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A model for communication and management support of natural hazards risk

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ABSTRACT

Natural disasters are still quite frequent throughout Europe but rare at a given site. As a result, the stakeholders responsible for mitigating natural hazard risk often have false perceptions about the risks, which tend to slow the development of management plans and owner actions to increase natural hazard resilience. To address this issue, this paper introduces a model for communication and management support of natural hazards risk to stakeholders, who are often non-experts in the field. The model incorporates a seven-grade scale consistent with European labelling of product energy consumption. However, the proposed implementation also includes a systematic distinction between long-term and short-term risk tolerance, enabling the introduction of a time-dependent grade reduction in cases where the estimated risk is intolerable in the long term. This approach helps improve stakeholders' perception of natural hazards risk while incentivising actions that help reduce that risk. The gradual reduction of grades over time enables systematically introducing increasingly detrimental actions if the risk is long-term intolerable, thus strengthening the risk management process.

1. Introduction

Natural disasters still cause significant losses, even in economically developed countries. From 2000 to 2022, 50 earthquakes with magnitudes between 4 and 7 occurred in Europe, causing approximately 780 deaths, more than 40 billion USD in damage costs [1] and long recovery times. In the same period, Europe experienced 460 extreme floods, responsible for approximately 2130 deaths [1]. Although extreme natural events are frequent in broader areas such as Europe, they are rare at a given site. Consequently, personal experience of extreme events seldom exists, making it difficult for people to develop an unbiased perception of natural hazards risk [2]. Interestingly, experience with a hazard event does not necessarily increase the perceived risk, as the latter is greatly influenced by the event's consequences on the individual, i.e. if the consequences for an individual were significant, the perceived risk of similar future events will increase and vice versa [3]. Another factor influencing risk perception is the level of trust in local authorities and experts. A lack of trust can increase or reduce the perceived risk [3]. In either case, a bias in risk perception impacts the decision-making related to natural disasters, as risk perception plays a major role in motivating individuals to take action and can influence both the design and the operational aspects of disaster risk management [4]. Therefore, underestimation of risk can lead to insufficient measures for strengthening a community's resilience against natural disasters. One of the ways to address the problem of biased risk perception is to enhance the models for communicating natural hazards risk to the public, which can then be used to establish a more rational approach to risk management.

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Risk communication has a significant role in building a resilient community able to withstand and recover after disaster events. The main aim of risk communication is to create a shared understanding of risk among all involved stakeholders through coordination, collecting and disseminating information, planning for a crisis and crisis management [5]. A key role of communication is encouraging people to adopt protective measures before adverse events [6]. Communication affects all stages of disaster management [5], which is often viewed as a continuous cycle of separate phases of action that are performed before, during and after a disaster occurs [7,8,9]. For example, FEMA [7] defines the following four phases of disaster management: mitigation, preparedness, response and recovery. In the mitigation phase, actions are taken to prevent or reduce the cause, impact and consequences of disasters before they happen (e.g. reinforcing structures and insuring properties). Communication of risk during the mitigation phase takes place primarily between and within organisations to establish rules and plans to minimize risk and then share risk information with the public [5]. In the preparedness phase, response organisations perform planning and training activities for an adequate response in case of unmitigated events. The response phase takes place immediately after an event occurs and involves medical aid, search and rescue missions and, for example, the establishment of shelters for displaced people. The duration and effectiveness of the response depend on the level of preparedness. The recovery phase consists of restoration and recovery actions as well as decreasing vulnerability to new events. Lessons learned during natural hazard events may be applied in the next mitigation phase.

Models for communication and management support have already been developed in other areas. Examples include labels and certificates that alert consumers to the energy usage of a particular device or building, thus enabling consumers to select products based on concerns such as environmental protection, human health considerations, or user-friendliness [10]. The use of certificates and labels can be mandatory, and their design is usually predetermined. For example, energy labels for household appliances, tyre or lighting energy labels, and car labels are all obligatory for new products in Europe (Regulation (EU) 2017/1369; [11]. Energy performance certificates are also required in Europe for most buildings (Directive 2010/31/EU; [12]. Numerous versions of the European grading scale, comprising grades from A to G, are routinely used as the communication component in these certificates and labels.

Similar certificates have also been introduced in the field of natural hazards risk. In particular, seismic certificates and classifications for buildings have been implemented in Italy [13], New Zealand [14] and the US [15], and are currently in the process of implementation in Croatia [16], as a consequence of the damaging earthquakes in 2020. These certificates communicate risk using several risk categories, where the highest rating is associated with the risk level implicitly guaranteed by the current design codes (e.g. Eurocode 8 [17] in European countries). Their purpose is not to replace the design codes but rather to complement them by indicating the seismic performance of existing buildings. However, the certificates also have a management component. The risk level associated with the highest rating is tolerated indefinitely, meaning that there are no additional restrictions scheduled in the foreseeable future for this risk level. On the other hand, higher levels of risk are often associated with designated actions for risk reduction, which are either voluntary (e.g. in Italy [13]) or involuntary (e.g. in New Zealand [14] and California [15]). Involuntary actions require that the risk be reduced within a specific period if it is significantly higher than the level guaranteed by the current design codes. The risk classes and the prescribed period in which the actions should be implemented are often based on the arbitrary decisions of regulators.

In this paper, we propose a new model for communication and management support of natural hazards risk. The model is focused on disaster risk mitigation. Its use is foreseen before a potential disaster event occurs to reduce the impact and consequences of such an event. Since it is recommended to use simple forms, familiar or fairly explained terms and easy-to-understand diagrams to communicate risk to the public [18], the proposed model builds on existing certificates in the fields of energy efficiency and seismic risk. As in the case of some existing certificates, we anticipate the possibility of involuntary actions for disaster risk reduction but propose that the risk classes and the periods prescribed for risk reduction are defined in a more systematic manner. In this context, we define a risk tolerance model that systematically distinguishes between long-term and short-term risk tolerance. Long-term risk tolerance corresponds to the capacity of society to absorb losses over long periods of time. However, the concept of short-term risk tolerance assumes that the tolerable risk in the short term may be greater than the risk in the long term, where the short term is defined by a period of years [19]. Allowing a higher level of risk for a short period enables risk mitigation measures to be prescribed and carried out thoughtfully without disrupting the normal functioning of society, while still motivating the stakeholders not to delay the planning of such measures.

In the following section, some of the existing communication and management support models are reviewed in more detail. The first type of model refers to the energy labels and certificates for products and buildings, while the second type corresponds to the seismic performance of buildings. Section 3 describes the theoretical background of the proposed model for communication and management support of natural hazard risk, starting with the generalization of concepts of short-term and long-term risk tolerance as introduced by Babič and Dolšek [19]. Then, these generalized concepts of risk tolerance are used to develop a seven-grade risk communication and management support model consistent with the European grading scale for the energy efficiency of products and buildings. The model is demonstrated in Section 4 by applying it to two masonry buildings exposed to seismic risk. In Section 5, the applicability of the model at the level of a building portfolio is discussed. Conclusions are presented in Section 6.

2. Overview of existing models for communication and management support of Energy and seismic losses

2.1. Existing energy labels and certificates

The energy label is probably the best-known approach for communicating a product property to the general public and promoting manufacturer innovations to consumers. It is used to advertise the energy efficiency of household appliances (e.g. air conditioners, ovens, washing machines, refrigerators, televisions, and heaters), lighting, tyres and buildings. The suppliers must ensure that all products placed on the market are accompanied by a valid energy label, and dealers must place the labels so that they are clearly visible to consumers.

Energy labels were established by EU Directive 92/75/EEC [20] and have been mandatory in Europe for many years. The current form of labels was introduced by Directive 2010/30/EU [21] and later repealed by Regulation (EU) 2017/1369 [11], which sets a framework for energy labelling, while several regulations governing specific individual products are also in force. As of January 1, 2019, manufacturers, importers, and authorised representatives must also register all products that require energy labels in the European Product Database for Energy Labelling (EPREL) before being allowed to sell them in the EU. The current label has an extended number of efficiency classes and varies slightly depending on the product type. The label form is precisely prescribed. Fig. 1 shows four basic examples of energy labels: washing machines (Regulation (EU) No 1061/2010 [22]), as a representative of household appliances (Fig. 1a), lamps and luminaries (Regulation (EU) No 874/2012 [23]; Fig. 1b and c) and tyres (Regulation (EC) No 1222/2009 [24]; Fig. 1d). An easy-to-use label generator is available for each product on the European Commission webpage [25]. The energy label usually consists of a graphic and a numerical part (see Fig. 1). It contains the supplier's name or trade mark (I), the model identifier (II), a seven- or ten-step colour scale, with grades ranging from A, A+, A++, or A+++ (green, most efficient) at the high end to G (red, least efficient) on the low end, pictograms for specific features and characteristics (e.g. volume, water consumption, capacity in terms of volume or weight) and, in most cases, the weighted annual energy consumption in kWh. The differences between efficiency classes are not negligible. For example, Class A appliances use about 55% less energy than Class G appliances, whereas Class D devices use about 30% less energy than Class G appliances [10]. In 2021, a label reform was initiated with the goal of eliminating grades A+, A++, and A+++ and reverting the grading system back to the A to G scale, which is clearer to customers.

In Europe, a car label is mandatory and must include a car's fuel efficiency and CO_2 emissions (Directive 1999/94/EC [26]). Its design is not as meticulously prescribed as for energy labels. However, a poster or electronic screen must be displayed at the point of sale for easier product comparison. It must contain all models, listed separately according to fuel type (e.g. petrol or diesel), along with their corresponding fuel consumption and CO_2 emissions.

Energy performance certificates for buildings (Fig. 2) are the most common certificates to communicate the performance of the built environment. The EU Directive 2010/31/EU [12] specifies which information must be included in the certificate but does not prescribe an explicit format, which vary by country. In general, the energy performance of a building should be determined based on the energy that is expected to be consumed annually. In Slovenia, the Energy Performance Certificate has been mandatory since 2014, and the content and format of the certificate are prescribed in detail (Official Gazette of the RS, No. 92/2014 [27]). It is mandatory for buildings constructed, sold, or rented out to a new tenant, or where a total useful floor area over 250 m^2 is occupied by a public authority and frequently visited by the public. The Energy Performance Certificate is not mandatory for cultural heritage buildings, buildings used for ceremonial purposes or religious activities, industrial buildings and warehouses, non-residential farms, and simple non-heated buildings.

2.2. Existing seismic risk certificates and classifications

Seismic risk certificates and classifications, which enable systematic communication and management of seismic risk, have been implemented in several countries. In this section, three examples of good practices from Italy, New Zealand and the US are presented.

In Italy, the latest seismic risk classification and certificate of buildings were introduced following recent major earthquakes (including L'Aquila 2009 and the Central Italy earthquakes in 2016 and 2017) as part of the Sisma Bonus programme [30], which was introduced to promote owner investments in improving the seismic performance of existing buildings. In Italy, buildings are ranked in risk classes according to one of two possible approaches (Table 1). In the conventional approach, risk classification is derived from the expected annual economic losses (*EAL*) and the safety index of the structure at the life safety limit state (*SI-SL*) [13]. The safety index *SI-SL* reflects the percentage of the current design seismic load the structure can withstand. Alternatively, in the simplified approach,

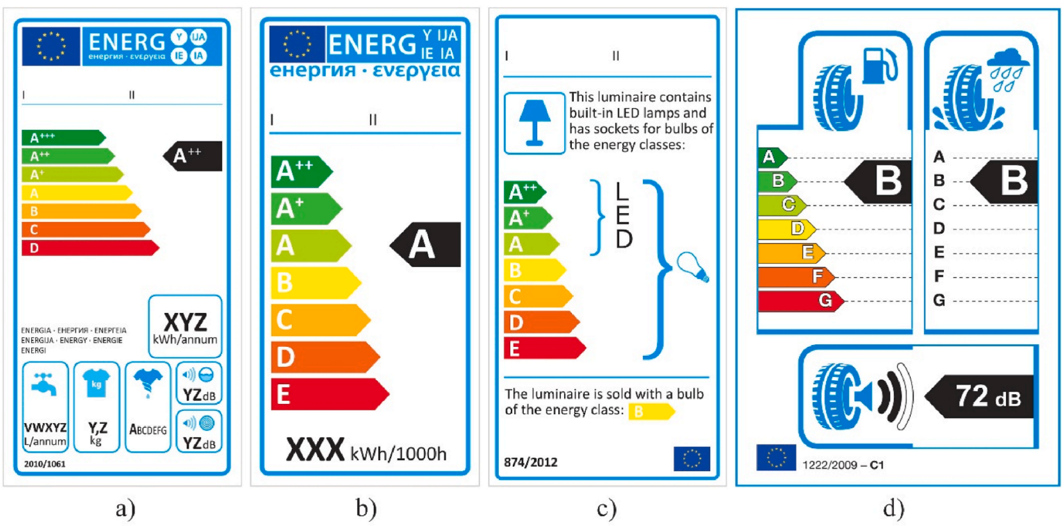
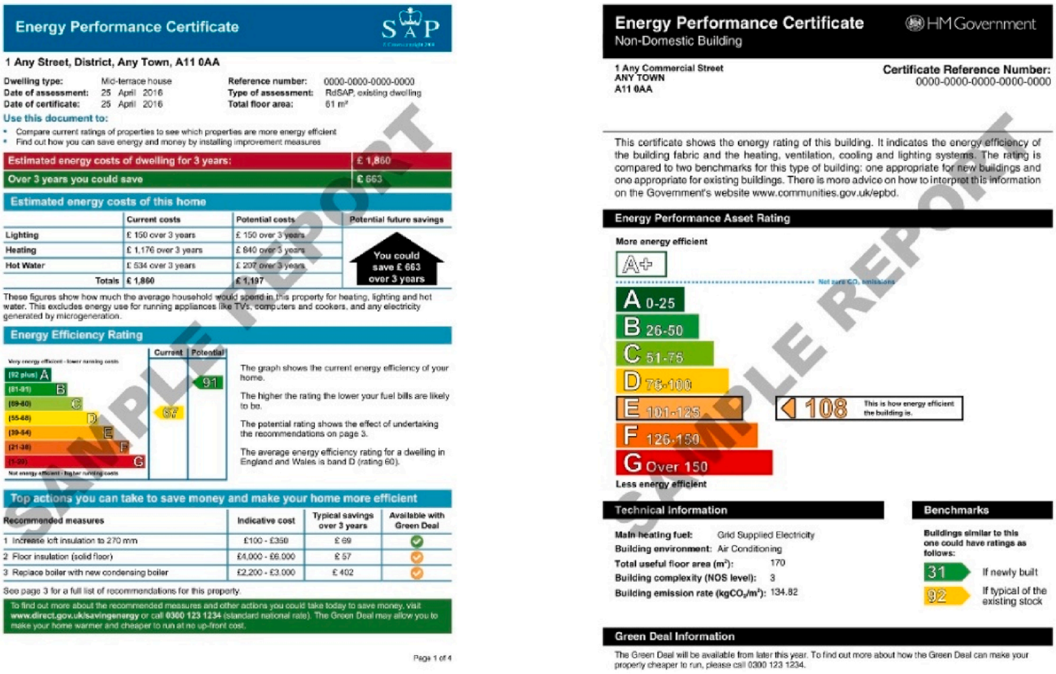


Fig. 1. Examples of energy label forms for a) washing machines, b) lamps (i.e. bulbs), c) luminaries and d) tyres [25].



a)   b)

Fig. 2. Examples of the first page of a) a domestic [28] and b) a commercial Energy Performance Certificate in the UK [29].

Table 1
Seismic risk class of a building defined by the expected annual losses (*EAL*) and the safety index (*SI-SL*) in Italy [13].

	Conventional approach		Simplified approach			
RISK CLASS	*EAL* (%)	*SI-SL* (%)	Zone 1	Zone 2	Zone 3	Zone 4
A+	*EAL* $\leq$ 0.5	100 $\leq$ *SI-LS*				V_1–V_2
A	0.5 $<$ *EAL* $\leq$ 1.0	80 $\leq$ *SI-LS* $<$ 100			V_1–V_2	V_3–V_4
B	1.0 $<$ *EAL* $\leq$ 1.5	60 $\leq$ *SI-LS* $<$ 80	V_1	V_1–V_2	V_3	V_5
C	1.5 $<$ *EAL* $\leq$ 2.5	45 $\leq$ *SI-LS* $<$ 60	V_2	V_3	V_4	V_6
D	2.5 $<$ *EAL* $\leq$ 3.5	30 $\leq$ *SI-LS* $<$ 45	V_3	V_4	V_5–V_6	
E	3.5 $<$ *EAL* $\leq$ 4.5	15 $\leq$ *SI-LS* $<$ 30	V_4	V_5		
F	4.5 $<$ *EAL* $\leq$ 7.5	*SI-SL* $\leq$ 15	V_5	V_6		
G	7.5 $<$ *EAL*		V_6			

vulnerability classes V_1 to V_6, which are assigned based on the type of masonry [31] and seismic hazard zones (1–4), are used to determine the building's risk class (see Table 1).

Recently, Calvi et al. [32] proposed an integrated assessment of energy efficiency and earthquake resilience, where the *EAL* and building resilience comply with the energy efficiency classification. Calvi et al. [32] showed that, although it is common practice to evaluate energy efficiency and seismic resilience independently, it is possible to directly compare these two terms. To this end, a proxy for building classification was proposed: the green and resilient indicator (*GRI*), which is defined with either EAL_E (energy expected annual losses) or EAL_S (expected annual losses due to seismic retrofitting) (see Table 2). The *EAL* is an interesting risk measure because it can be used to calculate the mutual investment return potential.

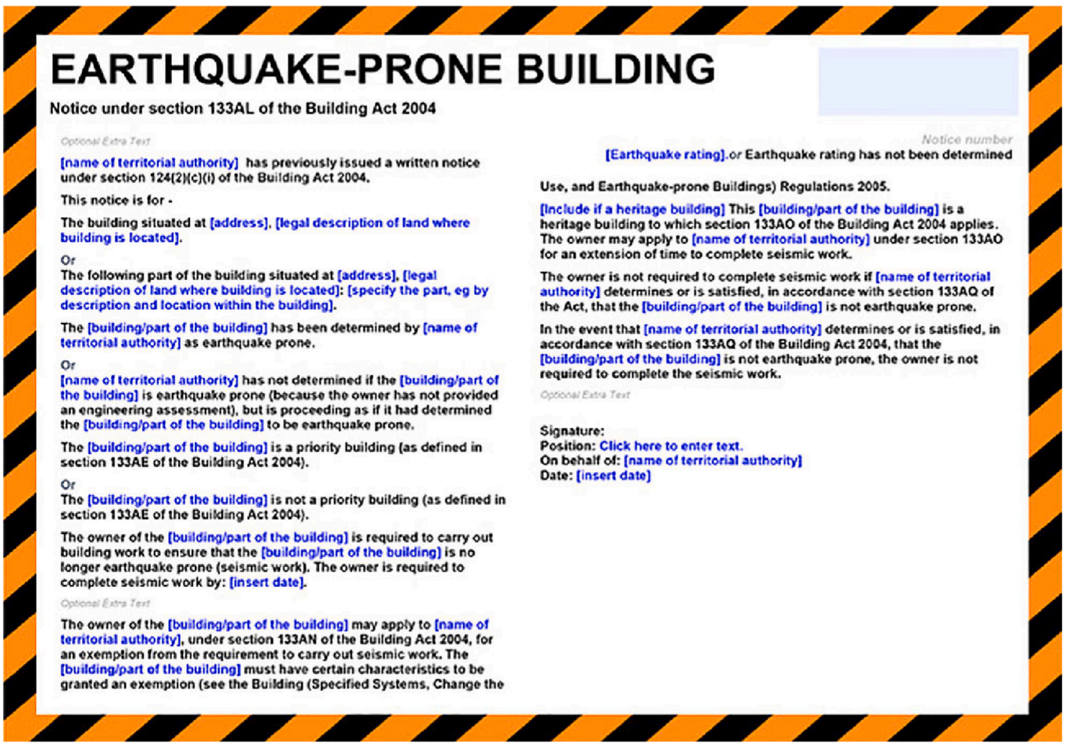
In New Zealand, the Society for Earthquake Engineering proposed guidelines for the mandatory seismic assessment of existing buildings [14] to identify vulnerabilities and property risk, as required by the Building Act 2004 [33]. Under section 133 AH of the Building Act, the territorial authority decides if a building is potentially earthquake-prone and must demand an engineering assessment of the building from the owner. This applies to non-residential and larger residential buildings, i.e. those with at least two storeys and three or more household units, or serving as a hostel, boarding house, or other accommodation. Farm buildings, retaining walls, fences, certain monuments, wharves, bridges, tunnels and storage tanks are excluded. The engineering assessment provides an earthquake rating for the building, which is expressed as the percentage of the new building standard (*%NBS*). The methods for determining *%NBS* are described in the guidelines for the seismic assessment of existing buildings [14], and it is defined as the ratio of the ultimate capacity of a building (or element) to the design ultimate limit state demands for a similar new building on the same site, expressed as a percentage. Therefore, it is comparable to the safety index *SI-SL* used in Italy (Table 1). As with energy performance cer-

Table 2
GRI classification based on the energy expected annual losses (EAL_E) and the expected annual losses due to seismic retrofitting (EAL_S) [32].

GRI	EAL_E or EAL_S (%)
A+	$EAL \leq 0.5$
A	$0.5 < EAL \leq 0.75$
B	$0.75 < EAL \leq 1.5$
C	$1.5 < EAL \leq 2.5$
D	$2.5 < EAL \leq 3.5$
E	$3.5 < EAL \leq 4.5$
F	$4.5 < EAL \leq 7.5$
G	$EAL > 7.5$

tificates of buildings, the engineer must receive special training in order to use the guidelines and adequately assess the seismic performance of a building. Two methods of assessment are provided, the Initial Seismic Assessment, which is used for a general indication of the seismic performance level of a building, and the Detailed Seismic Assessment, which is used for a more comprehensive seismic assessment. The Initial Seismic Assessment is sufficient if the engineer is confident that the result reflects the seismic behaviour of the building and the owner does not specifically request a Detailed Seismic Assessment. Otherwise, a Detailed Seismic Assessment is needed. A building, or its part, is considered earthquake-prone if the engineer estimates that it will exceed ultimate capacity under a moderate earthquake and if its collapse is likely to cause injury or death, or damage to any other property [34]. This translates to an earthquake rating of less than 34%*NBS*. If the building is identified as earthquake-prone, the territorial authority must issue an Earthquake-Prone Building (EPB) notice with a prescribed form (see Fig. 3, for example), which must be recorded in the EPB register.

The EPB notice must contain the earthquake rating, state whether the building is a priority building, and disclose the deadline to which the owner is required to carry out seismic work in order to ensure that the building or its part is no longer earthquake-prone. Seismic work is carried out in cooperation with experts. An overview of the key principles for reducing the seismic risk of buildings is given in the guidelines for the seismic assessment of existing buildings [14]. The usual time frame to carry out seismic work is 15 years in high-risk areas and 25 years in medium-risk areas, whereas for priority buildings (e.g. hospitals, and emergency and educational buildings located in high and medium seismic hazard areas), the seismic work should be completed within 6 months. If the building complies with specific conditions (e.g. has low current or expected use, its collapse is expected to cause limited harm and damage, or is not required in an emergency), the owner may apply for an exemption from the requirement to carry out seismic work, which is approved or rejected by the territorial authority. EPB notices have four different prescribed border colours to indicate which earthquake rating category the building is in. An orange and black striped border indicates that the rating in terms of %*NBS* is be-



EARTHQUAKE-PRONE BUILDING

Notice under section 133AL of the Building Act 2004

Optional Extra Text

[name of territorial authority] has previously issued a written notice under section 124(2)(c)(i) of the Building Act 2004.

This notice is for -

The building situated at [address], [legal description of land where building is located].

Or

The following part of the building situated at [address], [legal description of land where building is located]: [specify the part, eg by description and location within the building].

The [building/part of the building] has been determined by [name of territorial authority] as earthquake prone.

Or

[name of territorial authority] has not determined if the [building/part of the building] is earthquake prone (because the owner has not provided an engineering assessment), but is proceeding as if it had determined the [building/part of the building] to be earthquake prone.

The [building/part of the building] is a priority building (as defined in section 133AE of the Building Act 2004).

Or

The [building/part of the building] is not a priority building (as defined in section 133AE of the Building Act 2004).

The owner of the [building/part of the building] is required to carry out building work to ensure that the [building/part of the building] is no longer earthquake prone (seismic work). The owner is required to complete seismic work by: [insert date].

Optional Extra Text

The owner of the [building/part of the building] may apply to [name of territorial authority], under section 133AN of the Building Act 2004, for an exemption from the requirement to carry out seismic work. The [building/part of the building] must have certain characteristics to be granted an exemption (see the Building (Specified Systems, Change the

Notice number

[Earthquake rating] or Earthquake rating has not been determined

Use, and Earthquake-prone Buildings) Regulations 2005.

[Include if a heritage building] This [building/part of the building] is a heritage building to which section 133AO of the Building Act 2004 applies. The owner may apply to [name of territorial authority] under section 133AO for an extension of time to complete seismic work.

The owner is not required to complete seismic work if [name of territorial authority] determines or is satisfied, in accordance with section 133AQ of the Act, that the [building/part of the building] is not earthquake prone.

In the event that [name of territorial authority] determines or is satisfied, in accordance with section 133AQ of the Building Act 2004, that the [building/part of the building] is not earthquake prone, the owner is not required to complete the seismic work.

Optional Extra Text

Signature:
Position: Click here to enter text.
On behalf of: [name of territorial authority]
Date: [insert date]

Fig. 3. Sample of the New Zealand EPB notice [34].

tween 0% and 20% or the earthquake rating has not been determined (see Fig. 3), a white and black striped border corresponds to a rating of 20–34%, an orange border indicates the notice was issued before July 1, 2017 (when the new system was adopted), and a white and orange striped border indicates buildings exempted from seismic work. If the building owner does not display the EPB notice or does not undertake seismic work within the time frame provided, the territorial authority can issue a 1000 USDinfringement fee (New Zealand Government, 2017). Building owners who fail to comply with a warning to display the EPB notice or carry out seismic work can be brought to court. If convicted for failing to display an EPB notice or complete seismic work within the time frame, they can be fined up to 20,000 or 200,000 USD, respectively.

In the US, specifically in California, several grading systems for evaluating the seismic safety of buildings were developed in response to the damage caused by major earthquakes in the area (e.g. Loma Prieta 1989, Northridge 1994). The grading systems can be compulsory [15] or voluntary [35,36]. As early as 1994, the Senate Bill 1953 for California hospitals was introduced [15] with the aim of ensuring the operability of hospitals even after earthquakes, and it remains mandatory for all California general acute care hospitals. A seismic performance evaluation is conducted for buildings and building components to obtain both the building's structural performance category (SPC) and its non-structural performance category (NPC). The SPC rating ranges from 1 to 5, where rating SPC-1 indicates a building likely to collapse during a strong earthquake and SPC-5 indicates a building very likely to remain operational after a strong earthquake. Seismic Retrofit Regulations were developed to upgrade the seismic performance category of existing hospital buildings, and all general acute care hospital facilities were required to obtain at least the SPC-2 rating before January 1, 2013. Additionally, state law requires all SPC-1 and SPC-2 buildings be removed from providing general acute care services by 2020 and 2030, respectively.

The Structural Engineers Association of Northern California (SEAONC) developed a qualitative five-star rating system for each of the three separate rating components: safety, repair cost, and time to regain function (see Table 3) [35]. The rating system is voluntary and is intended to communicate the expected seismic performance of a building to a non-technical audience. The form of the rating presentation and its contents are also suggested by the association [37]. No specific seismic assessment methodology is proposed for use in conjunction with the rating system. Engineers should therefore use contemporary assessment methodologies and translate evaluation results into ratings. The SEAONC association has derived ratings from ASCE-31 [38] evaluations [35]. An alternative rating system was proposed by the US Resiliency Council (USRC), a non-profit organisation promoting the rating of building performance in natural disasters [36]. However, the USRC rating system is based on the SEAONC rating system. The rating is voluntary and is assigned by certified professionals and technically reviewed based on national standards, but it is not a precise estimate of building safety. It is intended for promotional, marketing and publicity purposes, or, for example, as a basis for increasing leasing rates, or define insurance products, etc. Four different types of badges can be assigned to a building depending on its performance: USCR platinum, gold or silver rating or USCR certified rating. As defined by the SEAONC association, each rating consists of a star rating for three rating components: safety, damage expressed with repair cost, and recovery time. The platinum and gold ratings are assigned for the highest level of performance exceeding modern code standards in terms of safety. The silver rating is intended for buildings that are expected to suffer significant damage after a major event (i.e. less than 20% of replacement cost), while the USRC certified rating is for buildings that comply with modern codes for performance, preserve life safety, and limit damage to less than 40% of replacement cost following a major event.

Table 3
Overview of the SEAONC rating levels [35].

Safety	
★★★★★	No entrapment
★★★★	No injuries
★★★	No death
★★	Death in isolated locations
★	Death in multiple or widespread locations
NR	No rating
Repair Cost	
★★★★★	Within operating budget (less than 5% of replacement value)
★★★★	Within insurance deductible (less than 10% of replacement value)
★★★	Within industry SEL limit (less than 20% of replacement value)
★★	Repairable damage (less than 40% of replacement value)
★	Irreparable damage (more than 40% of replacement value)
NR	No rating
Recovery	
★★★★★	Within hours
★★★★	Within days
★★★	Within weeks
★★	Within months
★	Within years
NR	No rating

2.3. Discussion on similarities and differences between certificates in the fields of energy efficiency and seismic risk

Energy efficiency and seismic risk certificates both assign a rating based on the performance of a product or a building. However, certificates use different measures to quantify that performance. The energy efficiency certificates quantify the performance of products and buildings by adverse consequences, such as CO_2 emissions and energy consumption in kWh. These consequences typically refer to a given period, which means they are expressed as, for example, the average consequences in one year. Therefore, they are directly aimed at reducing adverse consequences expected in a given period (and thus in the long term). On the other hand, the measures used to quantify the seismic performance conceptually differ from one seismic certificate to another. Some seismic certificates directly focus only on the seismic design level (e.g. EPB notice in New Zealand) or the consequences of one earthquake (e.g. SEAONC certificate in the US). However, as shown by the Italian example, it is viable to consider the consequences (i.e. economic losses) of all possible earthquakes at a building's location and average those consequences over a very long period. In this way, the seismic performance is quantified by the average consequences in a given period, analogously to the energy performance of products and buildings. It is worth noting that such characterisation of seismic performance is often used in seismic risk assessments (e.g. Refs. [39,40,41]) but not necessarily included in certificates or similar communication models.

Information on the average adverse consequences in a given period can stimulate the decision-making behaviour of stakeholders regardless of the type of certificate. Both the decision to buy a product based on the energy efficiency certificate and the decision to strengthen a building to mitigate seismic risk, as suggested by the seismic risk certificate, can be made with the goal of reducing the expected adverse consequences in the long term. This was also recognized by Calvi et al. [32], who proposed a common classification of buildings based on the expected annual economic losses due to energy consumption and earthquake-induced damage (Table 2).

However, there is an important distinction between the losses resulting from energy consumption and earthquakes. Losses from energy consumption occur every year and do not vary notably on a year-to-year basis. On the contrary, losses resulting from earthquakes vary significantly, as they are caused by events with very long return periods. Therefore, even if the long-term consequences are the same, the short-term consequences can differ, which can affect the risk perception and, consequently, the willingness to take action. This does not apply only to earthquakes but to extreme natural events in general. The following section presents an approach to address this characteristic of extreme natural events within a new risk communication and management support model.

3. A risk communication and management support model considering long-term and short-term risk tolerance

In this section, we develop a new model for communication and management support of natural hazards risk, aimed at enhancing the mitigation stage of the risk management cycle. The model builds on existing certificates in the fields of energy efficiency and seismic risk (Section 2). In particular, it integrates the European grading scale for energy efficiency of products and buildings, which is well-known to the general public. Moreover, it employs a grading framework that is based on average adverse consequences in a given period, consistently with the energy efficiency certificates and the seismic certificate introduced in Italy. Thus, the model assumes that the average adverse consequences in a given period are obtainable by the risk estimation methodology established in the field of the considered natural hazard. The adverse consequences of natural hazards in the proposed model are generally quantified by expected losses, which may represent, for example, economic losses, losses of human lives or losses of useable buildings. It is assumed that the grade determined based on such expected losses can affect the decision-making process regarding risk mitigation, similarly as in the case of purchasing energy-efficient products.

However, the novelty of the introduced model is that it recognizes that the year-to-year variation of losses resulting from natural hazards is much larger than that resulting from energy consumption. In particular, the model considers that adverse consequences of extreme events with very long return periods are not likely in the short term but that their long-term consequences are inevitable. This characteristic of extreme natural events is considered by distinguishing between long-term and short-term risk tolerance, which allows for an introduction of a grade reduction process. The grade reduction process strengthens risk perception and risk management, as it makes it possible to gradually introduce risk mitigation actions towards owners of buildings exposed to intolerable risk.

In the following, the concepts of long-term and short-term risk tolerance are first presented (Section 3.1). This is followed by the description of a general grading framework that considers both types of risk tolerance (Section 3.2). Such a grading framework sets the basis for developing a risk communication and management support model synchronized with the European grading scale (Section 3.3).

3.1. Long-term and short-term risk tolerance model

Risk tolerance refers to the willingness of an organisation or a community to take on risk [42]. Analogously, tolerable risk refers to the maximum risk that an organisation or a community is willing to take. If the risk is defined by the average losses caused by adverse natural events in a designated period [43], risk tolerance refers to the maximum losses that are, on average, tolerated within a designated period. This concept of risk tolerance is also the basis for one of the risk measures (i.e. *EAL*) used in seismic risk classification in Italy [13].

In this paper, we use a risk tolerance model that distinguishes between long-term and short-term risk tolerance. The concept of long-term risk tolerance is equivalent to the conventional concept of risk tolerance implemented in existing seismic risk certificates and classifications. It reflects the capacity of society to absorb the losses in the long run. Therefore, risk that is characterized as long-term tolerable is considered to be tolerated indefinitely. However, short-term risk tolerance corresponds to a specific, finite period during which the tolerable risk may be greater than in the long term [19]. By allowing a higher level of risk in a shorter timeframe, it considers not only the society's capability to absorb losses but also the period of time needed to design and implement risk mitigation measures, while accounting for the limited resources available for this mitigation. However, because it refers only to a specific time period, it does not change the long-term objective for reducing the risk to a tolerable level.

To construct the risk tolerance model, long-term tolerable and long-term intolerable risk levels are first separated by the long-term risk boundary R_{lt}, where R stands for risk, and *lt* stands for the long-term boundary. R_{lt} represents the value of the designated risk measure that is tolerated indefinitely. For example, it could refer to average losses per unit time that are tolerated indefinitely. In such cases, the period used in the definition of R_{lt} is equal to 1 year, as is usually the case in engineering applications, and thus R_{lt} represents average *annual* losses tolerated indefinitely. It should be emphasized that because long-term risk tolerance is considered time-independent, it is fully defined by R_{lt}. Therefore, to evaluate whether the risk is long-term tolerable, R_{lt} must be compared to the estimated value of the designated risk measure, R_{est}, which represents the building's performance.

The evaluation of short-term risk tolerance is more complex than for long-term risk tolerance. Short-term risk tolerance is defined for a specific time period. Thus, it makes sense to formulate such an evaluation in the time–cumulative risk (t–$\hat{R}$) domain (Fig. 4). This approach requires that both the estimated risk and the risk boundaries are defined in the t–$\hat{R}$ domain. In the simplest definition, the estimated cumulative risk, $\hat{R}_{est}(t)$, is the product of R_{est} and the period (in years), t:

$$\hat{R}_{est}(t) = R_{est} \cdot t \tag{1}$$

Eq. (1) assumes that the estimated risk is constant over time. This assumption is also considered in the following derivations. In general, however, the estimated risk may vary over time due to changes in the hazard, vulnerability or exposure, or due to new knowledge that does not affect the true risk but affects its estimate. Although the consideration of time-varying risk exceeds the scope of this paper, the concepts introduced herein are not limited to cases of constant risk over time and can be extended to more general cases in future studies. This could be done by replacing the straight line in the t–$\hat{R}$ domain (Fig. 4) representing constant estimated risk with a curved line, where the variation in slope would indicate the variation in the estimated risk.

Because the short-term tolerable risk is higher than the long-term tolerable risk, it makes sense to decompose the cumulative risk defined in Eq. (1) as follows:

$$\hat{R}_{est}(t) = \hat{R}_{lt}(t) + \Delta\hat{R}_{est}(t) \tag{2}$$

$$\hat{R}_{lt}(t) = R_{lt} \cdot t \tag{3}$$

$$\Delta\hat{R}_{est}(t) = \left(R_{est} - R_{lt}\right) \cdot t \tag{4}$$

where $\hat{R}_{lt}(t)$ is the time-dependent long-term tolerable cumulative risk boundary and $\Delta\hat{R}_{est}(t)$ is the cumulative risk increment above the $\hat{R}_{lt}(t)$. For better understanding, see Fig. 4, where $\Delta\hat{R}_{est}(t)$ is shown for a given time instance and $\hat{R}_{est}(t)$ line. Ideally, $\Delta\hat{R}_{est}(t)$ is less than 0, which means that the risk is long-term tolerable. However, in general, $\Delta\hat{R}_{est}(t)$ can exceed 0. In such cases, it is suggested that the risk is limited by the exposure time, as is the practice in some countries (e.g. in New Zealand or the US in the case of seismic risk; see Section 2.2). We suggest that the limitation on the exposure time be calculated by bounding $\Delta\hat{R}_{est}(t)$ to $\Delta\hat{R}_{st}$, which represents the short-term tolerated increment of cumulative risk above $\hat{R}_{lt}(t)$. $\Delta\hat{R}_{st}$ can be understood as an extra amount of cumulative risk (a constant) that is allowed in addition to the long-term tolerable amount (which increases with time). By defining $\Delta\hat{R}_{st}$ as a constant, each building is allowed to exceed the long-term tolerable cumulative risk by the same amount.

Based on this definition, the short-term tolerable cumulative risk boundary, $\hat{R}_{st}(t)$, can be formulated based on Eqs. (2) and (3) by replacing $\Delta\hat{R}_{est}(t)$ with $\Delta\hat{R}_{st}$:

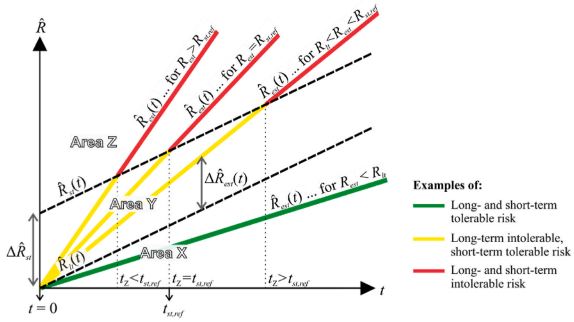


Fig. 4. Illustration of different levels of risk according to the long-term and short-term risk tolerance model in the time–cumulative risk (t–$\hat{R}$) domain, considering that the risk evaluation is performed at $t = 0$.

$$\hat{R}_{st}(t) = R_{lt} \cdot t + \Delta\hat{R}_{st} \tag{5}$$

The boundary $\hat{R}_{st}(t)$ is therefore defined by R_{lt} and $\Delta\hat{R}_{st}$. The latter can be defined directly by the regulator (i.e. the government authority responsible for planning risk mitigation actions), but it is suggested that it be decomposed into the risk and period by analogy to $\Delta\hat{R}_{est}(t)$ as defined in Eq. (4):

$$\Delta\hat{R}_{st} = \left(R_{st,ref} - R_{lt}\right) \cdot t_{st,ref} \tag{6}$$

where $R_{st,ref}$ is the reference value of short-term tolerable risk and $t_{st,ref}$ is the reference value of the allowed time period over which the risk may be equal to $R_{st,ref}$. Parameters $R_{st,ref}$ and $t_{st,ref}$ can be defined by the regulator based on relevant criteria (e.g. resource availability, or the time needed to design and implement risk mitigation measures), while $R_{st,ref}$ can be defined as a proportion of R_{lt}.

By introducing the short-term and long-term cumulative risk boundaries ($\hat{R}_{st}(t)$ and $\hat{R}_{lt}(t)$), the t–$\hat{R}$ domain is divided into three areas (Fig. 4): the area of long- and short-term tolerable risk (Area X), the area of long-term intolerable but short-term tolerable risk (Area Y), and the area of long- and short-term intolerable risk (Area Z). It can be observed that, at each point in time, $\hat{R}_{est}(t)$ is in one of areas X, Y and Z. It can also be observed that when R_{est} is lower than R_{lt}, $\hat{R}_{est}(t)$ starts and remains in area X indefinitely. However, when R_{est} is greater than R_{lt}, $\hat{R}_{est}(t)$ is at first in area Y and then crosses to area Z. This is because area Y represents a risk that is tolerable for a given time period but not over the long term; eventually, if not reduced, the risk becomes intolerable even in the short term, which is indicated by the crossing into area Z. However, if R_{est} is equal to $R_{st,ref}$, area Z is reached in the period of $t_{st,ref}$. Two other cases are also possible: if R_{est} is higher or lower than $R_{st,ref}$, the period of reaching area Z, t_Z, is shorter or longer than $t_{st,ref}$, respectively. The formula for calculating t_Z can be derived by replacing $R_{st,ref}$ and $t_{st,ref}$ in Eq. (6) with R_{est} and t_Z, respectively:

$$t_Z = \frac{\Delta\hat{R}_{st}}{R_{est} - R_{lt}} \tag{7}$$

In the borderline case where R_{est} is only negligibly larger than R_{lt}, t_Z is practically infinite. This is a favourable feature of the proposed risk tolerance model because it ensures a smooth transition from area X to area Y.

The areas X, Y and Z in the t–$\hat{R}$ domain can be assigned classes or grades for communication of risk to the stakeholders, i.e. the owners and other building users, as well as the regulator requiring the risk evaluation. Thus, the risk tolerance model inherently includes three risk classes or grades corresponding to areas X, Y and Z, which can then be further divided into additional grades, as discussed in the following section.

3.2. A grading framework incorporating long-term and short-term risk tolerance

Existing risk classifications (see Section 2.2) include more than three risk classes or grades introduced directly by the proposed short-term and long-term risk tolerance model (Section 3.1). The grading framework is thus introduced to integrate the proposed risk tolerance model with the existing risk classifications by further dividing grades X and Y (Fig. 4). However, grade Z is not sub-divided because it corresponds to average annual losses that are unbearable to society. Thus, it is assumed that the owners of buildings exposed to short-term intolerable risk (grade Z) face the same consequences regardless of how much the tolerable risk is exceeded. Additional grades (i.e. sub-grades) are defined by introducing new risk boundaries. The following demonstrates how grades X and Y can be divided into two sub-grades each. Additional subdivisions can then be performed using the same principles, as also shown in Section 3.3.

For subdividing grade X into two grades (denoted as X1 and X2), an additional cumulative risk boundary, $\hat{R}_{X1-X2}(t)$, is defined as:

$$\hat{R}_{X1-X2}(t) = R_{X1-X2} \cdot t \tag{8}$$

where $R_{X1\text{-}X2}$ is the (annual) risk boundary separating grades X1 and X2 (Fig. 5). The resulting subdivisions provide a way to distinguish between different levels of long-term tolerable risk. For example, an owner could decide to reduce risk even below the threshold that is tolerated indefinitely (R_{lt}). Such a decision of the owner could be officially recognized and rewarded with an improved grade if the regulator has defined a boundary $R_{X1\text{-}X2}$. From Fig. 5, it is obvious that grade X1 is assigned if R_{est} is lower than $R_{X1\text{-}X2}$. By analogy, X2 is assigned if R_{est} is higher than $R_{X1\text{-}X2}$ and lower than R_{lt}. Moreover, it is evident that grades X1 and X2 do not change over time since both $\hat{R}_{X1-X2}(t)$ and $\hat{R}_{est}(t)$ are linear in time. Therefore, if either of these sub-grades are assigned, they remain so indefinitely barring structural improvements or other external changes.

Subdividing grade Y into two grades (denoted as Y1 and Y2) is less trivial because grade Y is time-dependent and corresponds to short-term tolerable risk. Various models can be used to define grades Y1 and Y2. One option would be to subdivide region Y with an additional cumulative risk boundary that is parallel to $\hat{R}_{st}(t)$ and $\hat{R}_{lt}(t)$ and lies between them (see Fig. 4). Such a definition of the cumulative risk boundary would be simple, but it would not control the maximum tolerable period of grade Y2, i.e. the maximum possible period in which $\hat{R}_{est}(t)$ crosses into area Z if grade Y2 is assigned. Not controlling the maximum tolerable period of grade Y2 is a shortcoming that affects the management component of the proposed risk tolerance model. However, another disadvantage of defining an additional cumulative risk boundary parallel to $\hat{R}_{st}(t)$ and $\hat{R}_{lt}(t)$ is that all buildings with R_{est} greater than R_{lt} would initially get

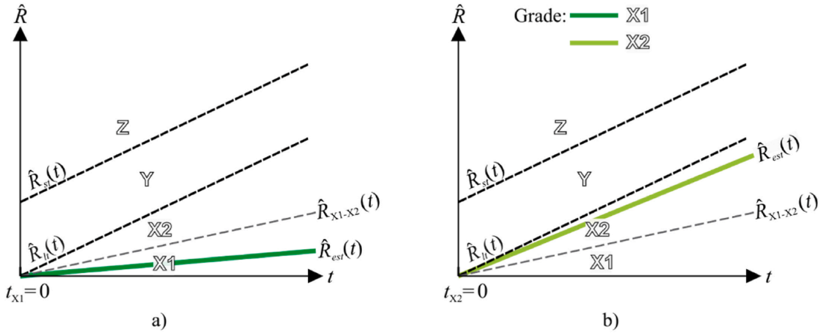


Fig. 5. Introduction of grades X1 and X2 by defining the cumulative risk boundary $\hat{R}_{X1-X2}(t)$ and an illustration of assignment of a) grade X1 and b) grade X2.

grade Y1. This would reduce the importance of the communication component of the model since the initially assigned grade would be only roughly related to the level of risk.

To address these issues, a different approach for subdividing grade Y into grades Y1 and Y2 is proposed based on the definition of the maximum tolerable time period of grade Y2, $\Delta t_{st,Y2}$, which can be defined by the regulator as an independent input parameter of the model. According to this definition, the time at which grade Y2 is assigned, t_{Y2}, can be calculated as follows (Fig. 6):

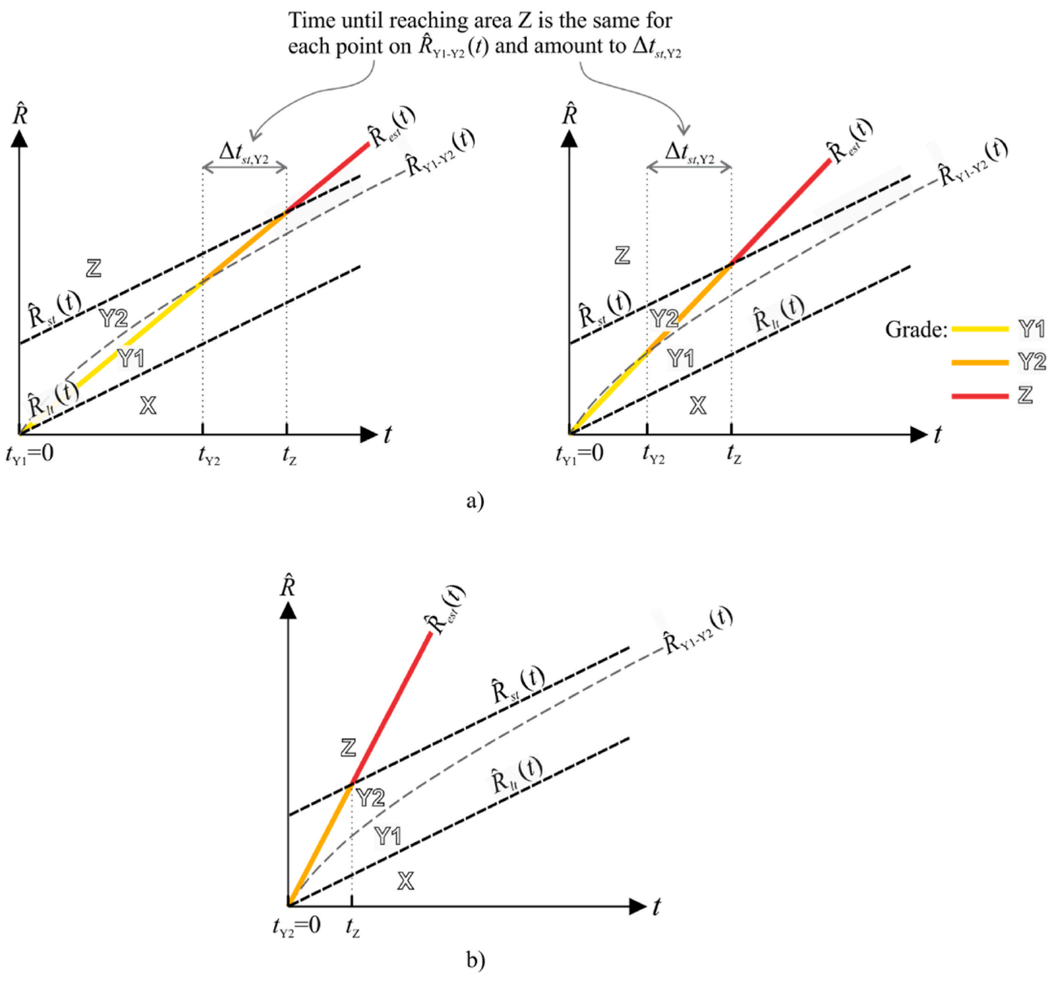


Fig. 6. Introduction of grades Y1 and Y2 by defining the cumulative risk boundary $\hat{R}_{Y1-Y2}(t)$ and an illustration of grade assignment for a) two cases with initial grade Y1 and b) one case with initial grade Y2.

$$t_{Y2} = \max\left(t_Z - \Delta t_{st,Y2}, 0\right) \tag{9}$$

In Eq. (9), t_{Y2} cannot be negative. If $t_Z - \Delta t_{st,Y2}$ is negative, then grade Y1 is initially assigned (Fig. 6a). Otherwise, grade Y2 is assigned (Fig. 6b). This makes the subdivision between grade Y1 and Y2 straightforward. However, to investigate grades Y1 and Y2 as a function of time, the cumulative risk boundary $\widehat{R}_{Y1-Y2}(t)$ for the entire time domain should be derived.

The derivation of $\widehat{R}_{Y1-Y2}(t)$ can be made in two steps. In the first step, the definition of $\widehat{R}_{est}(t)$ as given by Eq. (2) can be reformulated for cases where risk is short-term tolerable. In those cases, $\Delta\widehat{R}_{est}(t)$ can be calculated according to Eq. (4) by replacing $R_{est} - R_{lt}$ with $\Delta\widehat{R}_{st}/t_Z$, according to Eq. (7). Thus, Eq. (2) can be transformed into the following form:

$$\widehat{R}_{est}(t) = \widehat{R}_{lt}(t) + \frac{\Delta\widehat{R}_{st}}{t_Z}\cdot t \tag{10}$$

By then considering that $\widehat{R}_{est}(t)$ is equal to $\widehat{R}_{Y1-Y2}(t)$ when $t = t_Z - \Delta t_{st,Y2}$ (Fig. 6a), $\widehat{R}_{est}(t)$ and t_Z in Eq. (10) can be replaced with $\widehat{R}_{Y1-Y2}(t)$ and $\Delta t_{st,Y2} + t$, respectively:

$$\widehat{R}_{Y1-Y2}(t) = \widehat{R}_{lt}(t) + \frac{\Delta\widehat{R}_{st}\cdot t}{\Delta t_{st,Y2} + t} \tag{11}$$

From Eq. (11), it is evident that $\Delta t_{st,Y2}$ controls the cumulative risk boundary $\widehat{R}_{Y1-Y2}(t)$. If it is close to 0, then $\widehat{R}_{Y1-Y2}(t)$ tends towards $\widehat{R}_{st}(t)$ (Eq. (5)). However, if $\Delta t_{st,Y2}$ is very long, then $\widehat{R}_{Y1-Y2}(t)$ tends towards $\widehat{R}_{lt}(t)$.

By determining the assignment times of grades Y1 and Y2 (t_{Y1} and t_{Y2}, respectively) and by considering t_Z as defined in Eq. (7), the grade reduction process is defined (see also Fig. 6). The initial grade communicates the level of risk and thus strengthens the communication component of the proposed risk tolerance model. However, the gradual reduction of grades over time enables implementation of increasingly detrimental actions, thus strengthening the management component of the risk tolerance model.

The grade reduction process can be made more gradual by defining a greater number of sub-grades in area Y, as discussed in the following section, which attempts to integrate the risk tolerance model with the European grading scale (Section 2.1).

3.3. Application to a seven-grade risk communication and management support model

In this section, the grading framework for natural hazards risk introduced above is applied to a seven-grade risk communication and management support model, which is consistent with the European grading scale of the energy efficiency of products and buildings (grades from A to G; Section 2.1). However, each grade is also defined descriptively with a level of long-term and short-term risk tolerance, as well as the type of actions proposed for each grade (Fig. 7). Both long- and short-term risks can be considered tolerable or intolerable. In the case of long-term tolerable risk, two sub-levels of risk are defined: negligible and acceptable. An acceptable level of risk is also considered tolerable, but a tolerable level of risk is not necessarily acceptable, although different definitions are available in the literature, as discussed by Manuele [44]. In the case of short-term tolerable risk, an additional sub-level of risk known as justifiable risk is defined, and is associated with detrimental actions, as explained in the following.

Risk tolerance

Grade	Risk level accord. to the long-term risk tolerance	Risk level accord. to the short-term risk tolerance	Type of actions
A	TOLERABLE (negligible)	TOLERABLE (negligible)	BENEFICIAL
B	TOLERABLE (acceptable)	TOLERABLE (acceptable)	BENEFICIAL (transitioning towards neutral)
C			NEUTRAL
D			
E	INTOLERABLE	TOLERABLE (justifiable)	DETRIMENTAL (non-restrictive)
F			
G		INTOLERABLE	DETRIMENTAL (restrictive)

Fig. 7. The relationship between the grades, levels of long-term and short-term risk tolerance, and the type of actions envisioned for the seven-grade risk communication and management support model.

Grades A and B (Fig. 7) correspond to the long-term tolerable risk. It is envisioned that grade A would be assigned to buildings designed with a higher level of earthquake resistance than is required by modern codes. Consequently, the risk corresponding to grade A is considered practically negligible, and some form of owner benefits would be expected (e.g. tax deduction). Meanwhile, grade B is associated with a level of risk that is not negligible but still acceptable in the long term. It is envisioned that grade B would be given to buildings that have been designed to meet current building codes. However, grade B may also be assigned in cases where the building's structure fails to meet the requirements of today's codes, but the risk is nonetheless acceptable in the long term due to low seismic hazard or other design factors controlling the design of the structure. Grades A and B are consistent with grades X1 and X2, respectively, defined in the previous section.

It is proposed that the nature of the actions following a grade B assignment vary according to the risk. In cases where the risk is close to the grade A level, the actions should benefit the owner. However, it is envisioned that the benefits be gradually omitted in a smooth transition to neutral actions as the risk goes from grade B to the next grade, C. In this way, owners can be incentivized to design or upgrade their buildings according to an above-standard level, while at the same time, the standard level of safety is not associated with detrimental actions.

Grades from C to G are long-term intolerable. However, grades from C to F indicate that the risk is still tolerable in the short term (Fig. 7). The time in which the risk will become intolerable even in the short term differs for each grade. Thus, grades C, D, E and F are subdivided by three short-term cumulative risk boundaries ($\widehat{R}_{\text{C−D}}(t)$, $\widehat{R}_{\text{D−E}}(t)$, $\widehat{R}_{\text{E−F}}(t)$) that are defined by analogy to grades Y1 and Y2 (Eq. (11); see Section 3.2).

In the case of grade C, and if the risk is close to the long-term tolerable level (see also Section 3.2), the time in which the risk will become intolerable in the short term can be very long. Grade C therefore represents short-term acceptable risk and can be followed by neutral actions such that, for a given period, the owner does not need to take risk reduction actions.

However, grades D, E and F indicate higher risks that no longer border the long-term tolerable level. These grades are considered to represent short-term justifiable risk (Fig. 7). These risk levels are expected to be associated with detrimental actions that become more severe with each grade, but are still non-restrictive (an example of a non-restrictive detrimental action is a tax increase).

On the other hand, grade G indicates a level of risk that is not tolerable even in the short term (Fig. 7). Therefore, this grade is expected to be followed by restrictive detrimental actions (e.g. limited use of the building, ban of renting or selling the building).

There are some notable consequences of the above-described actions associated with grades C–G. Firstly, by imposing such actions, the owners of buildings close to the long-term tolerable risk level (grade C) would be given some time to upgrade the building before being faced with detrimental actions. The period given in such cases would depend on the level of risk, as explained in Section 3.2. Secondly, if an owner of a building with grade C failed to reduce the risk in due time, the grade would be reduced to a lower grade, thus triggering detrimental actions. Thirdly, for buildings with grade C and risk just above R_{lt}, the introduction of detrimental actions would be so far in the future as to be practically unattainable. Such buildings would thus be treated equally as the buildings with the risk just below R_{lt} (grade B), which is considered a desired consequence since both building types would be exposed to practically equal risk. This is an advantage of the proposed risk communication and management support model, since it is especially important not to significantly differentiate between buildings with risk just above and just below R_{lt} because the estimation of natural hazards risk is associated with many uncertainties. While two different analysts will inevitably estimate risk differently, the small differences in the estimation of risk arising from the inherent uncertainties should not drastically impact the grading implications. Of course, there may also be more significant differences between risk estimates provided by different analysts. In such situations, which can occur due to biased risk estimations, the uncertainties regarding grading implications would be higher. Dealing with uncertainties resulting from different risk estimations requires a systematic approach, such as the multiple-expert interaction and integration (MEI^3) protocol [43,45], a description of which exceeds the scope of this paper. Fourthly, the owners of buildings with grades from D to F would be immediately faced with detrimental actions, incentivising them not to postpone the building's upgrade. Fifthly, restrictive actions (grade G) could not be implemented straight after the risk evaluation regardless of the level of risk, thus reducing the societal disruptions that can occur if restrictions are imposed immediately. However, in cases where the risk would be extremely high, the owners would need to upgrade the building in the shortest time possible in order to avoid restrictive actions.

The proposed risk communication and management support model is defined by six cumulative risk boundaries which separate grades A–G (Fig. 8). A direct comparison between Figs. 4 and 8 shows that the cumulative risk boundary between grades B and C ($\widehat{R}_{\text{B−C}}(t)$) is identical to $\widehat{R}_{lt}(t)$. Therefore, the cumulative risk boundary $\widehat{R}_{\text{B−C}}(t)$ is defined by the long-term tolerable risk boundary R_{lt}. Similarly, the cumulative risk boundary $\widehat{R}_{\text{F−G}}(t)$ is identical to $\widehat{R}_{st}(t)$ and can therefore be defined by additionally specifying $R_{st,ref}$ and $t_{st,ref}$ (see Eqs. (5) and (6)). However, additional parameters are needed to define the other four cumulative risk boundaries. The cumulative risk boundary $\widehat{R}_{\text{A−B}}(t)$ is defined by introducing the risk boundary $R_{\text{A-B}}$ (see Eq. (12)), analogously to the risk boundary $R_{\text{X1-X2}}$ in Section 3.2, while the cumulative risk boundaries $\widehat{R}_{\text{C−D}}(t)$, $\widehat{R}_{\text{D−E}}(t)$ and $\widehat{R}_{\text{E−F}}(t)$ are defined by introducing short-term tolerable periods $\Delta t_{st,\text{C−D}}$, $\Delta t_{st,\text{D−E}}$ and $\Delta t_{st,\text{E−F}}$ by analogy to Eq. (11)). Therefore, the proposed seven-grade risk communication and management support model is defined by seven parameters: $R_{\text{A-B}}$, R_{lt}, $R_{st,ref}$, $t_{st,ref}$, $\Delta t_{st,\text{C−D}}$, $\Delta t_{st,\text{D−E}}$ and $\Delta t_{st,\text{E−F}}$.

The complexity of the model's required input data can be reduced by setting $\Delta t_{st,\text{C−D}}$ equal to $t_{st,ref}$. The result of this simplification is that grade C is initially assigned only in cases where the estimated risk R_{est} is between R_{lt} and $R_{st,ref}$, which also provides better insight into the definition of $R_{st,ref}$ because it indicates the level of risk above which detrimental actions are imposed immediately following the risk evaluation. An advantage of this definition is that it may make it easier for authorities to determine $R_{st,ref}$ in practice. A constant grade reduction rate is also suggested, meaning the allowed time periods for grades D, E and F are the same. This further simplifies the input data since $\Delta t_{st,\text{D−E}}$ and $\Delta t_{st,\text{E−F}}$ are then equal to 2/3 and 1/3 of $\Delta t_{st,\text{C−D}}$, respectively. Finally, $R_{\text{A-B}}$ can be defined by the ratio of R_{lt}: $R_{\text{A-B}} = \mu_{negl} \cdot R_{lt}$, where μ_{negl} is the ratio of R_{lt} indicating negligible risk. With these simplifications, only four parameters

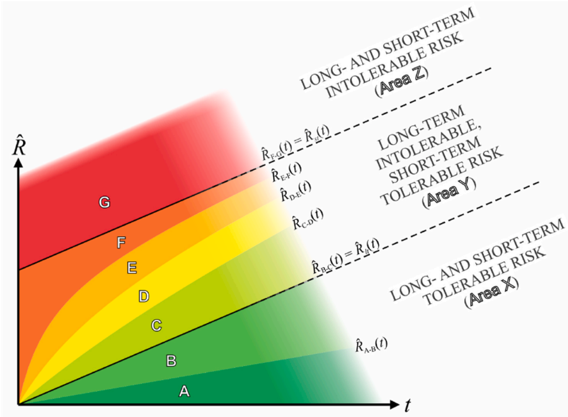


Fig. 8. The seven-grade risk communication and management support model in the cumulative risk–time domain.

are required to define the model's grading framework: R_{lt}, $R_{st,ref}$, μ_{negl} and $t_{st,ref}$. The cumulative risk boundaries of this grading framework can be formulated by analogy to Eqs. (3), (5), (8) and (11):

$$\hat{R}_{\mathrm{A-B}}(t) = \mu_{negl} \cdot R_{lt} \cdot t \tag{12}$$

$$\hat{R}_{\mathrm{B-C}}(t) = R_{lt} \cdot t \tag{13}$$

$$\hat{R}_{\mathrm{C-D}}(t) = R_{lt} \cdot t + \frac{\left(R_{st,ref} - R_{lt}\right) \cdot t_{st,ref} \cdot t}{t_{st,ref} + t} \tag{14}$$

$$\hat{R}_{\mathrm{D-E}}(t) = R_{lt} \cdot t + \frac{\left(R_{st,ref} - R_{lt}\right) \cdot t_{st,ref} \cdot t}{2/3 t_{st,ref} + t} \tag{15}$$

$$\hat{R}_{\mathrm{E-F}}(t) = R_{lt} \cdot t + \frac{\left(R_{st,ref} - R_{lt}\right) \cdot t_{st,ref} \cdot t}{1/3 t_{st,ref} + t} \tag{16}$$

$$\hat{R}_{\mathrm{F-G}}(t) = R_{lt} \cdot t + \left(R_{st,ref} - R_{lt}\right) \cdot t_{st,ref} \tag{17}$$

The proposed risk communication and management support model may take into account one or more risk measures. In cases where more than one risk measure is considered, it is suggested that the grading framework be formulated for each risk measure separately. The actions in such cases can then be determined by enveloping the grades for all individual risk measures, i.e. by considering the lowest grade at any given point in time.

4. Demonstration of the proposed risk communication and management support model to two masonry buildings exposed to seismic risk

The proposed risk communication and management support model is demonstrated by applying it to two masonry buildings that are exposed to seismic risk. The buildings and their risk estimates were obtained from a previous study [41] since it is beyond the scope of this paper to describe the seismic risk analysis. Both buildings have three storeys and share the same geometry (Fig. 9). They differ only in the quality of the material: the modern building is built of hollow clay masonry bricks, while the older one is constructed of solid bricks. This example thus demonstrates the outcome of the proposed risk communication and management support model for both modern and historical construction practices.

The seismic risk of each building was estimated [41] by using a simulation-based methodology in which simplified nonlinear building models were subjected to many recorded ground motions. The seismic risk was quantified by several risk measures, two of which are utilised in this demonstration. The first one is the annual collapse risk, which amounted to $1.81 \cdot 10^{-4}$ and $1.54 \cdot 10^{-3}$ for the modern and older building, respectively. The second risk measure is the expected annual economic loss, which was estimated at 75 and 191 EUR per 100 m^2 of the gross floor area, respectively, for the modern and older building. In the estimation of losses, the value-added taxes related to the repair and reconstruction costs were disregarded. While the estimated annual collapse risks and expected annual economic losses may not be informative to the owners and other stakeholders, they can serve as the basis for the proposed seven-grade risk communication and management support model.

To determine the appropriate grade for each building, the input parameters for the grading framework (R_{lt}, $R_{st,ref}$, μ_{negl} and $t_{st,ref}$, see Section 3.3) must first be defined for each risk measure separately. Ideally, the definition of these input parameters would be based on a target community resilience against natural hazards. However, research is still required to define such target metrics. Therefore, the input parameters for this example were defined based on existing studies and regulatory documents, as explained in the following paragraphs.

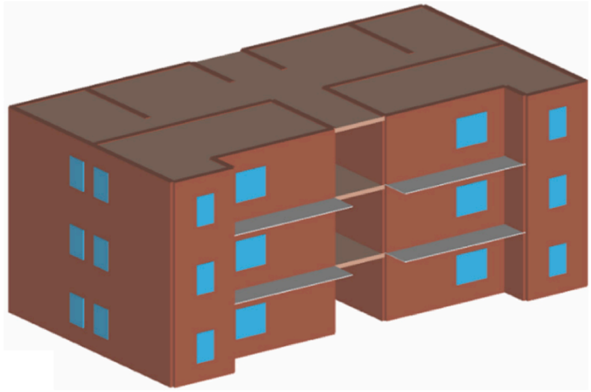


Fig. 9. Schematic representation of the structure of the analysed masonry buildings.

The long-term tolerable annual collapse risk, R_{lt} was set to $2 \cdot 10^{-4}$, which is the target collapse risk considered in designing new building structures in the US [46]. This value is relatively high and might be reduced in the future mainly due to the reduction of bias and epistemic uncertainties in the estimation of seismic collapse risk. For μ_{negl}, the value of 0.055 was used, which results in a collapse risk broadly accepted by experts and non-experts on the seismic risk in Slovenia ($1.1 \cdot 10^{-5}$) [47]. However, $R_{st,ref}$ was defined based on the acceptable individual fatality risk in existing buildings prescribed in the Netherlands [48], which amounts to 10^{-5} per year. The acceptable collapse risk was then obtained by dividing the acceptable fatality risk by the conditional probability of a fatality in the case of collapse, assumed to be 1.5% [49]. The $R_{st,ref}$ was therefore set to $6.7 \cdot 10^{-4}$, and for the mitigation implementation period, risk equal to $R_{st,ref}$ can be tolerated for a maximum of 30 years ($t_{st,ref} = 30$ years). This period is approximately half of the design lifespan of new buildings and denotes the period in which it is assumed that society can upgrade seismic resilience to an acceptable level. By setting $t_{st,ref}$ to 30 years, the period between successive grade reductions is ten years.

The grading scale for expected annual losses was established by assuming that seismic losses are as acceptable as losses due to heating of buildings, thus taking a similar approach as Calvi et al. [32]. In particular, parameters $R_{\text{A-B}}$, R_{lt}, $R_{st,ref}$ were assumed equal to the costs of heating corresponding to efficiency classes A, B and C in the energy performance certificate (Official Gazette of the RS, No. 92/2014 [27]). Thus, the losses corresponding to initial grades A, B and C in the proposed communication and management support model are roughly the same as the losses corresponding to grades A, B and C in the energy performance certificate. Risk boundaries R_{lt}, $R_{st,ref}$ were set to 90 and 160 EUR per 100 m^2 of the gross floor area, while μ_{negl} was set to 0.45. The cost of heating was assumed to be 0.04 EUR/kWh, which is approximately the average price of gas over the years 2019 and 2020. The value-added tax was excluded in order to be consistent with the usual loss estimation, and as done by Snoj and Dolšek [41]. Because the energy efficiency classes (Official Gazette of the RS, No. 92/2014 [27]) refer to the net conditioned floor area and the seismic losses in terms of EUR per 100 m^2 refer to the gross floor area [41], a loss conversion factor of 1.5 was used to help compensate for the difference in floor areas. As before, t_{ref} was set to 30 years.

Grades were then calculated separately for annual collapse risk and expected annual loss. For annual collapse risk, grades B and F were initially assigned to the modern and older building, respectively (Fig. 10). Therefore, the grade assigned to the modern building is expected to remain valid indefinitely, while the grade assigned to the older building is expected to reduce over time to grade G. The grade reduction for the older building would occur in 9.0 years (Eq. (7); Fig. 10).

In the case of the expected annual losses, the grade of the modern building was the same (Fig. 11), and the risk was considered long-term acceptable. However, the older building initially received grade D, which would eventually be reduced to a G (Fig. 11), with grade reductions set to occur in 0.9, 10.9 and 20.9 years.

The final grades are obtained by enveloping the grades resulting from both risk measures. For this particular example, the resulting final grade happens to correspond to the annual collapse risk grade.

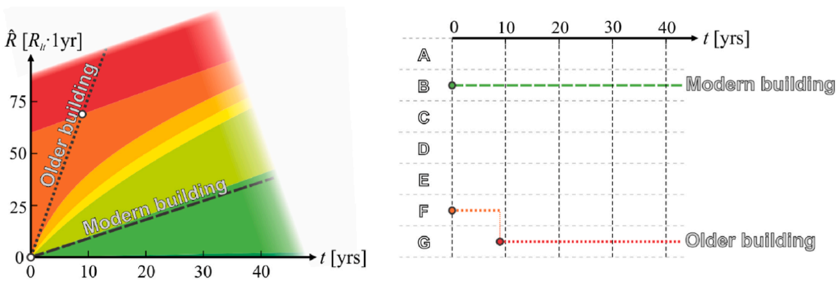


Fig. 10. Grading based on the annual collapse risk for the older and modern masonry buildings. The grading is presented in the cumulative risk–time format and grade–time format.

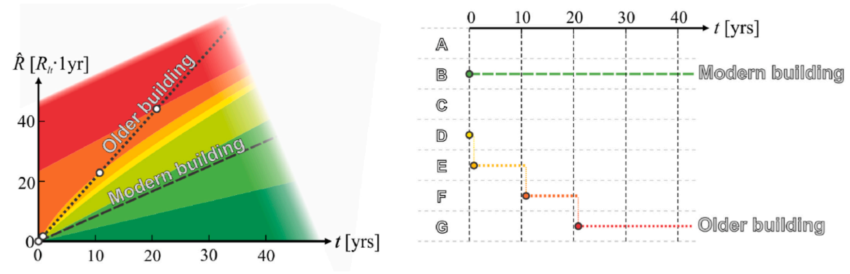


Fig. 11. Grading based on the expected annual losses for the older and modern masonry buildings. The grading is presented in the cumulative risk–time format and grade–time format.

The hypothetical incentives and actions resulting from the risk grades for these two investigated buildings also differ significantly. Slightly beneficial actions can be foreseen for the owner of the modern building. However, the owner of the older building would immediately be faced with detrimental but not restrictive actions. Presumably, such actions will incentivise the owner to start planning risk mitigation measures immediately in order to increase the grade to at least a C, which is associated with neutral actions, or to a B, which indicates long-term tolerable risk. Either way, it is likely the owner will want to reduce the risk within the 9.0 years allotted to avoid restrictive actions.

5. Discussion on the applicability of the proposed risk communication and management support model

The model proposed in this study was developed to support activities for mitigating natural hazards risk. These activities include evaluating the risk of the considered natural hazard to buildings, communicating the evaluated risk to the public and designing risk mitigation strategies, as demonstrated, for example, in Section 4 for two individual buildings.

For the model to be applied in a real-world setting, the mitigating activities must first be prescribed by the regulator (e.g. government authority responsible for planning risk mitigation actions). The range of buildings covered by the risk mitigation campaign may differ. It can be limited to essential public buildings, such as schools, hospitals, town halls and courthouses. However, for a more comprehensive campaign, residential and commercial buildings that support the normal functioning of society can also be included in the analysed portfolio. In either case, the number of buildings to be analysed can be substantial. To deal with this challenge, it is proposed that builings are classified based on their function and that the risk evaluation is performed in stages, starting with the buildings with the essential functions (e.g. schools and hospitals). Moreover, it is proposed that a deadline for completing the risk evaluation is prescribed for each function-based building class. Such a deadline would mark the beginning of the grade reduction process for the buildings exposed to long-term intolerable risk. Because the grade reduction process would start simultaneously for all buildings of the same class, the owners would not be penalized for potentially arranging for the evaluation of their building sooner than required.

For a successful implementation of the proposed model in a risk mitigation campaign, different stakeholders, such as the regulator, the scientific authority representatives, the building owners and the risk analysts, should be included. The role of the scientific authority representatives would be to propose, and the role of the regulator would be to prescribe the input parameters for the grading framework (R_{lt}, $R_{st,ref}$, μ_{negl} and $t_{st,ref}$; see Section 3.3), the actions associated with different grades, and the risk estimation methodology (further discussed in the next paragraphs). The responsibility of the owners would then be to arrange for the risk estimation of their buildings, performed by certified risk analysts. Based on the estimated risk, a grade would be assigned to each building, as explained in Section 3.3. In the case of long-term intolerable risk (initial grades C–F), grade reduction would also be scheduled. Based on the grade in any given time instance, the regulator would prescribe the actions towards the owner, as presented in Fig. 7 and demonstrated in Section 4. The grade of a building and the associated actions would need to be made accessible to all interested stakeholders, including the users other than the owner, to help increase their risk perception and allow them to make decisions with consideration of the risk they are exposed to.

Defining the grading input parameters is not an easy task. It is related to a more general challenge of defining tolerable risk of natural hazards, which exceeds the scope of this paper. Nevertheless, one possibility to define the parameters for the case of seismic risk is demonstrated in Section 4, where some of the input parameters are defined using existing studies and regulatory documents. It is suggested to focus further studies on defining such parameters based on a target community's resilience against natural hazards taking into account economic and social aspects.

The development of the actions associated with the grades can depend on the regulator's strategy for risk management. A few examples of beneficial and detrimental actions are given in Section 3.3. This includes a tax deduction or increase, a limited use of the building, and a ban on renting or selling the building. Actions affecting taxes could act as monetary incentives for the owners. However, a tax increase could also be one of resources for other risk mitigation programmes, e.g. aimed at providing retrofitting subsidies. Similarly, limited use of a building and a ban on renting, which are foreseen as actions related to the lowest grade, would not only motivate the owners to act but also affect the risk by limiting the occupancy of buildings exposed to high risk and thus reducing their exposure.

The role of the regulator is also to prescribe the risk estimation methodology proposed by scientific authority representatives. The prescribed methodology may differ between hazards. However, regardless of the hazard, the methodology should enable the risk analysts to quantify the estimated risk by the average adverse consequences (e.g. losses) in a given period, as the proposed communication and management support model is based on such quantification of risk.

The applicability of the proposed model was tested by implementing it in a seismic stress test of the building stock in Slovenia [50] performed for the Ministry of the Environment and Spatial Planning of the Republic of Slovenia, as presented elsewhere [51]. The aim of the study was to support the development of a resolution on the national strategy for seismic risk mitigation. Within the study, the seismic risk of the Slovenian building stock was estimated by simulating the risk of each individual building. The risk was quantified by average annual economic losses and average annual frequency of complete building damage. Many simulations were performed because the building data is reliable at the building stock level but still quite uncertain at the level of individual buildings. The estimated risk was then evaluated using the proposed risk communication and management support model, thus applying a grade to each building in each simulation. The study results showed that about 20% of the buildings in Slovenia are exposed to long-term intolerable risk. However, for most of those buildings, the risk exceeds the long-term tolerable level only slightly, which means that they should not be treated in a significantly different way than the buildings reaching the long-term goal. Thus, according to the proposed model and considering the input requirements defined in Section 4, about one-third of the buildings unsuitable for the long term are still acceptable in the next 30 years. On the contrary, other buildings exceeding the long-term intolerable risk should be strengthened in a period shorter than 30 years. It was estimated that there are about 35,000 such buildings in Slovenia, mostly concentrated in Ljubljana, where the hazard and exposure are relatively high compared to other regions in the country. Based on the findings of the study, it was suggested that the government launch a risk mitigation campaign focusing on identifying the buildings exposed to long-term intolerable risk. It was also suggested to introduce the proposed risk communication and management support model into practice to enhance the communication of risk and mitigation activities. The study outcomes were also discussed in the Slovenian Parliament. This resulted in the Committee on Infrastructure, Environment and Spatial Planning unanimously deciding that the Government of the Republic of Slovenia should prepare a resolution on the national strategy for seismic risk mitigation. The resolution was composed and is currently in public hearing.

The proposed model can be applied to mitigate the risk of natural hazards other than earthquakes, but with some limitations. Namely, the methodology established to estimate the risk of a given natural hazard should allow for the quantification of risk in terms of average adverse consequences in a given period. This would require a hazard model that provides a relationship between the hazard intensity and the mean return period. The development of such a seismic hazard model is standardized, which may not be the case for some other natural hazards. For example, the flood hazard model is often developed only for a limited range of return periods [52]. In such cases, interpolation and extrapolation may be needed to extend the hazard model to a wider range of return periods [53]. Moreover, the introduced risk communication and management support model was developed under the assumption that the owners themselves can take actions to mitigate the natural hazard risk. This is very often true in the case of seismic risk. However, risk mitigation can be beyond the owners' capabilities for some other natural hazards (e.g. tsunami hazard, volcano hazard). In such situations, the potential detrimental actions imposed in the case of long-term intolerable risk, which are otherwise foreseen to encourage the owners to act, would only penalize the owners for something they cannot affect. In future studies, the proposed model could be extended so that the actions would be directed towards entire communities, whose decision-makers have the capability to mitigate risk. Furthermore, the current study assumes that the risk is constant over time. If the risk of a given natural hazard changes over time, the concept of the grading framework would remain the same, as the grade would still be determined based on the cumulative risk. However, the mathematical formulations would change because the cumulative risk would increase non-linearly. An additional challenge would be to apply the model to hazards where the evolution of risk is difficult to predict (e.g. weather-related hazards, such as storms and floods). In such cases, the risk could be evaluated periodically, as suggested, for example, by Esposito et al. [43], which would enable updates of the predicted cumulative risk and the associated grade. Future studies are therefore needed to extend the proposed model to cases of time-varying risk and cases requiring periodical risk evaluation.

6. Conclusions

A model for communication and management support of natural hazards risk was introduced, incorporating a seven-step (A–G) grading scale similar to European grading systems for energy consumption and other product properties of interest. However, the model differs from other similar communication tools in that it systematically distinguishes between long-term and short-term risk tolerances. This makes it possible to introduce a time-dependent grade reduction in cases where the estimated risk is intolerable over long time periods. The inclusion of both long-term and short-term risk tolerance was made possible by considering cumulative risk measures, which are functions of time. Only four parameters are needed to fully define the seven-grade communication and management support model: the long-term tolerable risk, the ratio between the long-term negligible and long-term tolerable risk, the reference value of short-term tolerable risk and the corresponding reference value of the short-term tolerable period.

The proposed model has several advantages. As the European grading scale is well-known to the general public in Europe, it is suitable also for non-experts in the field of natural hazards risk. Thus, it can be used to improve the risk perception of stakeholders, including the owners and regulatory body representatives responsible for planning risk mitigation actions. In addition, it is believed that the perception of risk can also be improved by the time-dependent grade reduction, which translates the question of risk to the question of time over which the risk can be tolerated. Moreover, by assigning actions to each grade, the proposed model makes it possible to gradually introduce risk mitigation actions aimed at improving community resilience to natural hazards.

Both the improvement in the perception of risk and the systematic introduction of actions can help prevent or mitigate future catastrophes, such as the earthquakes that hit the Turkish-Syrian cross-border area in February 2023. By improving the perception of risk, the owners and the regulatory body representatives can better understand the severity of the risk and act accordingly rather than neglect the potential impact of disasters that are unlikely to occur in the short term. By establishing a framework for the gradual enhancement of community resilience, the proposed model enables systematically distributing the burden of risk mitigation over a longer period rather than requesting sudden action for all buildings exposed to long-term intolerable risk. Such a risk mitigation strategy can be especially efficient in the case of large building stocks, where the magnitude of the problem makes it difficult to reach the societal consensus needed to even start planning risk mitigation activities.

The proposed model was already implemented in a seismic stress test of the building stock in the Republic of Slovenia to support the Ministry of the Environmentand Spatial Planning in the development of a resolution on the national strategy for seismic risk mitigation [50]. However, more studies are needed to further validate the model and to assess if the model can be perceived as useful by the end-users. In addition, the implementation of the proposed model has some limitations. It requires that the risk of the considered natural hazard is quantified by average adverse consequences in a given period (e.g. average annual losses). Moreover, the model was developed under the assumption of constant risk over time. Future studies are therefore needed to extend the model to cases of time-varying risk and cases where the risk evolution is difficult to predict. Furthermore, the model is intended for risk communication and management in cases where the owner has the capabilities to mitigate the natural hazard risk. This limitation can also be overcome by future studies.

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.

Data availability

No data was used for the research described in the article.

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