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# Tools aiding decision-making for economic resources allocation in seismic retrofitting of residential buildings

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## ABSTRACT

A significant portion of the masonry and reinforced concrete buildings in Italy resides within regions of moderate to high seismic risk, rendering them especially susceptible to earthquakes. While urgent reinforcement measures are necessary, resources are limited, and retrofitting the entire existing building inventory is impractical. Therefore, optimizing resource allocation for reinforcement interventions becomes essential, considering cost constraints and various factors tied to repair and indirect expenses, such as population size, building priority, size, and vulnerability. This study focuses on making decisions about the most efficient budget distribution for proactive strengthening in seismic regions and reactive repairs post-earthquake. The objective is to minimize the count of uninhabitable buildings while factoring in their resident capacity. Utilizing a two-stage stochastic model with iterations, analyses are conducted, assuming a maximum cumulative budget for proactive strengthening and/or reactive reconstruction. The solution derived from this stochastic approach is compared to a scenario where the budget is solely allocated to reactive measures. The findings are presented and deliberated within the context of a specific case, a small town in Sicily, Italy.

## 1. Introduction

The large number of casualties and injuries and the extensive damage to the building stock and production activities generated by seismic events have highlighted the need to plan and implement interventions aimed at reducing the seismic vulnerability of the existing building stock.

These needs are particularly felt in heavily anthropized territories, characterized by the presence of cities and villages with historic centres equipped with masonry buildings of different ages and construction techniques (Marques et al., 2017 [1], [2]), where seismic events often have disastrous effects.

Despite the abundance of seismic retrofitting solutions available [3,4], resources allocated for strengthening purposes are limited, making the retrofitting of the entire existing building inventory unfeasible. Hence, optimizing resource distribution for retrofitting interventions becomes of paramount importance [5,6].

Budget allocation has been extensively studied in operational research, addressing various real-life applications such as historical building restoration [7], transportation infrastructure maintenance planning [8], and pavement maintenance [9]). However, these studies typically operate within deterministic settings where all input data are presumed known in advance, simplifying problem-solving. Yet, in scenarios like seismic events characterized by high uncertainty, a deterministic approach becomes

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impractical.

Regarding methods for prioritization of seismic interventions, available in the literature for various structural assets, Saler et al. [10] presented a procedure for prioritizing reinforced concrete buildings by their seismic vulnerability to plan further assessments and retrofits. The method combines visual inspections, qualitative evaluation (with a new deficiency form), and a simplified quantitative model that calculates a capacity-to-demand ratio. Applied to r.c. school buildings in Padova, Italy, the procedure effectively identified common vulnerability factors and showed that the qualitative and quantitative methods work well together, producing consistent outcomes. Anelli et al. [11] introduced a framework for prioritizing seismic retrofit interventions for school buildings, addressing the shortcomings of existing methods in linking risk analysis with decision-making. Their study integrates engineering, socio-economic, organizational, and political factors and introduces new metrics to assess costs, benefits, and resilience. Through probabilistic risk assessments, it predicts potential losses and system recovery after seismic events. The framework also examines various political scenarios and intervention strategies to guide decision-makers in selecting optimal mitigation approaches. Saler et al. [12] presented a procedure to prioritize retrofit interventions for bridges by considering both seismic vulnerability and deterioration effects. The procedure combines these factors into a multi-risk classification system, enabling more refined prioritization within each risk category using quantitative indices and multicriteria decision-making methods. Applied to the bridge stock in Padova, Italy, the study provides a detailed characterization of the bridges based on various parameters and identifies the types most vulnerable to seismic events or deterioration. The work presented by Perrone et al. [13] highlights the importance of hospitals remaining fully operational after earthquakes. It notes that hospital functionality is impacted by both structural and non-structural damage, including medical equipment. For large-scale seismic risk assessment, simplified methods are essential. The paper introduces a rapid visual screening (RVS) method to calculate a Safety Index for hospitals, assessing vulnerability through sidewalk surveys. The method was applied to two Italian hospitals in different seismic zones and validated against push-over analysis results. It was also tested on hospitals damaged in the 2009 L'Aquila and 2012 Emilia earthquakes. The paper produced by Jeswani et al. [14] presents a framework for seismic risk assessment of large asset portfolios, combining detailed vulnerability analyses (FEMA P-58, REdi) with systematic asset categorization. This method offers efficient portfolio-level evaluations, providing stakeholders with insights for seismic retrofit decisions. Applied to over 1000 public school buildings in Makati and Quezon City, Philippines, the framework proves effective in identifying key risk contributors and cost drivers. The study highlights the framework's reliability and computational efficiency in regional seismic risk assessments, supporting performance-based risk management.

Regarding methods for prioritization of seismic interventions based on multi-criteria decision analysis, Aljawhari et al. [15] presented a fragility-based method for seismic retrofit design, focusing on increasing a building's capacity-to-demand ratio for life safety (CDRLS) to reduce seismic vulnerability. By linking retrofitting improvements in CDRLS with changes in fragility medians, it identified a pseudo-linear trend that enables designers to set a target fragility and achieve the corresponding CDRLS. The method was validated on a reinforced concrete (RC) structure using retrofit techniques like fiber-reinforced polymer wrapping, RC jacketing, and steel jacketing. Carofilis Gallo et al [16] explored multi-criteria methods for evaluating seismic retrofit options for an RC school building, going beyond traditional economic and structural factors. By incorporating criteria such as structural performance, building operability, and economic impact, the study aimed to offer a more comprehensive assessment—crucial for strategic buildings like schools. Using a detailed model that simulates typical structural weaknesses, the study assessed seismic improvements and economic effects of various retrofits, factoring in seismic losses from non-structural components. Results showed that no single retrofit is optimal across all criteria, underscoring the complexity of selecting the best intervention. Caterino et al. [17] explored the use of multi-criteria decision-making (MCDM) methods to address the complex task of selecting a seismic retrofit strategy amidst numerous technologies and conflicting criteria. A case study on an underdesigned reinforced concrete structure highlighted the effectiveness of various MCDM methods, with TOPSIS and VIKOR emerging as the most suitable due to their ability to manage diverse criteria, provide clear outcomes, and offer user-friendly application. The study concluded that these methods are broadly useful for guiding retrofit decisions. Gentile and Galasso [18] used multi-criteria decision-making (MCDM) to identify optimal seismic retrofits for reinforced concrete (RC) buildings, emphasizing earthquake-induced economic loss. Through three analysis methods—Simple Lateral Mechanism, pushover, and time-history—the study assessed fragility and vulnerability for a deficient RC school building typical of developing countries, with retrofit options like concrete jacketing, concrete walls, and steel braces. The consistent ranking of retrofit choices across different analysis methods and economic loss metrics indicated that simplified methods are adequate for initial retrofit design planning.

There are limited works in literature addressing budget allocation problems within a stochastic environment. Feng et al. [19] explore allocating medical resources in an emergency department, while Dellaert et al. (2011)[20] focus on budget allocation for workforce in a company. Yin and Büyüktaktakın [21] study optimal medical resource allocation during an epidemic, extending to vaccines in their 2022 work [22], considering uncertainties in supply and disease transmission.

More in detail, the paper investigates the optimal budget allocation for Proactive Strengthening (PS) in seismic regions and Reactive Repair (RR) post-seismic events, aiming to minimize the number of evacuees of uninhabitable or damaged buildings. Employing a two-stage stochastic model with recursions, analyses are conducted assuming a maximum cumulative budget for proactive and/or reactive actions. The research exploits the first results of an innovative technique for assessing the seismic exposure of residential buildings, which is under development in Italy by ReLUIIS (Network of University Earthquake Engineering Laboratories), coordinated by the Italian Civil Protection Department. This technique consists in the use of interview-based CARTIS form [23,24] aiming at enriching and making reliable information useful for the assessment of seismic vulnerability and exposure of residential buildings, with the goal to formulate a taxonomy on territorial or regional scale [25]. Building-specific input data encompass vulnerability levels, costs of three intervention levels (seismic retrofitting, improvement, or local strengthening), as well as the vulnerability reduction achievable with each action [26]. Intervention costs are determined based on international literature [27] and recent seismic risk mitigation policies by the Italian government [28]. Additionally, repair costs for five post-earthquake damage levels

are defined based on data from recent reconstruction after the 2009 L'Aquila earthquake [29].

Mathematical formulations are devised for the two-stage stochastic problem, where first-stage variables address decisions on strengthening solutions and second-stage variables deal with repair strategies based on generated post-earthquake damage scenarios. The solution of this stochastic problem is compared with a scenario where proactive strengthening actions are not taken, and the entire budget is earmarked for reconstruction. The outcomes of analyses on a real case, a small town in Sicily (Southern Italy), will be presented and discussed.

The present work stands apart for two reasons. Firstly, it involves the possibility of applying different strengthening actions to the same buildings, each action having distinct costs and impacts on seismic behavior. Secondly, the total budget can be divided between proactive actions (strengthening pre-earthquake) and reactive actions (post-seismic repair). The damage level and subsequent repair costs hinge on the pre-strengthening actions. As far as it is known, no attempts have been made to formulate a stochastic model for budget allocation to mitigate residual earthquake damages.

In the following, each section will be dedicated to address one aspect of the study. In particular, the following sections will be presented and discussed: "Method and definition of input variables", which outlines methods for assessing seismic vulnerability, retrofitting strategies, costs, and damage scenarios, providing a framework to evaluate risks and interventions; "Cost-benefit analysis", which examines resource allocation for seismic interventions, comparing deterministic strategies to minimize evacuees and optimize limited budgets; "A two-stage stochastic model for budget allocation", which introduces a two-stage stochastic model to allocate resources between proactive strengthening and reactive repairs, minimizing evacuees under uncertainty; "Case study", which, using Patti, Sicily, as a case study, this chapter validates the stochastic model by analyzing building vulnerabilities, typologies, and damage scenarios; "Results", which presents the model's findings, demonstrating how optimized budget allocation balances proactive and reactive measures to reduce evacuees; "Conclusions", which highlights the study's findings, emphasizing the innovative stochastic approach and its implications for optimizing resources and guiding seismic retrofitting policies.

## 2. Method and definition of input variables

This section outlines a comprehensive methodology for assessing seismic vulnerability, optimized seismic risk reduction strategies, and related costs for residential buildings in earthquake-prone regions. To conduct the analyses, four types of data are required, namely the description of number and characteristics of residential buildings subject to intervention (exposure), the assessment of their seismic vulnerability, the type of interventions for vulnerability reduction and their efficiency in terms of vulnerability reduction, the costs associated to intervention typologies. The methodology integrates data from surveys, established engineering methods, and cost analysis models, offering a systematic framework to analyse both direct and indirect economic implications of seismic events. The text in the following is organized into subsections, addressing types of interventions, cost analysis methods, vulnerability assessments, and damage scenario generation.

### 2.1. Intervention types

Concerning the type of interventions, over recent decades, the scientific community has extensively researched different techniques for restoration of masonry [4,30,31] and RC structures [3,32]. This focus stems from the heightened seismic vulnerability of constructions in earthquake-prone regions [33,34].

Three intervention levels are outlined in the Italian Code [26]: seismic retrofitting, seismic improvement, or local strengthening. It is pertinent to provide the definitions outlined by the Italian Code [26] since these definitions will be employed throughout this study.

- Seismic retrofitting interventions: these interventions aim to enhance the existing structural safety, meeting the safety standards required by the code for new constructions. This involves achieving  $\zeta_E \geq 0.8$  or  $\zeta_E \geq 1$ , where  $\zeta_E$  represents the ratio between the capacity of the structure, expressed as the Peak Ground Acceleration (PGA) of the seismic action for which the structure satisfies the performance requirements at the Significant Damage Limit State (SDLS), and the PGA of seismic action used in designing a new construction. The minimum value of  $\zeta_E$ , namely  $\zeta_{E,SR} \geq 0.8$  or  $\zeta_{E,SR} \geq 1$ , can be chosen either based on the desired seismic performance or according to the Italian Code [26]. depending on type of intervention or construction.
- Seismic improvement: these interventions focus on increasing the pre-existing structural safety without meeting the safety levels obtained with a seismic retrofitting or mandated for new constructions ( $\zeta_{E,SI} < \zeta_{E,SR}$ ;  $\zeta_{E,SI} < 1$ ).
- Local strengthening interventions: these interventions target specific vulnerable structural elements, without modifying the existing global behaviour and, then, without compromising the existing safety conditions [35]; the intervention can instead potentially improve, even in a significant way, the global behaviour of the structure.

### 2.2. Cost analysis

In the past, the methods commonly used to predict the costs of seismic retrofit interventions have been the expert judgment of technicians and the regression analysis of data [36]. Lately, approaches using artificial neural networks have been formulated [37], e. g. Bayesian regression-based method for creating probabilistic cost models for seismic retrofit interventions [38]; effectiveness of machine learning algorithms for estimation of the seismic retrofit cost has been lately investigated [39]. Fung et al. [40] analyzed quantitative, qualitative and heuristic data to establish a taxonomy for evaluating both direct and indirect costs linked to seismic strengthening. Recently, a seismic retrofit cost model for Italian unreinforced masonry residential buildings has been proposed to

support territorial-scale risk analysis [41]. In this study, intervention costs were determined based on information provided in the FEMA document from 1994 [27]. This document comprises four tables detailing the costs of structural interventions for different building types across four seismicity levels: low, moderate, high, and very high. For brevity, only the table outlining typical structural costs for areas with very high seismicity is presented here (refer to Table 1b). To simplify the notation, in this work, the label "C01" denotes the structural cost linked to seismic strengthening interventions in low-seismicity areas, while "C02," "C03," and "C04" pertain to seismic strengthening interventions in moderate, high, and very high seismicity areas, respectively.

The costs cited in FEMA [27] were adjusted by comparing them with more recent costs documented in the Italian Ocdpc n. 780 of May 20, 2021 (DPCI, 2021). Specifically, all costs outlined in FEMA were multiplied by a coefficient of  $a = 23.30$ . This coefficient was derived from the ratio between the retrofitting cost for RC structures provided by DPCI 2021 (approximately 600 €/m<sup>2</sup>) and the corresponding cost detailed in FEMA (cost provided for C1 and C3 typologies in areas with very high seismicity and a small area, specifically 25.75 \$/sq.feet, as seen in Table 1b). Consequently, the updated costs (C<sub>U</sub>*i*) were calculated as  $C_{U_i} = C_{0i} * a$  ( $i = 1, 2, 3, 4$ ).

Since exposure was evaluated according to CARTIS form [23,43,44], while costs were evaluated according to typology description of the FEMA document [27], in order to take into account the different costs associated with different building typologies identified through the CARTIS method, the structural typologies outlined in the EMS98 macroseismic scale [42] (Table 1a) were correlated with the typologies presented in the FEMA table (FEMA 1994 [27]) (Table 1b). Due to the lack of direct correspondence between EMS98 and FEMA structural types, some EMS98 scale typologies were linked to the same typology in the FEMA table. For instance, M1 and M3 EMS98 types were associated with the URM FEMA type, while RC1, RC2, and RC3 EMS98 types were related to the C1/C3 FEMA type (see corresponding circles in Table 1a and b).

After establishing associations between typologies, the four different seismic strengthening intervention costs derived from FEMA tables, based on four seismicity levels, were allocated to each typology. These four levels were defined according to the Peak Ground Acceleration (PGA) values  $a_g$  associated with a return period of 475 years, delineated as  $a_g < 0.05g$ ,  $a_g = 0.15g$ ,  $a_g = 0.25g$ , and  $a_g = 0.35g$  for low, medium, high, and very high seismicity levels, respectively.

**Table 1**  
Building typologies: a) EMS98 macroseismic scale (EMS98) [42]; b) FEMA (FEMA 1994 [27]).

Typologies	Code	Building Type	Characteristic Values of the Vulnerability Index				
			VI <sub>min</sub>	VI <sup>-</sup>	VI*	VI <sup>+</sup>	VI <sub>max</sub>
Masonry	M1	Rubble stone	0.62	0.81	0.873	0.98	1.02
	M2	Adobe/earth bricks	0.62	0.687	0.84	0.98	1.02
	M3	Simple stone	0.46	0.65	0.74	0.83	1.02
	M4	Massive stone	0.3	0.49	0.616	0.793	0.86
	M5	U Masonry (old bricks)	0.46	0.65	0.74	0.83	1.02
	M6	U Masonry - r.c. floors	0.3	0.49	0.616	0.79	0.86
	M7	Reinforced /confined masonry	0.14	0.33	0.451	0.633	0.7
Reinforced concrete	RC1	Frame in RC (without E.R.D.)*	0.3	0.49	0.644	0.8	1.02
	RC2	Frame in RC (moderate E.R.D.)*	0.14	0.33	0.484	0.64	0.86
	RC3	Frame in RC (high E.R.D.)*	-0.02	0.17	0.324	0.48	0.7
	RC4	Shear walls (without E.R.D.)*	0.3	0.367	0.544	0.67	0.86
	RC5	Shear walls (moderate E.R.D.)*	0.14	0.21	0.384	0.51	0.7
	RC6	Shear walls (high E.R.D.)*	-0.02	0.047	0.224	0.35	0.54
Steel	S	Steel structures	-0.02	0.17	0.324	0.48	0.7
Wood	W	Wood structures	0.14	0.207	0.447	0.64	0.86

\*E.R.D. stands for "Earthquake Resistant Design"

TYPICAL STRUCTURAL COSTS FOR VERY HIGH SEISMICITY AND LIFE SAFETY (\$/sq.ft.)						
Building group	Model	FEMA Building types	Area			
			Small	Medium	Large	V-Large
1	URM	Unreinforced Masonry	18.22	18.04	17.14	14.43
2	W1	Wood Light Frame	14.07	14.79	18.56	23.78
	W2	Wood (Commercial or Industrial)				
3	PC1	Precast Concrete Tilt Up Walls	18.69	17.7	15.52	9.43
	RM1	Reinforced Masonry with Metal or Wood Diaphragm				
4	C1	Concrete Moment Frame	25.75	25.04	23.86	19.84
	C3	Concrete Frame with Infill Walls				
5	S1	Steel Moment Frame	25.82	25.37	24.26	18.47
6	S2	Steel Braced Frame	10.07	9.56	7.68	4.35
	S3	Steel Light Frame				
7	S5	Steel Frame with Infill Walls	29.47	29.28	28.05	24.65
8	C2	Concrete Shear Wall	22.67	22.06	20.83	16.95
	PC2	Precast Concrete Frame with Concrete Shear Walls				
	RM2	Reinforced Masonry with Precast Concrete Diaphragm				
	S4	Steel Frame with Concrete Walls				

As previously mentioned, the aim is to define costs and efficiency in terms of vulnerability index reduction, for three intervention levels specified in the Italian Code [26]. Referring to the FEMA tables, it's feasible to align the costs of each table with the seismic retrofitting cost for that corresponding level of seismicity. Hence, CU4 signifies the structural cost for interventions in a very high seismicity area, representing the seismic retrofitting cost there. Similarly, CU3, CU2, and CU1 denote the seismic retrofitting costs in high, medium, and low seismicity areas, respectively. Additionally, the seismic retrofitting intervention and cost in a high seismicity area (CU3) can be considered an improvement intervention with the related cost concerning a very high seismicity area. Likewise, the seismic retrofitting intervention and cost in a medium seismicity area (CU2) represents an improvement intervention and the related cost in a high seismicity area. This approach allows the costs from FEMA tables to be utilized as retrofitting and improvement costs across different seismicity levels.

However, this reasoning doesn't apply to local strengthening. For instance, considering CU2 as the local strengthening cost in a very high seismicity area would result in an unusually high ratio between CU2 and CU4 compared to the actual ratio between local strengthening and retrofitting costs. Literature data suggests this ratio falls between 0.22 [45] and 0.26 [46] for homogeneous interventions. Therefore, an average value of 0.24 is used here. Table 2 presents the criteria employed to derive cost values for different intervention levels across various seismicity areas.

Additional input data for the model includes repair costs categorized into five distinct levels of post-earthquake damage. These costs, known as direct costs, were sourced from Di Ludovico et al. [29] and were compiled in Table 3; they were derived by analysing data related to the reconstruction process of 4664 reinforced concrete and 3833 masonry residential buildings damaged by L'Aquila 2009 earthquake. Within this table, the repair costs are delineated as a percentage of the standard reference unit costs for a new building (1350 €/m<sup>2</sup>), %C<sub>r</sub>, relative to the severity of the damage state.

In accordance with the damage description reported in Lagomarsino and Giovinazzi [47], aligned with the EMS98 macroseismic scale [42], the model considers five damage levels, ranging from D1 to D5, where D1 denotes minimal damage and D5 indicates severe structural collapse. D0 represents null damage, when the building remains undamaged by the earthquake.

Regarding indirect costs, the assistance provided to the affected population constitutes a substantial portion of the overall losses (as highlighted in Ref. [48]). These losses are in addition to those resulting from the disruption of economic activities and the decline in industrial production. Hence, in order to comprehensively incorporate these indirect costs - a significant aspect of the expenses borne by the government in managing post-earthquake emergencies and reconstruction processes - the adopted repair cost values encompass both direct costs, as outlined in Table 3, and assistance costs, in Table 4. These assistance costs are also expressed as a percentage of the reference unit costs for square meter of a new building, %C<sub>a</sub>, in line with the methodology provided by Di Ludovico et al. [29]. Therefore, in subsequent discussions, the term "repair cost" will encompass the aggregate sum of direct costs and assistance costs.

### 2.3. Exposure and vulnerability assessment

The exposure information was gathered through a survey conducted by the Authors using the CARTIS form [23,43,44] and the vulnerability was assessed by the vulnerability index utilizing the Macroseismic [47] and the Heuristic [49] methods.

The assessment of the efficacy of each intervention type also includes evaluating the reduction in the vulnerability index resulting from various potential interventions. To accomplish this, establishing target vulnerability values for seismic retrofitting, denoted as V, corresponding to the vulnerability index values associated with new construction vulnerability, it is necessary. For RC buildings, the Macroseismic method provides the most probable vulnerability index V\* (white value) for structures designed according to current seismic codes, where V = 0.324. This value can be adopted for seismic retrofitted buildings.

Regarding masonry buildings, due to the absence of comparable data, the target value is assessed by considering values outlined in Table 5 proposed by Lagomarsino et al. [49]. This table associates the vulnerability index with both the year of construction and the building's height. The table refers to constructions until 1981, therefore, in the absence of vulnerability data for masonry buildings constructed after 2008, estimations are made to derive vulnerability indices for buildings constructed from 2008 onwards. Specifically, three indices corresponding to different building heights (high, medium, low) are derived. These vulnerability indices are regarded as representative of new masonry constructions and are considered the target V values for retrofitting masonry structures. To streamline, only the V associated with an average building height is utilized, approximately equal to V = 0.3.

To maintain consistency between masonry and RC constructions, a uniform target value of V = 0.3 is designated for both building types.

To compute the vulnerability index of buildings post-intervention (V<sub>f</sub>) from their initial vulnerability indices (V<sub>i</sub>) as described earlier, the following formula is employed:

$$V_f = (V_i) + (V_a - V_i) * \alpha = (V_i) + \delta_{i,C} \quad (C=H,M,L) \tag{1}$$

In this formula, V<sub>i</sub> represents the starting vulnerability index of the typology, V<sub>a</sub> is the target index associated with a new structure

**Table 2**  
Updated costs for different intervention levels in different seismicity areas (C<sub>U1</sub> = C<sub>0i</sub>\*a).

	Low Seismicity (€/m <sup>2</sup> )	Medium seismicity (€/m <sup>2</sup> )	High seismicity (€/m <sup>2</sup> )	Very high seismicity (€/m <sup>2</sup> )
<b>Local strengthening</b>	0.24*C <sub>U1</sub>	0.24*C <sub>U2</sub>	0.24*C <sub>U3</sub>	0.24*C <sub>U4</sub>
<b>Seismic improvement</b>	0.5*C <sub>U1</sub>	C <sub>U1</sub>	C <sub>U2</sub>	C <sub>U3</sub>
<b>Seismic retrofitting</b>	C <sub>U1</sub>	C <sub>U2</sub>	C <sub>U3</sub>	C <sub>U4</sub>

**Table 3**  
% C<sub>r</sub> as a function of Damage States (DS) [29].

Damage states	4.664 RC buildings					3.833 masonry buildings				
	DS1	DS2	DS3	DS4	DS5	DS1	DS2	DS3	DS4	DS5
N. of buildings	1.835	690	643	194	20	941	276	292	92	81
%Cr – 16th percentile	0 %	6 %	14 %	26 %	44 %	0 %	8 %	16 %	25 %	34 %
%Cr – median	3 %	14 %	34 %	59 %	81 %	4 %	17 %	33 %	52 %	72 %
%Cr – 84th percentile	13 %	29 %	64 %	95 %	107 %	17 %	5 %	78 %	96 %	95 %
%Cr – mean	6 %	19 %	39 %	62 %	78 %	8 %	22 %	41 %	59 %	67 %
%C – standard deviation	10 %	18 %	26 %	32 %	32 %	10 %	18 %	28 %	33 %	29 %
%Cr – CoV	64 %	105 %	149 %	195 %	191 %	76 %	116 %	157 %	163 %	235 %

**Table 4**  
Percentage assistance costs with respect to reference unit costs, % C<sub>a</sub>, as a function of Damage State (DS) [29].

Damage states	4.329 RC buildings					3.518 masonry buildings				
	DS1	DS2	DS3	DS4	DS5	DS1	DS2	DS3	DS4	DS5
N. of buildings	1.753	608	536	152	16	869	217	216	64	49
%Ca – 16th percentile	0 %	3 %	8 %	11 %	15 %	0 %	4 %	7 %	8 %	9 %
%Ca – median	0 %	10 %	20 %	25 %	38 %	0 %	11 %	16 %	19 %	18 %
%Ca – 84th percentile	10 %	25 %	37 %	40 %	47 %	11 %	24 %	36 %	29 %	46 %
%Ca – mean	4 %	14 %	23 %	27 %	35 %	5 %	14 %	21 %	22 %	23 %
%Ca – standard deviation	9 %	14 %	16 %	15 %	17 %	10 %	13 %	15 %	17 %	17 %
%Ca – CoV	206 %	95 %	71 %	55 %	51 %	206 %	93 %	74 %	78 %	75 %

**Table 5**  
Vulnerability indices representative of the ISTAT masonry sub-types [49].

ISTAT sub-type	A1 (<1919)			A2 (1919–1945)			A3 (1946–1961)			A4 (1962–1981)			A5 (>1981)		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
V	0.92	0.88	0.98	0.82	0.76	0.88	0.68	0.70	0.74	0.52	0.56	0.60	0.40	0.42	0.44

(assumed to be 0.3 for both masonry and RC typologies),  $\delta_{i,C}$  the vulnerability reduction. The variable ‘ $\alpha$ ’ takes the value of 1 (or 0.8, following [26] guidelines) for seismic retrofitting (C=H), 0.55 for seismic improvement (C = M), and 0.20 for local strengthening, respectively (C = L). This formula has been applied to derive the new vulnerability index values post-intervention across various intervention types and for the different construction typologies under consideration. It is important to note that, for an effective application of the method to different local realities, the values of  $\alpha$  should be recalibrated and a more accurate relationship than the linear one used in Eq. (1) should be formulated.

**Table 6**  
Minimum values of vulnerability index  $V_{min,k}$  for pre-established PGA values for which the k damage level is achieved.

TR [years]	30	50	72	101	140	201	475	975	2475	10000
Ag [g]	0.060	0.079	0.094	0.110	0.126	0.145	0.197	0.248	0.324	0.438
<b>Masonry</b>										
D0										
D1	1.112	1.007	0.941	0.882	0.830	0.777	0.661	0.573	0.472	0.357
D2	1.365	1.242	1.164	1.094	1.033	0.971	0.834	0.731	0.612	0.477
D3	1.838	1.680	1.581	1.491	1.413	1.333	1.158	1.026	0.873	0.701
D4	2.679	2.461	2.322	2.198	2.090	1.978	1.734	1.551	1.339	1.099
D5	4.053	3.735	3.533	3.351	3.194	3.031	2.676	2.409	2.099	1.750
<b>Reinforced concrete</b>										
D0										
D1	1.009	0.922	0.867	0.817	0.775	0.730	0.633	0.561	0.476	0.381
D2	1.111	1.024	0.970	0.920	0.877	0.833	0.736	0.663	0.579	0.484
D3	1.238	1.152	1.097	1.047	1.004	0.960	0.863	0.790	0.706	0.611
D4	1.366	1.279	1.224	1.174	1.131	1.087	0.990	0.918	0.833	0.738
D5	1.468	1.381	1.326	1.277	1.234	1.190	1.093	1.020	0.936	0.841

In order to derive the number of evacuees for each damage level suffered by a building, an average number of square meters of Habitable Surfaces per Inhabitant HSpI (m<sup>2</sup>), and a percentage of evacuee by level of damage p<sub>k</sub> (k = 1–5) must be defined for each type of construction.

## 2.4. Damage scenarios

Finally, the objective was to generate damage scenarios for predetermined PGA levels of the event. This was achieved by utilizing fragility curves calculated using the Heuristic method ([49], Colajanni and D'Anna 2023[50]) for masonry buildings, and the Macroseismic method [47] for RC buildings. For each predetermined PGA value and damage level denoted as 'k', the analysis involved determining the minimum vulnerability index value, referred to as  $V_{\min,k}$ , overcoming which the k level of damage is attained. Assuming a deterministic approach,  $V_{\min,k}$  can be calculated by referring to the mean value of PGA of the fragility curve associated to the k level of damage, given by Refs. [47,49]:

$$PGA_{Dk,Vi,k} = c_1 c_2^{[6,7-3,45Vi+(0,9+2,8Vi) \operatorname{atanh}(0,36k-1,08)]} \text{ for masonry buildings with } Vi > 0.38 \quad (2a)$$

$$PGADk,Vi,k = c_1 c_2^{[8,1-6,25Vi+2,3 \operatorname{atanh}(0,36k-1,0^8)]} \text{ for reinforced concrete buildings} \quad (2b)$$

By solving Eq. (2) with respect to the value of  $V_i$ , the value of  $V_{\min,k}$  can be calculated for each PGA value and damage level. In particular, the values of  $V_{\min,k}$  are provided for masonry and RC building, respectively, in Table 6.

## 3. Model for cost-benefit analysis

In this chapter a procedure for evaluating the economic efficiency of resource allocation for seismic interventions, focusing on the trade-offs between proactive strengthening and reactive repair is proposed. Using deterministic models, it identifies optimal intervention priorities based on parameters such as building vulnerability, intervention costs, and projected seismic impacts. Two key scenarios are analyzed: one where the percentage of evacuees per damage level remains constant across all levels and another where this percentage varies based on damage severity. The chapter emphasizes the procedure for minimizing evacuees by strategically distributing resources, highlighting the comparative benefits and limitations of different intervention types under fixed assumptions.

Following a determinist procedure, it is possible to determine the optimized economic resources allocation based on prioritizing. In this procedure, the main parameters, such as building vulnerability, costs, PGA values, average number of square meters of Habitable Surfaces per Inhabitant HSpI ( $m^2$ ), and percentage of evacuees by level of damage  $p_k$  ( $k = 1-5$ ) are assumed to be deterministic parameters, adopting assigned values. With these assumptions, it is possible to define the order to be followed to apply the different types of interventions (strengthening or repair), which allows the optimal budget allocation, taking into account the goal function, which is the reduction of the total number of evacuees across all scenarios.

To this aim, in Table 6 the values of the vulnerability index for which, for each fixed PGA level of the seismic event, the building suffers a certain damage level, is reported, for masonry and RC buildings. By means of Eq. (1), for any given value of the initial vulnerability index and for any intervention type, the value of the final vulnerability index can be easily evaluated. Thus, the expected damage level (for given PGA of the seismic event) can be evaluated according to data in Table 6. In order to provide the cost required to reduce the number of evacuees by one unit,  $C_{R1E}$ , the costs for the chosen type of intervention for the given level of seismicity of the zone,  $\beta \cdot C_{Ui}$  ( $\text{€}/m^2$ ) ( $\beta = 0.24$ , or  $0.5$ , or  $1$ , and  $C_{Ui}$  evaluated according to Table 2), must be multiplied by HSpI, and divided by the difference between the evacuation rate corresponding to the initial damage level,  $p_{ki}$ , and the one corresponding to final damage level,  $p_{kf}$ , i.e.  $C_{R1E,i} = \beta \cdot C_{Ui} \cdot \text{HSpI} 100 / (p_{ki} - p_{kf})$ . A numerical application of the above procedure will be developed in Section 4 for the case study.

## 4. A two-stage stochastic model for budget allocation

This section presents the mathematical formulation of a two-stage stochastic model. It explains how to balance proactive strengthening measures and reactive repair actions to minimize evacuees under uncertainty, considering several damage scenarios and budget constraints.

Determining the most effective budget allocation for strengthening and repair measures is a complex decision problem, which is here formulated as a two-stage stochastic model with recourse.

The decision-making process consists of two distinct moments, termed "stages". In the first stage, prior to the earthquake event, decisions regard the subset of building to be reinforced and the type of strengthening measures to be implemented on each building, respecting the maximum available budget. These actions result in a reduction of vulnerability for the involved buildings. Subsequently, in the second stage, after the occurrence of an earthquake, decisions concern allocation of residual budget to repair the occurred damages. It is important to underline that, whereas first-stage decisions are made only once and affect all the earthquake scenarios, second-stage decisions are contingent on individual scenarios and may vary among them. In accordance with stochastic optimization terminology, second-stage decisions are also referred to as recourse actions. It is important to note that the set of available recourse actions depends on the residual budget, which is a straightforward consequence of first-stage decisions. Notably, these decisions not only influence the residual vulnerability of buildings (and hence the resulting damages) but also affect the range of repair actions that can be implemented. In fact, if the entire budget would be allocated to strengthening actions during the first stage, no repair actions could be implemented in the post-earthquake scenario.

A more proactive approach would allocate a larger part of the budget to preventive strengthening actions, in order to reduce the expected damages, but the residual budget for repair interventions would be very limited. Conversely, a more reactive approach would reserve a limited amount of money for strengthening interventions, to preserve a larger part of the budget for repair. Moreover, a pure proactive and a pure reactive procedure may be applied. The former would invest the entire budget in strengthening interventions,

whereas the latter would focus only on repair of damaged buildings, without implementing any strengthening measure.

Given an earthquake intensity, the type of damage suffered by the buildings clearly depends on the level of strengthening measures applied. The higher this level, the lower the probability for the building to be damaged and the lower the severity of the damage. Repair costs are proportional to the type of damage. If a damaged building is not repaired, it is supposed that a given percentage  $p_k$  of the inhabitants must be evacuated. This percentage depends on the severity of the damage occurred,  $k$ , and it starts from 100 % for structural collapse or very severe damages, showing strong decreases for smaller damages.

A set of buildings, denoted as  $I$ , is considered and each building  $i$  is characterized by several features including: construction material (masonry or RC), total surface area  $s_i$ , number of inhabitants accommodated  $w_i$ , initial vulnerability level (if no strengthening measures are applied)  $V_i$ , costs associated with different type of strengthening actions, namely, seismic retrofitting ( $H, j = 1$ ), seismic improvement ( $M, j = 2$ ), or local strengthening ( $L, j = 3$ ) ( $b_1, b_2$  and  $b_3$ , respectively), corresponding achievable vulnerability reduction ( $\delta_{iH} = \delta_{i1}, \delta_{iM} = \delta_{i2}, \delta_{iL} = \delta_{i3}$ ).

The set of damages levels, ranging from D1 to D5, is denoted as  $K$ . Additionally, input data includes the costs required to repair the building  $i$  for a damage level  $k$ , denoted as  $c_{ik}$ . The total budget is identified as  $B$ .

A set of scenarios, denoted as  $S$ , is considered, where each scenario is characterized by a specific earthquake intensity in terms of PGA, and the corresponding damage sustained by buildings. These scenarios are formulated by considering the probability of an earthquake, with a specific intensity, to occur at a given site. For each scenario and building, the minimum vulnerability level for which a damage of level  $k$  occurs, here denoted as  $a_{iks}$ , is known. Such value is computed applying a small perturbation to the corresponding value  $V_{min,k}$ , in order to take into account that it is not always true that two earthquakes with the same intensity produce exactly same damages. Thus, this perturbation can be considered as a way to incorporate the variability in the structural response to seismic action, which is modelled by randomly varying the value of  $V_{min,k}$  given the PGA value (reported in Table 6), within a uniform distribution range [ $V_{min,k} - 0.05 \leq a_{iks} \leq V_{min,k} + 0.05$ ].

The stochastic variables used in the study are: the vulnerability of buildings, which is the same for all the considered scenarios; - the PGA of scenarios; - the PGA threshold that trigger a certain level of damage.

The objective of the decision problem is to minimize the total number of expected evacuees across all scenarios, i.e. the number of persons living in buildings that suffered a damage that could not be repaired due to budget restrictions.

The decision variables involved in the model are the following.

- $X_{ij}$ : binary variables assuming value 1 if strengthening action of type  $j$  is applied to building  $i$ , and 0 otherwise;
- $Y_{is}$ : binary variables assuming value 1 if building  $i$  has been repaired in scenario  $s$ , and 0 otherwise;
- $D_{iks}$ : binary variables assuming value 1 if building  $i$  has suffered damage of level  $k$  in scenario  $s$ , and 0 otherwise, i.e. in the scenario  $s$ ,  $\sum_{k=1}^5 D_{iks} = 0$  if the building is undamaged,  $\sum_{k=1}^5 D_{iks} = 1$  if it has suffered any level of damage;
- $Z_{iks}$ : binary variables representing the residual damage, assuming value 1 if building  $i$  has suffered the damage of level  $k$  in scenario  $s$  and has not been repaired, and 0 otherwise. It has a unit value if the building is damaged and it has not undergone repair intervention;
- $C_{is}$ : variables indicating the cost paid to repair building  $i$  in scenario  $s$ .

The two-stage mathematical model was formulated as follows:

$$\min \sum_i \sum_s \sum_k p_k w_i Z_{iks} \tag{3}$$

s.t.

$$\sum_{j=1}^3 X_{ij} \leq 1 \quad \forall i \in I \tag{4}$$

$$\sum_i \sum_j c_{ij} X_{ij} + \sum_i C_{is} \leq B \quad \forall s \in S \tag{5}$$

$$Y_{is} + \sum_k Z_{iks} = \sum_k D_{iks} \quad \forall s \in S \quad \forall i \in I \tag{6}$$

$$Z_{iks} \leq D_{iks} \quad \forall s \in S \quad \forall i \in I \quad \forall k \in K \tag{7}$$

$$D_{iks} \geq \left( V_i - \sum_j \delta_{ij} X_{ij} \right) - a_{iks} - \sum_{l \in \{k+1, \dots, K_{max}\}} D_{ils} \quad \forall s \in S \quad \forall i \in I \quad \forall k \in K \tag{8}$$

$$\sum_k D_{iks} \leq 1 \quad \forall s \in S \quad \forall i \in I \tag{9}$$

$$C_{is} \geq \sum_k c_{ik} D_{iks} - B(1 - Y_{is}) \quad \forall s \in S \quad \forall i \in I \tag{10}$$

$$C_{is} \geq 0 \quad \forall s \in S \quad \forall i \in I \tag{11}$$

The objective function, reported in Eq. (3), aims to minimize the overall expected number of evacuees across all scenarios. Constraints (4) state that each building can undergo at most one strengthening action. Constraints (5) ensure that the combined costs of strengthening, and repair actions do not exceed the maximum allowable budget B. Constraint (6) impose that if damage occurs, then the building must undergo a repair action or remain damaged, with a consequent expected evacuation of a percentage of inhabitants depending on the level of damage. Constraints (7) imply that the residual damage cannot be higher than the occurred one. Constraints (8) ensure that, for damage level k, if the final vulnerability at the end of the strengthening action, calculated as the initial vulnerability minus the vulnerability reduction achieved through strengthening actions, overcomes the threshold above which a specific damage level is likely to occur in a specific scenario ( $a_{iks}$ ), and there was no higher level damage, i.e. the  $\sum_{l \in \{k+1..K_{max}\}} D_{ils} = 0$ , the damage of level k occurred; if instead  $\sum_{l \in \{k+1..K_{max}\}} D_{ils} = 1$ ,  $D_{iks} = 0$  and the damage that occurred is of level higher than k. Constraints (9) enforce the limitation that only one damage level can occur at most. Constraints (10) allows computing the cost paid for repairing a building in a particular scenario, which depends on the damage occurred. In fact, if the building has been repaired,  $Y_{is} = 1$ , the cost spent to repair it is equal to the cost of the repair related to the damage suffered; if the building has not been repaired,  $Y_{is} = 0$ , and since B is the entire budget, the term on the left hand side of Eq. (10) is negative and the relationship is verified for any value of  $C_{is}$ . The value given to  $C_{is}$  will be set equal to 0 by the optimization procedure, in order to obtain the minimum in Eq. (3) according to Eq. (5). Finally, constraints (11) impose these costs to be non-negative.

### 5. Case study

Focusing on the municipality of Patti, Sicily, this chapter applies the proposed stochastic model to a real-world context. It describes the region’s building typologies, vulnerability indices, and simulated damage scenarios to validate the model’s effectiveness.

#### 5.1. Cost benefit analysis

This section evaluates, as an example, the economic efficiency of resource allocation for seismic interventions according to the procedure described in Section 3, applied to the considered case study for a given scenario. The application will be carried out assuming a scenario characterized by  $PGA = 0.248g$ .

The evaluation of strengthening costs associated to different levels of intervention and repair costs has been described in Section 2; for the sake of clarity, these costs are presented in the following Table 7.

Based on the costs in Table 7, assuming  $HSpI = 35 m^2$ , and a percentage of evacuees by damage level independent from building typology, the following tables (Tables 8 and 9) have been built, for masonry and reinforced concrete constructions. The tables have been constructed in the case of Constant Percentage of Evacuees (CPE) ( $p_k = 100\%$  for damage levels  $k = 1-5$ ,  $p_0 = 0$  for damage level D0) (Table 8) and in the case of Variable Percentage of Evacuees (VPE) ( $p_5 = p_4 = p_3 = 100\%$ ,  $p_2 = 50\%$ ,  $p_1 = 10\%$ ,  $p_0 = 0$ ) for selected damage levels [51] (Table 9), respectively. The tables show the prioritization (first column) of different types of interventions, with the aim to achieve the optimal budget allocation. In particular, interventions on masonry are highlighted in orange, while interventions on RC are underlined grey. The second column of the tables reports the costs, which are strengthening costs or repair costs (according to Table 7), with ascending order in Table 8, since a CPE is set. The third columns, presents the cost to reduce the total number of evacuees of one unit. It should be noted that, since for CPE  $100/(p_k-p_0) = 1$  for any damage levels  $k = 1-5$ , the cost/evacuee has been evaluated by multiplying the cost for  $m^2$  of intervention by  $HSpI = 35 m^2$ , being the latter the surface destined to a single person. Thus, both column of intervention cost/ $m^2$  and column of cost/evacuee are characterized by increasing cost values. Each cost is associated to a defined type of intervention (fourth column), according to Table 7, and each intervention is applied to buildings having a certain vulnerability. As for the vulnerability, Table 6 in Section 2 reports the minimum values of vulnerability index  $V_{min,k}$  for pre-established PGA values for which the k damage level is achieved; thus, these vulnerability values ( $V_{min,k}$ ) represent the thresholds with which comparing the vulnerability values of buildings (V), in order to define the damage level achieved. It should be noted that in the case of CPE, the objective function is the reduction of the total number of evacuees, taking into account that damaged buildings cannot host residents, regardless the damage level achieved (from D1 to D5). Thus, the actions useful to decrease the evacuee number are those that can guarantee a transition from any damage (D1-D5) to D0 level. Actions reducing damage from higher to lower levels, without reaching D0, could be efficiently applied only if combined with other actions (subsequent repair), in order to achieve the objective of no damage at the end of repair intervention. However, for the sake of brevity, in this case, only actions able to guarantee

**Table 7**  
Strengthening and repair costs for masonry and RC constructions.

STRENGTHENING COSTS (€/m <sup>2</sup> )		REPAIR COSTS (€/m <sup>2</sup> )					
Masonry	Seismic retrofitting	425.00	D1	D2	D3	D4	D5
	Seismic improvement	320.00	176.00	486.00	837.00	1094.00	1215.00
	Local strengthening	102.00					
Reinforced concrete	Seismic retrofitting	600.00	D1	D2	D3	D4	D5
	Seismic improvement	453.00	135.00	446.00	837.00	1202.00	1526.00
	Local strengthening	144.00					

**Table 8**

Prioritization of interventions on masonry and RC constructions, in the case of constant percentage of evacuees (CPE) ( $p_k = 100\%$ ) for all damage levels ( $k = 1-5$ ).

CPE			
Priority	Cost (euro/m <sup>2</sup> )	Cost/evacuee <sup>a</sup> (euro)	Action
I	102.00	3566.00	Local strengthening of masonry buildings to move from D1 to D0 damage
II	135.00	4725.00	Repair of RC buildings form D1 to D0 damage
III	176.00	6143.00	Repair of masonry buildings from D1 to D0 damage
IV	320.00	11206.00	Seismic improvement of masonry buildings to move from D1 to D0 damage
V	425.00	14859.00	Seismic retrofitting of masonry buildings to move from D1 to D0 damage
VI	445.00	15575.00	Repair of RC buildings form D2 to D0 damage
VII	452.00	15820.00	Seismic improvement of RC buildings to move from D1 to D0 damage
VIII	486.00	17010.00	Repair of masonry buildings form D2 to D0 damage
IX	600.00	21000.00	Seismic retrofitting of RC buildings to move from D1 to D0 damage
X	837.00	29295.00	Repair of RC buildings form D3 to D0 damage
XI	1202.00	42053.00	Repair of RC buildings form D4 to D0 damage

<sup>a</sup> Cost to reduce the total number of residual evacuees of one unit ( $C_{RIE}$ ).

**Table 9**

Prioritization of interventions on masonry and RC constructions, in the case of variable percentage of evacuees (VPE) for different damage levels ( $p_4 = p_3 = 100\%$ ,  $p_2 = 50\%$ ,  $p_1 = 10\%$ ).

VPE			
Priority	Cost (euro/m <sup>2</sup> )	Cost/evacuee <sup>a</sup> (euro)7	Action
I	102.00	7132.00	Local strengthening of masonry buildings to move from D3 to D2 damage.
II	102.00	8916.00	Local strengthening of masonry buildings to move from D2 to D1 damage.
III	144.00	10080.00	Local strengthening of RC buildings to move from D3 to D2 damage.
IV	144.00	10080.00	Local strengthening of RC buildings to move from D4 to D2 damage
V	144.00	12600.00	Local strengthening of RC buildings to move from D2 to D1 damage.
VI	320.00	28014.00	Seismic improvement of masonry buildings to move from D2 to D1 damage
VII	837.00	29295.00	Repair of RC buildings form D3 to D0 damage
VIII	445.00	31150.00	Repair of RC buildings form D2 to D0 damage
IX	486.00	34020.00	Repair of masonry buildings form D2 to D0 damage
X	102.00	35662.00	Local strengthening of masonry buildings to move from D1 to D0 damage
XI	452.00	39550.00	Seismic improvement of RC buildings to move from D2 to D1 damage
XII	1202.00	42053.00	Repair of RC buildings form D4 to D0 damage
XIII	135.00	47250.00	Repair of RC buildings form D1 to D0 damage
XIV	176.00	61425.00	Repair of masonry buildings from D1 to D0 damage
XV	320.00	112056.00	Seismic improvement of masonry buildings to move from D1 to D0 damage
XVI	425.00	148590.00	Seismic retrofitting of masonry buildings to move from D1 to D0 damage
XVII	452.00	158200.00	Seismic improvement of RC buildings to move from D1 to D0 damage
XVIII	600.00	210000.00	Seismic retrofitting of RC buildings to move from D1 to D0 damage

<sup>a</sup> Cost to reduce the total number of residual evacuees of one unit ( $C_{RIE}$ ).

transition to D0 damage are considered. As an example, the first line of [Table 8](#) reports the cost associated to the interventions of local strengthening on masonry buildings, which allows moving from D1 to D0 damage and it has priority I since it is the less expensive.

[Table 9](#) is constructed following the same procedure, but it shows some differences compared to [Table 8](#). The objective function is the same, measuring the reduction of the total number of evacuees, but the way the evacuees are evaluated according to suffered damages is different. Indeed, for VPE, since different percentage of evacuees are assigned to different damage levels, then it is also advantageous the transition from higher to lower damage levels characterized by lower percentage of evacuees, yielding various benefits based on the initial damage level and the extent of reduction. This leads to apply interventions previously not convenient for CPE, since they are now economically convenient according to the goal function and evacuees' percentage for damage level. Thus, in this case all the interventions are potentially convenient, with the priority order reported in the table (see [Table 9](#)) obtained by ascending cost for reduction of one evacuee (cost/evacuee). Therefore, in this scenario, the distribution of budget for various interventions does not adhere to a sequence where less expensive actions necessarily come before more costly ones, as the feasibility is influenced by the goal function.

In the following, this procedure will be compared to the results obtained through the adoption of a two-stage stochastic model used for determining the most effective budget allocation for strengthening and repair measures. It should be noted that the procedure described in the current section is a heuristic procedure in the deterministic field, thus it is possible that the optimal solution is not reached. In addition, as has been discussed in the previous sections, the stochastic model is able to take into account for uncertainties that in the deterministic model are not considered, such as the variation of PGA in different scenarios. Moreover, given two scenarios with the same PGA, it is not sure that there will be analogous damages and the stochastic model is able to include this possibility by introducing damage perturbation (through  $V_{\min,k}$  perturbation,  $[V_{\min,k} - 0.05, V_{\min,k} + 0.05]$ , see previous section) while keeping the same PGA. In particular, this perturbation will be introduced scenario by scenario and building by building.

5.2. Optimal budget allocation by stochastic analysis

The stochastic model outlined earlier has been employed in the case study of municipality of Patti, situated in Sicily (Italy), spanning approximately 50.08 square kilometers and comprising roughly 3787 building units, accommodating a population of around 13,347 residents. To evaluate seismic vulnerability via the CARTIS procedure [23,43,50], the area was divided into ten compartments, each containing distinct masonry and/or RC typologies. Table 10 offers a comprehensive breakdown, detailing the compartments, typologies, the quantity of buildings for each typology in every compartment, the initial vulnerability index  $V_i^*$ , the mean value of the sum of the modifiers  $\Delta V_i$ , and the total vulnerability index  $V_i = V_i^* + \Delta V_{i,m}$  [47]. The initial vulnerability index  $V_i^*$  characterizes the average vulnerability of the type identified based on the EMS98 macroseismic scale [42] (white value for the typology), while the mean value of the sum of the modifiers  $\Delta V_i$  characterizes the average variation of the vulnerability of the typology with respect to the white value  $V_i^*$ , due to the particular characteristics of the buildings in that compartment (number of floors, detailed characteristics of the masonry, type of slab and roof, regularity in plan and elevation, presence of chains or barbicans; etc ...).

This research marks the initial application of the procedure to a practical scenario. With the aim to limit the computational load for its implementation, hundred cluster of buildings, distributed across different compartments based on the actual percentage of typologies, is taken into account. Each cluster is formed by building belonging to the same typological class. Each cluster contains an average number of 3787/100 buildings, with small variations around the mean in order to exactly represent the number of buildings belonging to the given typology in the given sector. The grouping of buildings into clusters is also aimed at representing decision-making constraints on the application policies of seismic vulnerability reduction interventions, which force us to forecast interventions on clusters of buildings with pre-established typological characteristics, rather than on the single building.

The analysis involves simulating ten post-earthquake damage scenarios, generated by earthquakes with a randomly assigned PGA assumed constant throughout the municipality. The PGA is characterized as a random variable with a probability of exceeding the  $a_g$  value of peak ground acceleration on rocky and flat soil, given by  $P_{vr} (PGA > a_g) = 1 - \exp(-V_n/T_R)$ , where  $V_n$  represents the building's nominal life and  $T_R$  the return period as specified in the Italian code [26] for the municipality of Patti. Hence, for the ten S1-S10 scenarios, the following acceleration values were employed:  $a_g = 0.248$  ( $T_r = 975$ ) for scenarios S1 and S9;  $a_g = 0.126$  ( $T_r = 140$ ) for S2;  $a_g = 0.324$  ( $T_r = 2475$ ) for S3 to S5;  $a_g = 0.145$  ( $T_r = 201$ ) for S6 and S10;  $a_g = 0.197$  ( $T_r = 475$ ) for S7 and S8.

Regarding the initial vulnerability of each building, it was assessed as a Gaussian-distributed random variable, utilizing the mean value from Table 10 and a standard deviation equivalent to one-third of the value that ensures a 99 % probability of the typology vulnerability index falling within the  $[V_{i,min}, V_{i,max}]$  range of extreme vulnerability index values for that EMS98 typology.

The cost per unit area for various levels of strengthening interventions was derived from FEMA costs, updated with reference to the DPCI 2021, as outlined in the preceding section. To calculate the actual cost for building "i," the cost per square meter was multiplied by the building's surface area and the number of floors. The surface area was determined as a uniformly distributed random variable, based on the typology's maximum and minimum dimensions provided in the CARTIS form. A similar approach was taken for the

**Table 10**  
Vulnerability indices and percentages of typologies.

Compartment	Tot. Buildings	Typology	N. Buildings	% in compartment	TIP EMS98	$V_i^*$	$\Delta V_{i,m}$	$V_i$
C01	854	MUR 1	512	60	M1	0.893	0.067	0.9601
		MUR 2	128	15	M1	0.873	0.125	0.9978
		MUR 3	214	25	M1	0.853	0.025	0.8781
C02	1088	CAR 1	272	25	RC1	0.644	0.054	0.6975
		CAR 2	381	35	RC2	0.484	0.045	0.5285
		CAR 3	272	25	RC2	0.484	0.015	0.4985
		CAR 4	163	15	RC3	0.324	0.118	0.4420
C03	67	CAR 1	67	100	RC3	0.324	0.050	0.3740
C04	591	CAR 1	177	30	RC2	0.484	0.052	0.5355
		CAR 2	414	70	RC2	0.484	0.023	0.5065
C05	161	CAR 1	57	35	RC1	0.644	-0.013	0.6315
		CAR 2	32	20	RC1	0.644	0.053	0.6965
		CAR 3	56	35	RC2	0.484	0.034	0.5175
		CAR 4	16	10	RC2	0.484	0.033	0.5175
C06	113	CAR 1	45	40	RC3	0.324	-0.013	0.3115
		CAR 2	34	30	RC2	0.484	-0.008	0.4765
		CAR 3	34	30	RC2	0.484	0.045	0.5285
C07	604	MUR 1	121	20	M3	0.78	0.109	0.8885
		CAR 1	181	30	RC1	0.644	0.055	0.6985
		CAR 2	121	20	RC1	0.644	0.113	0.7565
		CAR 3	60	10	RC2	0.484	0.006	0.4900
C08	32	CAR 4	121	20	RC1	0.644	0.100	0.7440
		CAR 1	32	100	RC2	0.484	0.001	0.4845
C09	181	CAR 1	27	15	RC2	0.484	0.005	0.4886
		CAR 2	45	25	RC2	0.484	0.095	0.5793
		CAR 3	109	60	RC2	0.484	0.041	0.5245
C10	96	MUR 1	82	85	M3	0.78	0.105	0.8846
		MUR 2	14	15	M3	0.76	0.148	0.9075

number of floors, considering the maximum and minimum values for each typology.

The reduction in vulnerability following interventions was computed using Eq. (1). The number of inhabitants was correlated with the building's surface area and assessed as a random variable, featuring a Gaussian distribution centered around the mean value of  $HSpI = 35 \text{ m}^2$  of habitable surfaces per inhabitant and a standard deviation of  $1.67 \text{ m}^2$  per inhabitant.

The mathematical model was solved using the Xpress 8.13 commercial solver and executed on a machine equipped with an 11th Gen Intel Core i7-1185G7 processor and 32 GB of RAM. The model was run with a time limit of 1 h for each scenario, and if it did not converge to optimality, the best solution obtained up to that point was considered.

### 6. Results

In this section, the outcomes of the analyses performed by using the two-stage stochastic model with recursions are here presented and discussed with the support of the results of cost-benefit analysis.

The cases for which the optimal allocation of the budget was found are those up to budget 200.000 euros, for the case of constant percentage of evacuees (CPE); up to 1 million and, then, 1.3 million, 2 million and 4 million, for the case of variable percentage of evacuees (VPE).

Fig. 1 and 2 presents the optimization of percentage of budget allocated for proactive strengthening (PS) or reactive repair (RR) interventions as a function of the actual budget. Thus, the sum of percentage of the actual budget allocated for PS or RR is 100 % for each abscissa. The actual budget was defined as percentage respect to the Budget required for the seismic Retrofitting of All the Buildings (BRAB) of the municipality of Patti (€ 1614,000,000), evaluated as product between the total surface of the hundred cluster of sub-typologies (equal to about 388,900  $\text{m}^2$  for masonry sub-typologies and 2,415,000  $\text{m}^2$  for RC sub-typologies), and the seismic retrofitting cost per square meter (424.54 €/m<sup>2</sup> for masonry buildings and 600 €/m<sup>2</sup> for RC buildings). The curves are differentiated for the case of constant percentage of evacuees (CPE) ( $p_k = 100 \%$ ) for all damage levels and the case of variable percentage of evacuees (VPE) for different damage levels ( $p_5 = p_4 = p_3 = 100 \%$ ,  $p_2 = 50 \%$ ,  $p_1 = 10 \%$ ). The graph gives important information about the amount of the total budget that is convenient to allocate for preventive strengthening in order to minimize the number of evacuees after the seismic event, according to the available budget. This information can be correlated with the prioritization shown in Tables 8 and 9. However, it is important to point out that the prioritization of Tables 8 and 9 refers to a deterministic scenario, both for the peak acceleration value of the seismic event and for the vulnerability values to which the different levels of damage correspond; therefore, it can only be used to interpret the results of the stochastic model in an approximate way. Considering the graph, with reference to the case of CPE, for low budgets, consistently with the indication derived by Table 8, only a small percentage of money (about 2 %) should be used for proactive strengthening, while the rest is expected to be used for repair of RC building after the seismic event. As the allocated budget increases, there is an increment of the budget percentage to be used for strengthening actions with consequent corresponding decrement of the percentage of budget destined for repair. This trend is marked up to the budget value of about 6 % of BRAB and, after this point, the curves show similar behaviour, but with softer trend, up to the value of about 12 % of BRAB, which represents the value for which about 50 % of the budget should be allocated for preventive strengthening. After this point, with the further increase of the allocated budget, the graph shows that it is more convenient allocating more budget for strengthening intervention respect to repair interventions, and the ratio is higher as the available total budget increases.

The graph in Fig. 2b shows the percentage of BRAB used for proactive strengthening (PS) or reactive repair (RR) actions, with the variation of the actual budget, again expressed as percentage of the BRAB, in the case of CPE and VPE respectively. Thus, the sum of percentage of the BRAB allocated for PS or RR is equal to the percentage of BRAB for each abscissa. Considering CPE, as commented for the previous graph (Fig. 2a), if a low budget is available, it is used for almost only repair actions. When the total budget increases, it is used for both strengthening and repair interventions, in different amounts, higher for repair up to the budget of about 12 % of BRAB, and higher for strengthening for greater budgets.

The trend showed by the curves for CPE can be explained considering the goal function and making an analysis of the cost. More in detail, the objective is represented by the reduction of the total number of evacuees across all scenarios, considering that damaged buildings cannot host residents, independently from the damage level (from D1 to D5). Thus, it is clear that the first actions to be undertaken are those that can guarantee a transition from any damage level to D0. This condition fixed, the budget allocation for different interventions starts with the cheaper action that, according to Table 8 is the local strengthening of masonry buildings to pass from D1 to D0. However, for the considered case study, only a small amount of money (2–3% of intervention, up to 3.2 % of BRAB)

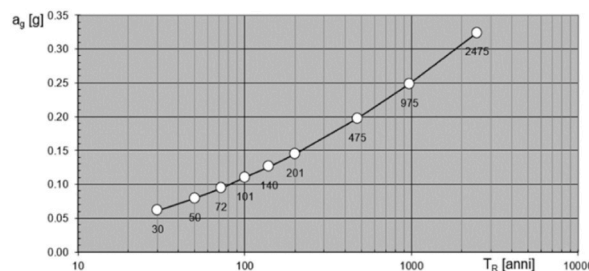


Fig. 1. Variation of  $a_g$  in relation to the return period  $T_R$  for the municipality of Patti.

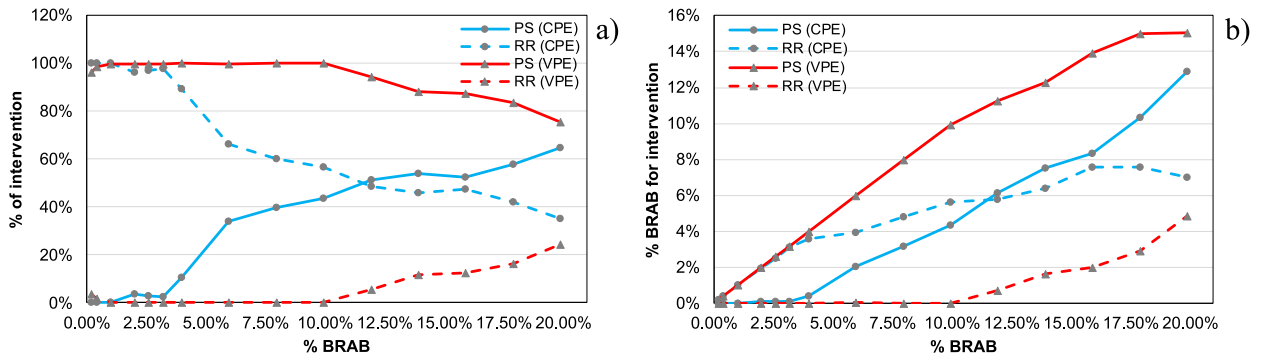


Fig. 2. a) and b) Percentage of actual budget allocated for optimized strengthening or repair, in the case of CPE and VPE.

should be used for strengthening masonry building, due to the circumstance that, considered the high vulnerability of masonry buildings of the municipality under study, the number of buildings that suffer D1 damage which could be reduced with a simple local strengthening intervention, is very small. The following interventions expected according to Table 8, which are actually the first relevant adopted actions, are the repair of RC and masonry buildings to move from D1 to D0 and this prediction is congruent with the results reported in Fig. 2, which predict almost only repair up to a budget of 3.20 % of BRAB. Afterward, Table 8 predicts strengthening actions (seismic improvement and retrofitting, respectively) on masonry buildings, followed by, alternatively, other strengthening and repair actions on masonry and RC constructions, as showed by Fig. 2 also.

Regarding the case of VPE, the trend is different compared to the case of CPE, and this can be explained referring to the different correlation between damage and number of evacuees. Although the goal function (reduction of evacuees' number) is the same for both cases, different outcomes are found based on the way the evacuees are estimated according to suffered damages. Thus, for VPE, taking into account the different percentage assigned to different damage levels, it is convenient also moving from higher to lower damage levels, obtaining different benefits depending on the starting damage level and the number of reduced damage levels. More in detail, a reduction of evacuees is obtained either by reducing suffered damage from D5, D4 and D3 to D2 (Reduction of Percentage of Evacuees RPE is 50 %), to D1 (RPE = 90 %), or to D0 (RPE = 100 %), but also by reducing damage from D2 to D1 (RPE = 40 %) or D0 (RPE = 50 %) and, lastly, from D1 to D0 (RPE = 10 %). Thus, in this case, the budget allocation for different interventions does not follow an order in which cheaper actions necessarily precede more expensive ones, since the convenience is influenced by the goal function. According to Table 9, where actions are prioritized based on the ratio between costs and reduced evacuee, first actions are those of local strengthening of masonry buildings first and reinforced concrete buildings later, and this is coherent with the outcomes presented in Fig. 2, which predicts only strengthening up to a budget of about 10 % of BRAB. After that budget, Table 9 also predicts repair actions on both RC and masonry buildings, followed by, alternatively, other strengthening and repair actions, as showed by Fig. 2. In particular, Fig. 2 points out that strengthening is the only action up to a budget value of about 10 % of BRAB. After this point, as the allocated budget increases, it can be detected an increment of the budget percentage destined to repair actions and a corresponding decrease of the budget to be used for strengthening. This trend continues up to the maximum budget value of about 20 % of BRAB, for which about 75 % of the budget should be allocated for preventive strengthening and 25 % for repair.

These results are confirmed by the curve reported in Fig. 2b (for VPE), which underlines that the whole budget is destined to strengthening actions, up to a value of about 10 % of BRAB, and the amount of budget for strengthening is always higher respect to that used for repair.

The comparison between curves in Fig. 2a, as well as between those in Fig. 2b, proves the paramount importance of the correlation between damage and number of evacuees in defining the optimization of priorities strengthening and repair actions must be conducted with.

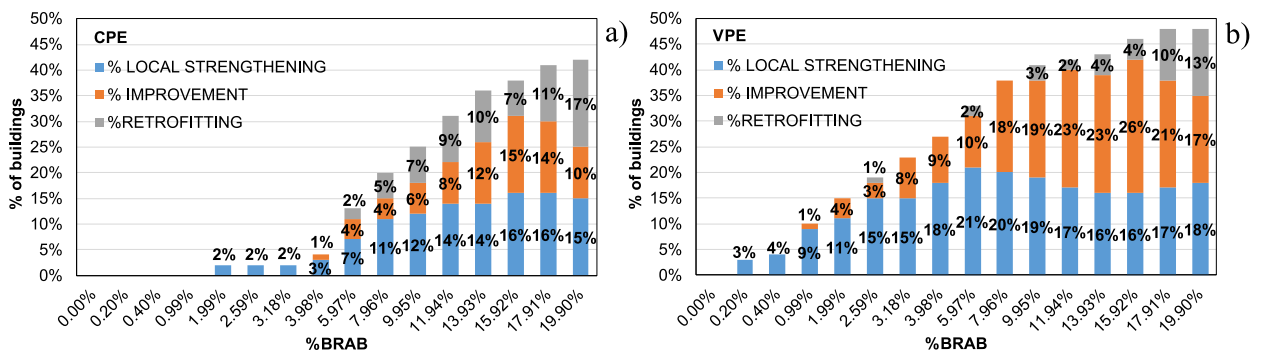


Fig. 3. a) and b) Percentage of buildings subjected to strengthening interventions of high, medium and low level, for CPE and VPE, respectively.

The graphs in Fig. 3a and b present the percentages of buildings subjected to different intervention, namely seismic retrofitting, seismic improvement, local strengthening, with the variation of the budget allocated, for CPE and VPE respectively. Considering the case of CPE (Fig. 3a), for very low values of the budget, up to 1 % of BRAB, all the percentages relative to different strengthening interventions are zero since buildings are subjected to repair interventions only. As the budget increases, a low percentage is invested for local strengthening of a small number of masonry buildings, and, starting from about 4 % of BRAB, also for seismic improvement on few masonry buildings (see Table 8). Considering a certain budget, the higher percentage of buildings is subjected to local strengthening intervention, followed by a considerable percentage subjected to improvement and seismic retrofitting. The latter are preponderant only for the maximum value of the budget considered. In general, the percentages of buildings subjected to different interventions increase with the increase of the available budget, with some exceptions due to fluctuations caused by the stochastic nature of the problem.

Considering the case of VPE (Fig. 3b), for very low budget values, local strengthening, first of masonry buildings and later of RC ones, is the only expected intervention, which increases gradually up to a budget value of about 6 %, following a subsequent small fluctuation. Starting from a budget value of about 1 % of BRAB, there is a small, but increasing percentage of buildings undergoing seismic improvement interventions. In particular, this percentage increases up to 16 % of BRAB, showing a following decrement. As for retrofitting, the percentage of buildings subjected to this intervention is almost not detectable up to a budget value of 8 % of BRAB, remaining very low also up to about 16 % of BRAB. After this point, the retrofitting is applied on considerable percentages of buildings, with corresponding decrease of seismic improvement, and the maximum percentage value is achieved for the maximum total budget (19.9 % of BRAB), for which 13 % of buildings undergoes retrofitting intervention.

The graphs in Fig. 4a–d show the same results of Fig. 3, but divided by masonry and R.C buildings, for CPE (Fig. 4a and Fig. 4b) and VPE respectively. From the graphs it is clear that, for masonry buildings, both in the case of CPE and VPE, local strengthening is the less common strengthening intervention, while retrofitting and Fig. 4c and Fig. 4d dimprovement are the dominant ones for CPE and VPE, respectively, i.e. depending on the percentage of evacuees in the definition of the target function. On the other hand, regarding R.C buildings, seismic retrofitting interventions are not adopted and local strengthening intervention is the main type of intervention type, regardless of whether CPE or VPE is taken.

The graph in Fig. 5a shows the curves (blue and red) of the percentage of evacuees remained after the final intervention of repair, with the variation of the allocated budget, for CPE and VPE respectively. The comparison is done between the case when the budget allocation is optimized between PS and RR (solid line), with the case in which all the budget is used for RR only (PS cost = 0 %) (dotted line). Both in the case of CPE and VPE, the curves point out that, as expected, the percentage of evacuees decreases with the increase of money allocation for interventions. Moreover, considering a fixed budget, the evacuees' percentage is lower for optimized PS + RR respect to RR budget allocation only, and the difference increases with the increment of the allocated budget, for both CPE and VPE. This is better pointed out by the grey curves, which represent, one for each case (CPE and VPE), the difference between remaining

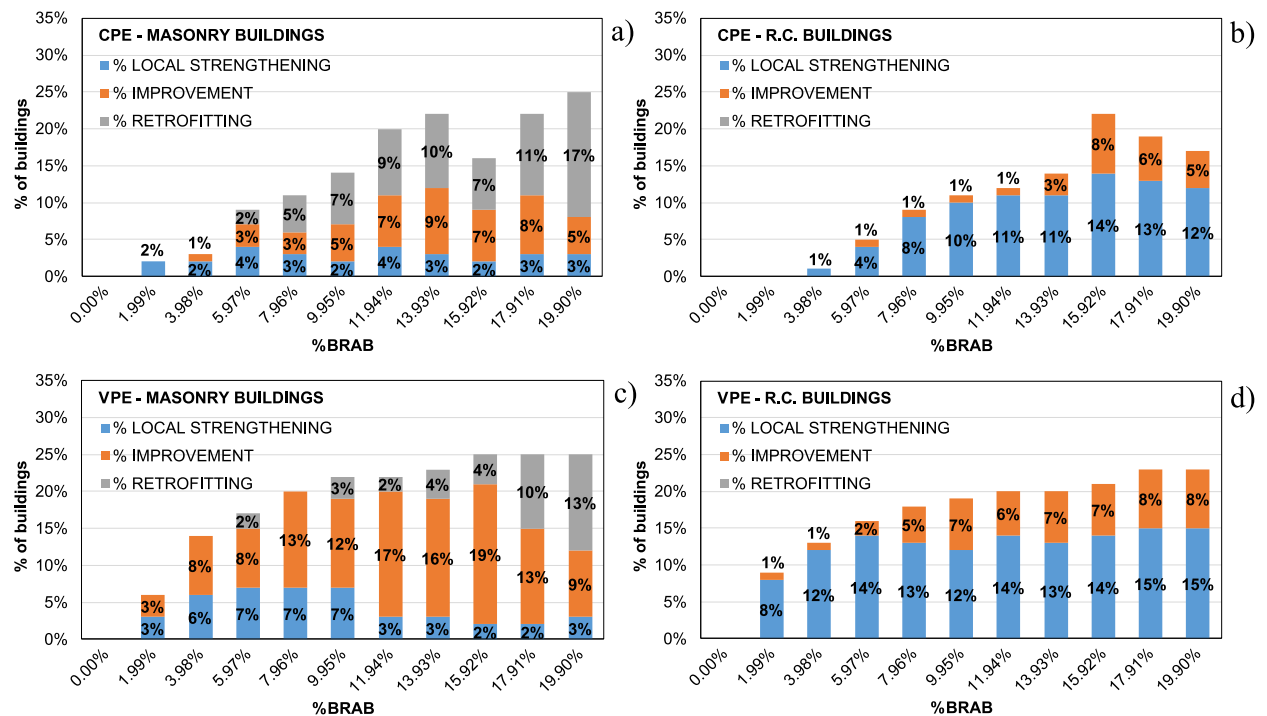


Fig. 4. a), b), c) and d) Percentage of masonry and R.C. buildings subjected to strengthening interventions of high, medium and low level, for CPE and VPE, respectively.

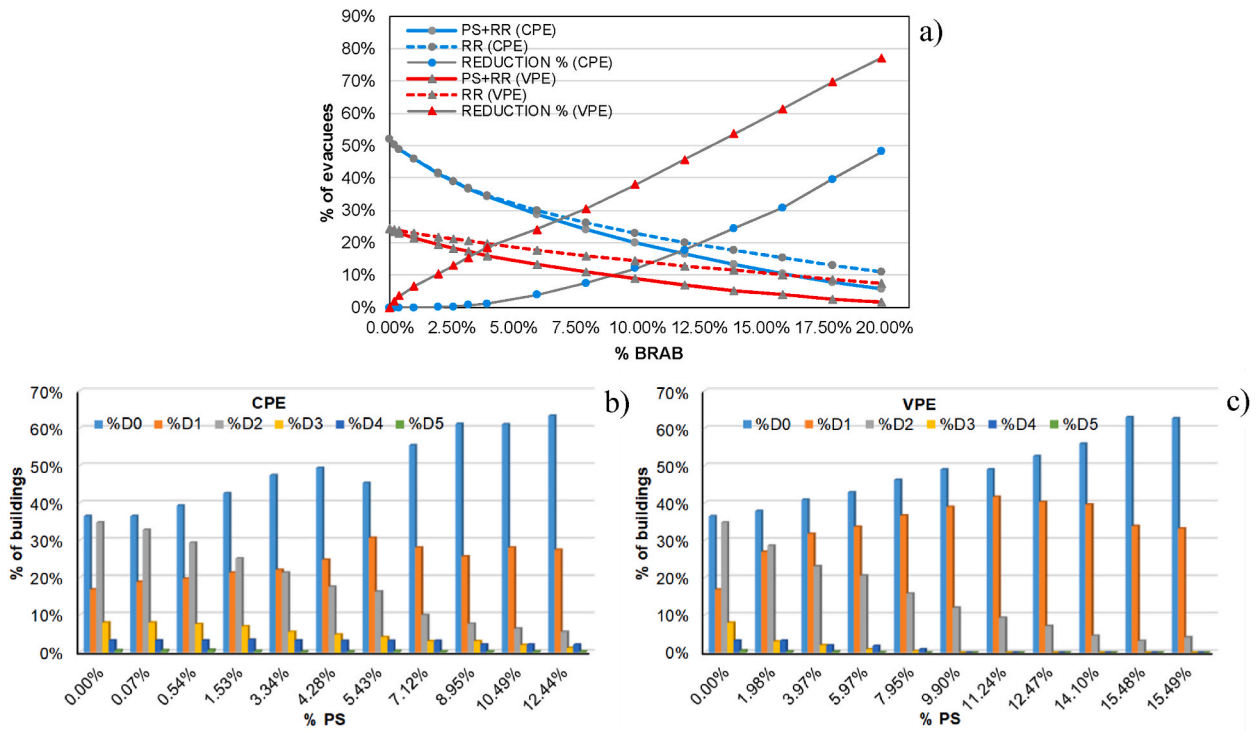


Fig. 5. a) Percentage of remaining evacuees for different budgets; Mean damage distributions after proactive strengthening actions in the case of b) CPE and c) VPE.

evacuees' percentage for RR and PS + RR, normalized respect to the evacuees' percentage for RR. The curves show that the larger the budget, the larger the difference in reduction in the remaining evacuees' percentage with PS + RR budget allocation and RR only.

In the graphs in Fig. 5b and c, for CPE and VPE respectively, the mean damage distribution (obtained as average values from all the considered scenarios) after PS interventions and the seismic event is presented, considering the variation of the budget destined to strengthening interventions only, as percentage respect to BRAB; these damage distribution is compared with the damage in absence of PS interventions (0 % PS). As previously underlined, the choice of the type and amount of strengthening intervention suggested by the optimization procedure is strongly influenced by the correlation between damage and number of evacuees, and the number of evacuees is affected even more significantly by this correlation. However, once the number and type of strengthening intervention have been decided, the distribution of damage is no longer dependent on the correlation between damage and evacuees. Therefore, the comparison between data in Fig. 5b and c allows verifying the changes in the expected damage after the earthquake, in relation to the choices generated by the two different laws of correlation between damage and evacuees.

Based on the results in the figure, the first thing to be underlined is that, in the case of both CPE and VPE, the percentages of buildings that after strengthening interventions suffered no damage (D0) or light damage (D1) grow as the invested budget increases, and D0 presents always the higher percentage. This is true for almost all considered budgets, with some exceptions involving the four largest budgets, which show reductions in D1 percentages due to larger increases in D0 percentages. For D2 damage level, the two graphs for CPE and VPE show a similar trend, characterized by a progressive decrease with the budget increment, but this effect is more marked for VPE case. The main difference between the two cases, CPE and VPE, is related to the reduction of percentage of buildings that suffer high damages, namely D3, D4, and D5, which are slightly and progressively reduced for the CPE correlation, while are quickly almost eliminated for VPE correlation. This circumstance prove that VPE correlation between damage level and percentage of evacuees, which is surely more realistic, is also more performing.

### 7. Conclusions

The paper addresses the decision-making aspects related to the optimal allocation of funds for both proactive reinforcement of residential buildings and reactive repair measures following an earthquake. The goal was to minimize the number of evacuees, namely the number of people that were resident in damaged buildings. To achieve this objective, a two-stage stochastic model with recursions was utilized to carried out the analyses, operating under the assumption of a predetermined maximum cumulative budget available for proactive and/or reactive measures.

The stochastic model was formulated considering the outcomes of an innovative technique for the assessment of seismic exposure of residential buildings, namely the use of interview-based CARTIS form, which is under development in Italy by ReLUIS, coordinated by the Italian Civil Protection Department. Vulnerability of residential buildings was evaluated according to the Heuristic method for

masonry buildings and the Macro seismic method for RC buildings. Intervention costs were determined based on international literature and recent seismic risk mitigation policies adopted by the Italian government. The effect of two correlations between damage level and evacuees' was investigated, namely one that involved evacuation of all inhabitants of damaged buildings, regardless of the damage degree sustained (CPE), and a second more realistic one that reduced the percentage of evacuees in buildings sustaining D2 (50 %) and D1 (10 %) damage (VPE). The procedure was applied to a small municipality of the west Sicily (Italy).

Based on the discussions reported in the previous sections, the following conclusions can be drawn.

- The percentage of evacuees decreases with the increase of resources allocation for interventions. For a fixed budget, the evacuees' percentage is lower for optimized budget allocation between PS + RR respect to budget allocation only for RR, and the difference increases with the increment of the allocated budget, for both CPE and VPE.
- The optimal budget allocation is very sensitive to the correlation between damage level of buildings and number of evacuees.
- Regarding the allocation of budget for proactive and reactive actions, considering the case of CPE, for low budgets, only a small percentage of resources should be used for strengthening, while the larger part is expected to be used for post-earthquake repair; in the case of VPE, with reference to low budgets, an opposite trend was detected. With the increase of the available total budget, the following outcomes were found. Considering CPE, an increment of the budget percentage to be used for strengthening actions was observed, with a correspondent decrement of the budget destined for repair; for high budget values, it was more convenient allocating higher budget for strengthening intervention respect to repair interventions. In the case of VPE, the larger part (75 %) of the budget should be destined to proactive strengthening and only a smaller part of budget (25 %) to repair.
- As for the percentage of buildings subjected to different strengthening interventions, the following results have been found. Considering the case of CPE, for low values of the budget, local strengthening is the only type of suggested intervention and should be applied to a low percentage of buildings; with the increase of the total available budget, an increment of the percentages of all type of proactive interventions was observed. For a fixed budget, local strengthening is always the intervention that should be applied to the largest percentage of buildings, followed by seismic improvement and seismic retrofitting. When the total budget reaches the 19.9 % of BRAB, almost the same number of buildings should be interested by seismic retrofitting and local strengthening, while the number of buildings subjected to seismic improvement should be about 35 % smaller respect to each of the other two interventions.
- For VPE, with very low budget allocation, local strengthening is prioritized, as found for CPE. However, unlike the CPE case, as the available budget increases, the growth in the percentage of buildings subject to local strengthening is faster, and is accompanied by an even faster growth in the percentage of buildings to be subjected to seismic improvement interventions. The retrofitting is suggested only in smaller percentages for high budget availability.
- Considering the damage distribution after proactive strengthening interventions, it was found that stochastic prioritization performed based on VPE correlation between damage level and evacuees' percentage is more realistic and performing allowing a quick reduction of percentage of buildings suffering high damage (D3, D4, and D5) and a constant increase of building suffering no damage (D0) or very light damage (D1).
- In order to develop the methodology presented in the current study, some assumptions has been made. As a consequence, the obtained results should not be considered as outcomes of general value to be applied everywhere, but a recalibration on the input data, based on different local realities, should be taken into account in case of other applications. Indeed, the main objective of the work is to provide an expeditious procedure for the allocation of resources and the adopted assumptions constitute a mean in order to develop this procedure. Surely, practical application requires further investigations and the presented results are not reliable in any case; however, the developed procedure is valid.

### **CRedit authorship contribution statement**

**Piero Colajanni:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jennifer D'Anna:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simona Mancini:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lidia La Mendola:** Writing – review & editing, Project administration, Funding acquisition.

### **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.

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## Data availability

Data will be made available on request.

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