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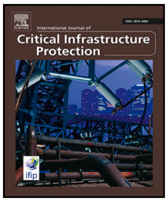

A multi-criteria model for the security assessment of large-infrastructure construction sites

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ABSTRACT

The construction of large infrastructures (e.g., railways, gas pipelines or power grids) is increasingly facing widespread and violent opposition of radical environmentalist and ideological groups. Therefore, it is necessary to consider also the risk related to violent opposition actions when selecting construction sites. However, the classical paradigm of risk considering probability and impact hardly applies in this context, especially because of the difficulty of assessing probabilities, due to the lack of historical and/or reliable data. This paper develops a novel framework to support the selection of construction sites for infrastructure development, considering the risk of attacks by radical or ideologically motivated groups. The main originality is that the risk of attacks is evaluated considering the attractiveness of the different locations for the attackers, based on several criteria. Specifically, a novel multi-criteria decision model is introduced, which involves fourteen criteria related to the effort required to the opponents for performing the attack and to the expected outcomes of the attack in terms of potential damage to the targeted infrastructures and visibility of the action; moreover, the lifespan of the construction site and its influence on the possibility of an attack are taken into account. The criteria have been selected by a pool of forty-four *Subject Matter Experts* (SMEs), i.e., security managers and experts from the academia, industry and law enforcement. With such criteria, it is possible to construct a holistic index of attractiveness and quantify it by the *Sparse Analytic Hierarchy Process* (SAHP), based on the evaluations of the criteria provided by the pool of SMEs. The proposed methodology is applied to support the localization of the construction sites for the cross-border section of the Turin–Lyon High Speed and High Capacity Railway, including a new base-tunnel. Indeed, such an 8.6 billion Euro project has experienced strong opposition in Italy and, hence, security has become one of the main issues to be considered. The proposed model constitutes a decision aid tool to support the selection of construction plans, considering attractiveness and impact of attack.

1. Introduction

Identifying the adequate location for the construction sites of a large-scale infrastructure (e.g., railways, gas pipelines or power grids) is a challenging task for several reasons. One of such reasons is the need to consider effective planning for construction sites that can withstand or discourage violent opposition episodes. In fact, in recent years, there has been a significant number of such episodes, involving, radical environmentalism movements or other ideological groups. It should be noted that, generally speaking, radical environmentalism is not a unitary and coherent movement, and several different shades exist, ranging from violent ones (e.g,. bio-terrorism, green anarchism) to legitimate, nonviolent movements (e.g., bioregionalism, echopsychology). The reader is referred to [1] for a comprehensive discussion. This study collects under the “radical” umbrella all groups that aim to act in order to cause damage (whether symbolic or not) to the construction sites, without speculating on the reasons behind their resolve. In this view, groups that manifest their dissent in a legitimate, lawful way are not included.

In some cases, these contrast activities are so violent and long-lasting that they cause severe consequences in terms of time scheduling of the construction activities, costs or even injuries to the site personnel. In 2012, protests against the construction of the first nuclear power

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plant in Egypt caused damage of several equipment and injuries to more than 40 people [2]. The construction of the Trans Adriatic Pipeline suffered a strong opposition in Italy, where hundreds of activists tried to stop the construction activities, damaged equipments and injured several law enforcement officers [3,4]. Adequate management of such violent oppositions requires to set up a security apparatus (generally a posteriori) in order to protect the site activities. As security is seldom considered at the design stage, the cost of adequate security levels soon becomes significant. An example of this is represented by the preliminary works on the Turin–Lyon High Speed and High Capacity railway, where about 30 million Euro of extra security costs were required in the first years of the project. Such an example demonstrates the need to consider security issues in the preliminary stages of any critical infrastructure project, including paying special attention to the identification of the construction location sites, for a trade-off between construction efficiency and security. Risk assessment could be used to guide the selection of construction sites, but this requires estimating the *probability* of “attack" (the term *probability* is used here to denote the extent to which an event is likely to occur), which might be difficult or impossible to ascertain, due to the subjective nature of the problem and the lack of historical and/or reliable data. To overcome such a drawback, in this paper we propose to evaluate the risk of attack candidate locations of the construction sites considering their *attractiveness* from the point of view of the attacker (for the scope of the paper, the *attractiveness* of a construction site is defined as the appeal for the attacker to target that specific location with respect to others; as it will be made clear later while discussing the proposed model, attractiveness encompasses several heterogeneous aspects, ranging from the expected damage to the visibility of the action, to the morphology of the site). To evaluate such attractiveness, a pool of forty-four *Subject Matter Experts* (SMEs) has been involved, i.e., security managers and experts from the academia, industry and law enforcement, to define a model that encompasses fourteen criteria (e.g., symbolic value of the site or number of daily accesses to the site, etc.) which can influence the appeal to attack a construction site, taking into account also the time at which the construction site is opened within the overall project and its lifespan. The fourteen criteria have been identified by first asking the individual SMEs to suggest potential criteria and, then, by critically reviewing them during dedicated focus groups organized with the SMEs. A multi-criteria decision model is, then, developed based on the numerical assessment by the pool of SMEs of the relative importance of pairs of criteria (e.g., “the criterion X is twice more important than the criterion Y”). For the assessment, we resort to the *Sparse Analytic Hierarchy Process* (SAHP) methodology [5]. The proposed methodology is applied to the High Speed and High Capacity Railway Tunnel from Turin to Lion, a 8.6 billion Euro project which has experienced a strong opposition in Italy.

1.1. Turin–Lyon High Speed and High Capacity Railway project

The Turin–Lyon High Speed and High Capacity Railway is listed among the Trans-European transport Networks (TENT), financed by the EU commission in order to improve European mobility [6]. This railway represents a piece of the Mediterranean Corridor which, with an estimated length of 3000 km, will connect Spain to Hungary via France, Italy, Slovenia and Croatia. The section from Lyon to Turin represents the most critical point of such a corridor, since the current connection relies on a tunnel–the Frejus tunnel–at an altitude of about 1300 m above the sea level and with a grade profile of up to 33‰. Conversely, the new base-tunnel will connect St Jean-de-Maurienne (France) to Susa (Italy) at an altitude of about 500 m and with a maximum grade profile of 12.5‰, thus allowing trains to circulate at speeds up to 220 km/h. The tunnel – it will be the longest railway tunnel in the world with a length of 57.5 km – has an estimated cost of 8.6 billion Euro and is expected to be completed in 2030. The company in charge of the construction and management of the tunnel is *Tunnel Euralpin Lyon Turin* (TELT), constituted as a collaboration between the Italian and French governments. Geognostic analyses have been completed in 2017 and both the French and Italian parliaments agreed to start the construction phase. The project has been widely criticized and opposed, as it has been deemed dangerous for the environment, too expensive, and unnecessary. Such an opposition has been particularly strong on the Italian side, where the “No-TAV" movement (the acronym TAV stands for “Treno ad Alta Velocitá" in Italian, i.e., high-speed train) gathered large visibility, also due to the presence of extremist groups, which were allegedly responsible of several attacks and sabotages to the construction sites, and to the companies operating on such sites. An illustrative example is the La Maddalena site, where geognostic tests have been conducted for the Italian side: over 200 violence episodes have been recorded in the period spanning from 2012 to 2016, resulting in more than 1000 injured among the law forces, large delays and concern among the population (which reflected in an almost complete drop of tourism in the zone). Such a site has constituted a valuable example for the development of the proposed model; in particular, the site has provided valuable body of knowledge for the modeling of the effect of the temporal dimension, as it will be made clear later in the paper. As a follow up, when the Italian Government ratified the agreement for the cross-border section (including the base-tunnel) it required a risk assessment to analyze the exposition of construction sites to security threats, even considering different locations to minimize risk, so as to reduce the cost for security while improving the safety of the workers and population with respect to possible violent opposition. The authors were involved in the assessment process and developed a specific risk assessment methodology in order to:

1. perform a security assessment of each potential construction site;
2. identify alternatives (in terms of construction site location and/or activities scheduling) to reduce the risk;
3. support public authorities to identify the best configuration – i.e., the set of construction sites – adequate to realize the cross-border section with minimum security risk.

The assessment has been quite complex because it considered more than 15 different construction sites, with a lifetime greater than 20 years and involving thousands of workers and a very complex and interdependent logistic system (one must take into account that approximately one million cubic meters of waste will have to be handled). Moreover, the orography of the area imposes several constraints on the configuration of the construction sites.

Finally one has to consider that violent opposition is largely performed by oppositions linked with the “antagonism" ideology which is typically loosely inspired to nature protection instances. Such violent opposition operates on the bases of the La Maddalena experience, with specific modus operandi, targets and approaches. First of all, the attackers typically aim to gain visibility and gratitude from the population. Hence, they tend to prefer targets with large visibility. In this view, their strategy consists of initiatives, generally carried out in groups of 30–300 individuals, occurring mostly at night when it is easier to hide in the vegetation around the construction site and there are fewer workers. This happens because they do not typically intend to cause side-effects (e.g., injuries or casualties), since their goal is typically to keep the disapproval from the population to a minimum. Their main purpose is thus to damage the equipment used for construction and, more generally, to interfere with the activities by trying to enter within the construction site premises. Quite often, they perform multiple attacks on the perimeter with the aim to distract the police and then gain access to the site. Attacks are typically carried out via throws of objects, including firecrackers (using also mortars), while they tend not to use guns, pistols or firearms.

2. Literature review

Security issues at construction sites are mainly focused on theft prevention (see, among other works, [7–9]). More recently, the focus on violent opposition acts (i.e., acts performed by people trying to maliciously interfere to delay or stop the construction activities) is gaining momentum also in the scientific literature. In this case, the situation is that, rather than aiming at making an illicit profit via robberies, perpetrators are driven by strong ideological motivations to contrast the construction activities. In [10], it has been analyzed how to include the security issue in the planning of construction site layouts. The problem is treated in [11] as a bilevel and multi-objective optimization problem. In [12], the problem to minimize construction-related security risks during airport expansion projects is analyzed.

This paper focuses on the problem of selecting construction sites. Specifically, the risk associated to different construction sites is evaluated in terms of the attractiveness of the sites for an attacker and a multi-criteria decision making perspective is adopted, based on several criteria. In order to develop a holistic metric of attractiveness, we rely on a panel of SMEs, implementing a methodology, namely *Sparse Analytic Hierarchy Process* (SAHP) [5,13,14], which extends the classical *Analytic Hierarchy Process* (AHP) methodology [15–17] and the *Incomplete Analytic Hierarchy Process* (IAHP) [18–23]), allowing to handle multiple sources of sparse information. Such a technique, based on the relative evaluations of experts (i.e., pairwise comparisons between criteria), aims to rank a set of alternatives taking into account several criteria. However, classical AHP poses a large burden on the experts, especially when the amount of considered criteria is large. In fact, AHP requires the experts to provide complete information, comparing all possible pairs of criteria. A possible approach adopted in the literature to manage such a complexity is to consider a hierarchical grouping of the criteria into macro-indicators (see, among other works, the approach in [24]). However, this subjective structure may introduce biases, resulting in weights that do not completely reflect the opinion of SMEs.

In order to reduce the effort required by the experts, while avoiding introducing subjective biases, a possible approach is to rely on an IAHP framework, which is able to deal with missing comparisons. Specifically, in this paper SAHP is used, which is an IAHP methodology able to consider multiple SMEs and to handle situations where the information provided by the individual SMEs, alone, is insufficient to reconstruct a ranking; this aspect will be clarified later in the paper. It should be remarked that within classical AHP, a ranking of a set of alternatives is obtained based on the knowledge of the relative preference of a SME on all pairs of alternatives, expressed in the form of a ratio between the intrinsic value of the alternatives. On the other hand, IAHP relaxes such constraint, allowing the SMEs to express their relative preference only on subsets of the alternatives, i.e., each SME limits the judgment on pairs of alternatives for which he/she is confident. SAHP further relaxes the constraint and allows the single SMEs to provide information that, alone, might be insufficient to reconstruct a ranking; this is possible because multiple SMEs are considered and their evaluations are suitably aggregated. Notice that when several SMEs are considered, a typical approach is to obtain an aggregated ranking for each SME or to compose their information via operations such as geometric means, which preserve the structure of the relative preference (see [25] and references therein). However, these approaches fail when the experts have considerably different backgrounds and provide information on disjoint sets of pairs of criteria. Moreover, each expert needs to provide sufficient information to be able to construct a ranking based on his/her preferences alone.

In the literature, some works have considered the risk of attackers targeting critical infrastructures and the related countermeasures for protection [26–28]. Also, the idea of considering the attractiveness of a target for an attacker is not completely new. For instance, in [29] a strategy for the optimal allocation of protection resources is considered, based on the attractiveness of potential terrorist targets; in [30] the vulnerability of nuclear sites is assessed via an empirical classification model that includes aspects related to the attractiveness of the sites for the attackers; in [31] attractiveness is introduced in the cyber security domain as a parameter to estimate the likelihood of an attack; in [32] the *critical nodes* in a network (e.g., power grid) are identified as those such that their combined removal causes maximum disconnections in the network; in [33] the problem is extended to a multi-objective setting by identifying tradeoffs in the attacker strategies between maximizing damage and minimizing the effort required to perform the attack. However, to the best of our knowledge, this is the first time that attractiveness is used in lieu of probability as a metric for risk analysis in physical security applications.

2.1. Contribution of the paper

The main contributions of the paper are as follows:

- the problem of selecting construction sites for infrastructure development is considered, taking into account the threats from attackers or violent opponents;
- the decision making process is originally framed in terms of the attractiveness of a construction site for an attacker;
- by closely interacting with a pool of SMEs, a multi-criteria decision model is developed and a holistic indicator of attractiveness is introduced, based on fourteen criteria that relate to both the effort required for the attack and to the outcome in terms of damage and visibility;
- the temporal dimension is explicitly considered, i.e., the lifespan and time scheduling of the construction site;
- the importance of the different criteria is assessed by eliciting pairwise comparisons from the pool of SMEs and treating missing comparisons by the SAHP methodology;
- the results of the SAHP methodology are critically analyzed in terms of the degree of inconsistency and consensus among the SMEs;
- by the application of the proposed framework, an overall ranking for different construction plans is provided (encompassing multiple locations);
- the proposed methodology is applied to a real case study related to the construction sites for the Turin–Lyon High Speed and High Capacity Railway.

Although our case study focuses on a specific application, the proposed methodology is general and can be applied to different types of construction sites (e.g., pipelines or power plants).

Finally, one of the most relevant criticism to the AHP approach is the bias in the result. Indeed, starting from knowledge on the ratios among the different values, one is able to reconstruct the absolute data up to a scaling factor. However, in the case of this paper, since the goal is the comparison among several configurations, the possible presence of a bias does not affect the results. This is because we are not interested in estimating the “effective" level of risk associated to the different construction sites but only to identify the one with smallest associated risk: in other terms, for the problem at hand, it is not relevant to estimate the absolute level of risk but only the relative ranking, since the question posed by the Italian government was not on the go/no-go of the project but to identify the configuration with least associated risk.

3. Methodology

3.1. Notation and preliminaries

Let us denote vectors via boldface letters, whereas matrices are shown with uppercase letters. We use A_{ij} to indicate the (i,j)-th entry of a matrix A and x_i for the ith entry of a vector $\mathbf{x}$. Moreover, let us write $\mathbf{1}_n$ and $\mathbf{0}_n$ to denote a vector with n components, all equal to one and zero, respectively; similarly, $1_{n\times m}$ and $0_{n\times m}$ denote $n \times m$ matrices all equal to one and zero, respectively. We denote by I_n the $n\times n$ identity matrix. Let us express by $exp(\boldsymbol{x})$ and $ln(\boldsymbol{x})$ the component-wise exponentiation or logarithm of the vector $\boldsymbol{x}$, i.e., a vector such that $exp(\boldsymbol{x})_i = e^{x_i}$ and $ln(\boldsymbol{x})_i = ln(x_i)$, respectively. Let $G = \{V, E\}$ be a *graph* with n nodes $V = \{v_1, \dots, v_n\}$ and e edges $E \subseteq V \times V \setminus \{(v_i, v_i) \mid v_i \in V\}$, where $(v_i, v_j) \in E$ captures the existence of a link from node v_i to node v_j. A graph is said to be *undirected* if $(v_i, v_j) \in E$ whenever $(v_j, v_i) \in E$ and is said to be *directed* otherwise. In the following, only undirected graphs are considered. A graph is *connected* if for each pair of nodes v_i, v_j there is a path over G that connects them. Let the neighborhood $\mathcal{N}_i$ of a node v_i be the set of nodes v_j that are connected to v_i via an edge (v_i, v_j) in E. The *degree* d_i of a node v_i is the number of its incoming edges, i.e., $d_i = |\mathcal{N}_i|$ (over undirected graphs, for each node v_i the number of its incoming and outgoing edges coincide). The *weighted adjacency matrix* A of a graph $G = \{V, E\}$ with n nodes is the $n\times n$ matrix such that $A_{ij} > 0$ if $(v_j, v_i) \in E$ and $A_{ij} = 0$, otherwise. The *Laplacian matrix* associated to a graph G is the $n \times n$ matrix $L(G)$, such that $L_{ii}(G) = d_i$, whereas for $i \neq j$ we have that $L_{ij} = -1$ if $(v_j, v_i) \in E$ and $L_{ij} = 0$, otherwise. It is well known that $L(G)$ has an eigenvalue equal to zero and that, in the case of undirected graphs, the multiplicity of such an eigenvalue corresponds to the number of connected components of G [34]. Therefore, the zero eigenvalue has multiplicity one if and only if the graph is connected.

3.2. Probability vs attractiveness

Risk $\mathcal{R}$ is often evaluated as $\mathcal{R} = \mathcal{P} \times \mathcal{C}$, which expresses the risk $\mathcal{R}$ as a function of the probability $\mathcal{P}$ of occurrence of an event and of the associated impact $\mathcal{C}$. Where possible, $\mathcal{P}$ is estimated by statistical inference based on historical data of event occurrence. However, in the case of construction sites, there are few data to adequately estimate $\mathcal{P}$. Specifically, in our case, there is a need to compare several hypotheses of construction sites' locations in a limited area, estimating the probability that any single site may be the target of a violent action. It should be noted that the security issues in the area of interest for this study lie in eco-radical-like motivations, which implies that the probability $\mathcal{P}$ cannot be assumed as an independent variable but it is a function of consequences $\mathcal{C}$, site vulnerability $\mathcal{V}$, environment $\mathcal{E}$ and time $\mathcal{T}$, i.e., $\mathcal{P} = \mathcal{P}(\mathcal{C}, \mathcal{V}, \mathcal{E}, \mathcal{T})$. In other words, the more an attack to a specific site is likely to create large problems/delays to the project and is feasible, the more it is attractive for the opponents. On the other hand, the more a site is vulnerable, the more it is attractive. In fact, the opponents are not specifically interested to damage a specific site, but their aim is to delay/block the whole project and, due to the complex logistics, any problem to any site might induce more or less large impact on the time schedule of the project. Furthermore, the environment ($\mathcal{E}$) may provide key elements to the opponents to facilitate their initiatives or, on the contrary, render them difficult due to the presence of physical hurdles. Moreover, the surrounding urban context is quite relevant, both in terms of social surveillance (which might discourage violent actions) and support to violent activities in terms of logistics. Notably, the likelihood of an attack to a specific site depends on its life time (obviously, the more a site is active, the longer it represents a possible target) and also on how soon the construction site is opened with respect to the overall schedule of the project (the earlier a construction site is opened, the more time there is for attacking it from the early stages). Finally, one has to consider also the interest that each type of attacks can gain on the media and, more in general, the visibility of such initiatives by the population.

To account for this, in this paper the risk associated to a construction site is estimated via the formula $\mathcal{R} = \mathcal{A} \times \mathcal{C}$, where $\mathcal{A}$ is the "attractiveness", i.e., a measure of how much a specific site represents a valuable target for the attackers. Specifically, as discussed in the next section, $\mathcal{A}$ is estimated considering $14+2$ parameters. Such parameters consider different aspects of the site topology/morphology, as well as the complexity of the working activity (e.g., the flow of workers to the site), the symbolic value and the temporal dimension.

Table 1
Risk assessment: the probability-based approach compared against the attractiveness-based approach.

	$\mathcal{R} = \mathcal{P} \times \mathcal{C}$	$\mathcal{R} = \mathcal{A} \times \mathcal{C}$
Requires objective data (e.g., historical series)	✓	✗
Based on subjective information	✗	✓
Encompasses a blend of different criteria	✗	✓
Able to handle non-conventional risk factors	✗	✓
Provides an absolute value for the risk	✓	✗
Manages situations when probability and consequences cannot be considered as independent variables	✗	✓

Table 1 summarizes the main differences between probability-based and attractiveness-based risk evaluation. As one can notice looking to the table, using probability to estimate the risk imposes the adoption of historical data but allows to provide absolute estimation of the risk. On the other side, the use of attractiveness allows to consider a priori information mixing the attackers' modus operandi with the characteristics of the different construction sites. In this view, the use of the attractiveness, even if more subjective with respect to probability, appears more flexible and able to manage incomplete and partial information. Notice that, relying on attractiveness to estimate the risk allows to easily consider also the presence of multiple classes of attackers. Indeed, it is enough to estimate with the support of SMEs, the relative importance of the different criteria on the base of the different modi operandi.

3.3. Attractiveness assessment

To identify the most effective location for the constructions sites, the n available alternatives $a_1, \dots, a_n$, each one representing a configuration of construction sites, are ranked. In more detail, each alternative a_i features n_i construction sites and each construction site is characterized by m indicators $\mathcal{I}_{j1}, \dots, \mathcal{I}_{jm}$, where $\mathcal{I}_{jh} \in \mathbb{R}_+$ is the numerical value describing the value assumed by the hth criterion for the jth construction site. For the sake of simplicity, it is assumed that all indicators have been normalized and satisfy $\mathcal{I}_{jh} \in [0, 1]$. Notice that the criteria are either quantitative and objective (e.g., perimeter, number of daily accesses, etc.) or qualitative and subjective (e.g., symbolic value, context, etc.). For the quantitative indicators, a value of one is associated to the largest value considering all possible construction sites and all configurations.

3.3.1. Ranking methodology

To rank the alternatives, a numerical indicator of the *attractiveness* of a construction site to an attack is introduced in the form $\mathcal{A}_{ij} = \alpha_{ij} \sum_{h=1}^{m} w_h \mathcal{I}_{jh}$, i.e., the weighted sum of the indicators $\mathcal{I}_{jh}$. The parameters α_{ij} take into account the temporal dimension of the construction site j, whereas the weight w_h reflects the specific importance of the hth criterion in the overall numerical indicator $\mathcal{A}_{ij}$. Based on such an indicator, an overall indicator $\mathcal{A}_i$ is developed for the ith alternative a_i (representing a configuration featuring m_i construction sites), defined as $\mathcal{A}_i = \sum_{j=1}^{m_i} \mathcal{A}_{ij}$. The index $\mathcal{A}_i$ is, then, used instead of the probability $\mathcal{P}$ in the risk assessment and for identifying the most effective configuration.

Fig. 1 provides a synoptic view of the proposed ranking methodology in the case of 3 construction sites grouped in two construction plans, when the attractiveness is estimated considering 3 criteria. Hence, on the base of the modus operandi of the attackers, the SMEs estimate the relevance of each criteria (step I) and using the characteristic of the each construction site (step II) and the temporal dimension (step III) it is possible to estimate the attractiveness of each site. Then aggregating the information about all the construction sites related to each construction plan (step IV), one can estimate the relative attractive of the two solution (step V).

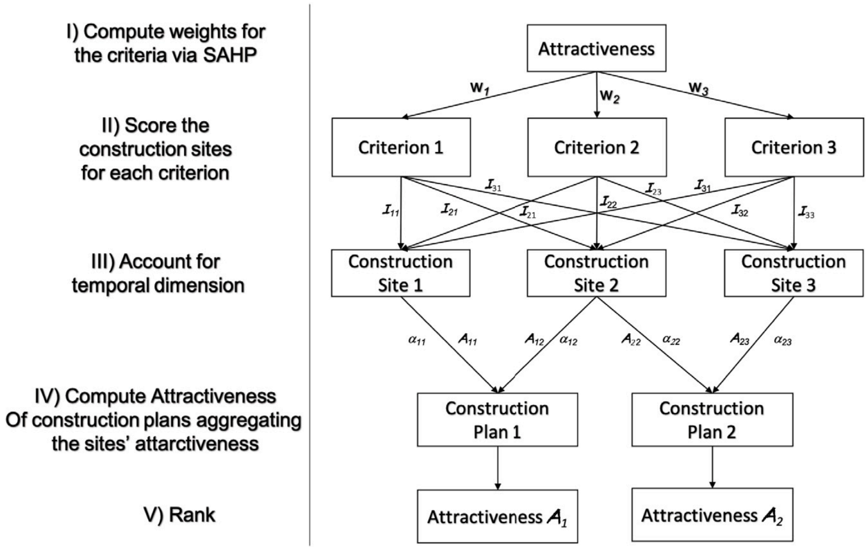


Fig. 1. Proposed ranking methodology, considering an example with $m = 3$ criteria, 3 construction sites and $n = 2$ construction plans.

$$\mathcal{W}^{(i)} = \begin{bmatrix} 0 & 2 & 7 & 0 \\ 1/2 & 4 & 0 & 8 \\ 1/7 & 1/4 & 2 & 0 \\ 0 & 1/8 & 1/2 & 0 \end{bmatrix}$$

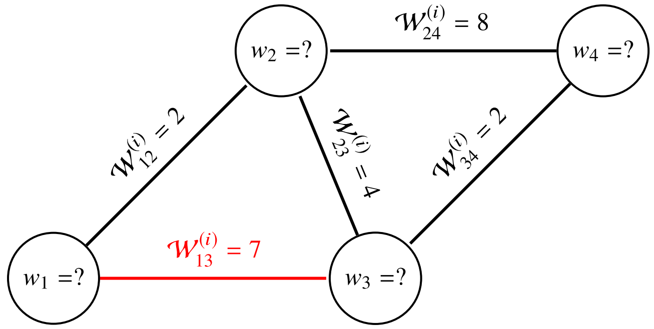


Fig. 2. Relation between a ratio matrix $\mathcal{W}$ with missing comparisons and its corresponding graph.

3.3.2. Weighting the criteria

The core issue to implement the quantitative analysis is the ranking w_h of the different criteria, which largely depends on the modus operandi of the attackers. To calculate the weights associated to the different criteria, based on relative information elicited from experts, the SAHP methodology is adopted [5,13,14]. The reason for this is that the SAHP approach allows accounting for missing information (thus reducing the burden for the SME) and to combine information provided by multiple information sources (i.e., the pool of SMEs). Let $\boldsymbol{w} \in \mathbb{R}_+^n$ be the stack of the weights w_h for all the criteria. In order to estimate the terms w_h, information provided by $q \geq 1$ SMEs is considered. Specifically, suppose we are given q matrices $\mathcal{W}^{(i)} \in \mathbb{R}^{n\times n}$, each modeling the preferences of an expert. In more detail, the nonzero entries $\mathcal{W}_{uv}^{(i)}$ represent the opinion of the ith SME on the ratio w_u/w_v, i.e., on how much the uth criterion is more relevant than the vth one; let us assume that for all nonzero $\mathcal{W}_{uv}^{(i)}$, it holds $\mathcal{W}_{vu}^{(i)} = (\mathcal{W}_{uv}^{(i)})^{-1}$. Differently from the standard Analytic Hierarchy Process (AHP) [35], SMEs are allowed to provide information only on those ratios he/she feels comfortable answering and $\mathcal{W}_{uv}^{(i)}$ is set to zero when the SME provides no information on the corresponding ratio. Each $\mathcal{W}^{(i)}$ corresponds to a graph $G_i = \{V, E_i\}$, where V is the set of criteria and it is the same for all graphs and E_i models the available information for the ith SME. Fig. 2 shows an example of the above procedure; it can be noted that, as experienced in any application of the AHP approach involving real data, the matrix $\mathcal{W}^{(i)}$ given in the example is not perfectly *consistent*; for example, $W_{12}^{(i)} = 2$, $W_{23}^{(i)} = 4$ but $W_{13}^{(i)} = 7 \neq W_{12}^{(i)} W_{23}^{(i)}$. Notably, the proposed methodology is able to calculate consistent weights for each node even if the available information has some inconsistencies. In the following, let us denote by $\mathcal{N}_a^{(i)}$ the *neighborhood* of the ath node in G_i. Let us now consider the overall *multi-graph* (a multi-graph is a graph where multiple edges connecting the same pair of nodes are allowed) $G = \{V, E\}$ where $E = \bigcup_{i=1}^n E_i$ is the union of the edges in E_i and let us allow multiple edges between pairs of nodes. In order to calculate the weights $\boldsymbol{w}$, the following technical assumption is required:

Assumption 1. The graphs G_i are all undirected, but not necessarily connected. The overall multigraph G is connected.

The aim is to solve the following problem:

Problem 1. Let Assumption 1 hold true. Find vector $\boldsymbol{w}^*$ that solves the following logarithmic least-squares problem:

$$\boldsymbol{w}^* = \exp\left(\operatorname*{arg\,min}_{\boldsymbol{y}\in\mathbb{R}^n} \left\{ \frac{1}{2} \sum_{i=1}^{q} \sum_{a=1}^{m} \sum_{b\in\mathcal{N}_a^{(i)}} \left(\ln(W_{ab}^{(i)}) - y_a + y_b \right)^2 \right\} \right),$$

where $\exp(\cdot)$ is the component-wise exponentiation.

The following theorem characterizes the global optimal solution to the above problem:

Theorem 1. *Let Assumption 1 hold true. Problem 1 has a global optimal solution in the form* $\boldsymbol{w}^* = \exp(\boldsymbol{y}^*)$*, where* $\boldsymbol{y}^*$ *satisfies* $\hat{L}\boldsymbol{y}^* = \hat{P}\mathbf{1}_n$*, with* $\hat{L} = \sum_{i=1}^{q} L^{(i)}$ *and* $\hat{P} = \sum_{i=1}^{q} P^{(i)}$*, where* $L^{(i)}$ *is the Laplacian matrix associated to the graph* G_i *and* $P^{(i)}$ *is an* $m \times m$ *matrix such that* $P_{ab}^{(i)} = \ln(W_{ab}^{(i)})$ *if* $W_{ab}^{(i)} > 0$ *and* $P_{ab}^{(i)} = 0$*, otherwise.*

Proof. Let us define $f(\boldsymbol{y}) = \frac{1}{2} \sum_{i=1}^{q} \sum_{a=1}^{m} \sum_{b\in\mathcal{N}_a^{(i)}} \left(\ln(W_{ab}^{(i)}) - y_a + y_b \right)^2$. Problem 1 is convex and unconstrained; therefore, its global minima are in the form $\boldsymbol{w}^* = \exp(\boldsymbol{y}^*)$, where $\boldsymbol{y}^*$ satisfies

$$\left.\frac{\partial f(\boldsymbol{y})}{\partial y_a}\right|_{\boldsymbol{y}=\boldsymbol{y}^*} = 0 \quad \Rightarrow \quad \sum_{i=1}^{q} \sum_{b\in\mathcal{N}_a^{(i)}} \left(\ln(W_{ab}^{(i)}) - y_a + y_b \right) = 0,$$

$\forall a = 1, \ldots, m.$

It is possible to express the above conditions in a compact form as

$$\sum_{i=1}^{q} L^{(i)} \boldsymbol{y}^* = \sum_{i=1}^{q} P^{(i)} \mathbf{1}_n,$$

which is the thesis. ■

Remark 1. Since, for hypothesis, G is undirected and connected, the matrix $\widehat{L}$ is a weighted symmetric Laplacian matrix and has rank $m-1$ [34]. Therefore, the vector $\boldsymbol{y}^*$ cannot be computed by matrix inversion.

In this paper, $\boldsymbol{y}^*$ is computed according to the following expression $\boldsymbol{y}^* = \widehat{L}^\dagger \widehat{\boldsymbol{P}} \mathbf{1}_n$, where $\widehat{L}^\dagger$ is the Moore–Penrose pseudoinverse of $\widehat{L}$ and, consequently, $\boldsymbol{w}^* = exp\left(\widehat{L}^\dagger \widehat{\boldsymbol{P}} \mathbf{1}_n\right)$.

3.4. Managing the time dimension

In order to correctly compare the exposition of the different configurations to security issues, one has to consider that some construction sites have a lifespan that is larger than others and that the duration of the same construction site within different configurations can change. Moreover, one has to consider that the construction sites that are set up in the early stages of the project typically suffer larger opposition than those activated at later stages of the project. In order to manage the temporal dimension of the construction sites, the parameter α_{ih} is introduced. Such a parameter is associated to the hth construction site in the ith configuration, and is defined as $\alpha_{ih} = \delta_{ih}\beta_{ih}$, where δ_{ih} accounts for the exposition of the construction site due to its duration Δ_{ih} (i.e., the longer the duration, the larger the exposition of the construction site to violent opposition). Specifically, δ_{ih} is the area below the curve reported in Fig. 3(a), which has been experimentally estimated on the basis of the actual cost spent monthly for security at the “La Maddalena" construction site.

Intuitively, we have that each time a new construction site is set up, it may be subject to strong contrast activities by opponents. Also, as the project progresses, the loss from an attack becomes higher than in the early stages. However, as time goes by, from one side a physiological reduction of violent initiatives is experienced, whereas from another side such a reduction is due to the increase in expertise of the security team in controlling and contrasting the activities of the opponents learned from the activities carried out by them. Indeed, as time goes by, fences, video-cameras and sensors are tuned in order to be more effective and better monitor the specific orography of the site, as well as to detect the specific modus operandi of the opponents. Eventually, the cost reaches a plateau value.

In order to adequately capture the temporal dimension, the factor β_{ij} is introduced, which takes into account the start time of the construction site with respect to the overall work schedule of the project (i.e., the sooner a construction site starts, the more it is exposed to security issues). Specifically, let us define the term β_{ij} according to the curve reported in Fig. 3(b), also in this case, estimated on the basis of experimental data by extrapolating the amount of people that, over time, attend street demonstrations against TAV. Notice that, even if such initiatives are generally non-violent and only a small fraction of the involved people actively participates to the attacks, the time series highlight a good correlation between such data and the number of monthly attacks at the “La Maddalena" site. Using such data, the curve of Fig. 3(b) has been estimated and the value of β_{ij} evaluated on the basis of the delay in the start of the jth construction site in the ith configuration with respect to the kick-off of the project.

4. Proposed model

With respect to the Turin–Lyon project, several criteria related to the construction site have been considered, plus two additional criteria related to the time dimension. The criteria have been identified in close cooperation with a pool of forty-four SMEs, following a two-step procedure: first, potentially relevant criteria have been identified via one-to-one meetings with a subset of the SMEs; then, the criteria have been critically reviewed in dedicated focus groups with the SMEs and the most relevant subset of criteria has been retained.

The effectiveness of the identified criteria is not limited to the Turin–Lyon project, but can be considered of interest for any construction project; however, their relative relevance might change, being largely dependent on the underlying attackers’ motivations that depend on the specific project. Notice that some criteria are intrinsically qualitative and, with the help of the SME panel, they have been estimated according to a scale ranging from zero to one, associating one to the largest value assumed by the specific criterion, considering all the potential locations and the possible configurations. The remaining quantitative metrics have been normalized in a scale from zero to one.

Specifically, the criteria considered to estimate the attractiveness $\mathcal{A}$ of each construction site are:

(1) **Accessibility:** The more a site is easy to reach (and to run away from) the more it is attractive for antagonists.

(2) **Symbolic value:** This criterion captures, overall, the symbolic value of the site. For instance, in the case of the Turin–Lyon High Speed and High Capacity Railway, it has been observed that the sites directly related to the tunnel have a greater symbolic value than the deposit sites. In the same way, the sites located in a particular area might be perceived as more valuable than others. Notably, the relevance of this criterion, as well as the actual symbolic value of a construction site, may change considerably depending on the context of the project and on the attackers’ motivations.

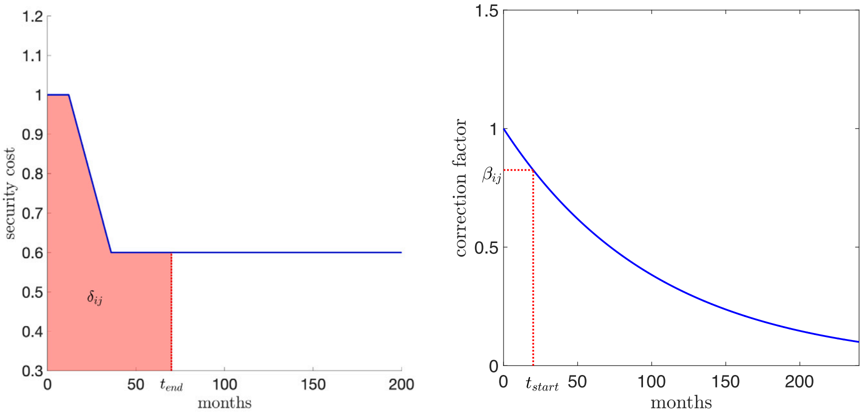
(3) **Daily accesses:** expected average number of daily accesses to the site. A large flow of people (e.g., workers) represents a fragility. To include in this criterion different typologies of access, the following formula is adopted to calculate the daily accesses Φ: $\Phi = \Psi + 3\left(\frac{\Psi}{20} + \Theta\right) + 10\Lambda$, where Ψ is the average number of workers, Θ is the average number of vehicles (e.g., trucks, concrete mixers, etc.) and Λ is the average number of trains that access the site on a daily basis.

(4) **Expected damage:** This criterion captures the potential impact of an attack or sabotage to the site. The main assumption behind this criterion is that a larger expected impact makes a site more attractive to antagonists. Notice that the level of impact taken into account in this case is the level from the opponent point of view (which is usually different from the effective level of damage).

(5) **Perimeter length:** the main assumption behind this metric is that a long perimeter is more complex and expensive to protect than a short one; hence, the longer is the perimeter the easier is the attack to the site.

(6) **Absence of collateral damage:** This metric aims at considering the extent of collateral damage to the population, in case of an attack to the site. The relevance of such a criterion largely depends on the ideological situation of the attacker. For example, a site with no associated collateral damage is more attractive to antagonists, which typically wish to have the support of the population and are, thus, very sensitive to possible consequences to the population—and in most cases to the workers too (as in the case of the Turin–Lyon base-tunnel). Interestingly, the relevance of this criterion may change considerably depending on the attackers’ motivations (e.g., international terrorism or violent opposition of radical groups living in the area).

(7) **Road accessibility:** This metric measures the number of roads accessible to vehicles that lead to the construction site. The main assumption here is that the more access points a site has, the more it is easy to attack (and hard to protect).



(a) (b)

Fig. 3. Panel (a): Exposition of the construction site depending on its duration. Panel (b): Correction factor which takes into account the start time of the construction site with respect to the overall work schedule of the project.

(8) **Site Logistics:** This metric considers the logistic aspects of the site in a holistic way. The main idea underlying this metric is that the presence of several operating employees and vehicles involved in complex activities may facilitate the opponents in sabotages or attacks.

(9) **Site extension:** This metric consists of the area of the site. The main assumption here is that the larger a site is, the harder it is to protect it and, thus, the more attractive to attackers it is.

(10) **Perimeter morphology:** This metric measures, in a holistic way, the morphology of the perimeter, e.g., the presence of natural barriers such as cliff walls. The larger this indicator is, the more the site is attractive due to the presence of favorable or unguarded access points to the site, whereas small values indicate the presence of natural barriers that may discourage the attackers.

(11) **Visibility:** Some sites are highly visible both from population and media point of view; the visibility has a strong impact on the attractiveness of a site because the effect of an action performed against a visible site will be emphasized by the media. Notice that this criterion is not completely overlapping with the symbolic value, in that an attack might be more visible in more peripheral sites, although the symbolic value might be smaller (e.g., an attack to a deposit that is far away and unguarded might have spectacular consequences, although being irrelevant in terms of symbolic value and actual damage). Notice that the relevance of the criterion may change considerably depending on the context and on the underlying attackers' motivations.

(12) **Site morphology:** This indicator considers the morphology of the site in a way similar to the perimeter morphology. In other words, this holistic indicator measures the attractiveness of the site due to natural or man-made features that are favorable or discouraging for an attacker (e.g., the construction site is on the top of a hill or at the bottom of a valley).

(13) **Isolation:** If a site is located in a remote area, any illegal action is easy to perform because of the lack of control. This indicator is a holistic measure of how much the site is isolated and, thus, vulnerable to attacks.

(14) **Environmental Context:** In the presence of an infrastructure spanning a large area, there are some geographical locations characterized by stronger feelings of the local population against the construction. This feeling generally results in concrete support to violent movements. Indeed, in these areas, opponents find a broad ideological and logistic support. This indicator, therefore, represents a holistic measure of the context in which the site is located, and higher values correspond to sites that are more attractive to antagonists and attackers. Also in this case, the relevance of the criterion may change considerably depending on the context and on the underlying attackers' motivations.

5. Experimental analysis

In this section, the results of the proposed procedure are shown. For simplicity and non-disclosure reasons, the methodology is illustrated with reference to three configurations, each composed of a single construction site and the analysis is limited to the set of fourteen criteria discussed above. The last subsection is devoted to illustrate the "true" result of the procedure, i.e., with reference to the four configurations analyzed to identify the definitive location of the Turin–Lyon base-tunnel construction sites. To perform the assessment, a group composed of forty-four Italian security managers, security experts and law enforcement officers, with specific competence in the management of eco-radicalism, were asked to specify their preferences among pairs of criteria. Specifically, each SME has been asked to take the standpoint of the attacker (e.g., No-Tav) and to evaluate the relevance of the different factors that contribute to make a site appealing for a violent contestation. In more detail, each SME was provided with a diagram where the criteria were arranged on a circle (the order of the criteria was randomly shuffled to mitigate presentation biases). The SMEs were asked to express their opinion by drawing arrows on the diagram: in case they considered the ith criterion to be more important than the jth one, they drew an arrow from the ith to the jth criterion (if the criteria were considered equally important, they were asked to draw a bidirectional arrow). Moreover, SMEs were asked to provide, for each arrow, a numerical assessment of the relative importance of the jth criterion over the ith one, using a scale between 1 and 10. Note that the scale adopted ranges from 1 to 10 and not from 1 to 9, as typically done in AHP [35]; the reason is that the experts felt more comfortable with the 1–10 voting scale, which is largely used for instance in the Italian education system. However, from a conceptual point of view, the proposed methodology can be implemented by using any scale. Notice further that the experts were asked to provide comparison only for those pairs of criteria they felt comfortable answering. An example of such a procedure is reported[1] in Fig. 4; it can be noted that in such an example, only five comparisons are provided, resulting in a disconnected graph. As a consequence, the information provided by the single SME is not enough to extract a ranking. Notice that only nine out of forty-four SMEs (i.e., 20.5%) provided a connected graph, whereas thirty-one SMEs provided graphs having at least two connected components (in two cases, only three pairs of criteria are compared).

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[1] The handwritten numbers on the upper half of the figure represent the value one, while the vertical numbers in the lower half of the figure represent the value five and the horizontal number in the lower half of the figure represents the value three.

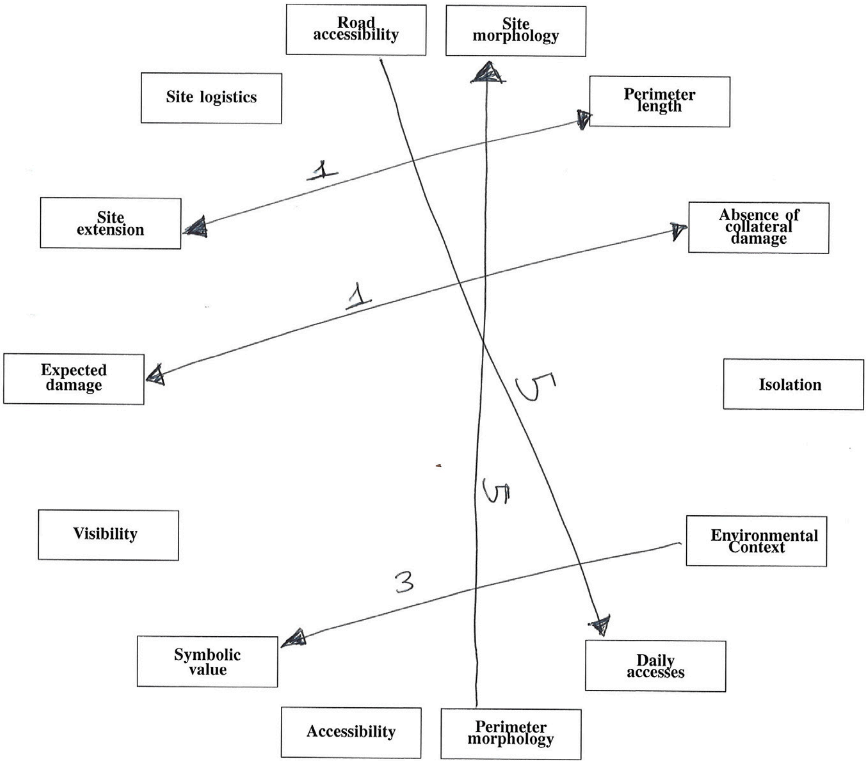


Fig. 4. Example of output of the proposed data collection procedure (actually handwritten by an SME).

Nevertheless, the information provided by each SME contributes to the overall multigraph.

As discussed previously in the paper, the information provided by each SME u is conveniently represented in terms of a graph G_u, where the criteria correspond to the nodes and the comparisons to the edges. Moreover, a sparse ratio matrix $W^{(u)}$ is constructed for each SME u, collecting the weights $W_{ij}^{(u)}$ associated to the edges (we make the graph undirected by taking $W_{ji}^{(u)} = (W_{ij}^{(u)})^{-1}$, whenever $W_{ij}^{(u)} > 0$). Then, the multi-graph containing the union of the edges of each graph G_u is built and the proposed methodology is applied to obtain the weight vector $\boldsymbol{w}^*$, which is fundamental to construct the aggregated measure $\mathcal{A}_i$ of criticality of each construction site i.

5.1. Analysis of collected data

Fig. 5 provides a more detailed view of the overall multigraph, as presented in Section 3.3.2; in particular, each node represents a criterion, and the numerical identifier associated to the node corresponds to the numerical identifier of the criterion, as shown in Table 2. Moreover, each edge represents the existence of at least one pairwise comparison (provided by at least one SME) among the criteria corresponding to the nodes. Finally, the width of an edge is proportional to the amount of comparisons provided for that pair of criteria (colors are given just for the sake of readability). It can be noted that, in spite of the sparsity of the graph associated to each single SME, the overall multigraph is almost a full graph (only three comparisons are missing) and most pairs of criteria are compared several times (up to a maximum of nineteen comparisons for the comparison between *symbolic value* and *visibility* – i.e., the link between nodes 2 and 11 – and for the one between *absence of collateral damage* and *expected damage*—i.e., the link between nodes 4 and 6).

In order to assess the quality of the available information provided by the SMEs, let us now analyze in Figs. 6 and 7 the degree of contradiction in the information elicited from the SMEs. Specifically, for each pair of criteria i and j, the minimum between the number of comparisons in which i is preferred to j and the number of comparisons in which j is preferred to i, is adopted as a measure of contradiction. Fig. 6 shows the distribution of such an index over all pairs of alternatives and it can be noted that twenty-three pairs (i.e., about 25.3%) show at least one contradiction, whereas six pairs (i.e., about 6.6%) show more than three contradictions and three pairs (3.3%) show more than four contradictions. Fig. 7 provides information on the specific pairs of criteria that exhibit contradiction, in that the width of the edges is proportional to the magnitude of the contradiction; it can be noted that the edge with larger associated contradiction corresponds to the comparison between *absence of collateral damage* and *expected damage* (i.e., the edge between nodes 6 and 4, with eight contradictions); the criterion involved in most of the contradictions is the one related to the *visibility* (node 11 with twenty-eight contradictions), whereas the criterion involved in the minimum amount of contradiction is the one related to the *perimeter length* (node 5 with seven contradictions). Overall, this analysis suggests that, in spite of the ample pool of SMEs considered, the degree of contradiction is indeed limited, thus justifying the development of the proposed multi-criteria decision framework based on such information. Let us now discuss the weight associated to the different criteria, based on the available information. Specifically, the weights obtained according to the procedure discussed in Problem 1 are reported in Table 2; notice that the weights have been normalized so that their sum is equal to one. Notably, the most important weights are those corresponding to the *symbolic value* (0.1406), *expected damage* (0.1140) and *visibility* (0.1053), whereas the least important ones correspond to the *site morphology* (0.0298), the *perimeter length* (0.0340) and the *perimeter morphology* (0.0440). This means that the SMEs prioritized more criteria related to the attackers' convenience or utility, rather than the ones that relate to the physical structure of the site. In other terms, for the problem at hand, the attractiveness of a target is largely influenced by the gratification for the attackers rather than the feasibility of the attack.

Table 2 also reports the sensitivity associated to each criterion i. Specifically, we assess the sensitivity by comparing the ordinal ranking

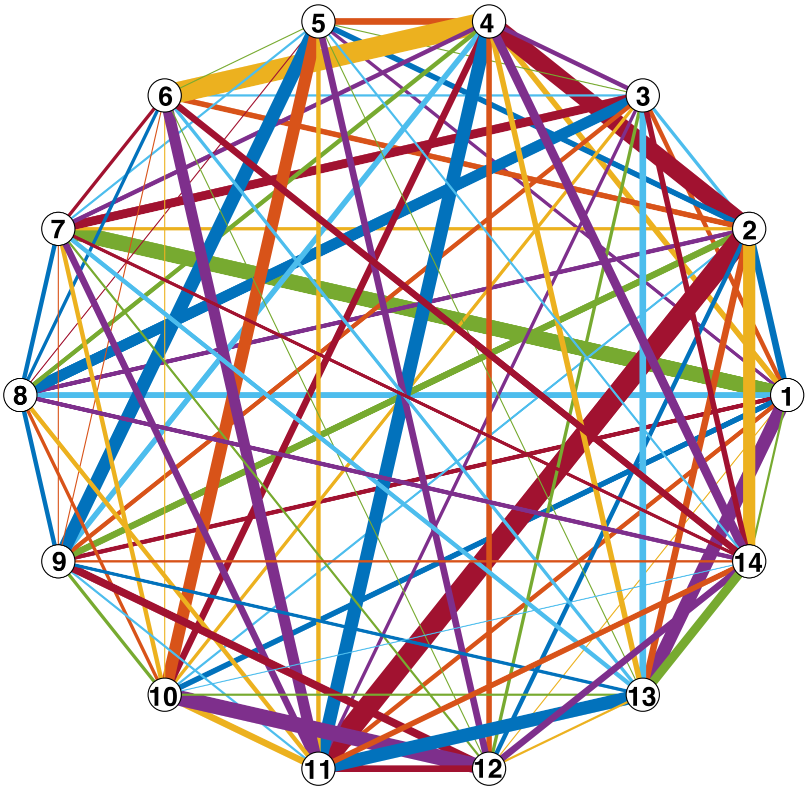


Fig. 5. Overall Multigraph obtained as a result of the union of the graphs associated to each SME. Each node represents a criterion and the numerical identifier associated to the node corresponds to the numerical identifier of the criterion, as shown in Table 2. Each edge represents the existence of at least one pairwise comparison among the criteria corresponding to the nodes. The width of the edges is proportional to the amount of comparisons provided for the corresponding pairs of alternatives (colors are given just for the sake of readability).

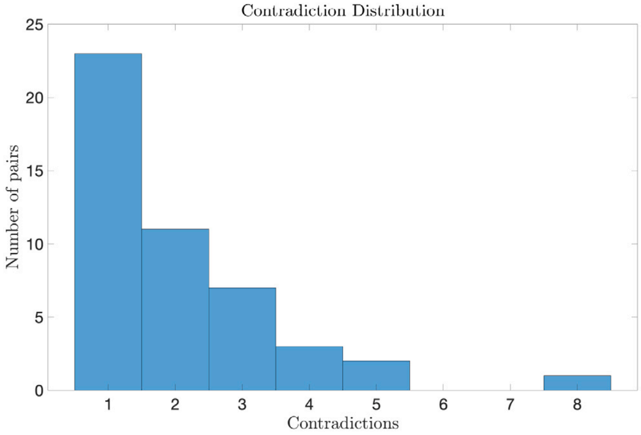


Fig. 6. Distribution of the amount of contradiction over the pairs of criteria.

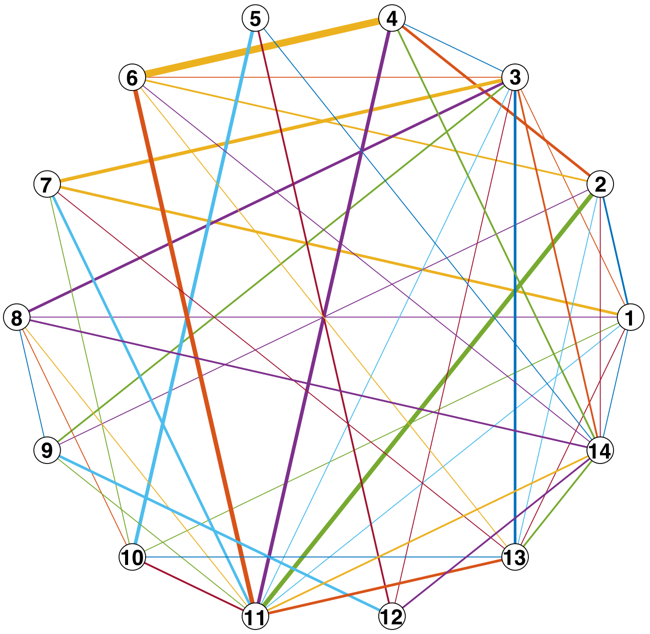


Fig. 7. Representation of the degree of contradiction for the different pairs of criteria. Each node represents a criterion and the numerical identifier associated to the node corresponds to the numerical identifier of the criterion, as shown in Table 2. Each edge represents the existence of at least one contradiction in the pairwise comparisons among the criteria corresponding to the nodes. The width of an edge is proportional to the amount of contradiction. (colors are given just for the sake of readability).

of the criteria with the ordinal ranking obtained by solving the problem without considering the ith criterion. The comparison is done in terms of the Kendall Correlation coefficient $\tau_i \in [-1, 1]$, which is a measure of how much two rankings are similar (it is equal to one when the rankings are identical, while it gets progressively smaller as the rankings exhibit differences and is equal to minus one when the rankings are in reverse order). In this view, we chose to quantify the sensitivity of the ranking on the ith criterion by

$$\sigma_i = \frac{1 - \tau_i}{2} \in [0, 1],$$

i.e., the sensitivity is zero when the rankings are identical, whereas it is proportional to the ordinal disagreement between the nominal ranking and the one obtained without considering the ith alternative. It can be noted that the sensitivity is quite small, being smaller than 0.3461, and

Table 2
Weights for the different criteria obtained via SAHP, using the information elicited from the SMEs. The weights have been normalized so that their sum is equal to one. The Table also reports the sensitivity σ_i associated to each criterion and the average sensitivity.

#	Criterion	Weight	Sensitivity
1	Accessibility	0.0859	0.0385
2	Symbolic value	0.1406	0.3461
3	Daily accesses	0.0695	0.0385
4	Expected damage	0.1140	0.2949
5	Perimeter length	0.0340	0.0000
6	Absence of collateral damage	0.0992	0.2051
7	Road accessibility	0.0756	0.0000
8	Site Logistics	0.0442	0.0000
9	Site extension	0.0322	0.0000
10	Perimeter morphology	0.0440	0.1410
11	Visibility	0.1053	0.0000
12	Site morphology	0.0298	0.0000
13	Isolation	0.0494	0.0000
14	Environmental context	0.0765	0.0000
		Average sensitivity	0.0760

with average of 0.0760. Overall, this analysis suggests that the ranking obtained via the proposed methodology is remarkably stable. Moreover, it can be noted that most of the criteria having large weights correspond to those that exhibit comparatively large sensitivity (and vice versa), thus contributing to validate the proposed ranking.

5.2. Weighting and ranking

To exemplify the application of the procedure, let us consider a case study with just three alternative configurations, each composed of a single construction site (namely A, B and C) and, for simplicity, let us assume $\alpha_{ij} = 1$ for all sites. Table 3 reports the scores $\mathcal{I}_{jh}$ associated to each configuration, according to the different criteria. Notice that the “raw" scores are either numerical or linguistic, depending on the specific criterion; in order to apply the proposed approach, the values have been converted and normalized to obtain the numerical values $\mathcal{I}_{jh}$ ranging from zero to one. Specifically, the normalization has been done by converting linguistic values to numerical values (i.e., assigning values from 1 to 7 to the linguistic concepts “low", “medium-low", “medium", “medium-high",“high", “very high" and “extremely high") and by dividing each value by the maximum attainable one (e.g., linguistic criteria are divided by 7 whereas numerical criteria are divided by the maximum value attained by a construction site in the project). To conclude, the last row in Table 3 shows the results for the three construction sites in terms of resulting attractiveness $\mathcal{A}_i$. Specifically, it is observed that site B is the less attractive, hence, it is preferable as a candidate construction site. Notice that, although site B has comparatively large perimeter and extension, it is characterized by the smallest value in terms of visibility.

5.3. Results of the security assessment for the Turin–Lyon High Speed and High Capacity Railway

The proposed procedure has been used to assess the construction sites foreseen in the nominal project (configuration n. 0). The results are reported in Fig. 8(a). Notice that the Figure reports the actual impact (which, in some cases, is significantly different from those attained considering the attacker point of view in criterion n.4) of a possible attack taking into account the modus operandi of the attacker and evaluating the consequences with respect to four criteria (the Figure reports an abstract aggregated value): impact on population (35% of contribution to the abstract aggregated value); impact on the workers (35%); impact on the operational continuity (15%) and economic impact (15%). The analysis emphasizes that there are two sites with high levels of attractiveness and impact (i.e., the red zone, corresponding to the upper right corner), and two other sites close to the border between the central zone (shown in yellow) and the zone in the upper-left corner (shown in red); hence, these four sites are very critical from the security point of view. Therefore, several alternative solutions have been analyzed for reducing the security risk. Specifically, three alternative configurations featuring from nine to eleven construction sites were considered. Fig. 8(b) reports the best solution that contains eleven sites (obtained introducing two new sites and removing one of the planned sites). By now, only one site is in the zone in the upper-left corner (shown in red) of the graph (with a significant reduction of its attractiveness and impact with respect to previous configurations) and none of the sites is close to the border between the zone in the upper-left corner (shown in red) and the central zone (shown in red). Specifically, thanks to a complete rearrangement of the construction activities in all the sites, there is a considerable reduction of the security risk level of each site. This has been obtained reducing and delaying the activities to be performed in areas with high visibility and symbolic value, preferring to undertake more tasks in the “La Maddalena" site, which is characterized by a small δ_{ij} index. Moreover, the new assignment of the activities allows improving the management of the space in some of the “critical" construction sites, reducing the potential impact of attacks.

6. Conclusions and future work

In this paper, a security assessment methodology is provided to guide the selection process of the construction sites of a large-scale infrastructure. Specifically, due to the lack of historical and/or reliable data, the analysis focuses on the *attractiveness* of the construction sites for the attackers and a multi-criteria decision making framework is implemented to assess the attractiveness. By resorting to a pool of SMEs, it is possible to identify several criteria and we obtain a numerical assessment of the relative importance of the different criteria, combining such information by means of the SAHP methodology into a holistic indicator of attractiveness. By quantifying the degree of contradiction in the information provided by the SMEs it can be concluded that information available is sufficiently consistent to justify the implementation of the multi-criteria decision framework that relies on such a body of knowledge. The methodology, although general, has been applied to the identification of the location of the construction sites for the 8.6 billion Euro Turin–Lyon High-Speed Railway cross-border section (including the base-tunnel). The outcomes of the analysis have contributed to the identification of the actual construction sites through a substantial rearrangement with respect to the nominal project. Considering the impact and attractiveness of the different construction plans, it can be noted that the one suggested by the proposed methodology corresponds to a reduction of both. Notably, based on the results of this study, TELT suggested a variation of the initial construction plan: the actually implemented plan coincides with the one suggested by this study.

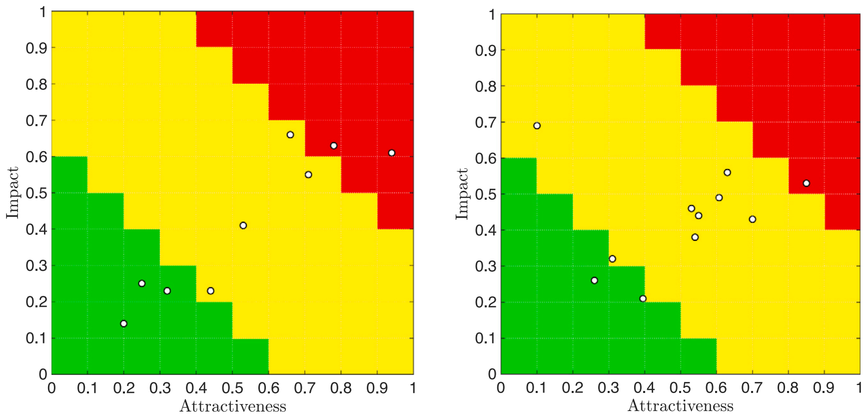
Notice that the solution illustrated in this paper considers a single class of “attackers" (i.e., antagonist No-TAV) with a specific mental scheme and modus operandi. However, the complete study has considered also the presence of other types of violent opposition (e.g. anarchists NO-TAV). Future work will be devoted to extending the method to several classes of attackers, each with its peculiarities and to integrating the outcomes of the specific analyses. Moreover, a consistency factor will be introduced to further deal with contradictory information and to take into account the degree of experience of the different SMEs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 3
Numerical value of the different criteria for the three construction sites. The last line shows the attractiveness associated to the different construction sites, based on the weights identified using the information elicited from the SMEs. The values have been converted to numerical ones and normalized so that they range from zero to one.

#	Criterion	Site A		Site B		Site C	
		Value	Normalized	Value	Normalized	Value	Normalized
1	Accessibility	High	0.7143	Medium	0.4286	High	0.7143
2	Symbolic value	High	0.7143	High	0.7143	High	0.7143
3	Daily accesses	1.37	1.0000	0.96	0.7000	0.48	0.3500
4	Expected damage	High	0.7143	High	0.7143	Extremely high	1.0000
5	Perimeter length	2 Km	0.2857	3 Km	0.4286	3 Km	0.4286
6	Absence of collateral damage	Medium	0.4286	Medium	0.4286	Medium	0.4286
7	Road accessibility	Medium	0.4286	Medium-high	0.5714	High	0.7143
8	Site Logistics	Medium	0.4286	High	0.7143	High	0.7143
9	Site extension	1 Km^2	0.3833	2.6 Km^2	1.0000	2.1 Km^2	0.8083
10	Perimeter morphology	Medium	0.4286	Medium	0.4286	High	0.7143
11	Visibility	High	0.7143	Medium	0.4286	High	0.7143
12	Site morphology	Medium-high	0.5714	Medium-high	0.5714	High	0.7143
13	Isolation	Medium-low	0.2857	Medium	0.4286	Medium	0.4286
14	Environmental context	High	0.7143	High	0.7143	High	0.7143
	Attractiveness	0.6084		0.5881		0.6724	



(a)   **(b)**

Fig. 8. Panel (a): results of the assessment for the ten sites that constitute the nominal configuration (reported by black circles with white interior). Panel (b): results of the risk assessment for the optimal configuration, involving eleven sites (reported by black circles with white interior).

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