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Article

A Simple Multi-Criteria Risk Assessment of Buildings and Infrastructures Under Snow Avalanche Hazard

Alessio Rubino [1,2,*], Barbara Frigo [1,2] and Bernardino M. Chiaia [1,2]

[1] Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, 10129 Turin, Italy; barbara.frigo@polito.it (B.F.); bernardino.chaia@polito.it (B.M.C.)
[2] Safety of Infrastructures and Constructions Interdepartmental Center (SISCON), Politecnico di Torino, 10129 Turin, Italy
* Correspondence: alessio.rubino@polito.it

Abstract

The increasing number of extreme events affecting buildings and strategic infrastructures in mountain areas requires reliable approaches for territorial risk assessment with respect to snow avalanches. Considering risk as the combination of hazard, vulnerability, and exposure factors, a simplified framework—recently adopted in Italian national guidelines—is proposed. Avalanche hazard is defined by considering the intrinsic avalanche susceptibility of the territory under investigation, typically described by means of hazard intensity maps. On the other hand, the vulnerability of the construction is determined by considering both the physical, or structural, vulnerability of the building and the functional vulnerability of network systems. Finally, the exposure level accounts for the direct and indirect losses resulting from the hazardous event, based on the typology, use, and potential occupancy of the building or infrastructure. A weighted classification system combining these three factors is adopted to derive risk matrices, in which the risk class of each exposed construction is defined across five levels (high, medium–high, medium, medium–low, low), thus enabling a hierarchical risk classification at the territory scale. The methodology is intended to bridge technical risk assessment and territorial governance, offering an operational decision-support tool for policymakers, emergency planners, and infrastructure operators to support resource allocation and mitigation strategies.

Keywords: snow avalanches; hazard; vulnerability; exposure; territorial governance; risk analysis; risk management

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1. Introduction

Urban areas in mountain regions are usually endangered by snow avalanches, often causing remarkable human and economic losses, together with severe damage to buildings and infrastructures [1]. Avalanches, by analogy to other natural and man-made phenomena, can be positioned in the broader framework of the so-called "swans theory" [2], widely adopted in the current literature to describe the probability of occurrence and the related impact of such natural events on the built environment.

Within this framework, "*white swans*" refer to well-known phenomena, for which their frequency and magnitude are well documented by historical records. These events are generally characterized by a relatively high probability of occurrence and limited consequences (Figure 1). In structural engineering practice, these events are explicitly accounted for through standardized approaches, in which their intensity is defined with respect to prescribed return periods, depending on the importance of the building.

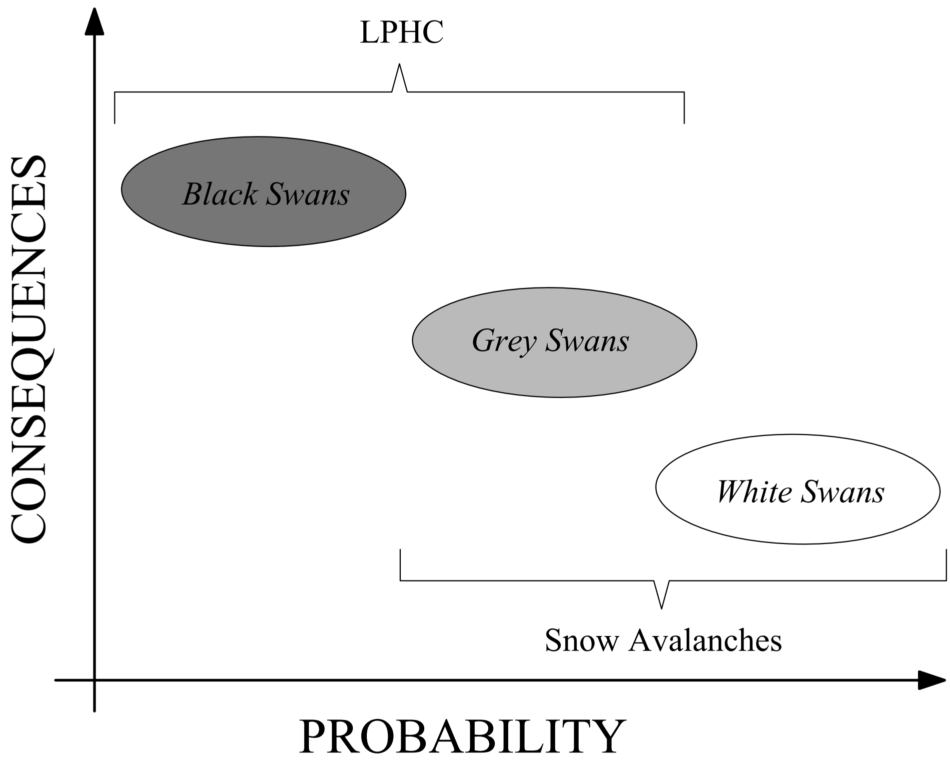

Figure 1. Conceptual representation of events in the probability–consequence space, including black, grey, and white swans, together with snow avalanches and low-probability high-consequence (LPHC) events.

A further category is represented by the so-called "*grey swans*", i.e., events that are known to exist, with likelihood and intensity supported by very limited data, thus making their predictability a challenging task. Due to their potentially severe consequences, they constitute the core of the so-called Low Probability–High Consequences (LPHC) events (Figure 1), which require the assumption of specific hazardous scenarios and the adoption of performance–based approaches in the structural design [3].

The spectrum of LPHC events includes the so-called "*black swans*", which are characterized by a fundamentally unpredictable nature and potentially extreme impacts for the built environment (Figure 1). Considering that, these events cannot be explicitly integrated into the conventional structural design procedures, the design philosophy shifts from prevention to damage control [4]. In structural engineering, this concept translates into providing buildings and infrastructures with adequate robustness, redundancy, and post-event recovery capacity (resilience).

In this context, snow avalanches can be reasonably positioned at the intersection between white and grey swans, depending on the availability of historical data within the selected territory under investigation. However, it is worth noting that ongoing climate change may significantly alter this classification by affecting both the frequency and intensity of such natural events [5,6], thus increasing uncertainties and promoting transition of such avalanche phenomena across the above-mentioned categories.

Such avalanche events may produce consequences of different nature. Direct losses can typically be quantified right after the catastrophic event, being related to the number of fatalities and injuries. Other adverse effects can only be recognized after the event, with an often significant time lag. A typical example is the indirect (economic) losses due to the period of business interruption, i.e., the so-called *down-time*. Other indirect consequences, which are more difficult to quantify, relate to the social, cultural, and public impact of the event on the involved territories and communities.

It is therefore evident that multiple factors need to be considered when assessing the risk of avalanche-prone territories [7], being aware that risk cannot be reduced to zero, and its absolute quantification is not always possible. Several methodological approaches can be adopted for natural hazards risk assessment, characterized by different levels of complexity and accuracy.

While qualitative methods represent the simplest approaches, being based on expert judgment [8,9], Quantitative Risk Analysis (QRA) represents the most rigorous tool for risk assessment, as it quantifies risk using loss metrics (e.g., number of injuries and/or fatalities, damage costs) defined per unit time and, depending on the application, per unit area or in a given avalanche path or for a given building [10–13]. Such quantitative approaches are also well-established for analogous gravity-induced phenomena, e.g., landslides and slope instabilities [14].

From an engineering perspective, for buildings and infrastructures exposed to natural hazards such as snow avalanches, risk can be expressed through a simplified chain of conditional probabilities:

$$R = \sum_{s} p(H_s) \times P(O|H_s) \times P(D|H_s, O) \times L_s \tag{1}$$

where H_s denotes the avalanche scenario s, characterized by a given intensity, $p(H_s)$ is the related annual probability of occurrence affecting the exposed structure, the term $P(O \mid H_s)$ is the conditional probability of occupancy or presence of exposed elements at the time of the event, while $P(D \mid H_s,O)$ represents the conditional probability of reaching a given damage state (e.g., collapse or functional disruption) of the structure due to the occurrence of the scenario H_s. Finally, L_s represents the associated human or financial loss incurred each time an event corresponding to the scenario s occurs.

The temporal dimension of Equation (1) is exclusively contained in the annual probability of occurrence $p(H_s)$, whereas the conditional probabilities $P(O \mid H_s)$ and $P(D \mid H_s,O)$ are dimensionless quantities. Accordingly, R represents the expected annual loss, i.e., expressed as fatalities or monetary losses (€/year), for a selected avalanche path, calculated over a set of relevant avalanche scenarios, typically defined on the basis of reference intensities and/or return periods.

The formulation provided by Equation (1) reflects the conditional structure of risk components, where the occurrence of the event, the presence of exposed elements, and the resulting damage are considered within a probabilistic framework. While such a formulation provides a rigorous basis for risk assessment, it requires extensive datasets for the calculation of each component contributing to the overall risk, considering both the historical records of the natural phenomenon and information related to the structural characteristics of the exposed buildings and their degree of occupancy.

A reasonable and practical compromise is often offered by semi-quantitative and class-based approaches, in which risk factors are categorized into predefined classes based on available data and information [15]. These methodologies do not aim at estimating an absolute value of risk, as defined in Equation (1), but rather at defining a relative classification of risk levels. They are widely implemented in practice and often preferred by policymakers, as they provide a straightforward and efficient prioritization of mitigation measures at a given territorial scale [16–18].

In this context, this paper describes an operational policy framework, recently adopted in Italy [19], for the risk assessment of buildings and infrastructures in avalanche-prone areas. In alignment with class-based methodologies, risk is represented by a Risk Index, which directly assigns a risk class to the exposed object (building or infrastructure), determined based on a scoring system as a function of three factors, i.e., hazard, vulnerability, and exposure. The main strength of the proposed approach lies in its ability to translate the fundamental components of risk into a unified and operational framework, enabling a direct application at the territorial scale for decision-making purposes. Dalmasso et al. (2025) [20] presented an application of the multi-criteria risk assessment at the valley scale.

The final goal is to provide a user-friendly decision-support tool to decision-makers and avalanche experts, in order to create a risk classification of territories of different scales and, consequently, set priorities between different mitigation strategies. Assigning monetary values to endangered assets, as recently proposed in Switzerland [17,21], is beyond the scope of the present approach, which instead aims to provide a hierarchical risk classification at the territorial scale. Accordingly, the aim is to assist the optimal allocation of public funds, which are often limited.

In the following sections, the general structure of the methodology will be discussed, including the procedure required for a straightforward application of the model within a given territory under investigation. A simple application example will conclude the paper, regarding the determination of the risk class of an electrical transmission tower in a small area located in Aosta Valley, northwestern Italian Alps.

2. Methods

The proposed approach is structured as a four-level procedure (see flowchart in Figure 2), in which the risk of buildings and infrastructures in avalanche-prone areas is gradually analysed. The general structure of the methodology recalls the one adopted in Italy in the aftermath of the collapse of the Polcevera viaduct (2018), in the risk analysis of existing bridges [22] and tunnels [23], respectively.

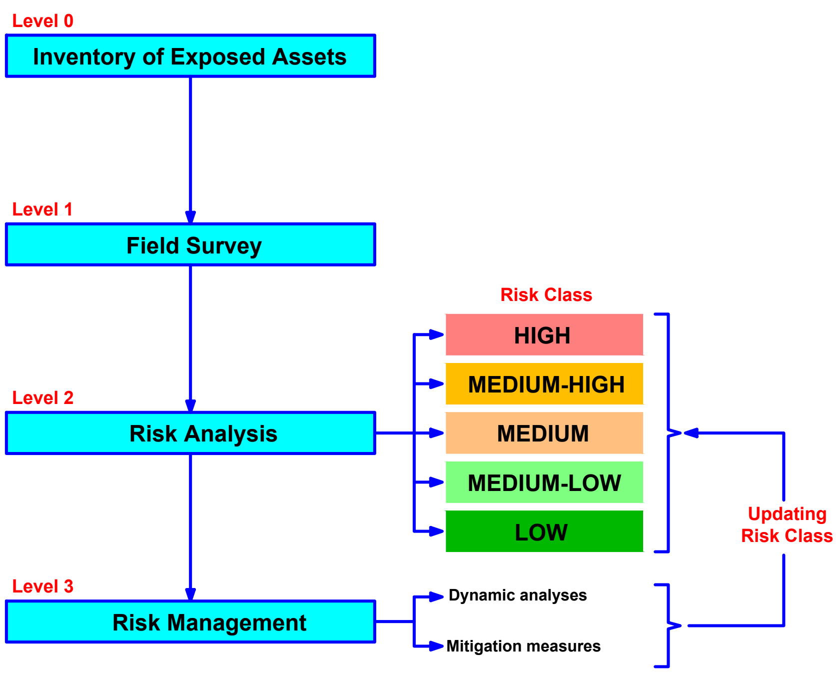

Figure 2. Flowchart of the proposed multi-level approach.

The starting step of the procedure, i.e., Level 0, is the setting up of a catalogue of the exposed buildings and infrastructures within the area under investigation. The catalogue collects the main information of each construction potentially endangered by snow avalanches based on the available technical and administrative documentation.

In parallel with Level 0, Level 1 consists of a field survey for each construction included in the defined catalogue to verify the information gathered in the previous level.

Level 2 represents the core of the model, i.e., the risk analysis of a given building and/or infrastructure system. As will be shown later, this level determines the risk class associated with a given construction system, within the five levels proposed in the approach (high, medium–high, medium, medium–low, low) based on the hazard, vulnerability, and exposure factors.

When the risk class of all buildings and infrastructures within a given territory is determined, it is possible to move to Level 3, which examines the risk management within the investigated territory. This step may include more detailed dynamic numerical analyses with respect to selected avalanche tracks, together with the planning and implementation of appropriate risk-mitigation measures at the chosen territory scale. A proper combination of the abovementioned operations often provides the best solution. The implementation of additional analyses and/or mitigation measures may lead to an update of the risk class related to several buildings and infrastructures, thus resulting in a dynamic risk-assessment procedure for the territory under investigation.

In the following section, the previously introduced levels will be discussed.

3. Risk Assessment Framework

3.1. Level 0 and Level 1

Level 0 and Level 1 both aim, even though with different tools, at a reliable knowledge of the state of buildings and infrastructure systems in avalanche-prone areas under investigation. In this sense, these levels should be considered as two preliminary steps to be conducted seamlessly.

As previously reported, Level 0 provides an infrastructure inventory, in which the main information of buildings and infrastructures exposed to avalanche phenomena are included. In this context, endangered constructions can be conceptually classified according to their geometric configuration:

- *isolated systems*, i.e., buildings or similar objects;
- *linear systems*, i.e., infrastructure networks (e.g., traffic routes, transmission lines, etc.);
- *inhabited areas*, i.e., small villages, etc.

Depending on the system under investigation, the specific information should be obtained, firstly, the exact position of the construction with respect to the endangered area. Easy to address in the case of isolated buildings, this task can become more demanding for large systems, such as infrastructure networks, partially or totally located in hazardous areas within the avalanche basin.

Focusing on the structural features of the system, its geometric and mechanical characteristics are of paramount importance to evaluate the mechanical performance and the system vulnerability with respect to the additional loads induced by an avalanche event.

While the above-mentioned information primarily contributes to the assessment of structural vulnerability, additional information is related to the use and management of the system, which is directly connected to the potential losses in the case of avalanche impacts. In this sense, the most important information regards the number of building inhabitants or, in the case of infrastructure networks (i.e., traffic routes or energy transport systems), the number of linear system users. In addition, information related to the socio-economic role of the exposed object should also be considered.

These data may be obtained by an in-depth analysis of all the technical and administrative documentation for each construction. The collection of such information typically requires the collaboration of local administrative authorities, infrastructure operators, and technical offices, which play a vital role in the collection of the available information. The amount and level of detail of the data may strongly vary depending on the objectives and scale of the assessment, ranging from simplified territorial-scale applications based on typological information to more detailed analyses tailored for specific exposed elements.

When this is completed, it is possible to move to Level 1, which aims to validate the information collected in the previous level through visual inspections and field surveys conducted by structural and avalanche experts. In this level of the investigation, the conservation state and serviceability conditions of buildings and infrastructures must be verified, with reference to critical elements the effectiveness of which can be crucial with respect to avalanche phenomena. The latter include, for instance, avalanche mitigation measures in the surrounding area of the construction, thus requiring the field survey to be extended to the whole area endangered by the potential avalanche track.

3.2. Level 2: Risk Analysis

This level constitutes the core of the proposed approach and analyzes the risk to buildings and infrastructures under consideration. The proposed methodology aims to provide a relative classification of exposed elements within a selected territory exposed to avalanche hazard, rather than estimating an absolute value of risk, as provided by QRA frameworks. Accordingly, Level 2 of the methodology focuses on the determination of a dimensionless Risk Index (*RI*), which is intended to support ranking and prioritization among exposed elements, without quantifying monetary losses. For each exposed building or infrastructure, *RI* is obtained by combining Hazard (*H*), Vulnerability (*V*), and Exposure (*E*) factors through a weighted-average procedure:

$$RI = f\ (H,\ V,\ E) = (w_{\mathrm{H}} \times H) + (w_{\mathrm{V}} \times V) + (w_{\mathrm{E}} \times E) \tag{2}$$

Unlike QRA formulations, where risk is obtained through the probabilistic multiplication of hazard-related quantities and consequences, Equation (2) combines ordinal scores through an additive weighted formulation aimed at supporting relative ranking and prioritization. From a mathematical perspective, Equation (2) corresponds to a linear combination of the three factors (H, V, E) through the weighting coefficients (w_{H}, w_{V}, w_{E}), defining *RI*. However, this assumption is specific to the proposed methodology and should not be regarded as unique. Alternative functions f (H, V, E) may be adopted to efficiently derive *RI* from the three factors, provided that they ensure a consistent prioritization of the exposed elements.

Within this formulation, the scoring system provided by Equation (2) can still be interpreted as a representation of the main components involved in QRA frameworks. Specifically, hazard factor (*H*) reflects the likelihood and intensity of the avalanche event, vulnerability factor (*V*) the susceptibility of the structures to experience damage, and exposure factor (*E*) the potential consequences. The key conceptual difference is that these factors do not describe probabilistic quantities but are expressed through ordinal classes, ranging from 1 (low) to 5 (high), whose weighted combination defines *RI*, and the corresponding risk class, for each exposed element.

This combination is carried out through three factors w_{H}, w_{V}, and w_{E}, which are the weighting factors for hazard, vulnerability, and exposure classes, respectively. These weights are used to account for the relative role played by each factor, contributing to the overall risk classification. They are normalized so that

$$w_{\mathrm{H}} + w_{\mathrm{V}} + w_{\mathrm{E}} = 1, \text{ with } w_{\mathrm{H}}, w_{\mathrm{V}}, w_{\mathrm{E}} \geq 0 \tag{3}$$

thus ensuring that *RI* remains within the same range from 1 to 5 as *H*, *V* and *E*. In practice, the weighting factors provide flexibility in the application of the methodology, allowing the relative importance of each factor to be adapted according to the confidence associated with the corresponding assessment, which depends on the available data and the level of detail of the analyses performed.

It is worth noting that this interpretation of the risk concept and the related factors is of general validity, although in this work it is addressed with respect to the specific case of buildings and infrastructures exposed to avalanche phenomena. Indeed, the three factors (hazard, vulnerability, and exposure) are considered as independent contributors to the risk analysis. This assumption, even though it is not always true, permits a clear, yet simple, identification and assessment of the main factors affecting the risk assessment, together with a sound framework for the implementation of adequate risk-mitigation measures. Furthermore, the structure of the proposed framework may be extended to other natural hazards through suitable modifications of the hazard, vulnerability, and exposure factors, according to the characteristics of the hazardous phenomenon and the exposed elements, thus paving the way for broader multi-risk applications.

The proposed method adopts a five-level classification (high, medium–high, medium, medium–low, low) of each of the three factors, defined through primary and secondary parameters, as schematically represented in Figure 3. In the following sub-sections, the determination of the hazard, vulnerability, exposure, and risk classes is discussed.

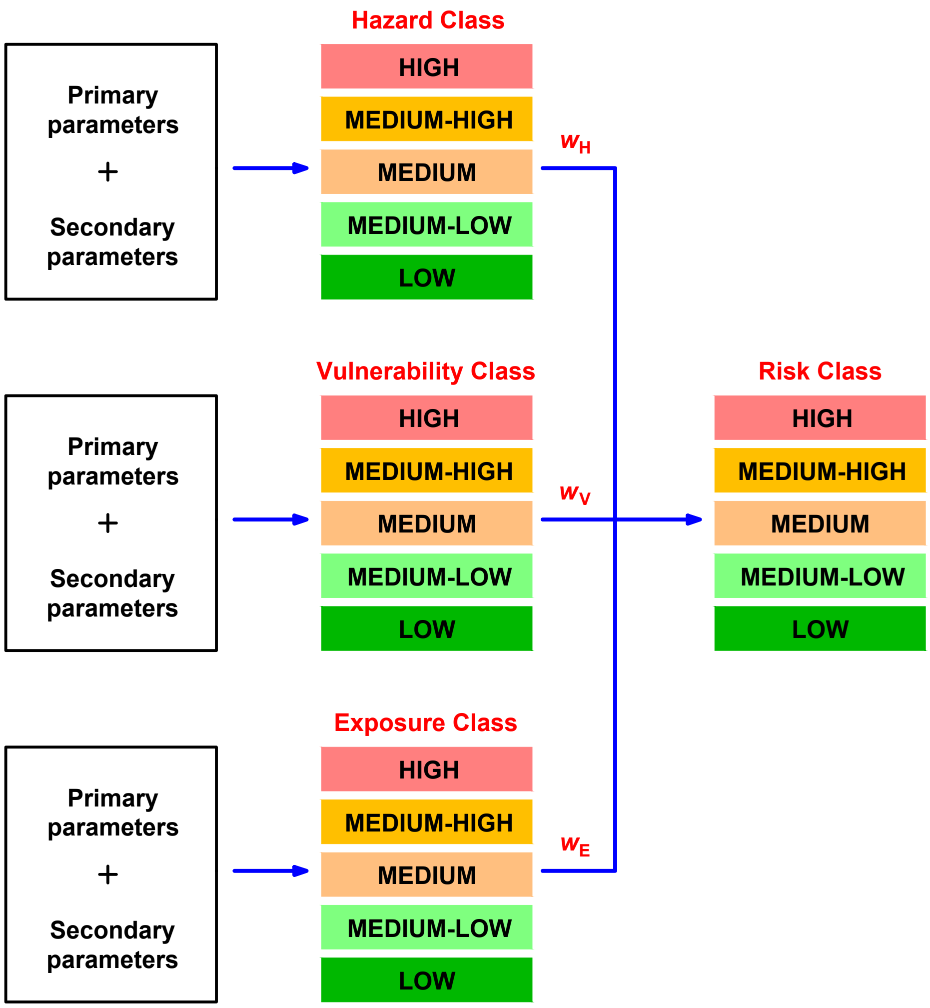

Figure 3. Definition of the risk class. w_H, w_V, and w_E are the weight parameters related to hazard, vulnerability, and exposure classes, respectively.

3.2.1. Hazard Class

The hazard class is intended to quantify the susceptibility of the mountain region with respect to snow avalanches, regardless of the exposed elements and their characteristics. By analogy with other natural extreme events, snow avalanches are described by their intensity—related to the distribution of impact pressures along the avalanche track—and the corresponding frequency, i.e., the return period. Impact pressures and return period are commonly used as key parameters to describe avalanche intensity maps in mountain regions.

Similar hazard-zoning approaches are widely adopted across different countries, although with differences in nomenclature and, most importantly, reference thresholds for pressure and return periods [16–19]. In general, avalanche zoning procedures combine avalanche intensity and event frequency through pressure-based criteria within hazard maps, as summarized in Table 1.

Table 1. Hazard zoning criteria adopted in different countries.

Country	Zoning Criteria	Intensity	Frequency
Canada [16]	Red/blue/white zones	1, 3, and 30 kPa	30/300 y
France [17]	A1/A2/A3 zoning	1, 3, and 30 kPa	100 y/Exceptional
Switzerland [18]	Red/blue/yellow zones	3 and 30 kPa	30/300 y
Italy [19]	Three-level zoning	3 and 15 kPa	30/100 y

Although different hazard-zoning criteria can be adopted within the proposed framework, the Italian classification is used herein as a reference because the methodology has been recently adopted in the corresponding Italian guidelines [19]. According to this procedure, avalanche-prone areas are classified into three hazard levels, depending on the impact pressure (p) and reference return periods (T):

- *High*: $p \geq 3$ kPa for $T = 30$ years, or $p \geq 15$ kPa for $T = 100$ years;
- *Moderate*: $p < 3$ kPa for $T = 30$ years, and $3 \leq p < 15$ kPa for $T = 100$ years;
- *Low*: $p < 3$ kPa for $T = 100$ years.

Despite the different zoning criteria among national procedures, the above-mentioned approaches rely on hazard mapping as the reference tool to provide a synthetic representation of avalanche scenarios through pressure thresholds and return periods. In this sense, hazard maps implicitly account for multiple avalanche scenarios characterized by different combinations of intensity and frequency, including information from historical records and avalanche dynamics simulations.

Accordingly, the proposed approach adopts the hazard classification provided by hazard maps as the basis for defining the intrinsic hazard class, where the lowest, moderate and highest hazard degrees are respectively associated with low, medium, and high hazard classes (see the left column of Figure 4). This classification can subsequently be refined through secondary parameters, thus leading to a five-level hazard classification.

This method is not strictly tied to a specific national zoning criterion. Different hazard classifications may be adopted, provided that the hazard levels are consistently associated with the hazard classes. In all cases, the classification should be applied consistently within the investigated area to ensure a homogeneous prioritization of exposed elements, which represents the main objective of this methodology, rather than the absolute comparison of hazard levels between different regions or countries.

The effectiveness of the determination of the hazard class is directly connected to the reliability of the adopted hazard intensity maps and, therefore, to the quality and quantity of historical records (data) available for the territory under investigation. The proposed procedure assumes the availability of hazard intensity maps as a pre-requisite.

Nevertheless, in Italy, for instance, such conditions are often not met in practice, considering the large amount of undocumented mountain areas in which avalanche hazard maps are not available. This is mainly due to the substantial lack of historic event records, making the knowledge of previous events often fragmentary or, in the worst case, completely absent [24].

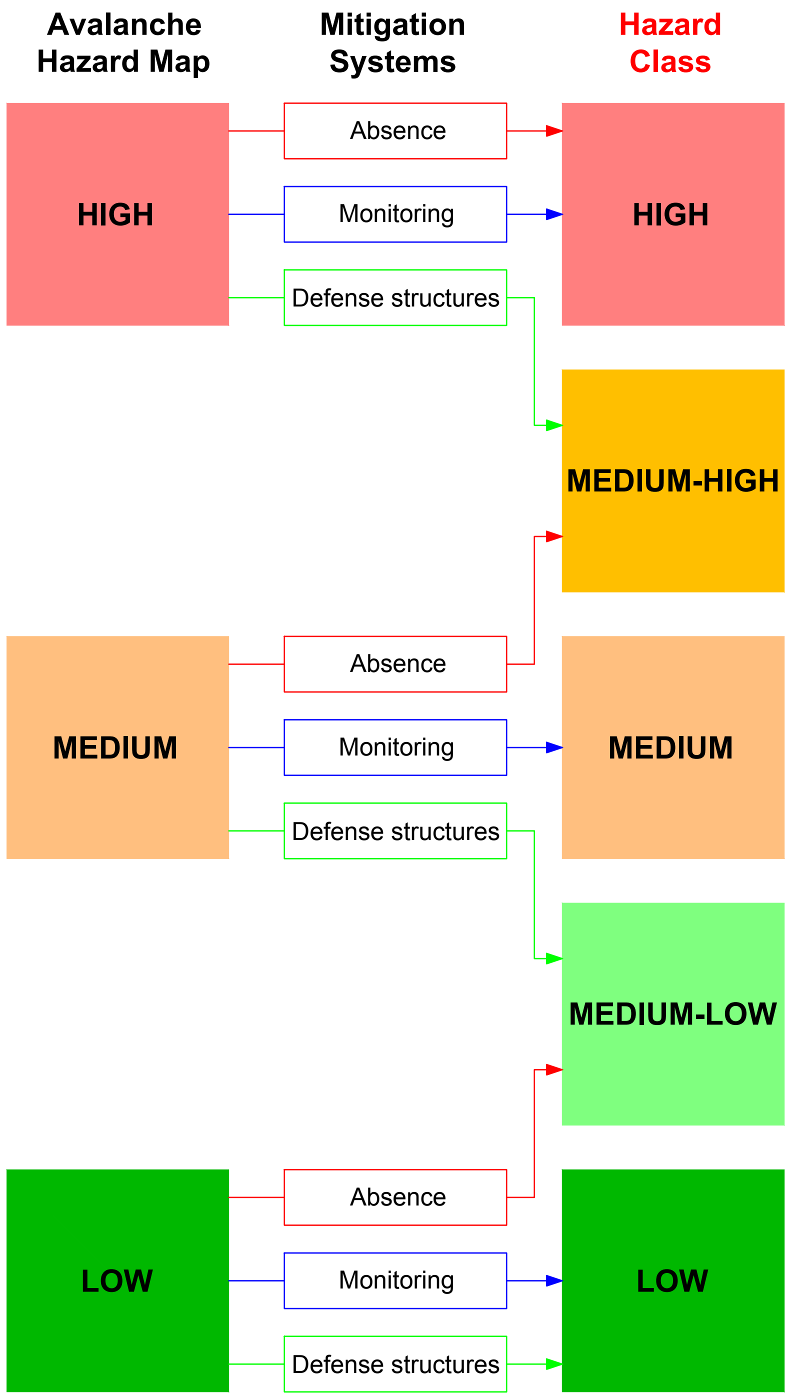

Figure 4. Definition of the hazard class.

In these cases, the proposed classification can still be used when previous avalanche events are known, even in the absence of hazard intensity maps. Under these circumstances, the most harmful event and the related maximum impact pressures—they can be estimated, for instance, on the basis of structural back-analyses on damaged elements [25,26]—will define the hazard class, regardless of the frequency (return period) of the event.

In this context, it is worth mentioning the significant efforts of scientists and researchers working in this field, who recently discussed different procedures for the automated definition of *Potential Avalanche Release Areas* (PRAs). These methodologies are mainly based on the use of *Digital Elevation Models* (DEMs), focusing on the geometric features of the terrain, such as slope, curvature, and roughness, which are found to be critical parameters affecting PRAs [27,28]. The effectiveness of these approaches has been discussed in several Alpine regions [29–33] and Norway [34], thus paving the way for the so-called *Large-Scale Hazard Mapping* (LSHM).

When these methods are used in combination with avalanche dynamics simulation tools—e.g., RAMMS [35] and AvaFrame [36]—and/or with structural back-analyses related to previous harmful events, they can serve as a basis for the hazard intensity mapping with respect to the surrounding built environment. In this sense, the proposed approach could take advantage of the above-mentioned methodologies, thus extending its application also in the case of undocumented areas, where hazard mapping is not available.

However, the hazard class derived from hazard maps can then be adjusted by accounting for the influence of mitigation systems as a secondary parameter. This subsequent modification is not intended to affect the intrinsic hazard itself, but rather accounts for the residual hazard, considering the presence of protective and monitoring measures within the endangered area.

In all cases, the presence and effectiveness of such systems must be evaluated by avalanche experts based on the characteristics, state of maintenance, and expected performance of the protection measures. The adjustment thus depends on the evaluated effectiveness of mitigation measures, rather than the specific type of protection system adopted. For this reason, this adjustment is intentionally limited to one hazard level, consistent with the philosophy of the proposed framework.

When the presence of effective protective measures—such as snow-supporting and snow-deflecting systems, snow sheds, snow fences [37]—is confirmed, the hazard class is reduced by one level (see the right-side column of Figure 4). On the other hand, when effective monitoring systems are present, the hazard class is kept unchanged, since they do not alter the physical hazard along the avalanche track, but support emergency and risk management activities. When neither avalanche protective structures nor monitoring systems are present, the hazard class is increased by one level.

3.2.2. Vulnerability Class

Vulnerability can be defined as the propensity of a given system to be damaged or disrupted when subjected to a certain endangering phenomenon. In the proposed framework, the vulnerability class is supposed to measure the capacity of buildings and infrastructure systems to cope with extreme events, such as snow avalanches [38]. Consequently, this definition must be adapted depending both on the exposed object and the hazardous phenomenon under consideration.

The vulnerability of building structures, or similar systems, depends on the capability of the structural system to withstand the abnormal loads produced by the LPHC event [39,40], which are not typically considered in the design stage. From a physical perspective, snow avalanches exert distributed impact pressures on exposed structures, depending on both the properties of the avalanche flow (e.g., velocity profiles, flow depth, impact pressure) and the properties of the exposed object. Avalanche dynamics is typically evaluated through numerical models, such as RAMMS, whose outputs provide the key input parameters to model structural loading.

The structural response must then be related to the hazard intensity through vulnerability relationships, connecting the Intensity Measure (*IM*) of the avalanche to the conditional probability of exceeding a predefined Damage State (*DS*), described through suitable Engineering Demand Parameters (*EDPs*). Within infrastructure engineering, these relationships are commonly referred to as "*fragility curves*".

In buildings, fragility curves are strongly related to the capability of the structural system to accommodate load redistribution after local failures [41,42]. This property is commonly referred to as Alternate Load Path (ALP), a robustness-oriented design strategy against progressive collapse, widely addressed in scientific literature [43–45], as well as in technical guidelines [46,47] and design codes [48–51]. Structural engineers typically evaluate the response of a structural system to avalanche-induced loads through approaches of different complexity, ranging from simplified linear elastic models to nonlinear dynamic analyses. The resulting responses are used to derive fragility curves by associating structural response key-parameters (e.g., displacements or internal forces) with predefined damage thresholds [52].

While this framework is well established for buildings, its extension to linear infrastructures and network systems requires a transition from structural performance to system functionality. In this case, fragility is associated with service degradation and loss of functionality, expressed through system-level performance indicators, such as loss of connectivity, increase in travel time, or reduction in network capacity. Network vulnerability assessment requires the contribution of experts in network and transport system analysis and may involve both component-level and global system-level approaches accounting for redundancy and alternative paths [53–56].

Network systems exposed to avalanches, such as alpine roads, are typically located in inter-urban mountain environments, where redundancy and interdependency are generally limited [57]. Under these conditions, local structural vulnerability is expected to play the dominant role, whereas functional or network-related effects mainly emerge at the system scale through service degradation and loss of connectivity [58].

Within the proposed framework, the structural vulnerability is assumed as the primary parameter, since it directly describes the local physical response of the exposed element to avalanche-induced loads. Functional vulnerability, which mainly emerges at the network scale, is instead treated as a secondary parameter. This choice is consistent with the philosophy of the proposed methodology, where the primary parameters are intended to represent the dominant local mechanisms governing the risk assessment, whereas secondary parameters account for system-level or context-dependent effects.

For the classification of the structural vulnerability, at least two approaches can be identified. From a fragility-based perspective, the fragility curve of each specific exposed element represents the rigorous analytical basis to define the vulnerability class among the five levels adopted in the proposed methodology. Following this approach, the conditional probability of exceeding a selected Damage State (DS), e.g., collapse, must be defined as a function of the Intensity Measure (*IM*), e.g., avalanche pressure (Figure 5). The reference intensity measure, *IM**, used to derive the structural vulnerability classification, should be consistent with the adopted hazard scenario and the corresponding hazard zoning, since it should be representative of the expected impact of the avalanche on the exposed building. Under these assumptions, the corresponding conditional probability, $P^*(IM^*)$, can be used to define the vulnerability class as follows:

- *High* $\longrightarrow 0.8 \leq P^*(IM^*) \leq 1.0$;
- *Medium–high* $\longrightarrow 0.6 \leq P^*(IM^*) < 0.8$;
- *Medium* $\longrightarrow 0.4 \leq P^*(IM^*) < 0.6$;
- *Medium–low* $\longrightarrow 0.2 \leq P^*(IM^*) < 0.4$;
- *Low* $\longrightarrow 0 \leq P^*(IM^*) < 0.2$.

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While this approach is rigorous, it demands a large amount of data and structural analyses, since the fragility curve should be derived specifically for each exposed structure. As a direct consequence, this approach risks becoming impractical for territorial-scale applications. Under these circumstances, class-based approaches represent a viable alternative, where vulnerability classes are assigned through typological criteria. Similar typological approaches are commonly adopted in territorial-scale seismic vulnerability assessments [59]. In contrast to fragility-based approaches, typological classifications rely primarily on structural and functional characteristics of the exposed elements, without requiring explicit scenario-based structural analyses. Different classification criteria can be adopted:

- Structural typology (low-rise buildings, industrial buildings, towers, bridges);
- Load-bearing system (framed structures, wall systems, braced or truss systems);
- Construction material (reinforced concrete, structural steel, masonry, timber);
- Number of stories or structural height;
- Robustness-oriented features.

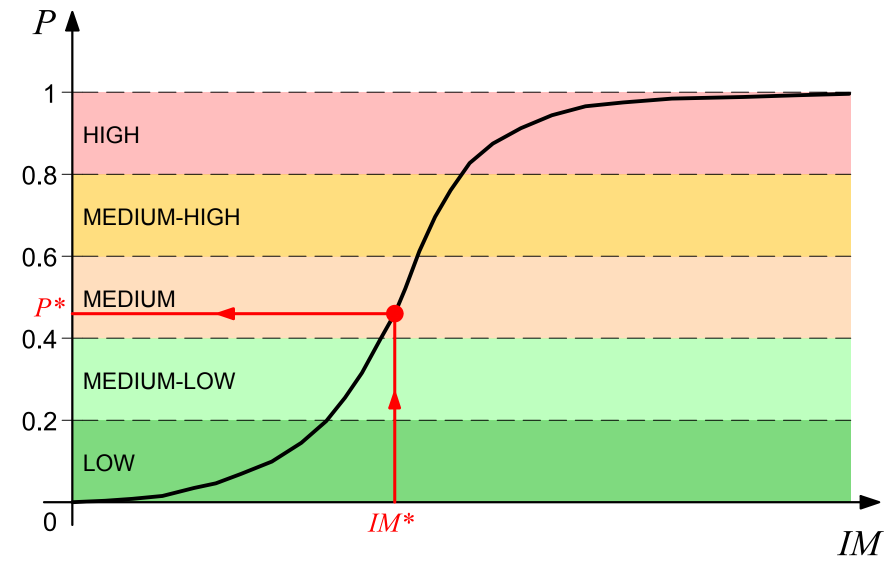


Figure 5. Definition of the vulnerability class depending on the fragility curve, for the selected reference scenario. *IM** and *P** correspond to the intensity measure and the corresponding probability of the reference scenario.

In all cases, the same classification criteria must be applied consistently across the investigated area to ensure a homogeneous vulnerability classification. Both fragility-based and typological approaches involve a certain degree of expert judgment. In the former case, the vulnerability assessment depends on structural modelling assumptions and structural analysis procedures, whereas in the latter case, the classification depends more strongly on the adopted criteria and expert interpretation.

Once the primary parameter (i.e., structural vulnerability) is defined, two adjustments can be applied with secondary parameters. The first secondary adjustment accounts for the geometric interaction between the avalanche flow and the exposed element by comparing the portion of the object directly hit by the avalanche relative to its total size. A one-level increase in the vulnerability class is provided when the object is fully impacted by the avalanche flow (see the central column of Figure 6).

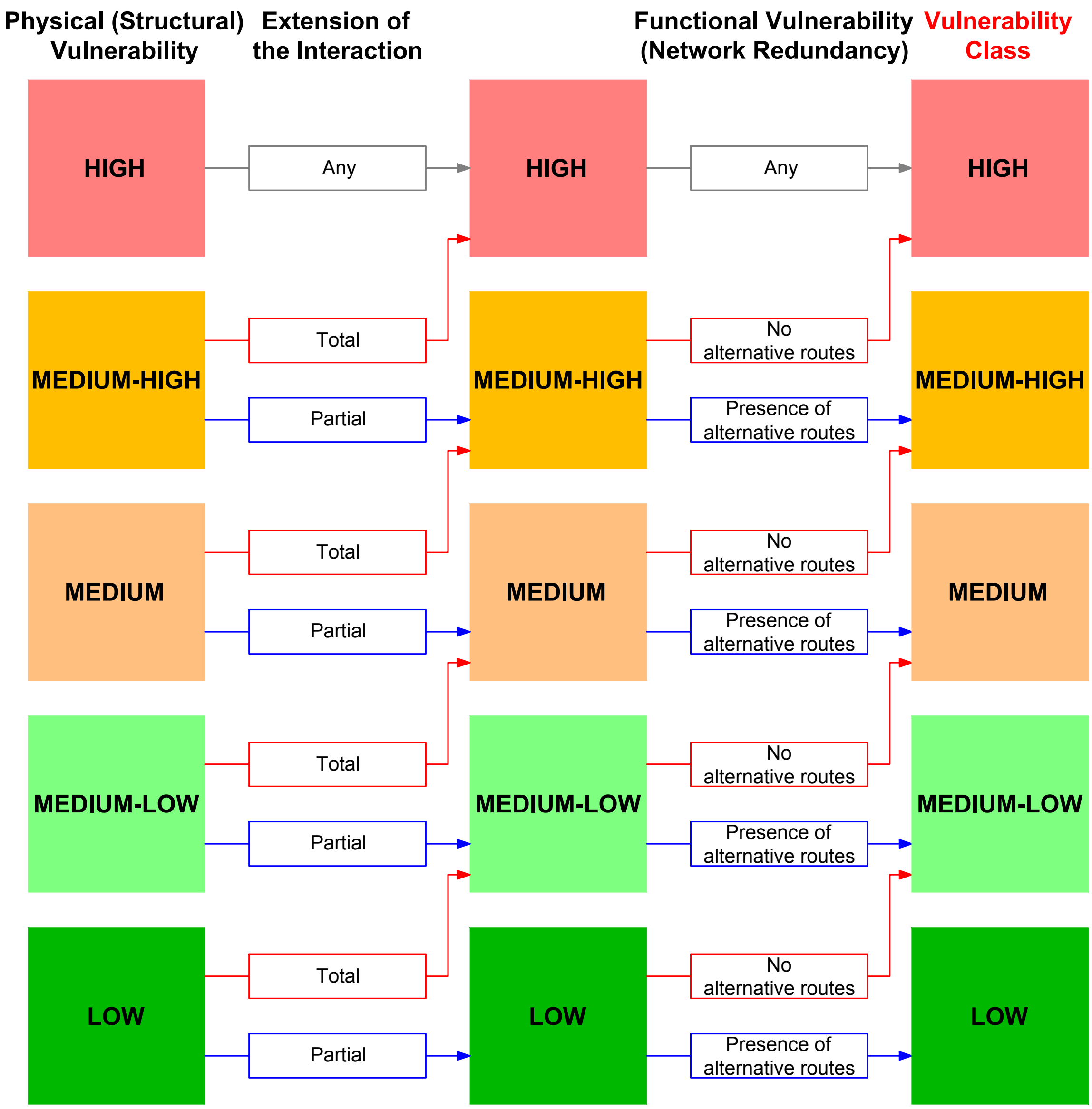


Figure 6. Definition of the vulnerability class.

The assessment is sufficient for isolated systems such as individual buildings. Additional considerations arise when dealing with network systems (e.g., road networks, railways, power lines, pipelines, transmission lines), where network-level effects may provide an additional adjustment to the vulnerability class. When effective alternative paths are available, the vulnerability class remains unchanged. Conversely, the vulnerability class increases by one level when no alternatives are identified (see the right-hand side column of Figure 6). Finally, the overall vulnerability class of the infrastructure is obtained by integrating its structural (local) and network (global) features.

3.2.3. Exposure Class

The exposure class describes the potential losses when an object, building, or infrastructure is subjected to a hazardous event. For this purpose, a useful classification can be performed with respect to direct and indirect losses. The former can be defined as tangible losses, which are immediately caused by the hazardous event. On the other hand, indirect losses are often intangible losses, which are not directly related to the hazardous event, resulting from the direct losses. For this reason, they are also referred to as consequential losses.

In the case of snow avalanches, the most relevant direct losses are death or grave injury of persons, the number of which is directly connected to the average number of building inhabitants, together with the potential structural repair costs.

In addition, several indirect losses can be accounted for, depending on the type of asset under consideration. In the case of industrial plants, the main economic losses are due to the loss of income in the period of business interruption, i.e., the so-called down-time. A similar consideration applies in the case of infrastructures facing a disruption, whereby indirect losses are related to the closing period of the network system (traffic routes, power supplies, water facilities), with potential isolation of a large part of the territory. Moreover, when historical and cultural heritage buildings are severely damaged, the intangible losses relate to the social value in the territory under investigation. In many cases, indirect losses, even though they are secondary to direct losses, can exceed direct losses.

Similar to vulnerability assessment, exposure can be evaluated either through quantitative indicators (e.g., occupancy, economic losses, number of users) or through simplified class-based approaches suitable for territorial-scale applications. The proposed methodology does not aim at explicitly monetizing or directly comparing human and economic losses, which would require quantitative risk analyses and societal assumptions on the valuation of human life. Instead, the exposure class provides a simplified ordinal representation of the potential consequences associated with the exposed element, suitable for territorial-scale prioritization and decision-making.

In simplified territorial-scale applications, the typology and use of the exposed object represent the primary indicators of the expected human, economic, and functional consequences associated with the hazardous event. For this reason, a class-based exposure classification is adopted, whereby the endangered objects are classified within five levels of exposure. The classification recently adopted in Italy [19] is used here:

- *High*: densely-populated systems (buildings, hotels, ski resorts), villages;
- *Medium–high*: infrastructures, industrial plants, cultural heritage buildings;
- *Medium*: local roads;
- *Medium–low*: mountain huts, mountain pastures;
- *Low*: uninhabited buildings.

In the proposed classification, objects belonging to the same typological category are associated with the same exposure class, even though the actual monetary value may differ.

This classification represents a simplified territorial-scale approach aimed at ensuring straightforward applicability of the methodology. However, when more detailed analyses are feasible, the exposure assessment can be refined through quantitative indicators and official data sources. In buildings, this may include occupancy data and population exposure, whereas in infrastructures, the analysis may account for the number of daily users served by the system. In industrial facilities, the analysis should include the economic value associated with business interruption, whereas in cultural heritage assets, ad hoc socio-economic evaluations are required. Therefore, the proposed class-based classification should be interpreted as a simplified framework that can be progressively refined according to the available data and the required level of detail.

Finally, the criticality of the infrastructure [60] under consideration is treated as a secondary parameter. Following Directive 2022/2557 on the resilience of critical entities [61], critical infrastructures are defined as entities providing essential services for the maintenance of vital societal functions, economic activities, public health and safety, or the environment. Within the proposed framework, infrastructures are classified as critical only when formally identified as critical entities according to the applicable national or European regulations. This approach avoids arbitrary evaluations of infrastructure criticality within the proposed methodology. In such cases, a one-level increase in the exposure class is applied to account for the strategic role of the provided service (Figure 7).

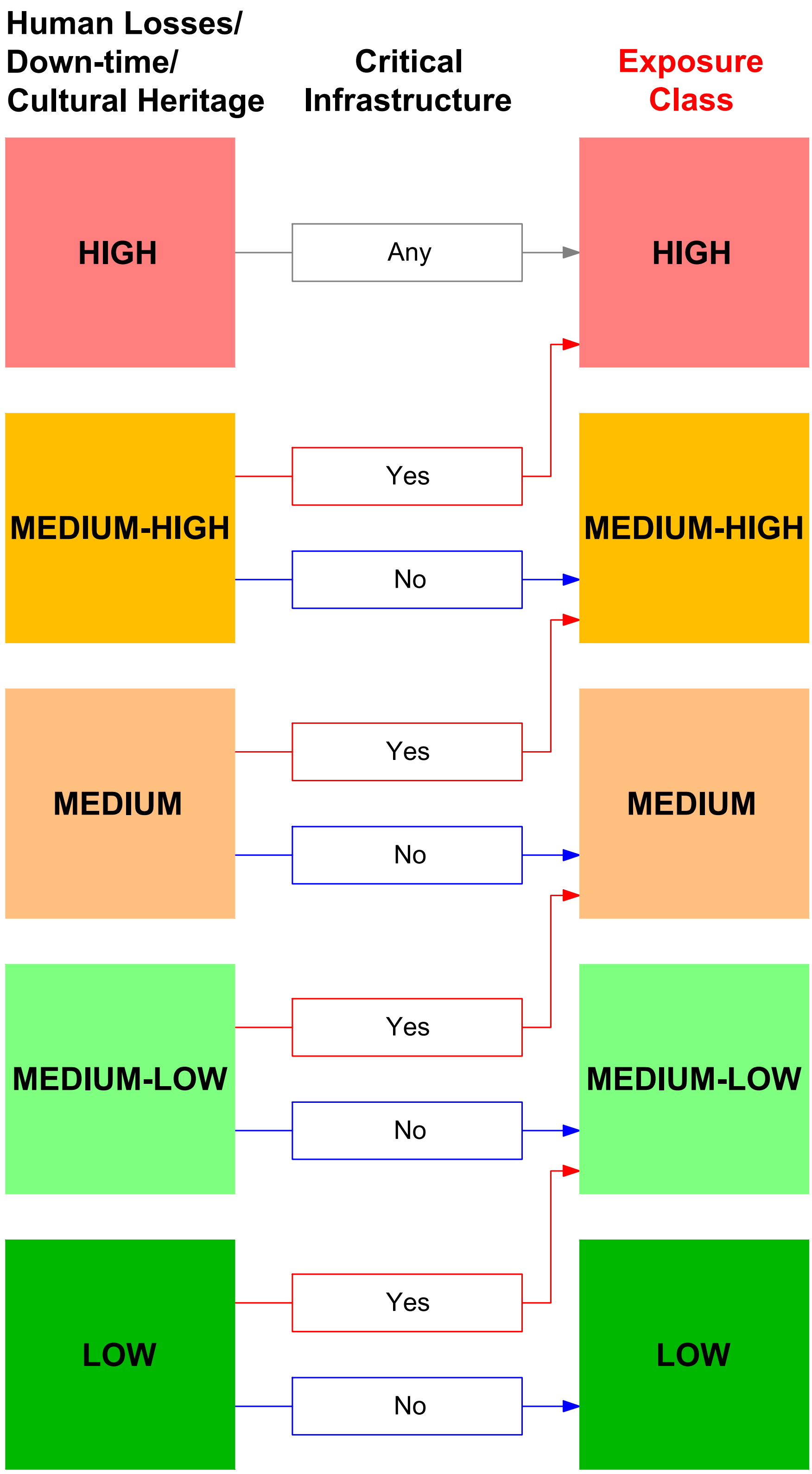


Figure 7. Definition of the exposure class.

3.2.4. Risk Class

The risk class for each exposed element is determined based on the Risk Index (*RI*), calculated through Equation (2). The calculation requires the assignment of a value for each component (H, V, E). An integer value, ranging between 1 and 5, is assigned to each factor, corresponding to the associated class, i.e., 1 for low class and 5 for high class. In addition, a set of weighting parameters (w_{H}, w_{V}, w_{E}) must be chosen, in all cases satisfying the condition given by Equation (3). In this way, the resulting *RI* ranges between 1 and 5.

Considering the adopted scoring system, it should be recalled that the proposed classification applies only to buildings and infrastructures located within avalanche-prone areas. Accordingly, the minimum value equal to 1 does not represent the absence of hazard, vulnerability, or exposure, but rather the lowest level among the exposed elements included in the territorial assessment. Buildings and infrastructures located outside avalanche-prone areas are excluded a priori from the assessment procedure and do not participate in the risk-classification process. For the sake of completeness, they may be conceptually associated with a level equal to 0, which lies outside the proposed classification framework.

Then, the associated risk class can be determined according to the following predefined threshold intervals:

- *Low* $\longrightarrow 1.0 \leq RI < 1.5$;
- *Medium–low* $\longrightarrow 1.5 \leq RI < 2.5$;
- *Medium* $\longrightarrow 2.5 \leq RI < 3.5$;
- *Medium–high* $\longrightarrow 3.5 \leq RI < 4.5$;
- *High* $\longrightarrow 4.5 \leq RI \leq 5.0$.

Both *RI* and the resulting risk class vary between 1 and 5, but the former changes continuously as a function of the factors and the triplet of weights, whereas the latter varies discretely, in agreement with the adopted five-level classification. The discrete intervals above are valid for any set of weighting parameters satisfying Equation (3), whereas the value of *RI* depends on the combination of w_{H}, w_{V}, and w_{E}. The adopted combination must reflect the relative role played by each factor in the overall risk evaluation.

Figure 8 shows the risk classification related to a specific set of weighting factors, i.e., $w_{\mathrm{H}} = w_{\mathrm{E}} = 0.40$, $w_{\mathrm{V}}= 0.20$, as recently adopted in Italian guidelines [19]. Results are collected in five risk matrices, where the risk class is obtained for each hazard class, as a function of the vulnerability (rows) and exposure (columns) classes. Different risk matrices would be obtained for other combinations of weighting factors.

The hazard and exposure factors are generally considered more robust and reliable within the proposed framework, although for different reasons. Hazard is determined based on hazard (avalanche) intensity maps, whereas exposure is directly connected to the potential human and economic losses. Different considerations apply to vulnerability. Despite its importance, a standardized metric for structural vulnerability (robustness) is not yet available, thus requiring a case-by-case analysis by expert structural engineers. Consequently, it is clear how the vulnerability analysis is influenced by the expertise of structural engineers, and therefore implicitly involves a certain degree of subjectivity. For this reason, a smaller value of w_{V} with respect to w_{H} and w_{E} is recommended for the application of the methodology.

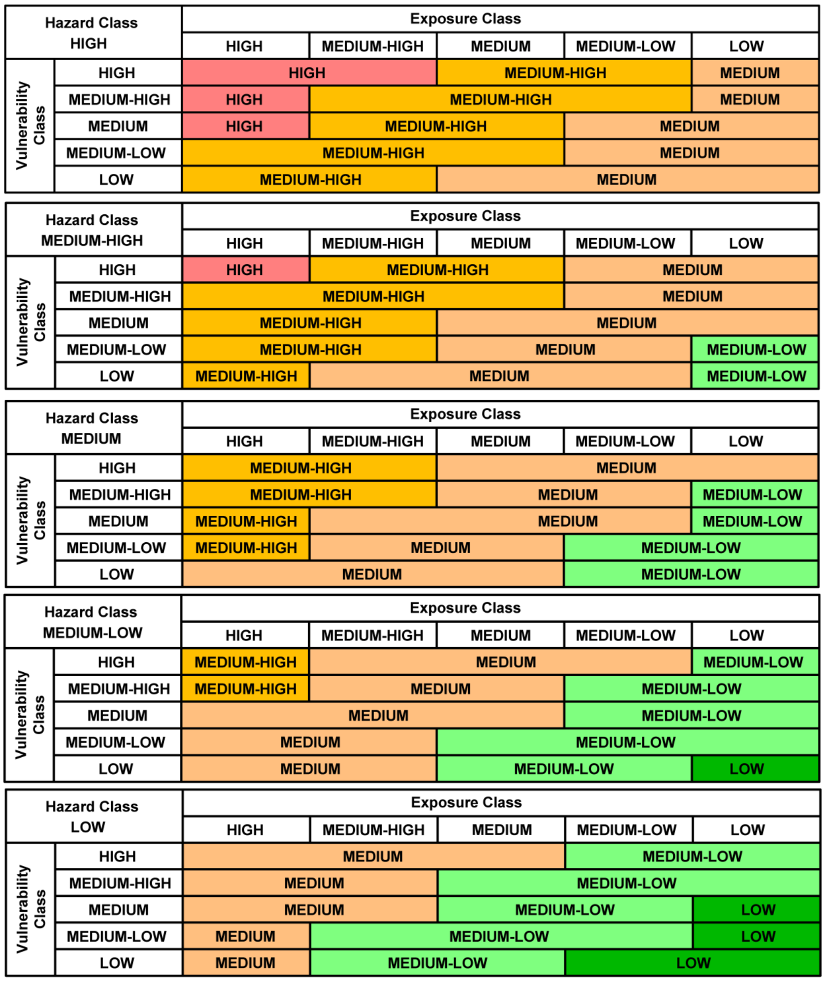


Figure 8. Risk matrices for different hazard classes, by using $w_H = 0.40$, $w_V = 0.20$, $w_E = 0.40$.

3.3. Level 3: Risk Management

Considering a given territory under investigation, risk matrices permit a hierarchical evaluation of the risk class at the scale of the territory or avalanche basin. This supports avalanche experts and decision-makers in setting priorities among different mitigation strategies, thus providing a more efficient risk management and urban planning.

From this perspective, mitigation actions of different nature can be undertaken. Firstly, more detailed case-by-case analyses can be carried out with respect to selected potential avalanche tracks and the related exposed objects. These advanced analyses can be focused on both the dynamics of the avalanche flow and the structural performance of the exposed building. In the former case, suitable numerical tools for modelling the dynamics of gravity-induced phenomena, e.g., RAMMS and AvaFrame, are suggested, thus providing also the distribution of impact pressures along the selected avalanche paths. The latter investigation, which can also be used to evaluate or modify the hazard class, provides the input parameter in structural analyses, carried out to investigate the response to abnormal loads.

Depending on the selected strategy, policymakers may opt for a direct implementation of risk-mitigation measures, which can involve each of the three factors contributing to the overall risk classification. In this sense, the decomposition of risk proposed in this framework (Equation (2)) allows a more rational implementation of mitigation measures. For instance, planning and construction of avalanche defense structures, such as snow-supporting and snow-deflecting systems, snow sheds, and snow fences, provide a reduction of the hazard class (Figure 4). In contrast, structural retrofitting measures would modify the structural vulnerability class (Figures 5 and 6). A similar result is obtained if the resilience of network systems is increased. A further option consists of the change of the building use, thus modifying the exposure class (Figure 7). In practice, however, this is the least frequent solution. In all cases, the implementation of mitigation measures and/or additional analyses may modify the hazard, vulnerability, and exposure classes of the exposed elements, thus requiring a periodic reassessment of the corresponding risk classes.

Although the proposed methodology is primarily intended as a territorial-scale prioritization tool, the resulting risk classification may support subsequent cost-effectiveness analyses aimed at optimizing mitigation strategies. In this context, decision-makers may assess the cost-effectiveness of the above-mentioned solutions in order to optimize the allocation of financial resources. A well-established approach is given by Bohnenblust and Slovic (1998) [62], whereby the optimization procedure, the so-called "cost-effectiveness analysis", is characterized by the following steps:

- Identification of all possible mitigation measures, including all their feasible combinations;
- Evaluation of costs and risk reduction due to the implementation of all solutions defined in the previous step;
- Construction of the risk-cost diagram, in which each solution is represented by a point in the cost-residual risk plane;
- Definition of the optimal front, by considering for each cost level, the maximum risk reduction. In this sense, the procedure is analogous to Pareto's approach for multi-objective optimization;
- Definition of the optimal mitigation strategy, at the point corresponding to the marginal cost criterion.

In Figure 9, an example of a risk–cost diagram is represented, including the indication of the efficient front and the optimal solution, the latter defined by the so-called "marginal cost criterion" as the lowest-lying point on the efficient front, for which the risk reduction exceeds the cost increment [13,62].

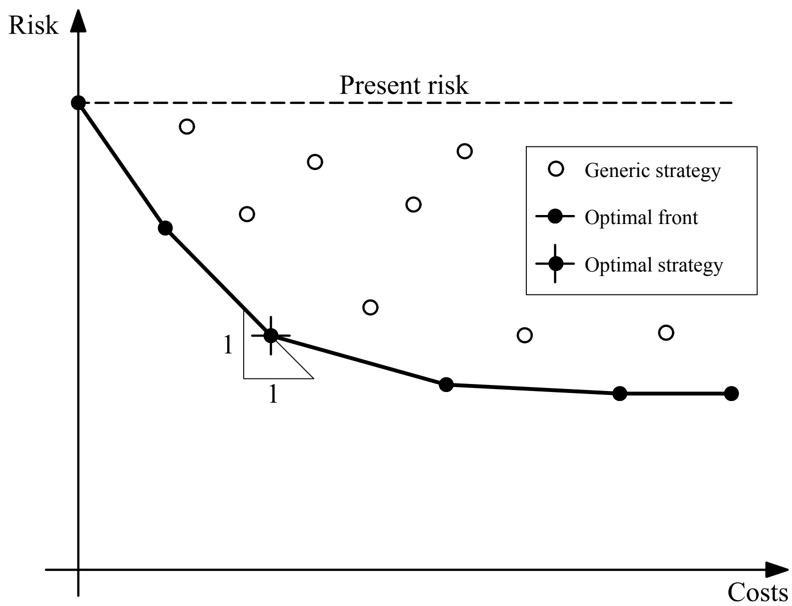


Figure 9. Risk-cost curve and optimal risk-reduction strategy [13,62].

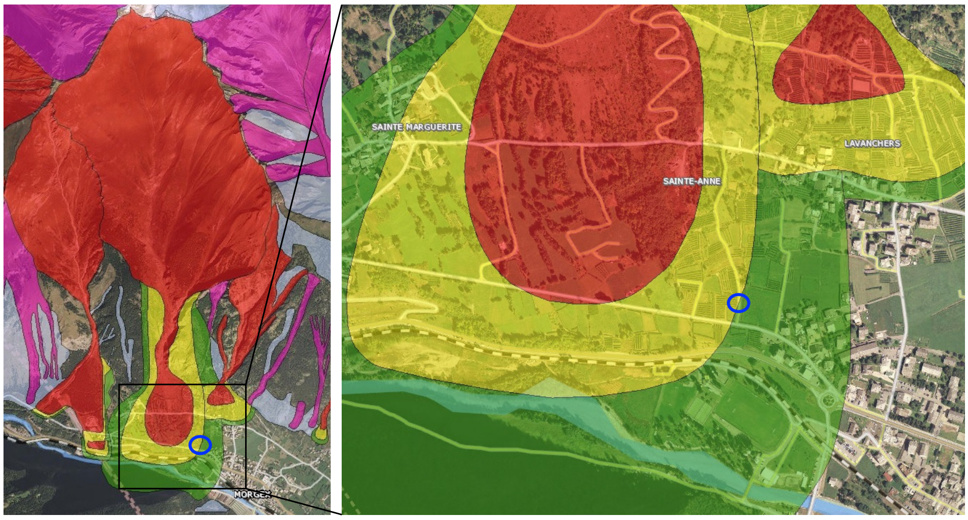
4. Application and Discussion

In this section, the proposed method will be applied to a simple example, regarding an electrical transmission tower located in the Aosta Valley region, in the northwestern

Italy. The transmission tower (Figure 10) belongs to a medium-voltage transmission line, used to supply electric power within the Valdigne, the northern Italian area at the foot of Mont Blanc, including the well-known municipality of Courmayeur. The latter has about 2600 residents (out of the approximately 8500 in the entire Valdigne), but they increase tenfold during the peak tourist season (e.g., in January 2024, just over 47,000 presences were recorded). More precisely, the tower is located in the municipality of Morgex, at approximately 1000 m a.s.l., between the hamlets of Dailley and Lavancher, located on either side of the Lavancher avalanche conoid (n. 16-006 of the Aosta Valley avalanche cadastre—https://valangheweb.partout.it/ (accessed on 1 June 2026)), approximately 35 m from the local road that connects the two hamlets and is often closed in winter due to potential avalanche danger (Figure 11a).

The objective of the following application example is not to provide a detailed process-based avalanche risk assessment, but rather to illustrate the practical implementation of the proposed classification framework. More specifically, the proposed case study is focused on the determination of the risk class of a single infrastructure, whereas the application of the methodology to an entire territorial domain, including the prioritization between different exposed elements, is the subject of ongoing research activities.

Figure 10. Transmission tower under investigation.



(a) **(b)**

Figure 11. Official avalanche hazard map for the Lavancher avalanche path, Aosta Valley, Italy. (**a**) Basin overview; (**b**) Magnification of the area under investigation. The shaded red area indicates a high degree of avalanche hazard, the yellow area indicates a medium degree of avalanche hazard, the shaded green area indicates a low degree of hazard, whereas the blue circle identifies the location of the tower under investigation. The hazard zoning represents the intrinsic avalanche hazard of the area and does not account for the effects of existing mitigation measures.

As previously discussed, the proposed approach provides the so-called risk class of the infrastructure under investigation, on the basis of the hazard, vulnerability, and exposure classes, which are independently assessed depending on primary and secondary parameters. Firstly, the hazard class is defined on the basis of the hazard intensity maps. The latter, considering the mountain region of Aosta Valley, are available online on the Regione Autonoma Valle d'Aosta website, where the information about all the documented avalanches is freely accessible [63]. The cartography displays three levels of avalanche hazard—high (red area), medium (yellow), and low (green)—, the electric tower (blue circle in Figure 11) being located at the border between a low hazard area and a medium hazard area.

This hazard zoning was defined in the aftermath of the extreme event that occurred on 23rd of February 1999, where the avalanche flow covered an area of about 116 ha, killing one person. After this event, approximately 4350 m of snow nets, and about forty "inverted tree" windbreaks—covering about 350 m of the ridge—were constructed. In addition, monitoring devices were installed, such as an automatic nivo-meteorological station at the top of the basin (2850 m a.s.l.) and a webcam for monitoring the detachment zone. Following the flowchart of Figure 4, a medium intrinsic hazard class is assumed, subsequently reduced to medium–low because of the above-described defense structures.

The vulnerability class is evaluated starting from the structural vulnerability of the exposed element. In the present example, the vulnerability class is assigned through the simplified typological approach discussed in Section 3.2.2, without the explicit derivation of fragility curves for the investigated structure. Accordingly, the structural vulnerability is discussed through qualitative structural considerations related to the building typology and structural configuration of the exposed element.

From a structural perspective, the tower consists of a cantilever-like metallic truss, subjected to a pressure distributed along its height. In general, the pressure distribution can be described by a trapezoidal-like diagram, as qualitatively represented in Figure 12a. Considering that the tower behaves analogously to a cantilever beam fixed at the ground, significant structural demands involve the base of the structure, which may trigger the overturning of the structure, thus resulting in a so-called disproportionate, even though not progressive, global collapse of the structure (Figure 12b) [64]. In the absence of detailed structural analyses and design documentation, the mast is conservatively assumed to be highly vulnerable within the proposed typological classification. This assumption seems to be reasonable, at least as a first assessment, when the determination of the fragility curves is not performed [65].

Moreover, by considering that the tower is fully within the avalanche-prone area and that the presence of alternative systems able to deliver electric power in the case of disruption cannot be ascertained, the flowchart of Figure 6 indicates that the power mast is to be considered highly vulnerable.

The exposure class of the transmission tower can be defined following the simplified typological approach discussed in Section 3.2.3, whereby infrastructure systems are associated with a medium–high exposure level. Considering that no formal classification as critical infrastructure was verified within the present application example, no additional increase in the exposure class is applied.

When the hazard, vulnerability, and exposure classes are defined, it is possible to determine the risk class of the infrastructure under investigation through the risk matrices of Figure 8, which associate the infrastructure under analysis with a medium risk class. The obtained results are summarized in Table 2.

Table 2. Summary of the hazard, vulnerability, exposure, and resulting risk class for the investigated transmission tower.

Factor	Primary Parameter	Secondary Parameter	Final Class
Hazard	Hazard mapping	Mitigation systems	Medium–low
Vulnerability	Structural typology	Network redundancy	High
Exposure	Building typology	Criticality (not applied)	Medium–high
Risk	-	-	Medium

By applying the procedure to other exposed constructions and infrastructures within the endangered area, and providing the related risk class, it is possible to obtain a hierarchical risk classification at the chosen territory scale. The example highlights how the proposed methodology can support the hierarchical prioritization of exposed infrastructures within avalanche-prone territories, without requiring detailed quantitative avalanche-risk analyses for each exposed element.

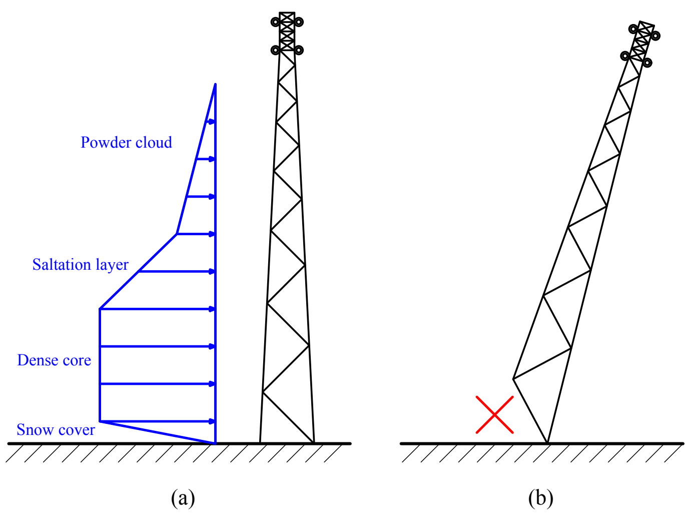


Figure 12. (**a**) Qualitative pressure distribution (in blue) applied on the tower; (**b**) Potential damage and the consequent disproportionate non-progressive collapse (global overturning), triggered by the failure of a structural element at the base of the tower (red cross).

5. Conclusions

In this paper, a simplified multi-step framework is proposed for the risk assessment of buildings and infrastructures endangered by snow avalanches. The framework is based on the identification of the main factors affecting the three risk components, i.e., hazard, vulnerability, and exposure, which are evaluated through a class-based approach. The final goal of the analysis is to assist authorities and decision-makers at the local, regional and state levels with an operational tool for defining priorities among different risk-mitigation strategies. In this sense, the proposed framework is intended to bridge the gap between technical risk assessment and risk management processes, supporting more informed decision-making and ultimately enhancing the resilience of mountain communities to avalanche hazards.

Despite the simplicity of the proposed methodology, its general formulation represents a major advantage, as it promotes large-scale application across different mountain territories. The approach can be applied in avalanche-prone areas endangering multiple buildings and/or infrastructures simultaneously, thus providing a straightforward risk classification within the mountain area under investigation. In all cases, this is possible as long as reliable hazard intensity maps and basic information about the exposed elements are available. Future developments will focus on the applicability of the proposed approach with respect to actual case studies in Italian mountain areas of different scales.

Moreover, the proposed approach can be extended to other natural or man-made hazards, through suitable modifications of the hazard, vulnerability, and exposure factors according to the characteristics of the investigated phenomenon and the exposed elements. This framework supports multi-risk assessment of territories and communities endangered by different hazards, such as seismic events and other gravity-induced phenomena, e.g., debris flows and floods. More precisely, the current formulation of the model allows the independent assessment of multiple hazards of different nature and impact. However, more complex scenarios involving correlated or cascading phenomena (e.g., avalanches caused by a preceding earthquake) as well as sequences of successive events (e.g., multiple avalanches in the same site), remain beyond the scope of the present methodology.

Despite the potential of this methodology, several aspects require further development. A major limitation of the proposed framework is the need for reliable hazard intensity maps, which are still unavailable in many mountain regions worldwide. In this context, this model can take advantage of recently proposed methods for automatically generating hazard indication/intensity maps.

Another critical aspect concerns the determination of the structural vulnerability class by means of fragility curves, or alternative simplified criteria, which is based on the expertise of structural engineers and technicians. As a result, the assessment may suffer from a lack of objectivity and consistency, especially when different experts are operating in the same territory. An additional limitation emerges in the case of linear infrastructures, where the inclusion of the network redundancy as a secondary parameter can lead to an oversimplified analysis when complex and critical systems are involved. In such cases, a tailored network-level analysis by field experts is recommended.

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