Rome (Italy), Department of Italian Civil Protection

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Cost Action IS1304

Expert Judgment Network: Bridging the Gap Between Scientific Uncertainty and Evidence-Based Decision Making

Workshop on "Science, uncertainty and decision making in the mitigation of natural risks"

ASSESSING VULNERABILITY AND FRAGILITY CURVES FOR VOLCANIC RISK

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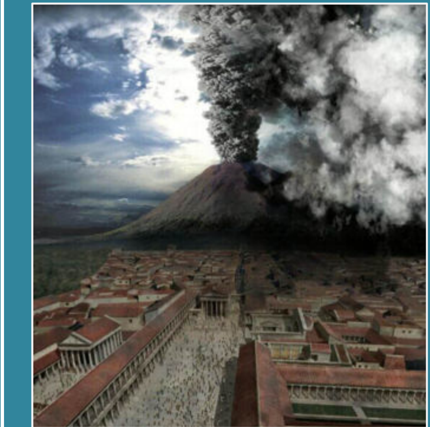
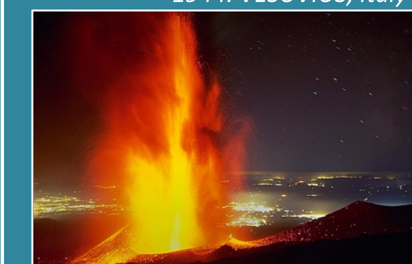
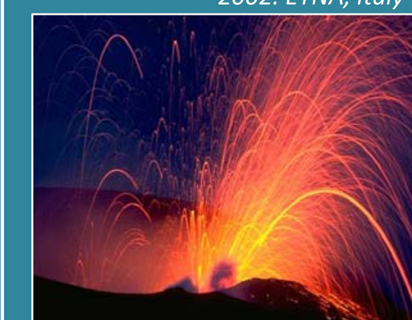


79dC. VESUVIUS, Italy

1944. VESUVIUS, Italy



2002. ETNA, Italy



1997. STROMBOLI, Italy

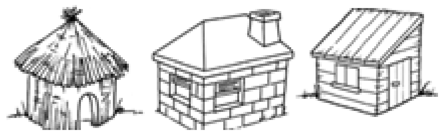
VOLCANIC RISK

VOLCANIC RISK = HAZARD × EXPOSURE × VULNERABILITY

HAZARD = probability that, in a specific area, volcanic events occurs during a specific time.

EXPOSURE = extension, quantity and quality of different anthropic elements which characterize the examined area (population, buildings, facilities, etc.), whose conditions and/ or functioning can be damaged, altered or destroyed by volcanic events.

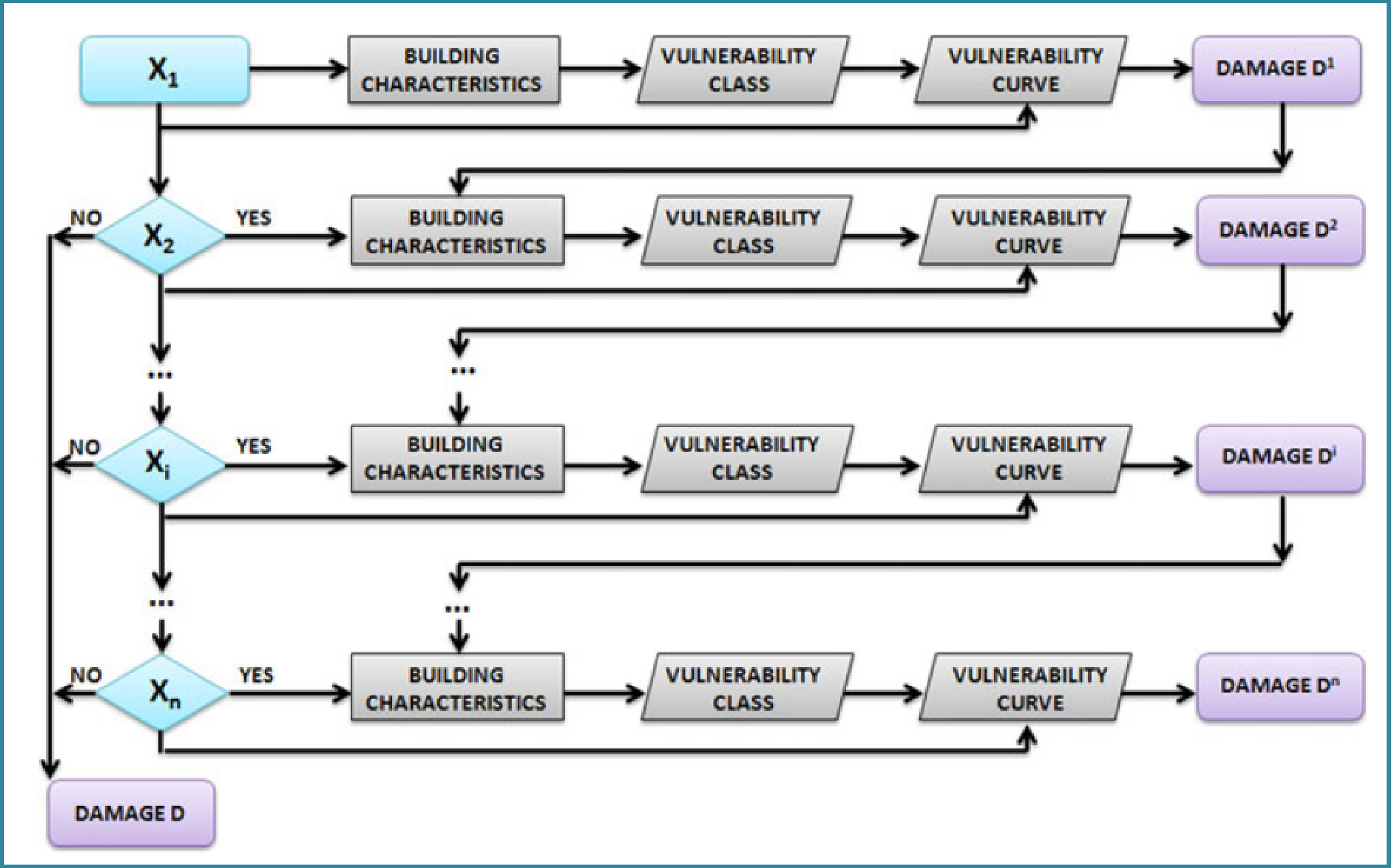
VULNERABILITY = probability that elements at risk (people, buildings, settlements) suffer injury, damage or other changes in the status quo following impacts from volcanic hazards.



In contrast to single catastrophic natural events (such as tectonic earthquakes, landslides, etc.), during a volcanic eruption, several phenomena may be generated (lava flows, earthquakes, ash fall, pyroclastic flows, ballistics, debris flows, tsunami and lahars) in different spatial areas and at different times. The sequence of these separate hazards in an eruption may modify the resistance of the exposed element at each stage and, in consequence, the vulnerability evaluation may require sequential analyses focusing on cumulative damage or changes.

VOLCANIC RISK

FLOW CHART RELATING TO THE PROCESS TO ASSES THE CUMULATIVE DAMAGE FOR EACH POSSIBLE TIME–SPACE SEQUENCE OF EVENTS {X1, X2, …, Xi, …, Xn }



BUILDINGS

The attention is focused on the vulnerability analysis of **buildings** under effect of main volcanic phenomena: **earthquake, ash fall and pyroclastic flows**.

1944. Vesuvius, ITALY

VULNERABILITY ELEMENTS and DAMAGE SCALE

Building vulnerability is the degree to which a system (entire building), subsystems (walls, frames, roofs, etc.), or system components (beams, columns, infill panels, windows, doors, etc.) are likely to experience damage due to exposure to hazards.

Building vulnerability is a function of resistance and technological aspects of the elements that constitute it:

- structural elements (such as walls, frames, floors, roofs, etc.)
- non- structural elements (infill panels, windows, openings, etc.).

Damage Scale

(S: structural elements; I: infill walls; O: openings – doors and windows -).

Damage state		Damage description	
D0	No damage	Absence of damage	
D1	Slight Damage	S:	Negligible damage to structural elements
		I:	Negligible damage to infill panels
		O:	Breakthrough of large or weak openings
D2	Moderate Damage	S:	Moderate damage to structural elements
		I:	Moderate damage to the infill panels in RC buildings
		O:	Breakthrough of windows mildly resistant
D3	Heavy Damage	S:	Severe damage to structural elements
		I:	Severe damage to infill panels in RC buildings. In few cases, total collapse of infill panels
		O:	Breakthrough of strong windows
D4	Partial Collapse	S:	Partial of structural elements
		I:	Breakthrough of strong infill
D5	Collapse	O:	Total collapse of structural elements

VULNERABILITY ASSESSMENT METHODS

1. **EMPIRICAL METHODS**: vulnerability assessment is based on damage observed during past events.
2. **ANALYTICAL METHODS**: vulnerability assessment is based on computational analyses.
3. **HYBRID METHODS**: vulnerability assessment is based on the combination of post- event damage statistics with simulated, analytical damage statistics from a mathematical model of the building typology under consideration.

DAMAGE PROBABILITY MATRICES (DPM) (discrete)

VULNERABILITY FUNCTIONS (continuous)

DAMAGE PROBABILITY MATRICES

DAMAGE PROBABILITY MATRICES (DPM) express, in a discrete form, the conditional probability of obtaining a **damage level Dj**, due to **intensity hazard i** : P (D=j │ i) for a given class of buildings.

Whitman et al. (1973) first proposed the use of damage probability matrices for the probabilistic prediction of damage to buildings from earthquakes.
Whitman et al. (1973) compiled DPMs for various structural typologies according to the damaged sustained in over 1600 buildings after the 1971 San Fernando earthquake (that the damage ratio represents the ratio of cost of repair to cost of replacement).

Whitman et al. (1973)

Damage State	Structural Damage	Non-structural Damage	Damage Ratio (%)	Intensity of Earthquake				
				V	VI	VII	VIII	IX
0	None	None	0-0.05	10.4	-	-	-	-
1	None	Minor	0.05-0.3	16.4	0.5	-	-	-
2	None	Localised	0.3-1.25	40.0	22.5	-	-	-
3	Not noticeable	Widespread	1.25-3.5	20.0	30.0	2.7	-	-
4	Minor	Substantial	3.5-4.5	13.2	47.1	92.3	58.8	14.7
5	Substantial	Extensive	7.5-20	-	0.2	5.0	41.2	83.0
6	Major	Nearly total	20-65	-	-	-	-	2.3
7	Building condemned		100	-	-	-	-	-
8	Collapse		100	-	-	-	-	-
				100	100	100	100	100

DAMAGE PROBABILITY MATRICES

DAMAGE PROBABILITY MATRICES (DPM) express, in a discrete form, the conditional probability of obtaining a **damage level Dj**, due to **intensity hazard i** : P (D=j | i) for a given class of buildings.

DPM after Irpinia earthquake (Braga, Dolce, Liberatore 1980)

Building of CLASS A (weak masonry)

Intensity	Damage Level					
	0	1	2	3	4	5
VI	0,188	0,373	0,296	0,117	0,023	0,002
VII	0,064	0,234	0,344	0,252	0,092	0,014
VIII	0,002	0,020	0,108	0,287	0,381	0,202
IX	0,0	0,001	0,017	0,111	0,372	0,498
X	0,0	0,0	0,002	0,030	0,234	0,734

Binomial coefficient

$$V_{khi} = \frac{5!}{k!(5-k)!} \cdot p_{hi}^{k} (1 - p_{hi})^{5-k}$$

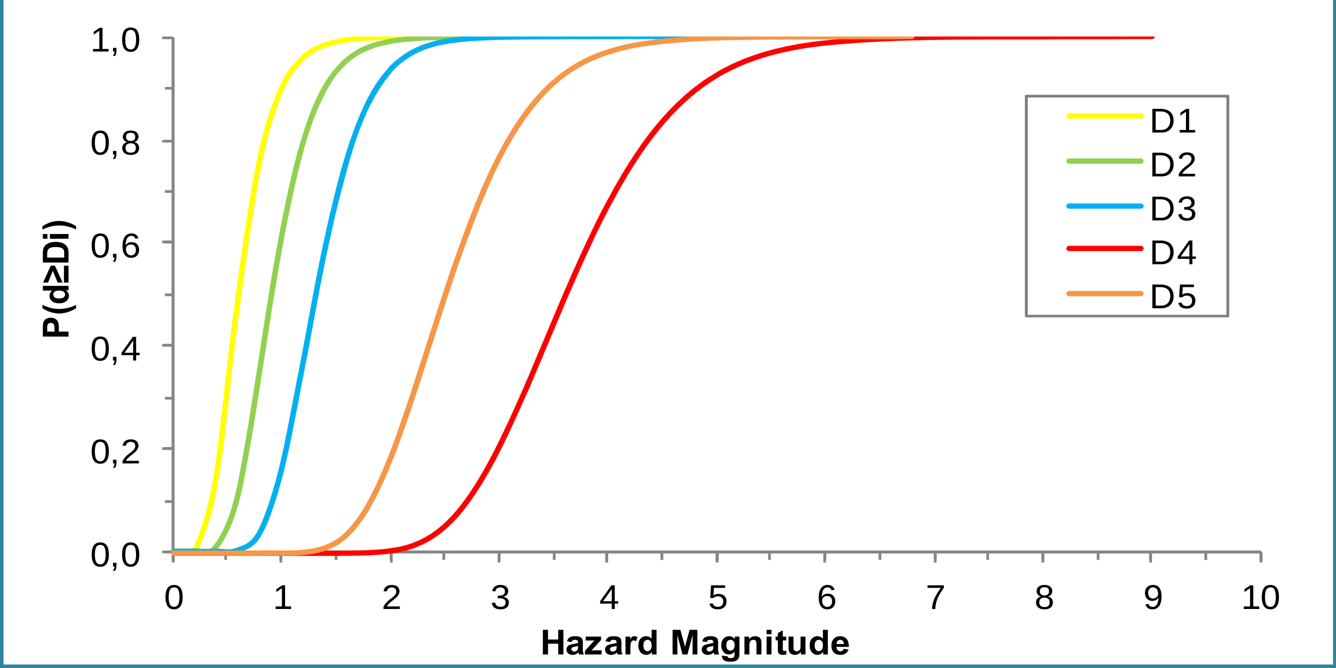
Level of damage (0-5)

VULNERABILITY FUNCTIONS

VULNERABILITY FUNCTIONS express the probability that a given **'building vulnerability class'** (with similar behaviour with respect to the individual volcanic phenomenon) exceeds a certain level of damage (Di), given a level of hazard magnitude v.

$$F(v) = \int_{-\infty}^{+\infty} \frac{1}{\sigma\sqrt{2\pi}} \frac{1}{v} \exp\left[-\frac{1}{2\sigma^2}(\ln v - \mu)^2\right] \mathrm{d}v.$$

v = hazard magnitude;
F(v) = log-normal cumulative distribution

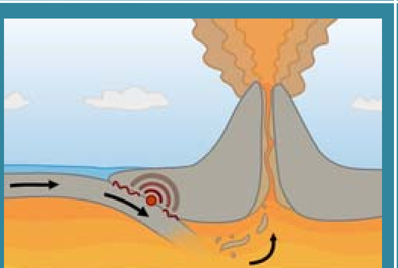


VOLCANIC VULNERABILITY

2002.Santa Venerina, ITALY

Magnitudo: 4.4

EARTHQUAKE



2002. Santa Venerina, ITALY

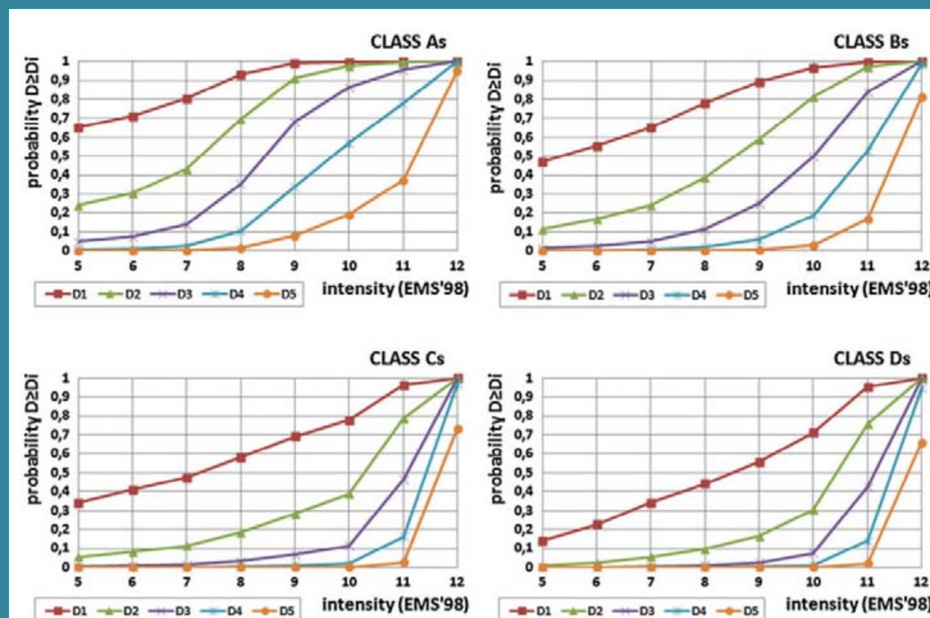
EARTHQUAKE

VULNERABILITY CLASSES

VERTICAL STRUCTURES	HORIZONTAL STRUCTURES				
	Poor stiffness	Poor technology	Medium stiffness	Medium high stiffness	High stiffness
	Metal sheet, vaults and/or wooden floor (without ties)	(e.g. "SAP" floor*)	Vaults and/or wooden floor (without ties)	Iron beam floor	Reinforced concrete and steel floors
Weak masonry Rubble masonry neglected	As	As	As	As	As
Medium quality Rubble masonry maintained	As	As	Bs	Bs	Bs
Good masonry Squared masonry	As	As	Bs	Bs	Cs
Framed structures (RC or steel)	-	Bs	-	-	Ds

* SAP floor (self- supporting floor) is a typical Italian horizontal structure, made of clay/cement mix with smooth bars at intrados. This technology is considered very dangerous because of the cement casting superior slab does not cover the reinforcement bars inserted in the hollow tile.

VULNERABILITY CURVES



For the Vesuvian area, the seismic vulnerability curves have been assessed through an **empirical approach** founded on numerous in situ damage distribution surveys (about 170,000 buildings) related to past seismic events (Zuccaro 2004; Zuccaro et al. 2008).

VOLCANIC VULNERABILITY

1994. *Rabaul*, Papua New Guinea

ASH FALL

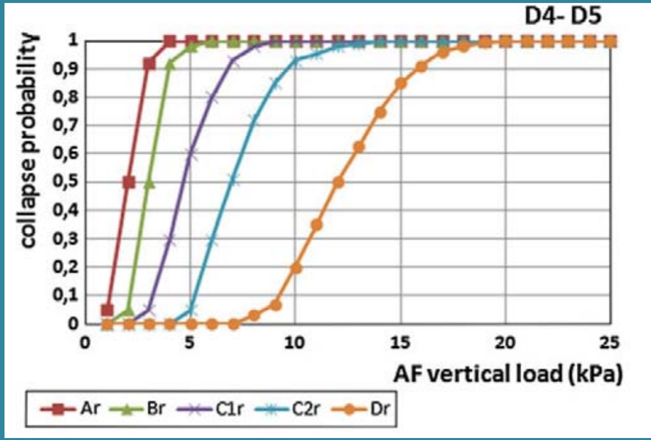
1991. *Pinatubo*, Filippine

ASH FALL

VULNERABILITY CLASSES

Type	Description
Ar	Weak pitched wooden roof
Br	Flat standard wooden roof
	Reinforced concrete flat roof- SAP type
	Weak steel flat roof
C1r	Old flat RC roof
	Weak pitched steel roof
C2r	Recent flat RC roof
	Recent flat steel roof
Dr	Recent pitched RC roof
	Recent pitched steel roof

FRAGILTY CURVES



For each vulnerability class in the Vesuvian area, ash fall fragility curves have been calculated through a hybrid method characterized by the following steps:

1.A robust data set was collected by survey in the study-area (about 19,000 roofs). It was elaborated statistically with the aim to assess the statistical distribution of roof typologies (main structures, materials, slopes, dimensions, etc.) in the Vesuvian area.

2.A representative sample of roof typologies was generated on the basis of their main characteristics (main structures, materials, slopes, dimensions, etc.). It was developed using a Monte Carlo simulation, in accordance with the statistical information obtained by the data set of Step 1.

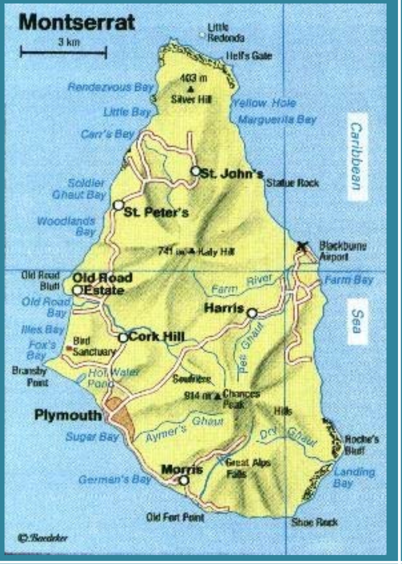
3.The collapse load of each roof generated by the Monte Carlo simulation was determined and compared with experimental tests developed on different typologies of roofs located in the Vesuvian area (Spence et al. 2005).

4.The vulnerability curves were obtained as log- normal cumulative distributions of collapse load calculated in the step 3 (Spence et al. 2005; Zuccaro et al., 2008).

Montserrat Lesson

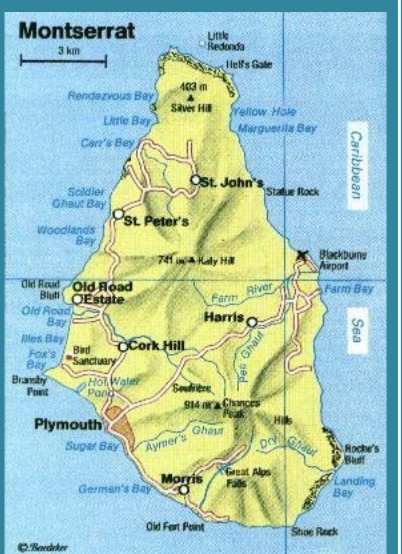
Montserrat Lesson

Center of flow: complete devastation



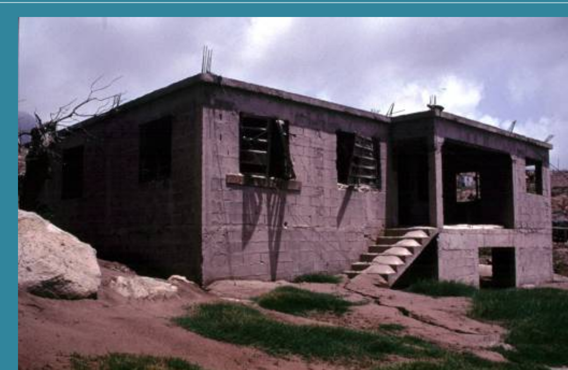
Montserrat Lesson

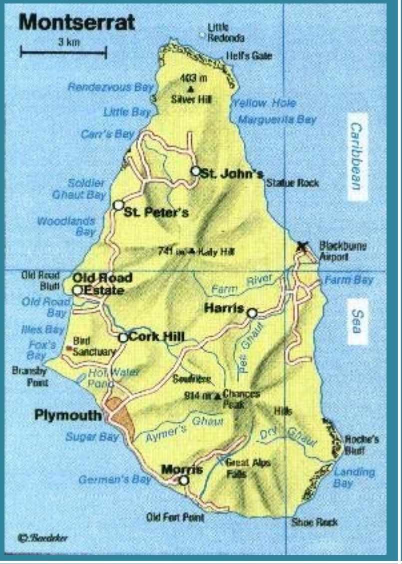
Along the edges of the flow



Montserrat Lesson

More than 5km from the crater: vulnerability factors.

Openings	Roofs
	
Infill panels	Orographic shielding
	



Montserrat Lesson

ANOTHER FACTOR CONDITIONING:

Barrier of built environment

VOLCANIC VULNERABILITY: Campania Region experience

1991. *Pinatubo*, Filippine

2002. *Soufr.Hills*, Montserrat, UK

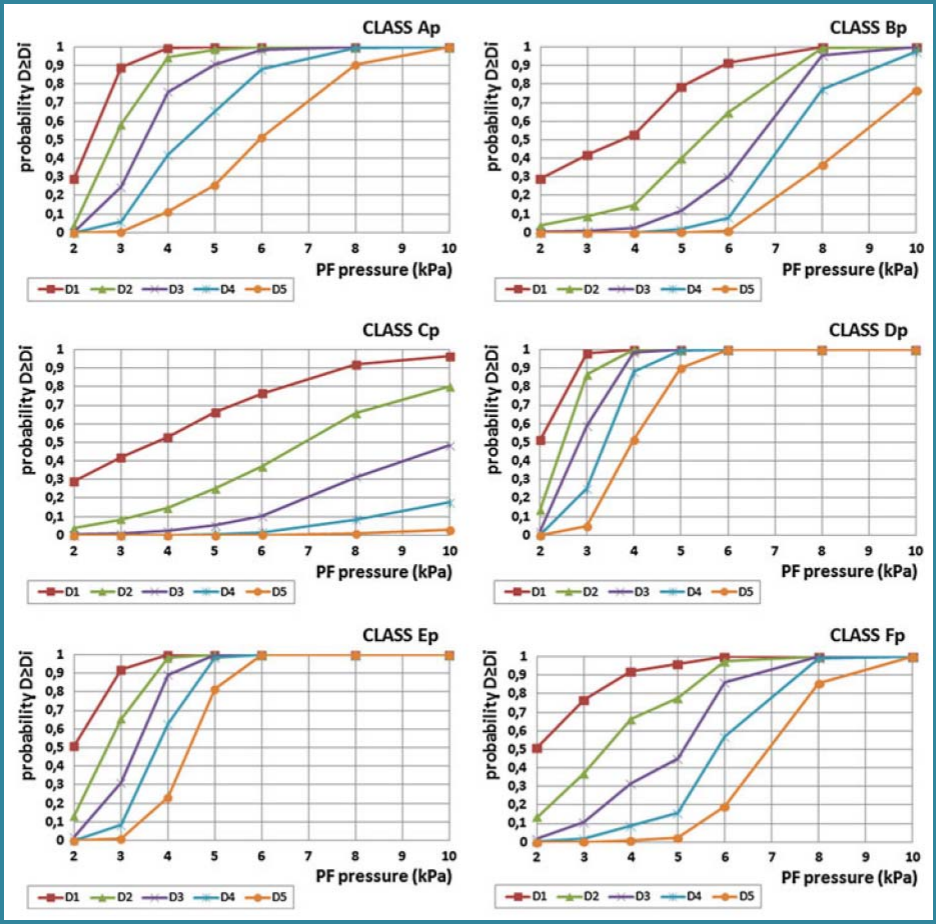
PYROCLASTIC FLOWS (structural elements)

VULNERABILITY CLASSES

STRUCTURAL ELEMENTS	
Type	Description
Ap	Weak masonry buildings of 3-4 storeys with deformable floor
	Weak or strong masonry buildings with more than 4 storeys
Bp	Medium masonry buildings of 1-2 storeys with deformable floor
	Strong masonry buildings of 3 or more storeys with rigid floor
Cp	Strong masonry buildings of 1-2 storeys with rigid floor
Dp	Non- aseismic RC buildings of more than 6 storeys (high)
Ep	Non- aseismic RC buildings of 4-6 storeys (medium)
Fp	Non- aseismic RC buildings of 1-3 storeys (low)

For each structural class Ap-Fp, vulnerability functions have been defined (Zuccaro et al., 2008). As for the ash fall case, they have been determined through a hybrid method based on typological analysis of about 90,000 buildings surveyed in the Vesuvian area (Spence et al. 2004a, b; Zuccaro et al. 2008)

VULNERABILITY CURVES



1991. *Pinatubo*, Filippine

2002. *Soufr.Hills*, Montserrat, UK

PYROCLASTIC FLOWS (not structural elements)

VULNERABILITY CLASSES and COLLAPSE LOAD

NOT STRUCTURAL ELEMENTS		
Type	Description	**COLLAPSE LOAD[kPa]**
Ap*	Windows glass of ordinary buildings	<1,5
Bp*	Aluminium window in bad condition	1,5
Cp*	Aluminium window in good condition	3,0
Dp*	Old wooden door	3,5
Ep*	Yellow tuff masonry wall	4,2-7,4
Fp*	Old wooden window	5,0
Gp*	Terra cotta tile in-fill panel without window	5,5
Hp*	Terra cotta tile in-fill panel with window	7,6-8,9

For non-structural classes A*p– F*p, the vulnerability curves are not yet available, but the collapse load R has been determined thanks to experimental tests carried out in situ on typical windows, doors and infill panels of the Vesuvian area (Spence et al. 2004b) and damage studies in the Montserrat eruption (Baxter et al., 2005).

MULTICRITERIA ANALYSES and VULNERABILITY

Building vulnerability is strongly linked to the vulnerability typological classes.
The methodology illustrated here proposes a 'global' volcanic vulnerability index (as a value between zero and one) to be used to define building vulnerability 'attitude' for a whole geographical area and for given hazard severity levels. The aim is to supply a quick method to compare typologies of buildings in various geographical areas differentiating the expected response to several hazards.
The vulnerability judgment is based on the analysis of *n* criteria *Cj* chosen as an element able to influence the volcanic vulnerability of buildings.
The Criteria are VULNERABILITY CLASSES FOR EARRTHQUAKE, PYROCLASTIC FLOWS AND ASH FALL.

For two assigned given volcanic eruptions

Probabilty [0-1] for each criterion that the damage *D* exceeds the damage *D5* for two given eruptions, medium M and small S, characterized by assigned level of seismic intensity I, vertical ash fall load q and horizontal pyroclastic pressure p (desumed by vulnerability curves)

CRITERIA		MEDIUM ERUPTION (M)			SMALL ERUPTION (S)		
		I=8 (EMS'98)	p=6kPa	q=15kPa	I=5 (EMS'98)	p=2kPa	q=3kPa
SEISM	As	0,103	-	-	0,006	-	-
	Bs	0,018	-	-	0,001	-	-
	Cs	0,003	-	-	0,000	-	-
	Ds	0,001	-	-	0,000	-	-
PYROCLASTIC FLOWS	Ap	-	0,879	-	-	0,000	-
	Bp	-	0,080	-	-	0,000	-
	Cp	-	0,016	-	-	0,000	-
	Dp	-	1,000	-	-	0,001	-
	Ep	-	1,000	-	-	0,001	-
	Fp	-	0,570	-	-	0,001	-
	Ap*	-	1,000	-	-	1,000	-
	Bp*	-	1,000	-	-	1,000	-
	Cp*	-	1,000	-	-	0,000	-
	Dp*	-	1,000	-	-	0,000	-
	Ep*	-	1,000	-	-	0,000	-
	Fp*	-	1,000	-	-	0,000	-
	Gp*	-	1,000	-	-	0,000	-
	Hp*	-	0,000	-	-	0,000	-
ASH FALL	Ar	-	-	1,000	-	-	0,920
	Br	-	-	1,000	-	-	0,500
	C1r	-	-	1,000	-	-	0,050
	C2r	-	-	1,000	-	-	0,000
	Dr	-	-	0,850	-	-	0,000

MULTICRITERIA ANALYSES and VULNERABILITY

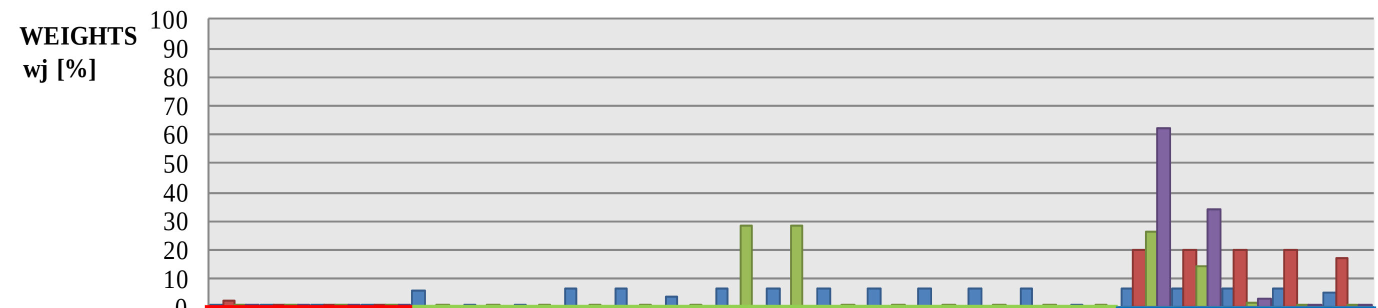
The weights calculation has been carried out on the basis of binary comparisons *a*ij between criteria *C*i e *C*j organized in the so called *weights matrix* **A**$_{nxn}$.
In particular, fixed beforehand the level of the three hazards *H* considered (macroseismic intensity vertical ash fall load , horizontal pyroclastic pressure), the generic element *a*ij is calculated as in the following ratio.

$$a_{ij} = \frac{Pcj\,(D \geq D5 | H = (I \text{ or } q \text{ or p}))}{Pci\,(D \geq D5 | H = (I \text{ or } q \text{ or } p))}$$

PCi and PCj are the probabilities that the damage D exceeds the damage D5 for a given level of hazards, respectively for the criteria Ci and Cj

The weights *wj* assigned to each criterion *Cj* are calculated by dividing the geometric mean Mg_i of each criterion for the sum of the geometric means of the criteria

$$wj = \frac{Mg_i}{\sum_{i=1}^{n} Mg_i} = \frac{(a1j \cdot \ldots \cdot anj)^{\frac{1}{n}}}{\sum_{i=1}^{n} Mg_i}$$



	As	Bs	Cs	Ds	Ap	Bp	Cp	Dp	Ep	Fp	Ap*	Bp*	Cp*	Dp*	Ep*	Fp*	Gp*	Hp*	Ar	Br	C1r	C2r	Dr
M (EQ+PF+AF)	0,7	0,1	0,0	0,0	5,7	0,5	0,1	6,4	6,4	3,7	6,4	6,4	6,4	6,4	6,4	6,4	6,4	0,0	6,4	6,4	6,4	6,4	5,5
M (EQ+AF)	2,1	0,4	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	20,1	20,1	20,1	20,1	17,1
S (EQ+PF+AF)	0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	28,7	28,7	0,0	0,0	0,0	0,0	0,0	0,0	26,4	14,4	1,4	0,0	0,0
S (EQ+AF)	0,4	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	62,3	33,9	3,4	0,0	0,0

CRITERIA Cj (VULNERABILITY CLASSES)

EARTHQUAKE (As–Ds) | PYROCLASTIC FLOWS (Ap–Hp*) | ASH FALL (Ar–Dr)

- Saaty, T.L., 1980. The Analytic Hierarchy Process, New York, McGraw Hill.
- Hwang, C. L. and Yoon, K., 1981. Multiple Attribute Decision Making Methods and Applications. Berlin, Heidelberg, New York: Springer Verlag

MULTICRITERIA ANALYSES and VULNERABILITY

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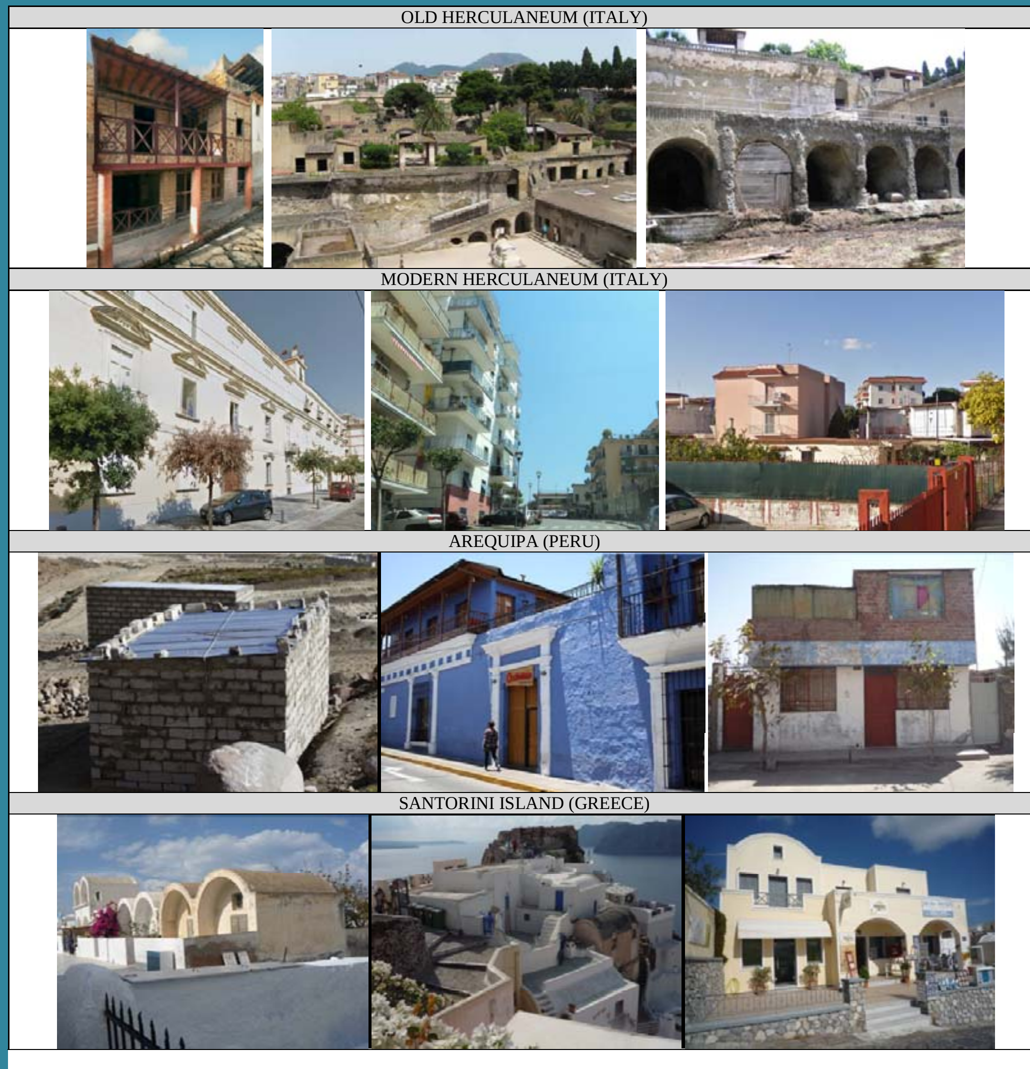
Multicriteria method has been applied to compare 4 locations Ai: Old Herculaneum, Herculaneum 2013, Arequipa, Santorini.



Old Herculaneum

Modern Herculaneum

Arequipa (Peru)

Santorini (Greece)

MULTICRITERIA ANALYSES and VULNERABILITY

- Saaty, T.L., 1980. The Analytic Hierarchy Process, New York, McGraw Hill.
- Hwang, C. L. and Yoon, K., 1981. Multiple Attribute Decision Making Methods and Applications. Berlin, Heidelberg, New York: Springer Verlag

The measures dij of the criterion Cj with respect to the alternative i are collected in the decision matrix D_{mxn} (n= number of criteria; m= number of towns), whose generic terms (d_{ij}) are the percentage distribution of criterion Cj (vulnerability class) in the alternative i (town).

Subsequently, the matrix terms should be normalised and combined with the criteria weights, obtaining the new matrix V_{mxn}, whose generic terms are achieved as it follows :

$$v_{i,j} = \frac{w_j \cdot d_{i,j}}{\sqrt{\sum_{i=1}^{n} d_{i,j}^2}}$$

Applying the **Topsis method** (Technique for Order Preference by Similarity to Ideal Solution) for each town a VULNERABILITY INDEX (0-1) can be calculated.

The real alternatives are characterised by the rows of the decision matrix normalised and weighted (**V**), each one is represented by the following row-vector.

$$A_i = \{v_{i1}, v_{i2}, \dots, v_{in}\}$$

we find 2 virtual extreme optimal solution

$$A^+ = \{\max v_{ij}, j = 1, 2, \dots, n\} = \{v_1^+, v_2^+, \dots, v_n^+\}$$

$$A^- = \{\min v_{ij}, j = 1, 2, \dots, n\} = \{v_1^-, v_2^-, \dots, v_n^-\}$$

MULTICRITERIA ANALYSES and VULNERABILITY

- Saaty, T.L., 1980. The Analytic Hierarchy Process, New York, McGraw Hill.
- Hwang, C. L. and Yoon, K., 1981. Multiple Attribute Decision Making Methods and Applications. Berlin, Heidelberg, New York: Springer Verlag

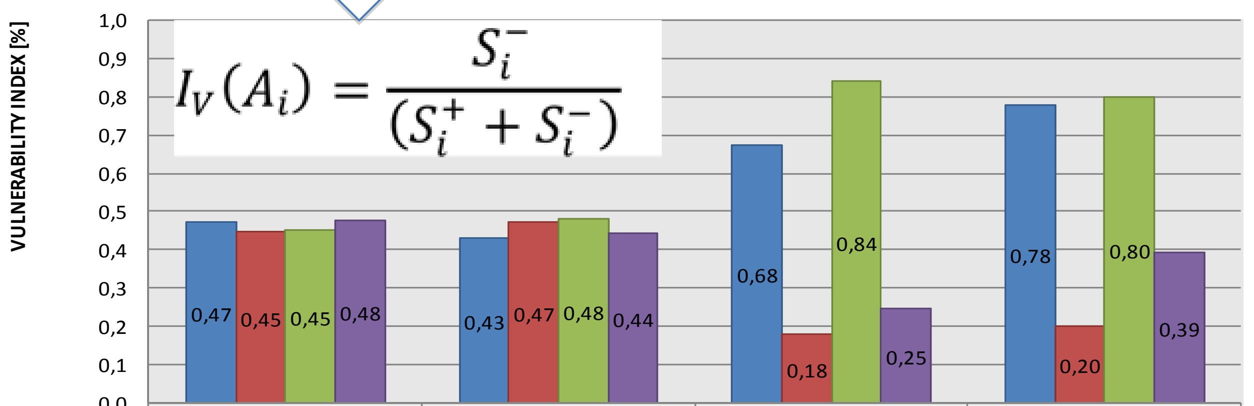
the Euclidean distances between the real alternative A_i and the ideal ones can be calculated as it follows.

$$S_i^+ = |A_i - A^+| = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2}$$

$$S_i^- = |A_i - A^-| = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2}$$

So as the vulnerability index is expressed through the following relationship .

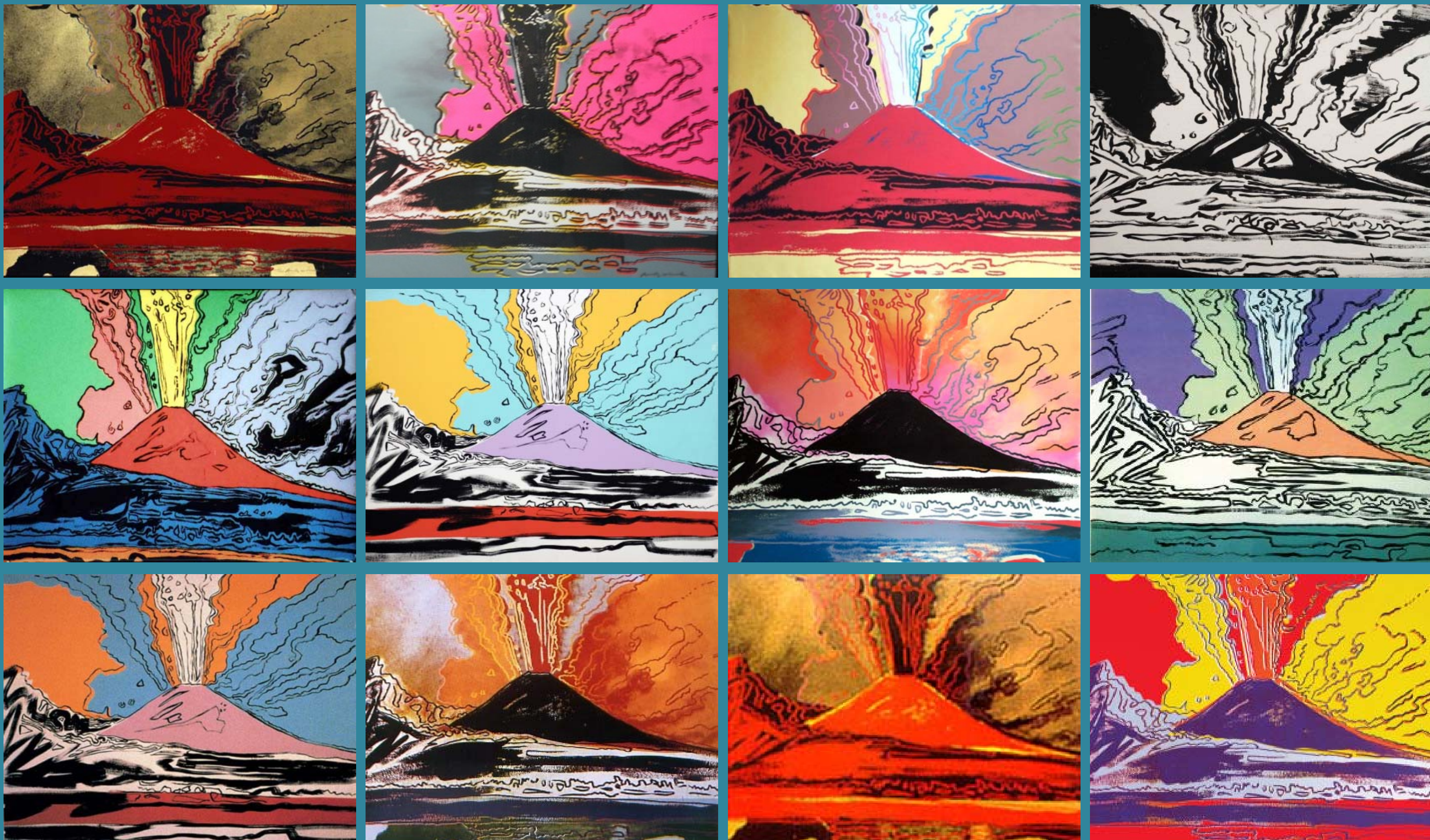
$$I_V(A_i) = \frac{S_i^-}{(S_i^+ + S_i^-)}$$



	M (EQ+PF+AF)	M (EQ+AF)	S (EQ+PF+AF)	S (EQ+AF)
Old Herculaneum (Italy)	0,47	0,43	0,68	0,78
Herculaneum 2013 (Italy)	0,45	0,47	0,18	0,20
Arequipa (Peru)	0,45	0,48	0,84	0,80
Santorini I. (Greece)	0,48	0,44	0,25	0,39

This methodology may also be applied by taking individual buildings as alternatives to compare. In this case, the measures *d*ij of the criterion *C*j with respect to the alternative *i* can be 1 or 0 when for the i-th building the criterion *C*j is present or absent, respectively.

Vesuvius, Andy Warhol. 1985



THANKS FOR YOUR ATTENTION.