = 0.2 and β = 0.9

between the primary and multiple coverage of the points. This results is also highlighted in Fig. 18 where the percentage of primary and multiple covered points varying β is reported.

Finally, as an instance, in Fig. 19 the solutions obtained using p = 39 cameras (8 + 12 orientations) with β = 0.2 and β = 0.9 are shown. It is important to observe how the solution with β = 0.2 covers almost all the region of interest, whereas the solutions with β = 0.9 covers more than once the same zones of railway station scheme.

6 Conclusions

In this chapter we presented the combinatorial optimization models used in the Optimization Module of the methodological tool developed in the European project METRIP, aimed at supporting the design of a security system for the protection of the railway infrastructure system assets.

We described four models that the designer can use alternatively in accordance to the specific security and economic needs that the project has to satisfy. Moreover we also discussed some issues that can be integrated in these models in order to take into account other security requirements related to usage of video-analysis algorithms.

The presented models have been experienced on two different test cases, characterized by very different geometrical properties obtaining good solutions with acceptable computation time, so confirming their effective applicability.

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