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5 **A QUANTITATIVE FRAMEWORK TO ASSESS RESILIENCE AND RISK AT** 6 **THE COUNTRY LEVEL**

7 Omar Kammouh¹ Glen Dervishaj², and Gian Paolo Cimellaro³

8 **Abstract**

9 This paper presents a quantitative method to assess the resilience and the resilience-based risk at the country level. The
10 approach is inspired by the classical risk analysis, in which risk is a function of vulnerability, hazard, and exposure. In the
11 proposed analysis, resilience-based risk is a function of resilience, hazard, and exposure. In the new formula, the resilience
12 parameter is evaluated using the data provided by the Hyogo Framework for Action (HFA). HFA scores and ranks countries
13 based on a number of equally weighted indicators. To use those indicators in the resilience assessment, the contribution of
14 each indicator towards resilience must be determined. To do that, three methods to weight and combine the different HFA
15 indicators are proposed. The first two methods are based on the Dependence Tree Analysis (DTA), while the third method
16 is based on a geometrical combination of the indicators using spider plots. The proposed methodology has been applied to
17 a case study composed of 37 countries for which both the Resilience (R) and the Resilience-Based Risk (RBR) indexes
18 have been determined.

19
20 **Keywords:** Community resilience; Vulnerability; Risk management; Hyogo Framework for Action; Resilience metrics

21 **INTRODUCTION**

22 Over the years, community resilience has attracted remarkable attention due to the increasing number of natural and
23 man-made disasters. Communities that are able to absorb the impacts and recover quickly after disasters are fairly resilient

¹Ph.D. Student, Dept. of Structural, Geotechnical and Building Engineering (DISEG), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy, E-mail: omar.kammouh@polito.it.

²Graduate student, Dept. of Structural, Geotechnical and Building Engineering (DISEG), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy, E-mail: arch.glen@gmail.com.

³ Visiting Professor, Dept. of Structural & Environmental Engineering, University of California, Berkeley, Davis Hall, Berkeley, 94720-1710 USA (Corresponding author) E-mail: gianpaolo.cimellaro@polito.it.

24 communities, while communities whose recovery capacity is exceeded need to improve their resilience in order to facilitate
25 a faster recovery. Resilience can be viewed either as an outcome or as a process (Cutter 2016). It can be applied to multiple
26 different scales and units of analysis, ranging from the individual scale (e.g person, building, etc.) to the global scale (e.g.
27 community, state, etc.). The concept of resilience is multi-dimensional, and therefore involves various subjects of different
28 disciplines (Bonstrom and Corotis 2014; Chang et al. 2014; Cimellaro et al. (2016a-b) . Resilience is defined as “the ability
29 of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and
30 carry out recovery activities in ways to minimize social disruption and mitigate the effects of further earthquakes” (Bruneau
31 et al. 2003; Cimellaro et al. 2010). Allenby and Fink (2005) defined resilience as “the capability of a system to stay in a
32 functional state and to degrade gracefully in the face of internal and external changes”. In engineering, resilience is the
33 ability to “withstand stress, survive, adapt, and bounce back from a crisis or disaster and rapidly move on” (Wagner and
34 Breil 2013). Other researchers have also tackled other disciplines linked to resilience and proposed a more inclusive
35 definition in relation to risk and uncertainty. For example, Ayyub (2015) suggested that “the resilience of a system is the
36 persistence of its functions and performances under uncertainty in the face of disturbances”. From the several definitions
37 provided above, it is clear that it is still difficult to find a generally accepted definition for engineering resilience, mainly
38 because this concept has only recently been applied in the engineering field.

39 Measuring resilience has been an exploding field of inquiry in the last decade. Bruneau et al. (2003) stated that the
40 resilience of a system depends on its serviceability performance. In this conceptual approach, the performance of any
41 system can range between 0% and 100%, where 100% indicates ‘no drop in service’ and 0% means ‘no service is available’.
42 Disastrous events usually cause the serviceability of a system to drop to a lower level. The restoration of the system starts
43 immediately after the disaster and it finishes when the serviceability reaches its initial state (see Fig. 1). The loss of
44 resilience is thought to be equal to the service degradation of the system over the whole restoration period. Mathematically,
45 it is defined as follows:

$$46 \quad LOR = \int_{t_0}^{t_f} [100 - Q(t)] dt \quad (1)$$

47 where LOR is the loss-in-resilience measure, t_0 is the time at which a disastrous event occurs, t_f is the time at which
48 the system recovers to 100% of its initial serviceability, $Q(t)$ is the serviceability of the system at a given time t .

49 Fig. 1 near here

50 Many options for measuring resilience ranging from specific measurements to scorecards to indices are available
51 (Cimellaro et al. 2014; 2015) . Liu et al. (2017) proposed a framework that combines dynamic modeling with resilience
52 analysis. Two interconnected critical infrastructures have been analyzed using the framework by performing a numerical
53 calculation of the resilience conditions in terms of design, operation, and control parameters values for given failure

54 scenarios. Cimellaro et al. (2016c; 2017) proposed a resilience index for water distribution networks that is the product of
55 three indices and they used to compare different restoration plans in a small town in the South of Italy. Ayyub (2015)
56 proposed simplified resilience metrics to meet logically consistent requirements drawn from measure theory. In his work,
57 the recovery process, with its classifications based on level, spatial, and temporal considerations has also been tackled.
58 More specific work has been done regarding the economic advantage of actions that boost a system's resilience (Gilbert
59 and Ayyub 2016). In that work, microeconomic models that enable improving the resiliency of systems to meet target
60 levels were introduced. Reviewing the available measurements allows distinguishing some features that separate them.
61 Some are related to top-down measurement schemes, others are bottom-up, some measurements schemes are purely
62 qualitative in their approach, and others are quantitative. These measurement systems are also spatially variable and they
63 differ in their focus and application. Some of the many existing top-down approaches include the PEOPLES framework
64 (Cimellaro 2016b). The acronym combines seven dimensions: **P**opulation; **E**nvironment; **O**rganized government services;
65 **P**hysical infrastructure; **L**ifestyle; **E**conomic; and **S**ocial capital. It is classified as a quantitative framework for designing
66 and measuring resilience of communities. Another measurement tool is the Baseline Resilience Indicator for communities
67 (BRIC) (Cutter et al. 2014). This measurement tool is also quantitative but it focuses on the pre-existing resilience of
68 communities. Unlike the PEOPLES framework, BRIC is practically oriented towards the fieldwork. San Francisco
69 Planning and Urban Research Association framework (SPUR) (SPUR 2009) is a qualitative framework that measures the
70 ability to recover from earthquakes. The framework considers the restoration of buildings, infrastructures, and services.
71 Other top-down approaches are: the Hyogo Framework for Action (HFA) (UNISDR 2005); the UK Department for
72 International Development (DFID) Interagency Group (Twigg 2009); ResilUS (Miles and Chang 2011); etc. There are also
73 few bottom-up approaches, which are usually designed for communities to help them predict and plan for resilience. These
74 bottom-up measurement tools take an all-hazards approach in their assessment. They are generally qualitative types of
75 assessments that the community does itself, or it works with local stakeholders to derive its assessment. Some bottom-up
76 approaches include: the Conjoint Community Resiliency Assessment Measure (CCRAM) (Cohen et al. 2013), the
77 Communities Advancing Resilience Toolkit (CART) (Pfefferbaum et al. 2011), the Community Resilient System (White
78 et al. 2015), etc. A more exhaustive list of resilience measurement tools classified according to several characteristics can
79 be found in (Cutter 2016).

80 The absence of a concise and methodological approach makes resilience extremely difficult to determine. The progress
81 in the Hyogo Framework for Action (HFA) (UNISDR 2005; 2011)— a work developed by the United Nations — has led
82 to the formulation of an international blueprint that is very useful for building the resilience of nations and communities.
83 The methodology adopted by the HFA focuses on implementing detailed measures at the governmental level through
84 policies. The goal is to encourage the countries to implement the HFA in their respective laws. The lifespan for the

85 implementation was from 2005 to 2015, after which each of the participating countries was required to submit a report on
86 their own progress. A score was then given by the UN to each of the submitted reports on the basis of the progress each
87 country had made. Using the results of the Hyogo framework, a quantitative method to assess the resilience and the
88 resilience based risk of countries is proposed and applied to a case study composed of 37 countries.

89 **VULNERABILITY AND RESILIENCE ANALYSIS**

90 One of the many topics discussed when referring to resilience is its relationship with vulnerability and whether they are
91 similar enough to be considered the same. Vulnerability is an elusive concept whose definition varies across disciplines,
92 ranging from engineering to economics to psychology. Despite the range of approaches to measuring vulnerability, several
93 best practices in vulnerability assessment emerge. For instance, Peng et al. (2016) have developed an engineering-based
94 damage assessment models to assess the vulnerability of low-rise buildings against tornadoes. The models can be
95 implemented in any region regardless of the tornado size and strength. The output of this model is a percentage damage
96 index and the overall building damage ratio. One of the most adopted tools for vulnerability and risk assessment is HAZUS.
97 HAZUS is a standardized risk assessment software developed by the US Federal Emergency Management Agency (FEMA,
98 fema.gov/hazus) for evaluating potential losses caused by natural hazards (Nastev and Todorov 2013). HAZUS integrates
99 engineering and science-based knowledge with the geographic information systems (GIS) to determine the loss and damage
100 before or after a disaster occurs. It consists of four main models:

- 101 1. The Hazus earthquake model: provides loss estimates of buildings, facilities, transportation, and utility lifelines
102 based on scenario earthquakes to support decision making process for preparedness and disaster response
103 planning (Whitman et al. 1997). The model considers debris generation, fire-following, casualties and shelter
104 requirements. Direct losses are estimated based on physical damage to structures, contents, inventory and
105 building interiors. The Hazus earthquake framework consists of six interdependent modules with the output of
106 one module acting as input to another. More information about the framework algorithm and the modules can
107 be found in (Kircher et al. 2006). In addition, a new extension module “*Advance Engineering Building Module*”
108 (AEBM) has been integrated in the Hazus earthquake model to help seismic engineering experts in the
109 development of building-specific damage and loss functions (NIBS 2002).
- 110 2. The Hazus Hurricane Wind Model: allows estimating hurricane winds and damage to different types of
111 buildings. It also estimates direct economic loss, post-storm shelter needs and building and tree debris
112 quantities and allows assessing the structural changes to buildings to strengthen them for mitigation. This
113 model has been initially developed using principles of wind engineering to allow accurately estimating damage
114 and loss to buildings due to hurricanes (Vickery et al. 2006a). The approach adopted in this model has been
115 previously calibrated and validated using simulations and field observations of the wind speeds over more than

116 140 locations (Vickery et al. 2000a; 2000b). The HAZUS-MH Hurricane Model comprises five model
117 components (hurricane hazard, terrain, wind Load/debris Modeling, damage, and loss Estimation). The first
118 three components are described in (Vickery et al. 2006a) while the last two are discussed in a companion paper
119 (Vickery et al. 2006b).

120 3. The Hazus Flood Model: evaluates potential damage to buildings, essential facilities, transportation lifelines,
121 utility lifelines, vehicles and agricultural crops caused by riverine and coastal flooding. The model also
122 considers building debris generation and shelter requirements. Direct losses are estimated based on physical
123 damage to structures and to buildings' contents and interiors. Scawthorn et al. (2006a) provide a discussion of
124 the capability of the software in characterizing riverine and coastal flooding. They also discuss the Flood
125 Information Tool, which allows a quick and convenient analysis of various stream discharge data and
126 topographic mapping to determine flood-frequencies over entire floodplains (Scawthorn et al. 2006a). In a
127 companion paper, Scawthorn et al. (2006b) tackle the damage and loss estimation capability of the flood model.
128 The model contains over 900 damage curves to estimate the damage of different types of buildings and
129 infrastructures.

130 4. The Hazus Tsunami Model: represents the most recent disaster module for the Hazus software in the last
131 decade. The model is a joint effort of tsunami experts, engineers, modelers, emergency planners, economists,
132 social scientists, geographic information system (GIS) analysts, and software developers. New features are
133 continuously added to this model in attempt to increase its capabilities.

134 Although vulnerability is strongly linked to the concept of risk assessment (Papadopoulos 2016), it has been pointed out
135 that the concept of vulnerability is associated with resilience under various scientific disciplines (Richard et al. 1998).
136 Meanwhile, vulnerability has been identified as the lack of capacity (Cardon et al. 2012). Under this context, the
137 vulnerability is reduced by increasing the system's capacity. Moreover, some literary publications provide the same
138 definitions for resilience and vulnerability (Klein et al. 2003), while others identified some instances where scholars had
139 different views for the two concepts (Cutter 2016), admitting that they may overlap in some areas (Gallopín 2006). Table
140 1 shows a comparison between vulnerability and resilience on different scales. The comparison suggests that resilience is
141 concerned more with the human capacity to recover from a disaster within a short time and with no outside assistance,
142 while vulnerability is the property of resisting the stress caused by a natural hazard.

143 Table 1 near here

144 Due to the uncertainty involved in the resilience assessment process, a probabilistic approach similar to the classical
145 vulnerability analysis can be established. Fig. 3 illustrates the conceptual approaches of both vulnerability and resilience

146 analyses. In the vulnerability analysis, a number of fragility curves are built to interpret the vulnerability of a system. The
147 curves represent the system's probability of exceeding a certain damage state under different hazard intensity levels. In the
148 proposed resilience analysis, the fragility curves describe the probability of a system to be below a predefined resilience
149 threshold under a certain intensity level (see Fig. 3).

150 It is important to note that the resilience quantity is affected by both the restoration period T_{re} and the rapidity of
151 restoration r (see Fig. 1). Therefore, both quantities should be taken into account when estimating resilience. Fig. 3 shows
152 the surface fragility curves when considering both intensity measures. Those curves represent the probability of a system
153 having a certain recovery speed and a certain restoration period to be below a predefined resilience threshold.

154 Fig. 3 near here

155 The restoration speed (or rapidity) is one of the most important parameters when evaluating resilience. Generally, the
156 rapidity of restoration r depends on several factors, such as the human resources, the restoration plan, the financial
157 resources, etc. Thus, the graphical configuration of the restoration phase can be of infinite shapes. Fig. 4 shows three types
158 of restoration curves (exponential function, step function, and random function). The rapidity of restoration r can be
159 considered as the slope of the best-fitting line obtained by applying a linear regression to the restoration curve. In this way,
160 r can express the rapidity of any restoration curve regardless of its actual configuration.

161 Fig. 4 near here

162 **RESILIENCE-BASED RISK ANALYSIS**

163 In the classical risk assessment methodology, Risk is the combination of Vulnerability, Hazard, and Exposure. Instead, in
164 the proposed formulation, Resilience-Based Risk is a function of Resilience, Hazard, and Exposure (Fig. 2). While the
165 three parameters can be obtained from various sources, for the specific case study considered in this research, the exposure
166 is obtained from the World Risk Report (WRR), while the effect of hazard is neglected due to the lack of the necessary
167 hazard maps. The third parameter, resilience, is determined using the data provided by the Hyogo Framework for Action
168 (HFA). HFA ranks and scores countries based on a number of equally weighted indicators. However, in order to be used
169 in the resilience assessment, the HFA indicators must be weighted according to their contribution toward resilience. To do
170 that, three weighting methods are introduced. The first two methods are based on the Dependence Tree Analysis (DTA)
171 (Kammouh et al. 2016a; Kammouh et al. 2016b). DTA is a method that determines the correlation between a component
172 and its sub-components (i.e., between resilience and its indicators), assigning different weights to the sub-components
173 accordingly. The third method, Spider Plot Analysis (SPA), is based on a geometrical combination of the indicators using
174 spider plots. In this method, the score of each indicator is plotted on one of the spider plot's axes. Resilience is then
175 quantified as normalized value of the area inside the enclosed shape made by linking the adjacent indicators' scores. The

176 outputs of the resilience generated by each of the three methods are subsequently used in the evaluation of RBR (by
177 combining them with exposure and hazard). To illustrate the use of the methodology, a case study composed of 37 countries
178 is presented in this paper, where the resilience and the resilience-based risk indexes of each country are evaluated and
179 compared.

180 Fig. 2 near here

181 **THE WORLD RISK REPORT (WRR)**

182 The World Risk Report is a research performed by the United Nations University for Environment and Human Security
183 (UNU-EHS), and published by the relief organizations in the Alliance Development Works (Mucke 2015). The report
184 adopts different measures to rank the countries around the world according to their vulnerability, exposure, and risk levels.
185 In this study, the data on exposure level of the WRR is used for the resilience-based risk assessment. The strategy adopted
186 by the WRR to evaluate the exposure of the countries is illustrated in Fig. 5. The exposure is computed as a combination
187 between the people who are exposed to different types of hazards in a country divided over the total population in that
188 country. Fig. 6 shows the exposure values of the ten most exposed countries according to the WRR.

189 Fig. 5 near here

190 Fig. 6 near here

191 **HYOGO FRAMEWORK FOR ACTION (HFA)**

192 Hyogo Framework for Action (HFA) was originally conceptualized in Kobe, Japan. It was eventually adopted as a
193 global blueprint for minimizing risk associated with natural hazards by implementing national laws regarding risk
194 management and control (UNISDR 2005; UNISDR 2011). HFA is the product of a long initiative by an affiliate within the
195 United Nations known as the International Strategy of Disaster Reduction (ISDR) (Cimellaro 2016). The International
196 Strategy of Disaster Reduction was developed as the result of the experience gained in the International Decade for Natural
197 Disaster Reduction (1990-1999).

198 The aim of HFA was to boost awareness on disaster risk and to guide committed countries in executing a master plan
199 to avert the loss of lives and the economic impact caused by natural hazards. The HFA consists of five priorities for action.
200 Each priority is satisfied with a number of indicators, with a total of 22 indicators for all five priorities (Table 2). The major
201 role of the five priorities of HFA is to identify the specific sectors that every country should focus on to endorse disaster
202 resilience. The indicators are assessed using a detailed survey, which contains a set of questions that aim to provide
203 information about the resilience progress each country has made. The authority of each country is requested to fill the
204 questionnaire and then return it to the UN for further processing. Table 3 shows the sort of questions presented in the
205 questionnaire. The answers to the questions can be either 'YES/NO' or 'description text'. The progress recorded by every

206 government is computed on the basis of a five-point scale for each of indicator, where ‘one point’ indicates weak progress
207 and poor signs of planning and actions, while ‘five points’ implies a great endeavor and commitment in that specific area
208 (UNISDR 2008).

209 The level of accuracy of the data collected by the UN is subjected to the authority personnel who fills the report.
210 However, the authorities of the countries are aware that providing a good quality data allows them to track their resilience
211 progress more accurately.

212

213 Table 2 near here

214 The expiration of Hyogo and its ten-year plan prompted a new framework known as Sendai Framework. This framework
215 is the evolved version of the HFA and is meant to replace HFA in coming years. The Sendai Framework is a product of
216 the Third World Conference on Disaster Risk Reduction in Sendai, Japan (2015) (UNISDR 2015). Even though the HFA
217 was widely credited as raising awareness for disaster risk reduction, a significant loss of lives was recorded during the 10-
218 year span of its implementation. Consequently, the Sendai framework stresses on the significance of risk assessment and
219 early warning systems. The UN have set a plan to define the risk bases and to embrace new indicators to quantify the
220 resilience improvement made by the participating countries, and this is anticipated to be discussed at another session in
221 2017 (UNISDR 2015). The new framework outlines the following four priorities for action:

- 222 1. Understanding disaster risk;
- 223 2. Strengthening disaster risk governance to manage disaster risk;
- 224 3. Investing in disaster risk reduction for resilience;
- 225 4. Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation
226 and reconstruction.

227 Table 3 near here

228 **THE METHODOLOGY: RESILIENCE-BASED RISK ASSESSMENT OF COUNTRIES**

229 The primary goal of the paper is to provide an index that enables comparing countries in terms of resilience and its
230 corresponding risk. In this work, risk is the probability of not achieving a certain resilience level, and is referred to as
231 resilience-based risk. The RBR is dependent on not only the internal characteristics of a system (resilience) but also on the
232 external factors (exposure and hazard). Fig. 7 illustrates the proposed framework, where risk is the combination of
233 resilience, exposure and hazard. The mathematical expression of RBR is given by:

$$234 \quad RBR = (1 - R) \times E \times H \quad (2)$$

235 where RBR is the resilience-based risk index, R represents the resilience index, E is the exposure to natural hazards, H
236 contains information about the hazard. For the purpose of the study, we have chosen public data sources to illustrate the
237 methodology. For example, to compute the resilience parameter, we used the data provided by the Hyogo Framework for
238 Action, which uses a number between 0 and 1 to assess the different resilience indicators of the countries. As already
239 indicated, the 22 indicators in HFA are equally weighted, and this implies that all indicators have the same level of
240 importance. However, it has been found that the indicators vary in importance, and therefore they must be weighted in a
241 specific way in order to be used in the resilience assessment. To do that, three different weighting methods are applied to
242 the HFA indicators, and the corresponding resilience results are compared. In the following, the three weighting methods
243 are explained in detail.

244 Fig. 7 near here

245 **Method 1: Dependence Tree Analysis (DTA)**

246 In this section, the Dependence Tree Analysis (DTA) is introduced. The method captures the correlation between a
247 component and its sub-components in a quantitative manner. The DTA is applied to the HFA's indicators in order to
248 combine them according to their contribution towards resilience. Building the dependence tree begins with the
249 identification of all potential components that are capable of influencing the main output. The most common way to do
250 this is by brainstorming or relating to lessons learned. The types of components that exist are: the main component, the
251 intermediate component, and the basic component. The task required to get out of a system is known as the main
252 component, and this component is located on the top of the dependence tree. The essential components required for the
253 successful achievement of the main component are known as the intermediate components, while the basic components
254 refer to those that cannot be split any further into sub-components. Fig. 8 illustrates how the components are arranged in
255 the dependence tree. The components are presented in the dependence tree according to their logical relationship with one
256 another. The components can show in the dependence tree more than once, and this depends on the importance of that
257 component. In this work, resilience is considered as the main component, while the HFA's indicators are the intermediate
258 and the basic components. Therefore, all sub-components will hereafter be referred to as indicators, while the main
259 component will be referred to as resilience. The results obtained using the DTA are highly dependent on the tree structure
260 which describes the links between the different indicators. Furthermore another limitation of the method is that only
261 numerical indicators can be combined (e.g. boolean indicators can not be used with this methodology) .

262 Fig. 8 near here

263 The analysis begins with the identification of the indicators and their relationships. The indicators' scores obtained from
264 HFA are normalized with respect to their maximum value ($I_{\max}=5$) using Equation (3). Afterward, resilience is computed

265 using the DTA by combining the indicators' scores in such a way that the indicators that are in series are multiplied, while
 266 the weighted average of those in parallel is considered. This leads to obtaining a normalized resilience output that is ranged
 267 between 0 and 1.

$$268 \quad I_{iN} = \frac{I_i}{I_{i,max}} \quad (3)$$

269 where I_{iN} is the normalized score of indicator i ($0 \leq I_{iN} \leq 1$), I_i is the score of indicator i obtained from HFA
 270 ($0 \leq I_i \leq 5$), $I_{i,max}$ is the maximum score that can be achieved by indicator i ($I_{max} = 5$).

271 **Method 2: Weighted Average Analysis (WAA)**

272 In this method, the dependence tree analysis is used only to find weighting factors for the indicators. Then, the resilience
 273 is evaluated as the weighted average of the indicators' weighted scores. The weights are obtained by performing a
 274 sensitivity analysis. This is done by setting the score of each indicator to zero once at a time while assigning maximum
 275 values to all other indicators. The value of the resilience is computed for each time an indicator is set to zero. A low value
 276 of resilience indicates a high importance of that indicator. Therefore, the importance factor of the indicator is the opposite
 277 of the resilience value when that indicator is set to zero. Equation (4) is used to compute the importance factors.

$$278 \quad IF_i = 1 - R_i \quad \text{for } I_{iN} = 0; I_{jN} = I_{j,max,N} = 1 \quad (i = 1 \rightarrow k \text{ and } j \neq i) \quad (4)$$

279 where IF_i is the importance factor of indicator i , R_i is the value of resilience when indicator i is set to zero while all
 280 other indicators are equal to 1, k is the total number of indicators (i.e. $k = 22$).

281 The execution of the sensitivity analysis enables classifying the indicators starting from the most to the least important.
 282 A weighting factor for every indicator of the HFA is subsequently calculated using Equation (5). In this equation, the
 283 weighting factor uses the results of the sensitivity analysis conducted in the previous step.

$$284 \quad W_i = \frac{1 - IF_i}{\sum_{n=1}^k (1 - IF_n)} \quad (5)$$

285 where W_i is the weighting factor of indicator i . The new indicator's score is obtained by multiplying the original
 286 indicator's normalized score by its corresponding weighting factor:

$$287 \quad I_{i,NW} = W_i \cdot I_{i,N} \quad (6)$$

288 where $I_{i,NW}$ is the normalized weighted score of indicator i .

289 Finally, the resilience value R is the weighted average of the indicators' modified scores. The mathematical equation
 290 of resilience is given as follows:

291
$$R = \sum_{n=1}^k I_{n,NW} \quad (7)$$

292 **Method 3: Spider Plot Weighted Area Analysis (SPA)**

293 In this last method, the indicators are represented by means of a spider plot (Fig. 9). Resilience is simply the enclosed
294 area generated by linking the adjacent indicators, normalized with respect to the total area of the polygon. The mathematical
295 expression of resilience is given in Equation (8). One can say that the arrangement of indicators could affect the area in the
296 enclosed shape. To illustrate this, a statistical analysis was performed on the indicators' scores of one country. Different
297 arrangements of the indicators were tried using the permutation command in the software Matlab (Guide 1998), and the
298 area of each arrangement was computed. It was found that the values of the areas were normally distributed with a standard
299 deviation of 5%. This implies that the value of the area inside the enclosed shape is not very sensitive to the indicators'
300 arrangement order.

301
$$R = \frac{A}{A_{max}} \quad (8)$$

302 where R is the resilience index, A is the area of the geometrical shape obtained by connecting the scores of adjacent
303 indicators, A_{max} is the total area of the polygon (i.e. maximum area that could be achieved if all indicators are equal to 5).
304 Fig. 9 near here

305 **THE CASE STUDY**

306 The methodology described in the paper has been applied to a number of countries that took part in the Hyogo
307 Framework evaluation project. The chosen countries are 37 in total, and they were selected randomly from all five
308 continents. For each country, the resilience index R is evaluated, and then the corresponding risk index RBR is computed
309 by combining the results of resilience, exposure, and hazard.

310 In Table 4, the indicators' scores of the various countries are listed as presented in the HFA reports. The latest reports
311 to date are used to fill the scores. The indicators' scores of each country are summed up into a single total score (out of 110
312 points). This score is also presented in percentage form (%), where 100 indicates a maximum score of 5 in all indicators.
313 The final set of total scores act as a data source for the proposed methodology.

314 Table 4 near here

315 **Resilience results**

316 In this section, the resilience indexes of the analyzed countries are computed using the proposed methods and then
317 compared.

318

Method 1: Dependence Tree Analysis (DTA) results

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Fig. 10 shows the final form of the dependence tree, in which all the indicators have been arranged according to their logical relationship with one another. One indicator can take more than one place, and this depends on how significant the indicator is.

Fig. 10 near here

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327

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As we mentioned before, the 22 indicators' scores of each country (obtained from HFA) are normalized with respect to their maximum value. The maximum value that can be achieved by an indicator is "5"; therefore, all indicators are divided over five. Once the indicators are normalized, the resilience index of each country is computed by combining the indicators' scores. In the dependence tree, the indicators in series are multiplied by each other, whereas averaging was taken for those indicators in parallel. The resilience index of each country can be obtained by replacing each indicator with its corresponding normalized score value from Eq. (3). The general formula to compute the resilience R_c of a country c is given Eq. (9). Using the equation, the resilience results of the analyzed countries can be computed.

330

$$R_c = \frac{1}{10} \left[\begin{aligned} & I_{13N} I_{1N} I_{9N} I_{2N} + I_{14N} \left(\frac{I_{1N} I_{9N} I_{2N} + I_{3N} \left(\frac{I_{9N} I_{2N} + I_{10N} I_{2N} + I_{12N} I_{2N}}{3} \right)}{2} \right) + I_{15N} \left(\frac{I_{1N} I_{9N} I_{2N} + I_{4N} + I_{6N} I_{1N} I_{9N} I_{2N}}{3} \right) \\ & + I_{16N} \left(\frac{I_{1N} I_{9N} I_{2N} + I_{9N} I_{2N}}{2} \right) + I_{17N} \left(\frac{I_{5N} I_{9N} I_{2N} + I_{4N}}{2} \right) + I_{18N} \left(\frac{I_{1N} I_{9N} I_{2N} + I_{4N} + I_{5N} I_{9N} I_{2N} + I_{8N}}{4} \right) \\ & + I_{19N} \left(\frac{I_{1N} I_{9N} I_{2N} + I_{2N} + I_{4N} + I_{5N} I_{9N} I_{2N}}{4} \right) + I_{20N} \left(\frac{I_{6N} I_{1N} I_{9N} I_{2N} + I_{7N} I_{2N}}{2} \right) + I_{21N} \left(\frac{I_{1N} I_{9N} I_{2N} + I_{11N} I_{2N}}{2} \right) \\ & + I_{22N} I_{1N} I_{9N} I_{2N} \end{aligned} \right] \quad (9)$$

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Method 2: Weighted Average Analysis (WAA) results

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In this method, the Dependence Tree Analysis (DTA) is used to weight the indicators shown in Table 2. A sensitivity analysis is performed to capture the difference in the indicators' contribution in the resilience assessment. This leads to assigning a single weighting factor to each of the 22 indicators. Following the procedure described above, and by using Equations (4) and (5), a list of importance and weighting factors for the 22 indicators is generated (Table 5). We can clearly notice the difference in the indicators' weights. For instance, indicator 2 (I-2) recorded the highest weighting factor '0.225'. In fact, this indicator 'Dedicated and adequate resources are available to implement disaster risk reduction plans and activities at all administrative levels' is a financial indicator, and almost all other indicators were dependent on it in the dependence tree (Fig. 10). Generally, financial indicators are very important because financial resources are necessary for the accomplishment of any task, and this justifies the high weighting factor obtained by that indicator.

341 Table 5 near here

342 The weighting factors shown in the table above are multiplied by the corresponding indicators' normalized scores using
343 Equation (6). The new 22 indicators' scores are subsequently summed up using Equation (7). The result obtained represents
344 the resilience index R_c of the country c .

345 ***Method 3: Spider Plot Weighted Area Analysis (SPA) results***

346 The indicators' spider chart of each country is plotted and the area inside the enclosed shape made by linking the adjacent
347 indicators' scores is obtained. Fig. 11 shows two examples of the spider plot method corresponding to the countries France
348 and Monaco. Using Equation (8), The resilience index R_c of a country c is obtained by normalizing the area inside the
349 enclosed shape A_c with respect to the maximum area $A_{c,max}$ (i.e. the maximum area is obtained when all indicators are
350 maximum '5').

351 Fig. 11 near here

352 Fig. 12 compares the results of the resilience obtained with the three methods. Interestingly, the results coming from all
353 three methods follow the same trend. The third method (SPA) acts as an average for the first (DTA) and the second (WWA)
354 methods, except for Fiji country, which acquired equal scores in the second and third methods, slightly higher than the
355 score obtained from the first method. All together, these results suggest that the resilience outputs are very sensitive to the
356 weighting method. The first method (DTA) provides the highest difference between the largest and the lowest scores,
357 whereas the variability in the results obtained using the second method (WWA) is the lowest, with a difference of 0.58
358 between the highest value (0.98) and the lowest value (0.4). This can be considered in the favor of the first method as it
359 magnifies the range of the resilience results, which allows having a clearer picture on the difference in resilience between
360 countries. In addition, the first method (DTA) does not allow very high values of resilience; for instance, the highest
361 resilience score achieved using the DTA method is that of the Fiji country ($R=0.84$). This assumes that there is no country
362 that is considered fully resilient, and this is a more reasonable result than in the other two methods where the resilience
363 index of Fiji is 0.98, which implies that Fiji can hardly get any better in terms of resilience.

364 Moreover, the resilience results shows that Fiji has always achieved the first position in the resilience ranking, which is
365 rather unexpected. This may be attributed to several reasons, such as the subjectivity in filling the HFA reports in the first
366 place. Fiji has initially achieved a score of 109 out of 110 in the HFA evaluation (Table 4), which implies that whatever
367 weighting strategy was adopted, it would still be ineffective in changing the ranking of Fiji. Nevertheless, this does not
368 affect the validity of the Hyogo framework data as there is absolutely no benefit for any country to provide fake data and
369 information. In addition, the results obtained in this study are to give an indication on how well each country is doing in
370 terms of resilience. The results can be used for comparing the countries rather than knowing their actual resilience. The

371 actual resilience of the country may vary significantly inside the country itself; therefore, we do not intent to provide
372 exhaustive resilience values for the countries, which is absolutely not feasible considering the complexity involved in the
373 process.

374 Fig. 12 near here

375 **Resilience-Based Risk results**

376 In this framework, the last step is to quantify the resilience-based risk index (RBR). As already indicated, the risk
377 index is the combination between resilience, exposure, and hazard. For the sake of this example, the hazard is assumed to
378 be '1' in an attempt to disregard its effect. Therefore, in this specific case study, the risk index is presented in terms of the
379 hazard parameter, which upon availability it can be combined directly with the results obtained in this study. The table
380 below shows the resilience results derived using the three methods and the exposure of every country obtained from the
381 WRR. The resilience-based risk index of every country is subsequently computed using Equation (2).

382 Table 6 near here

383 The numerical results obtained by combining resilience (Fig. 12) with exposure (Fig. 13) using Equation (2) are
384 presented in Fig. 14. It is clear that the risk and the resilience results are far from proportional, and this supports the notion
385 that the most prepared countries (i.e. having high resilience) do not necessarily have the lowest risk. For instance, Japan is
386 widely known for its high preparedness level against natural disasters. Although it is classified among the 'best' countries
387 in the resilience ranking (Fig. 12), Japan is placed among the countries with the highest risk (Fig. 14), and this is because
388 Japan is highly exposed to disasters (Fig. 13). Therefore, the resilience by itself is not a good indicator of the probability
389 of being under a certain resilience level, because the process depends also on the exposure level.

390 Fig. 13 near here

391 Fig. 14 near here

392 **CONCLUSIONS**

393 Resilience measurements are important tools for communities to understand the benefit cost of implementing resilience
394 actions and to evaluate the effects of these actions by looking at different policies and approaches. They can give an idea
395 on where additional resources should be allocated. Although these measurement tools cannot create resilient communities,
396 they can certainly help show and illustrate a path that the community can take to become safer and stronger and more
397 vibrant in the face of unanticipated events.

398 This paper presents a new analytical approach for calculating the resilience and the resilience-based risk of countries.
399 The resilience-based risk is defined as the probability of being below a certain resilience threshold, and is computed by
400 combining resilience, exposure, and hazard. In this paper, the resilience parameter is evaluated using the results of Hyogo

401 Framework for Action, which ranks the countries based on 22 indicators. The indicators of the HFA are combined using
402 three different methods to determine the resilience index. The first two methods are based on the Dependence Tree
403 Analysis. DTA is a method that identifies the correlation between resilience and its indicators in a quantitative manner,
404 giving weighting factors the indicators accordingly. The third method is a geometrical method in which the indicators'
405 scores are plotted on the spider chart' axes. The resilience is quantified as a normalized value of the area inside the enclosed
406 shape made by linking the adjacent indicators' scores.

407 The applicability of the proposed methodology has been tested on 37 countries by calculating their respective resilience
408 and risk indexes. Although the results obtained from the three methods are proportional, the sensitivity on the resilience
409 results provided by each method is different. The first method (DTA) is preferred with respect to the other two because it
410 amplifies the score range of the resilience results of the countries. Then, the resilience-based risk index *RBR* for each
411 country is computed. The obtained numerical results show that the risk of being below a certain resilience threshold depends
412 greatly on the exposure level of that country.

413 In conclusion, in the paper a specific data set collected by United Nation has been used to illustrate the methodology.
414 However, the proposed approach is general and it can be applied using more reliable data as soon as they are available,
415 such as the data that will be provided in the "Sendai Framework".

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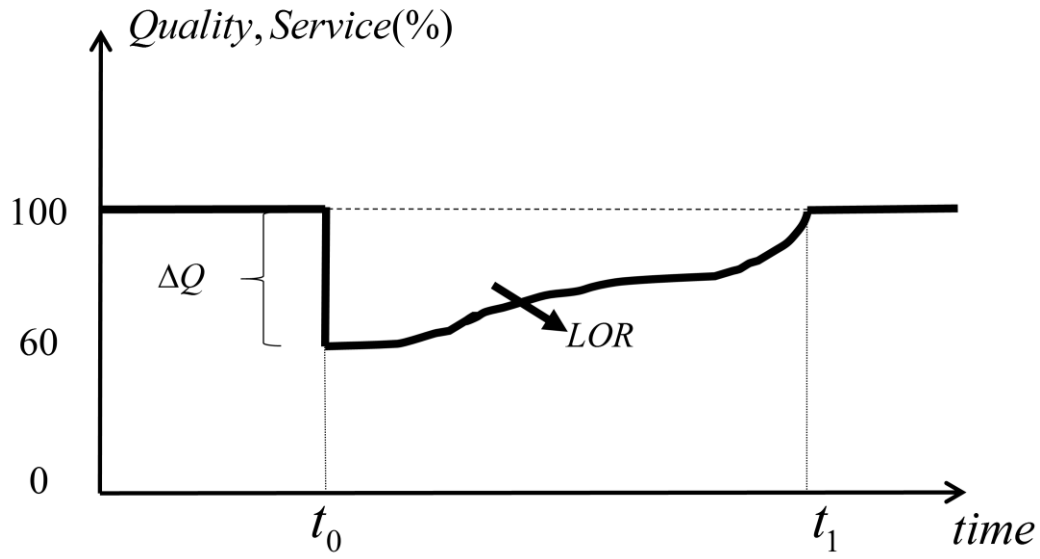
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- Fig. 1 A conceptual representation of engineering resilience



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- Fig. 2 Resilience-based risk analysis Venn diagram

Resilience analysis

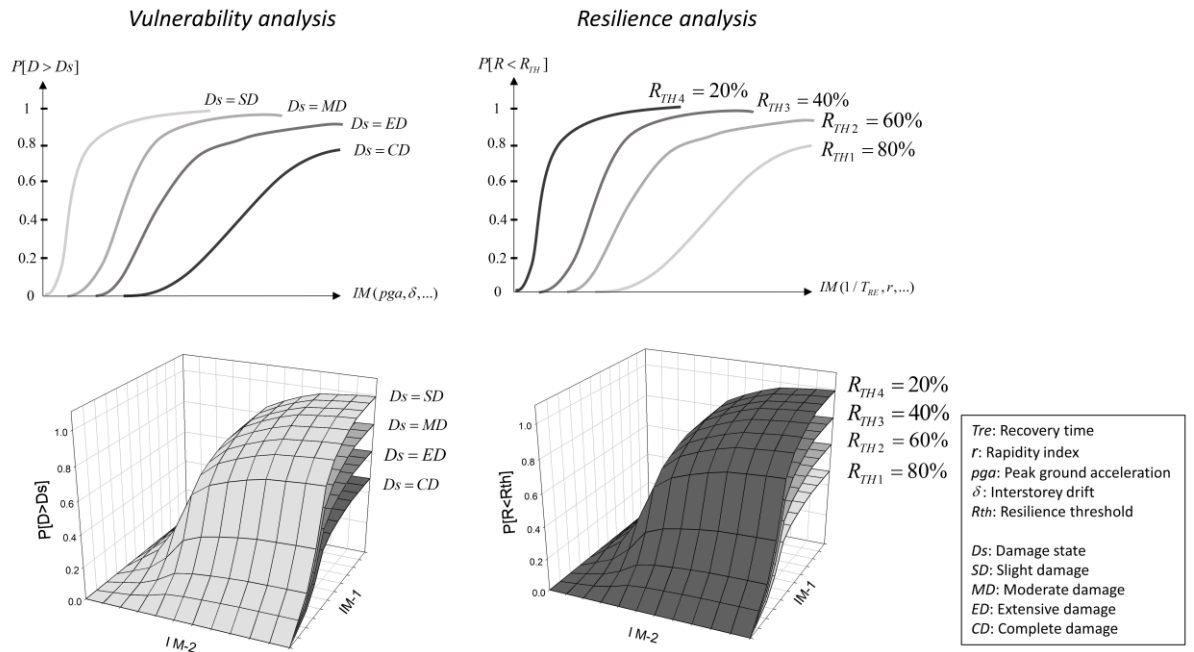


$$Risk = R \times E \times H$$

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- Fig. 3 Comparison between the vulnerability and the resilience analyses



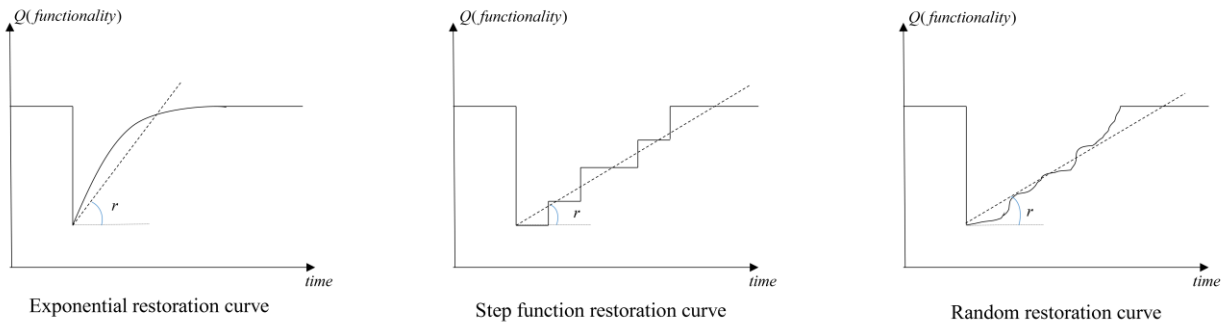
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- Fig. 4 Typical restoration models

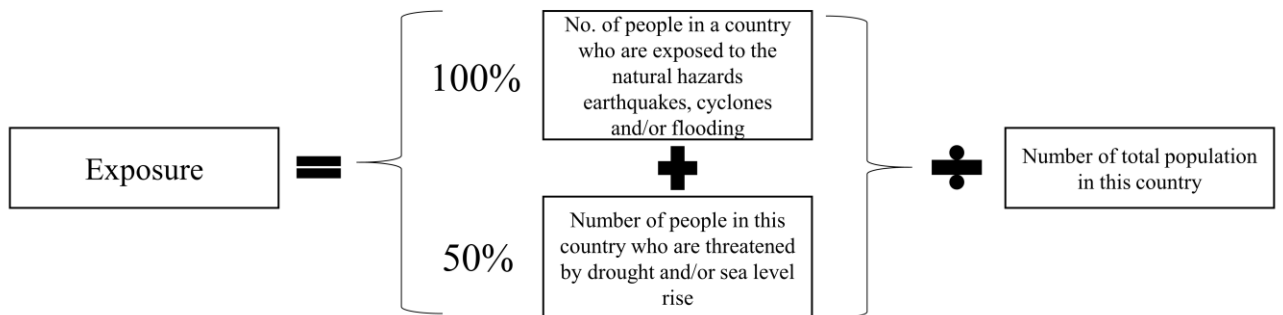


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- Fig. 5 Exposure analysis in the World Risk Report



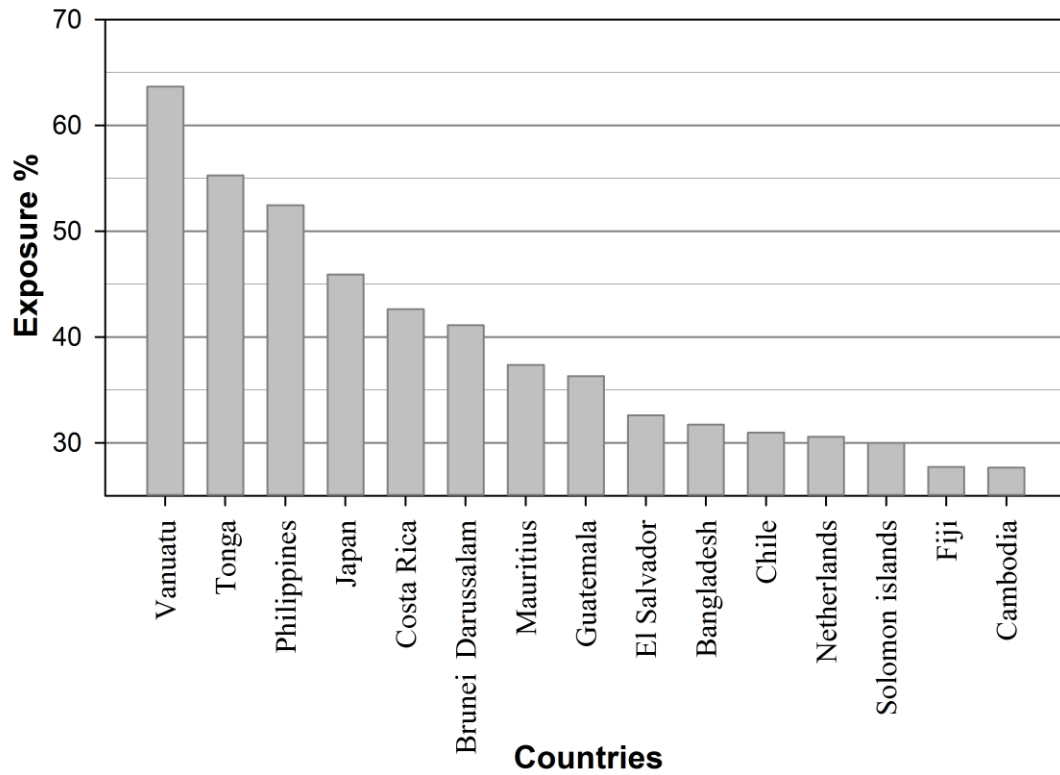
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- Fig. 6 The ten most exposed countries according to the WRR



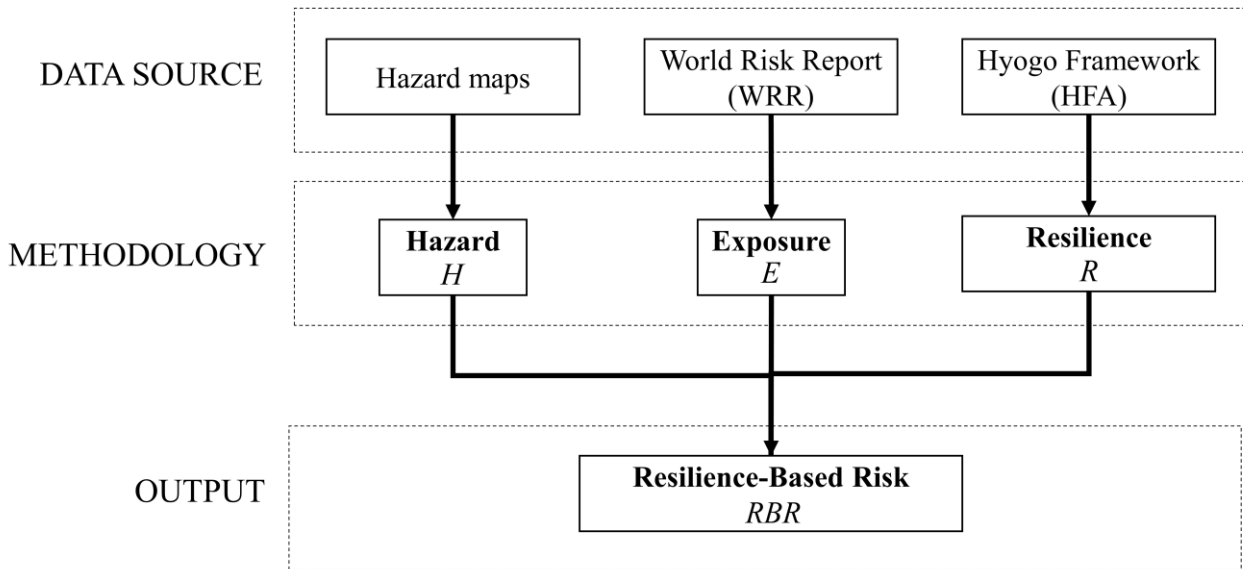
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• Fig. 7 Framework of the proposed methodology



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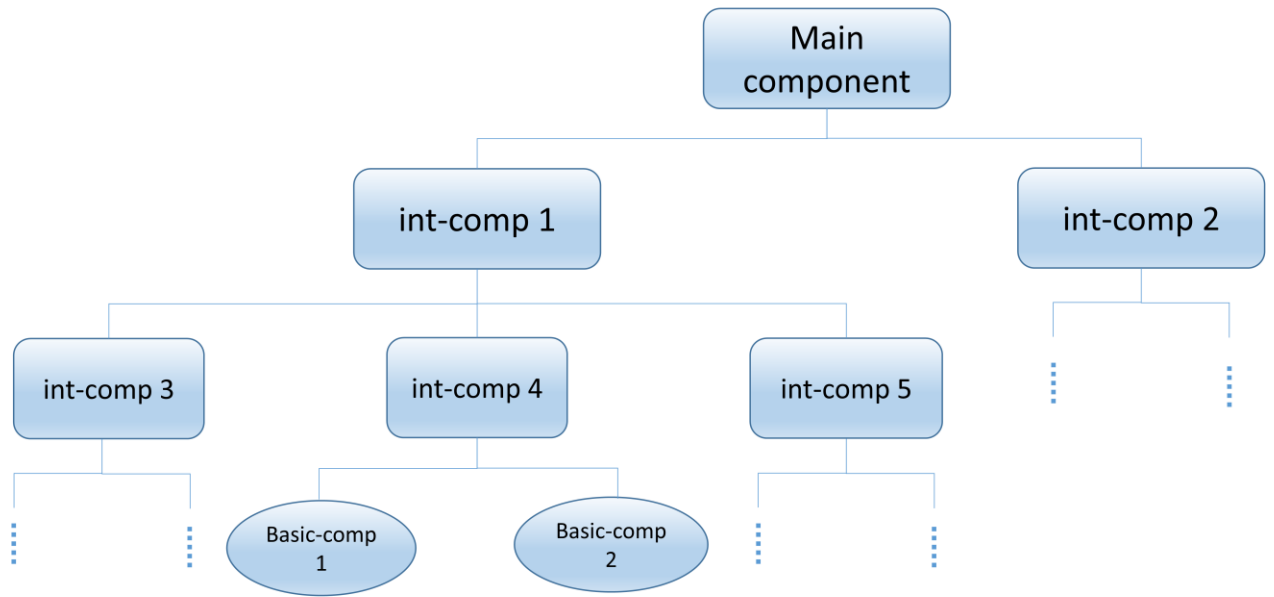
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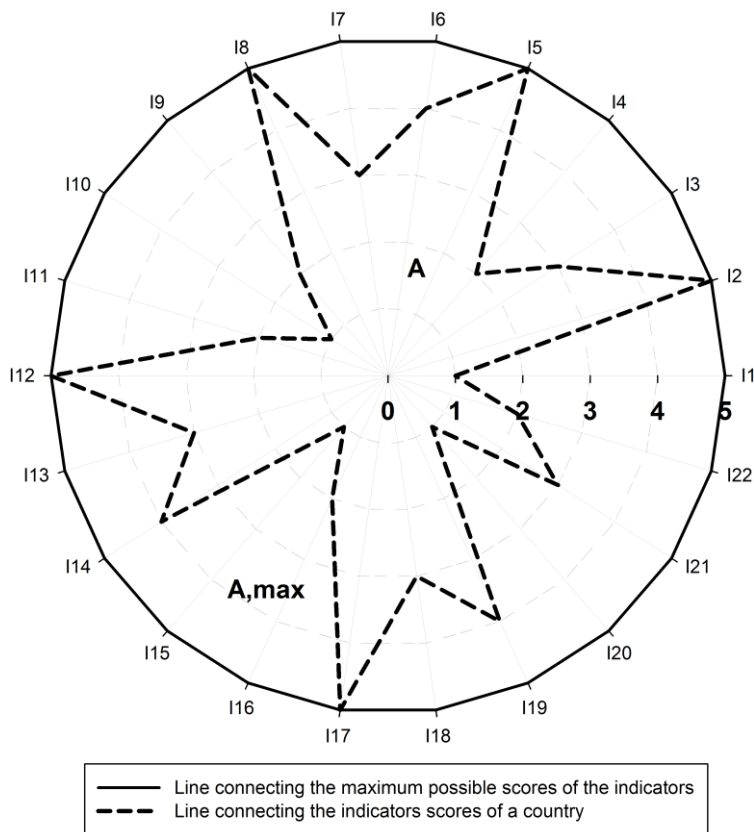
551 • Fig. 8 A dependence tree diagram showing the different types of components



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554 • Fig. 9 Spider plot representation of the HFA indicators scores



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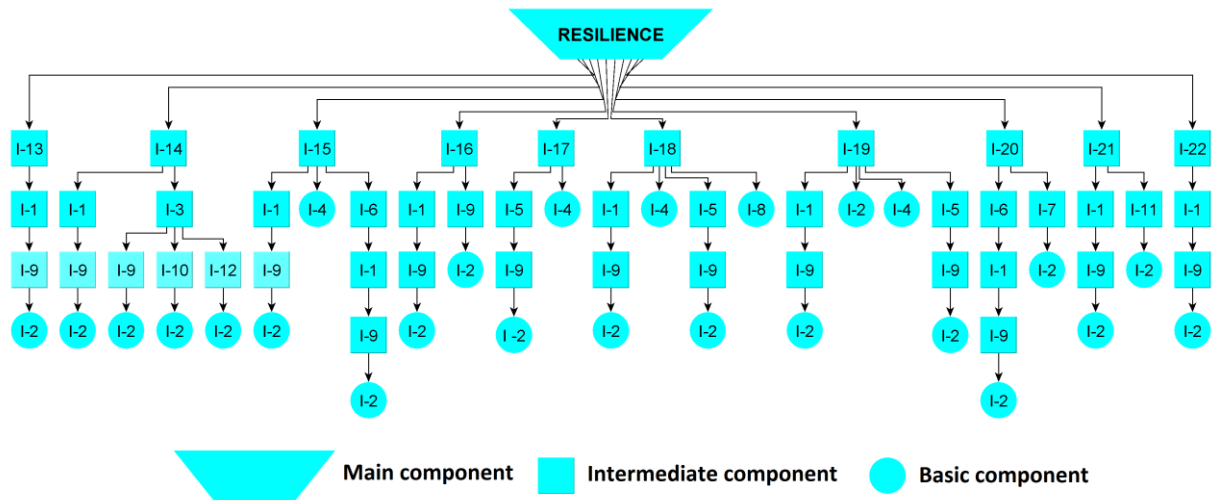
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- Fig. 10 The dependence tree of the HFA's indicators

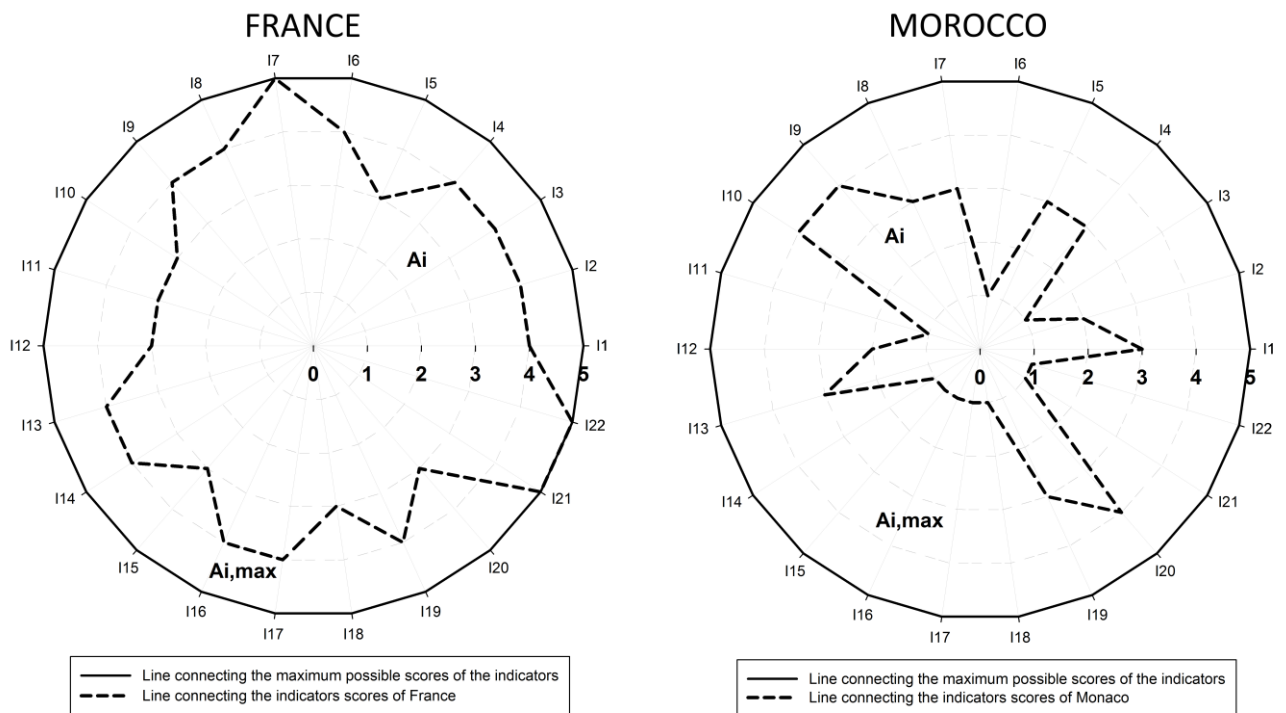


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- Fig. 11 Examples of the spider plot method for two countries (France and Monaco)

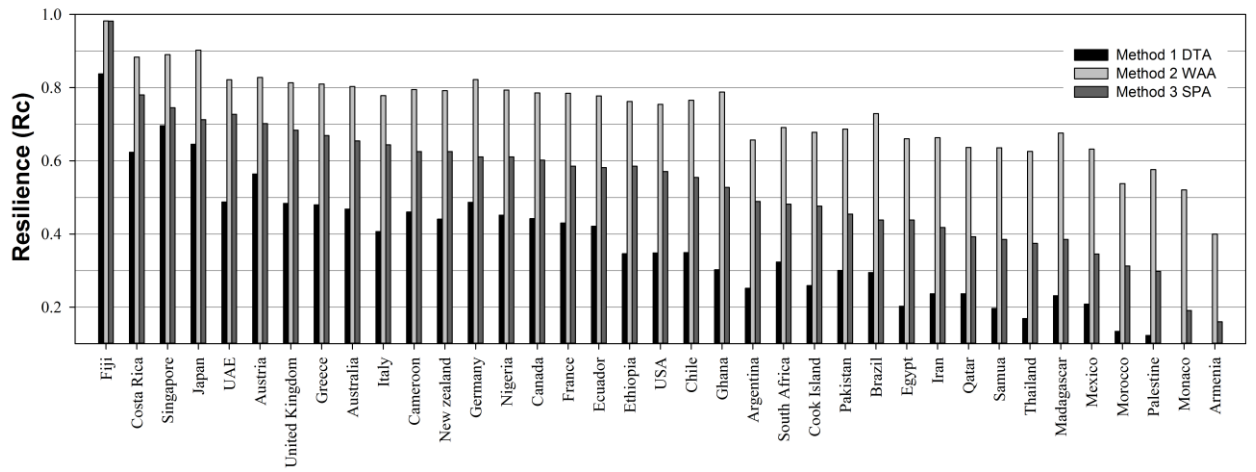


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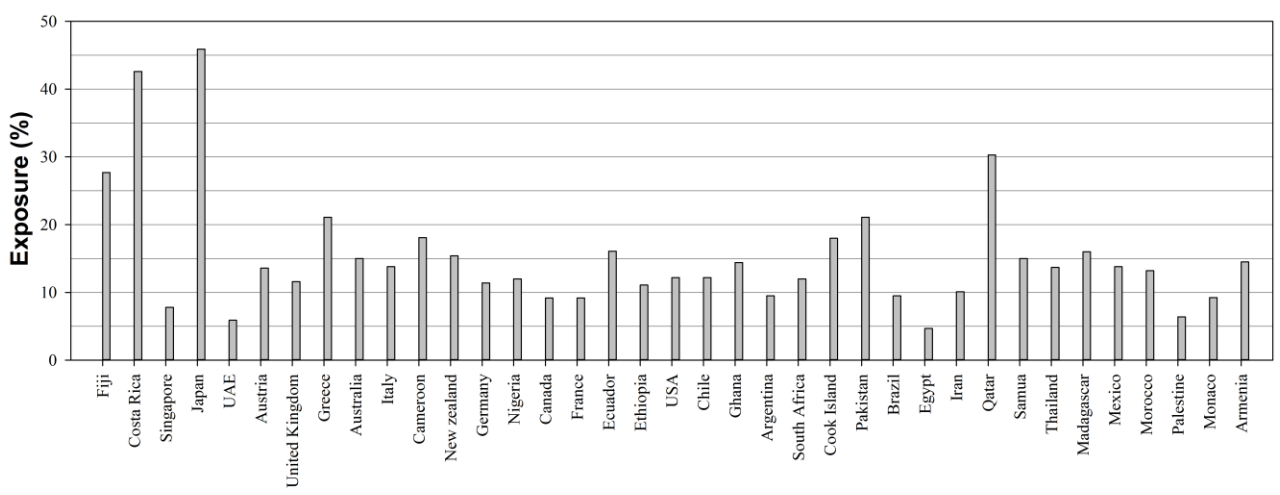
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- Fig. 12 Resilience results obtained by the three methods



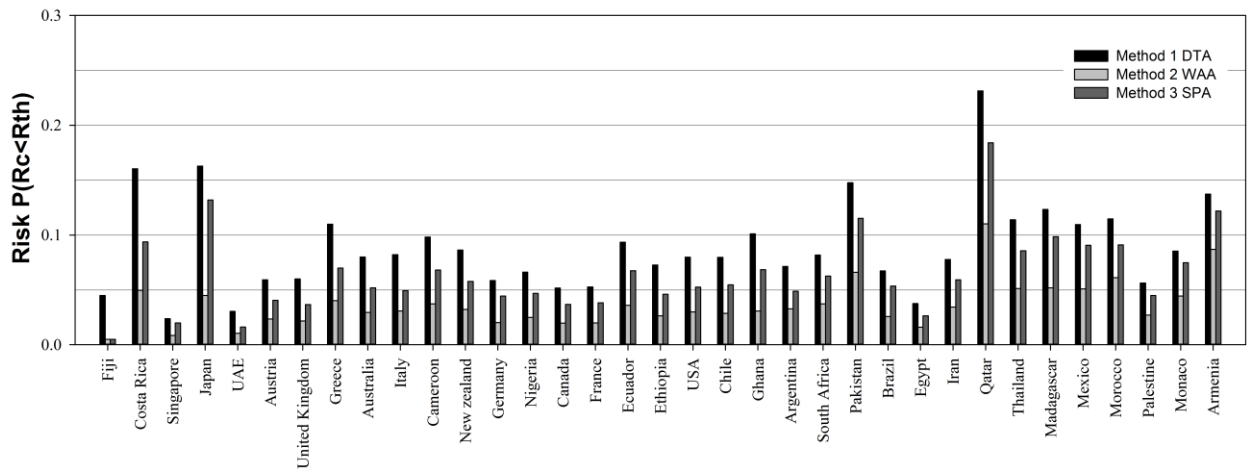
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• Fig. 13 Exposure results of the studied countries obtained from the WRR



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• Fig. 14 Risk results obtained using the results of resilience obtained by the three method



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573 **Table 1.** Difference between vulnerability and resilience at different levels. Adapted from (Cimellaro 2016a)

Vulnerability	Resilience
Resistance	Recovery
Force bound	Time bound
Safety	Bounce back
Mitigation	Adaptation
Institutional	Community-based
System	Network
Engineering	Culture
Risk assessment	Vulnerability and capacity analysis
Outcome	Process
Standards	Institution

574

575 **Table 2.** Priorities and indicators used in the assessment of Hyogo Framework for Action. Adapted from (UNISDR
576 2011)

PRIORITY 1:

Ensure that disaster risk reduction (DRR) is a national and a local priority with a strong institutional basis for implementation

- I 1 National policy and legal framework for disaster risk reduction exists with decentralized responsibilities and capacities at all levels.
- I 2 Dedicated and adequate resources are available to implement disaster risk reduction plans and activities at all administrative levels
- I 3 Community Participation and decentralization is ensured through the delegation of authority and resources to local levels
- I 4 A national multi sectoral platform for disaster risk reduction is functioning.

PRIORITY 2:

Identify, assess and monitor disaster risks and enhance early warning

- I 5 National and local risk assessments based on hazard data and vulnerability information are available and include risk assessments for key sectors.
- I 6 Systems are in place to monitor, archive and disseminate data on key hazards and vulnerabilities
- I 7 Early warning systems are in place for all major hazards, with outreach to communities.
- I 8 National and local risk assessments take account of regional / trans boundary risks, with a view to regional cooperation on risk reduction.

PRIORITY 3:

Use knowledge, innovation, and education to build a culture of safety and resilience at all levels

- I 9 Relevant information on disasters is available and accessible at all levels, to all stakeholders (through networks, development of information sharing systems etc.)
- I 10 School curricula, education material and relevant trainings include disaster risk reduction and recovery concepts and practices.
- I 11 Research methods and tools for multi-risk assessments and cost benefit analysis are developed and strengthened.
- I 12 Countrywide public awareness strategy exists to stimulate a culture of disaster resilience, with outreach to urban and rural communities.

PRIORITY 4:

Reduce the underlying risk factors

- I 13 Disaster risk reduction is an integral objective of environment related policies and plans, including for land use natural resource management and adaptation to climate change.
- I 14 Social development policies and plans are being implemented to reduce the vulnerability of populations most at risk.
- I 15 Economic and productive sectorial policies and plans have been implemented to reduce the vulnerability of economic activities
- I 16 Planning and management of human settlements incorporate disaster risk reduction components, including enforcement of building codes.
- I 17 Disaster risk reduction measures are integrated into post disaster recovery and rehabilitation processes
- I 18 Procedures are in place to assess the disaster risk impacts of major development projects, especially infrastructure.

PRIORITY 5:

Strengthen disaster preparedness for effective response at all levels

- I 19 Strong policy, technical and institutional capacities and mechanisms for disaster risk management, with a disaster risk reduction perspective are in place.
- I 20 Disaster preparedness plans and contingency plans are in place at all administrative levels, and regular training drills and rehearsals are held to test and develop disaster response programs.
- I 21 Financial reserves and contingency mechanisms are in place to support effective response and recovery when required.
- I 22 Procedures are in place to exchange relevant information during hazard events and disasters, and to undertake post-event reviews

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Table 3. The questions asked by the UN to assess the first indicator. Adapted from (UNISDR 2011)

Indicator 1	National policy and legal framework for disaster risk reduction exists with decentralized responsibilities and capacities at all levels.	Answer type
Questions	<ul style="list-style-type: none"> -Is disaster risk taken into account in public investment and planning decisions? -National development plan -Sector strategies and plans -Climate change policy and strategy -Poverty reduction strategy papers -CCA/ UNDAF (Common Country Assessment/ UN Development Assistance Framework) -Civil defense policy, strategy and contingency planning -Have legislative and/or regulatory provisions been made for managing disaster risk? -Description -Context & Constraints 	<ul style="list-style-type: none"> YES/NO YES/NO YES/NO YES/NO YES/NO YES/NO YES/NO YES/NO Write text Write text
	Level of progress achieved: (1 to 5)	

Table 4. Indicators scores for the analyzed countries

Countries	Indicators																						Total (per 110)	Total (%)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22		
1-Fiji	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	109	99.1
2-Costa Rica	5	4	4	5	3	4	5	4	4	4	5	4	4	4	3	5	5	5	5	5	5	5	97	88.2
3-Singapore	5	5	5	2	5	5	5	5	5	5	5	5	2	5	5	4	1	1	5	5	4	5	94	85.5
4-Japan	5	4	4	5	4	4	4	4	5	4	3	5	4	4	4	4	4	5	5	4	4	4	93	84.5
5-UAE	5	4	5	4	4	4	3	3	3	4	4	5	5	5	5	5	5	5	4	4	3	4	93	84.5
6-Austria	4	5	5	3	4	4	5	5	4	4	3	4	4	4	4	4	4	5	5	4	4	4	92	83.6
7-UK	4	4	5	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	91	82.7
8-Greece	4	4	4	4	4	4	5	4	4	4	4	4	4	4	4	5	4	4	4	4	4	4	90	81.8
9-Australia	4	4	4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	89	80.9
10-Italy	2	4	4	4	4	4	5	4	5	4	4	4	4	3	3	3	5	4	5	5	4	4	88	80.0
11-Cameroon	4	4	4	5	4	4	4	4	4	4	4	4	4	3	4	4	4	4	4	3	4	4	87	79.1
12-New Zealand	4	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	87	79.1
13-Germany	5	4	4	4	4	4	4	4	4	3	4	4	4	5	3	4	3	3	4	4	4	4	86	78.2
14-Nigeria	4	4	2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	86	78.2
15-Canada	4	4	5	4	3	4	4	4	4	3	3	4	3	3	4	4	5	4	5	5	3	3	85	77.3
16-France	4	4	4	4	3	4	5	4	4	3	3	3	4	4	3	4	4	3	4	3	5	5	84	76.4
17-Ecuador	4	4	4	4	3	4	3	4	4	4	4	4	4	4	4	4	4	3	4	4	3	4	84	76.4
18-Ethiopia	4	3	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	4	4	4	4	4	84	76.4
19-USA	4	4	4	3	4	4	4	4	3	4	4	4	3	3	3	4	4	4	4	4	4	4	83	75.5
20-Chile	4	3	3	4	4	3	4	3	4	4	2	4	3	4	4	4	4	4	4	4	5	4	82	74.5
21-Ghana	4	2	2	4	4	4	4	4	5	1	4	4	4	4	3	3	4	4	4	4	4	4	80	72.7
22-Argentina	3	3	4	4	4	3	4	4	3	3	3	4	3	3	3	4	4	4	4	4	2	4	77	70.0
23-South Africa	4	4	4	4	3	3	3	3	3	3	3	3	4	3	3	3	4	4	3	4	4	4	76	69.1
24-Cook Island	4	3	4	4	3	4	4	4	3	3	3	4	4	3	3	3	4	3	4	3	3	3	76	69.1
25-Pakistan	4	4	4	4	3	3	3	4	3	3	3	3	3	3	3	3	4	3	3	4	4	3	74	67.3
26-Brazil	4	3	4	3	4	5	1	2	4	2	2	3	3	5	3	4	4	3	3	4	3	4	73	66.4
27-Egypt	4	2	4	4	4	3	3	3	3	3	2	4	4	3	4	3	3	3	4	4	3	3	73	66.4
28-Iran	4	3	4	4	3	3	2	2	3	4	3	3	3	3	3	4	3	3	4	3	4	3	71	64.5
29-Qatar	3	4	3	3	4	3	3	3	3	2	3	3	4	3	3	3	3	3	4	3	3	3	69	62.7
30-Samua	4	3	3	4	4	2	3	4	3	3	3	4	4	3	3	2	2	1	4	3	3	3	68	61.8
31-Thailand	4	2	4	4	2	2	4	3	3	3	2	4	3	4	2	3	2	3	4	4	4	2	68	61.8
32-Madagascar	4	3	4	4	4	2	2	2	4	5	4	2	2	1	2	2	4	2	4	4	2	4	67	60.9
33-Mexico	4	3	3	4	2	3	4	3	3	2	3	2	3	3	3	2	3	3	3	2	4	3	65	59.1
34-Morocco	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	3	3	3	61	55.5
35-Palestine	3	2	3	4	3	2	4	4	4	3	2	4	3	2	1	2	2	2	3	3	1	2	59	53.6
36-Monaco	3	2	1	3	3	1	3	3	4	4	1	2	3	1	1	1	1	1	3	4	1	1	47	42.7
37-Armenia	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	44	40.0

Table 5. Importance and weighting factors of the HFA indicators

Indicator	Importance factor IF	Weighting factor W_i	Indicator	Importance factor IF	Weighting factor W_i	Indicator	Importance factor IF	Weighting factor W_i
I-1	0.54	0.154	I-9	0.65	0.187	I-17	0.1	0.028
I-2	0.79	0.225	I-10	0.017	0.005	I-18	0.1	0.028
I-3	0.05	0.014	I-11	0.05	0.014	I-19	0.1	0.028
I-4	0.13	0.038	I-12	0.02	0.006	I-20	0.1	0.028
I-5	0.10	0.028	I-13	0.1	0.028	I-21	0.1	0.028
I-6	0.08	0.024	I-14	0.1	0.028	I-22	0.1	0.028
I-7	0.05	0.014	I-15	0.1	0.028			
I-8	0.025	0.007	I-16	0.1	0.028			

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Table 6. Resilience results obtained from the three methods and the exposure of each country

Country	R ₁	R ₂	R ₃	E (%)	Country	R ₁	R ₂	R ₃	E (%)	Country	R ₁	R ₂	R ₃	E (%)
Fiji	0.84	0.98	0.98	27.7	Germany	0.49	0.82	0.61	11.4	Brazil	0.29	0.73	0.44	9.5
Costa Rica	0.62	0.88	0.78	42.6	Nigeria	0.45	0.79	0.61	12.0	Egypt	0.20	0.66	0.44	4.7
Singapore	0.70	0.89	0.75	7.8	Canada	0.44	0.79	0.60	9.2	Iran	0.24	0.66	0.42	10.1
Japan	0.65	0.90	0.71	45.9	France	0.43	0.78	0.59	9.2	Qatar	0.24	0.64	0.39	30.3
UAE	0.49	0.82	0.73	5.9	Ecuador	0.42	0.78	0.58	16.1	Thailand	0.17	0.63	0.37	13.7
Austria	0.56	0.83	0.70	13.6	Ethiopia	0.35	0.76	0.59	11.1	Madagascar	0.23	0.68	0.39	16.0
United Kingdom	0.48	0.81	0.68	11.6	USA	0.35	0.75	0.57	12.2	Mexico	0.21	0.63	0.35	13.8
Greece	0.48	0.81	0.67	21.1	Chile	0.35	0.77	0.55	12.2	Morocco	0.13	0.54	0.31	13.2
Australia	0.47	0.80	0.65	15.0	Ghana	0.30	0.79	0.53	14.4	Palestine	0.12	0.58	0.30	6.4
Italy	0.41	0.78	0.64	13.8	Argentina	0.25	0.66	0.49	9.5	Monaco	0.08	0.52	0.19	9.25
Cameroon	0.46	0.80	0.63	18.1	South Africa	0.32	0.69	0.48	12.0	Armenia	0.05	0.40	0.16	14.5
New Zealand	0.44	0.79	0.63	15.4	Pakistan	0.30	0.69	0.45	21.1					

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