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APPLICATION OF ANALYTIC HIERARCHY PROCESS (AHP) IN EARTHQUAKE RISK ASSESSMENT

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Abstract

Different types of disasters, including earthquakes, are causing social, health, economic, and environmental damage worldwide. In this regard, the need for comprehensive and effective disaster and risk management becomes even more recognised, especially from public institutions. Risk management includes careful identification, analysis, and development of risk mitigation strategies, which implies planning and a certain degree of prediction of future events and their consequences. However, all risk components of earthquakes are not measurable or have a very high degree of uncertainty. Therefore, earthquake risk management activities are challenging throughout entire earthquake risk management activities. In this paper, the Analytic hierarchy process (AHP) for effective earthquake risk assessment is presented. AHP belongs to the group of multi-criteria analysis that combines quantitative and qualitative data with the aim of making decisions in defining the priorities of alternative solutions to a given problem. It is particularly suitable in cases where there is a lack of statistical data to conduct the analysis. The use of AHP is explored in the context of producing earthquake risk priority lists for a certain geographical region. A hierarchical model for risk assessment of five different counties was developed. The three main criteria that have influence on the earthquake risk are used: hazard, exposure, and vulnerability of the built environment. AHP was used to determine the priority list of counties according to these three criteria. The resulting priority list of counties can be used to produce earthquake risk maps, thus provide a useful tool for allocation of available mitigation resources.

Keywords: analytical hierarchy process (AHP), decision making, earthquake risk assessment, risk management

1. Introduction

Due to the large consequences on human lives, health, finances, and environment, natural disasters such as earthquakes have been attracting more and more attention from scientific community. Moreover, public institutions with the aim of mitigating natural disasters and governments across the world acknowledge the importance of building resilience of nations and communities to disasters. In that regard, the new UN's *Sendai Framework for Disaster Risk Reduction 2015-2030* [1] emphasises the importance of management of disaster risks, instead of disaster management. The main objective of the Sendai Framework and similar initiatives is to prevent new and reduce the existing risk of disasters through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political, and institutional measures. In Europe, similar initiative is set by JRC's *Recommendations for National Risk Assessment for Disaster Risk Management in EU* [2]. In these guidelines, disaster risks are approached from the point of view of the ISO 31000 standard [3], and the emphasis is given to four steps of risk management: identification; analysis; evaluation; and response to disaster risks.

Earthquake risk or seismic risk describes the negative consequences caused by an earthquake (victims, number of damaged and collapsed buildings, financial losses, etc.) and the probability of their occurrence for a certain level of seismic activity. Earthquake risk is usually calculated using a set of variables or elements of earthquake risk: earthquake hazard (or seismic hazard), exposure and vulnerability. These elements represent the input data for earthquake risk assessment, but in many cases

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are not measurable or have a very high degree of uncertainty. In recent years, several big projects with the aim of collecting more input data for earthquake risk management have been implemented across the world (see for example GEM [4] and SERA [5]). Nevertheless, the lack of correct input data remains the major challenge in earthquake risk assessment.

In the case when there is not a large enough number of input data, the analytical hierarchy process (AHP) method has proven to be very accurate and suitable for risk assessment. AHP is a multi-criteria analysis that combines quantitative and qualitative data with the aim of making decisions in defining the priorities of alternative solutions to a given problem. It is particularly suitable in cases where we do not have a sufficient number of statistical data, when almost all risk components are not measurable or have a very high degree of uncertainty. In the case of earthquake risk, the input data have the same uncertain characteristics, and therefore AHP is a suitable and widely applicable method for its assessment. The application of the AHP method in earthquake risks can be found in many scientific papers and case studies of practical examples. AHP is used to assess earthquake risk independently or in combination with other methods in the scientific studies by Fariza et al. [6], Nyimbili et al. [7], Jena et al. [8], Jena and Pradhan [9], Özkazanç et al. [10], Shadmaan and Islam [11].

In this paper, AHP is described in more detail and an example of its application for earthquake risk assessment of certain geographical areas is given.

2. An overview of Analytic hierarchy process (AHP)

AHP was developed by Thomas L. Saaty as a decision aid [12-14] that results in the priorities of different alternative options compared according to complex or multiple criteria. By simple comparisons of pairs of model elements, AHP obtains the weight value of each alternative option. AHP can best be used for multi-criteria problems in which it is not possible to precisely quantify how alternatives impact decision making. Values for comparison can be obtained by actual or relative measurements, or subjective assessments by experts with extensive experience.

The method is applied to numerous concrete examples of various types of decision making. Subjective assessments and objective facts are incorporated into a logical hierarchical AHP framework to provide decision makers with an intuitive and common-sense approach in quantifying the importance of each decision element through a comparison process. This process enables decision makers to reduce a complex problem to a hierarchical form with several levels, with a minimum of three: the goal of analysis, criteria, and alternatives [15].

The first step in implementing the model is dividing the decision problem into hierarchical levels [15-17]. This means that at least three levels of decision making should be defined: goal, criteria, and alternatives.

Each model has a hierarchical structure and consists of several levels. The highest level on the hierarchical scale is the goal. Then follow the criteria, possibly sub-criteria, and alternatives. The hierarchical structure of the decision making model is shown schematically in Fig. 1.

The second step is forming comparative matrices for all hierarchical levels [17, 18]. This step is the most important and sensitive step. It is also the only subjective step (in case we do not have quantified input parameters) and depends on professional knowledge, experience and personal priorities defined by the decision maker. For each level, it is necessary to compare and evaluate the elements of that level in relation to each element of a higher level. For the previously defined three levels, this means that at level 1, a comparison of all set criteria will be performed in relation to the given goal, while at level 2, all alternatives will be compared with each other, i.e. evaluated in relation to the given criteria. The process starts by determining the relative importance of particular alternatives with respect to the criteria and the sub-criteria [16]. Then the criteria are compared with respect to the goal. Finally, the results of these two analyses are synthesised by calculating the relative importance of the alternatives with respect to achieving the goal. The process of comparison is represented by forming a comparative matrix [12]. If the analyst has at his disposal n alternatives, or criteria that form the comparative matrix, then he must make *n(n-1)/2* evaluations [17]. In order to quantify the comparative evaluation, it is necessary to perform standardization. The proposal of one such standardization is presented in Table 1.

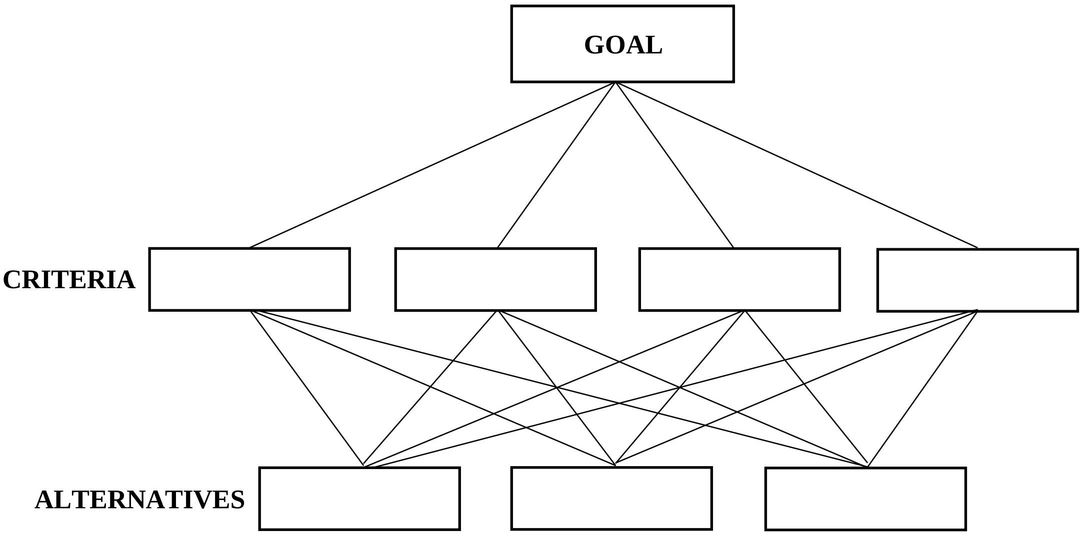

Figure 1. Hierarchical structure of the AHP model.

Table 1 – The scale for pairwise comparisons [13, 19]

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour one element over another
5	Essential or strong importance	Experience and judgment strongly favour one element over another
7	Very strong importance	An element is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

Examples of using Table 1:

- If the decision maker estimates that criterion 1 is extremely more important than criterion 2 with regard to the set goal, then the matrix element gets the value 9.
- If the decision maker estimates that alternative 1 is moderately more important than alternative 2 with regard to criterion 2, then the matrix element gets the value 3.

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Furthermore, Table 2 shows that criterion 1 is moderately (3) more important than criterion 2, considering the goal of decision making. Table 3 shows that alternative 2 is moderately to strongly (4) more important than alternative 5, with regard to criterion 2.

Table 2 – Example of a comparative matrix with regard to level 1 of the hierarchy

With regard to Goal	Criterion 1	Criterion 2	Criterion 3
Criterion 1	1	3	5
Criterion 2	1/3	1	4
Criterion 3	1/5	1/4	1

Table 3 – Example of a comparative matrix with regard to level 2 of the hierarchy

With regard to Criterion 2	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Alternative 1	1	1/3	½	1/4	2
Alternative 2	3	1	2	1/2	4
Alternative 3	2	1/2	1	1/3	3
Alternative 4	4	2	3	1	5
Alternative 5	1/2	1/4	1/3	1/5	1

The third step is calculating regional eigenvectors and eigenvalues for the comparative matrices for all hierarchical levels. The normalized eigenvector of each comparative matrix is the priority list, while the maximum eigenvalue gives the measure of consistency in making the assessment or comparison. On the level of criteria the regional eigenvector defines the priority, with respect to weight, of the individual criteria for achieving the goal, while on the level of alternatives the regional eigenvector defines the priority of the alternatives with respect to the given criterion. The synthesised eigenvector is the global sequence of the alternatives with respect to achieving the goal. A global consistency ratio smaller than 0.10 is acceptable, otherwise the assessments must be revised.

The eigenvector and the maximum eigenvalue of the comparative matrix are determined by solving the general problem of eigenvalues:

$$AW = \lambda_{max} W \tag{1}$$

where

A – comparative matrix,

$W = (W_1, W_2, W_3, W_4, W_5)^T$ – eigenvector, and

λ_{max} – maximum eigenvalue.

The fourth step is calculating the consistency ratio for each comparative matrix on all levels, and this is determined from the eigenvalue of the comparative matrix. AHP calculates a consistency ratio comparing the consistency index of the matrix versus the consistency index of a random matrix. A random matrix is a matrix where the judgments have been entered randomly. Therefore, it is expected to be highly inconsistent. If the consistency ratio exceeds 0.10 then inconsistent assessments were made in forming the comparative matrices on particular hierarchical levels and such matrices must be formed anew. If the consistency ratio is smaller than 0.10 then it is possible to move on to the next step.

Consistency index (CI) is calculated according to the expression:

$$CI = (\lambda_{max} - n) / (n-1) \tag{2}$$

where

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λ_{max} – maximum eigenvalue of the comparison matrix,

n - dimension of the comparison matrix.

Consistency ratio (CR) is calculated according to the expression:

$$CR = CI / RI \tag{3}$$

where random consistency index (RI) is given in Table 4.

Table 4 – Random consistency index (RI) values

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The fifth step is synthesising the calculation results from all levels and weighting each alternative in relation to achieving the goal. The global eigenvector and the global consistency ratio are calculated. If the global consistency ratio exceeds 0.10 then inconsistent judgments still exist and the comparative matrices must be redefined. If the consistency ratio is smaller than 0.10 then the process of defining the weight and interdependency of the alternatives with respect to the given goal has been concluded.

3. Application of AHP in earthquake risk assessment

The application of AHP is shown on the example of earthquake risk assessment for individual geographic areas. With the help of the AHP, it is possible to determine a list of priorities of individual districts, cities, counties, countries, etc., according to the severity of the earthquake risk. In this way, it is possible to create and display comprehensive risk maps of an area, which include all elements of earthquake risk (hazard, exposure, vulnerability, but also cost, social and other aspects of earthquakes).

The *Super Decisions* software for decision support [20] based on the AHP method is used as an auxiliary tool in this analysis.

3.1 Hierarchical levels

The problem of prioritizing certain geographical areas is divided into three hierarchical levels: goal, criteria, and alternatives.

Level 1 always represents the set goal to be achieved by the analysis, and in this case it refers to the earthquake risk assessment. It is the highest hierarchical level whose priority is quantified by the priority index for each individual alternative, that is, the geographical area we are observing. In the given example, the goal is to determine the earthquake risk of the counties.

Level 2 contains criteria that are assumed to be important attributes with regard to meeting the goal at level 1. Setting these criteria is a very important step, because they must cover all important elements of earthquake risk. In this example, the criteria are:

- **Exposure** – the extent of human activity (for example, the presence of buildings) in areas exposed to seismic hazard. The most important part of the exposure data refers to the list of existing buildings (fund) which significantly contributes to social and economic risk.
- **Hazard** – potentially devastating effects of an earthquake (for example, ground shaking, liquefaction, landslides, tsunamis, etc.) at the observed location.
- **Vulnerability** – susceptibility of exposed buildings to the effects of earthquakes (damages) described with structural features of the building fund.

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Level 3 provides alternatives that are compared with respect to the criteria at level 2, all in function of the goal set at level 1. At the national level, the alternatives could be counties or cities and municipalities. In this example, several arbitrary counties will be displayed, for the purpose of presenting the method:

- County 1,
- County 2,
- County 3,
- County 4,
- County 5.

The model described in this way is defined in the *Super Decisions* software (Fig. 2).

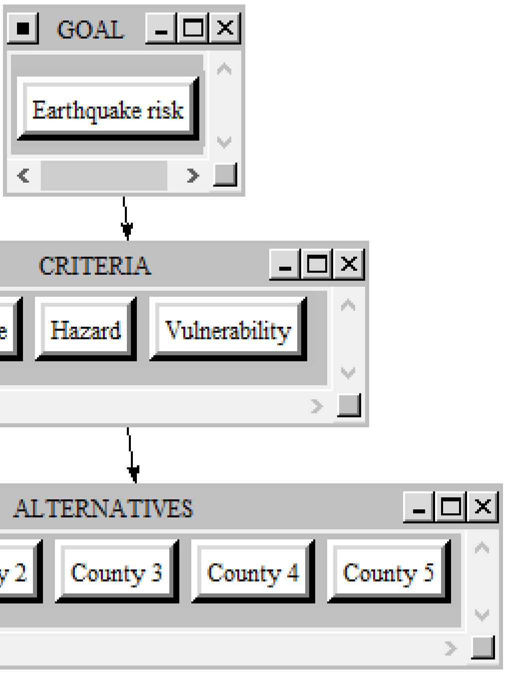

Figure 2. Decision making model in the *Super Decisions*.

3.2 Comparative matrices

After defining a model with a minimum of three hierarchical levels, it is possible to format the comparative matrices. In this example, there are four comparison matrices: one in relation to level 1 (goal level) and three in relation to level 2 (criteria level). The number of comparisons that need to be made within each matrix is $n(n-1)/2$, if n is the number of defined criteria or alternatives. In this example, the evaluation was carried out based on the standardization from Table 1.

Table 5 shows a comparative matrix with regard to level 1, in which the defined criteria are compared. The importance of individual criteria in relation to the defined goal is determined by the decision maker. Such decisions are subjective, but based on the knowledge available to the decision maker at the time of analysis.

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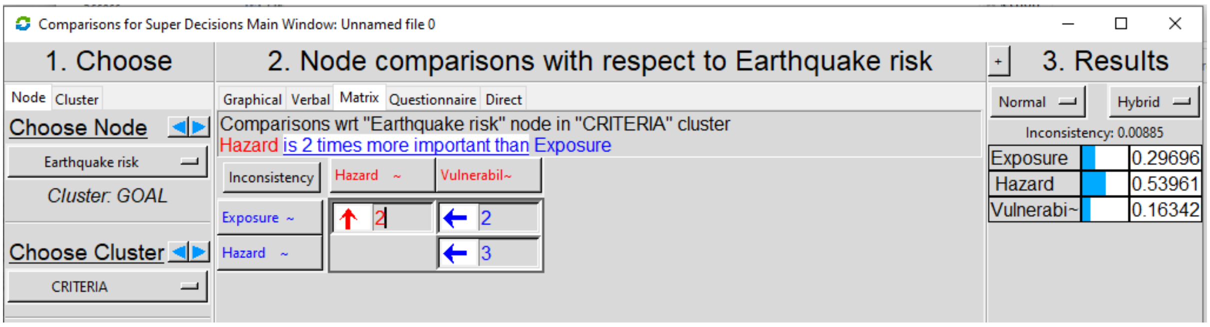
Table 5 – Comparison matrix with respect to goal

Wrt Earthquake risk	Exposure	Hazard	Vulnerability
Exposure	1	1/2	2
Hazard	2	1	3
Vulnerability	1/2	1/3	1

As shown in Table 5, hazard is rated as equally to slightly (2) more important than exposure in terms of determining earthquake risk. This applies only for our example of specific counties, and does not provide a general conclusion on the importance of earthquake elements. Fig. 3 shows a screenshot from the *Super Decisions*, where the value of the eigenvector W_c and the consistency ratio CR_c for level 1 are calculated as:

$W_c = (W_1, W_2, W_3)^T = (\mathbf{0.297, 0.540, 0.163})^T$

$CR_c = \mathbf{0.009} < 0.10$



Comparisons wrt "Earthquake risk" node in "CRITERIA" cluster
Hazard is 2 times more important than Exposure

Inconsistency: 0.00885

Exposure	0.29696
Hazard	0.53961
Vulnerabi~	0.16342

Figure 3. Comparison of criteria in relation to the goal – *Super Decisions*.

Table 6 shows a comparative matrix with regard to level 2, in which the defined alternatives are compared with each other with regard to the criterion of exposure of the built environment. The importance of individual alternatives in relation to the exposure criterion can be determined on the basis of input data on exposure in the territory of each county. When comparing alternatives, the county in whose territory the exposure of the built environment is higher, that is, the losses due to earthquakes are higher, receives higher marks.

Table 6 – Comparison matrix with respect to level 2 – criterion: exposure

Wrt Exposure	County 1	County 2	County 3	County 4	County 5
County 1	1	3	9	2	3
County 2	1/3	1	6	1/2	1
County 3	1/9	1/6	1	1/6	1/5
County 4	1/2	2	6	1	2
County 5	1/3	1	5	1/2	1

As shown in Table 6, in County 1 the exposure of buildings is extremely higher (9) than in County 3. Fig. 4 shows a screenshot from the *Super Decisions*, where the value of the eigenvector W_{a1} and consistency ratio CR_{a1} for level 2 are calculated as:

$W_{a1} = (W_1, W_2, W_3, W_4, W_5)^T = (\mathbf{0.419, 0.152, 0.035, 0.249, 0.145})^T$

$CR_{a1} = \mathbf{0.016} < 0.10$

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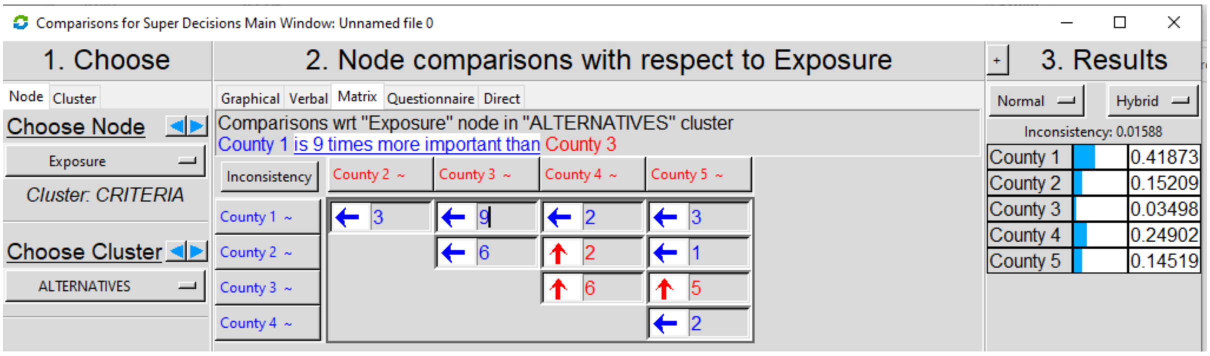


Comparisons wrt "Exposure" node in "ALTERNATIVES" cluster
County 1 is 9 times more important than County 3

Inconsistency	County 2	County 3	County 4	County 5
County 1	← 3	← 9	← 2	← 3
County 2		← 6	↑ 2	← 1
County 3			↑ 6	↑ 5
County 4				← 2

Inconsistency: 0.01588

County 1	0.41873
County 2	0.15209
County 3	0.03498
County 4	0.24902
County 5	0.14519

Figure 4. Comparison of alternatives in relation to the exposure criterion – *Super Decisions.*

Table 7 shows a comparative matrix with regard to level 2, in which the defined alternatives are compared with each other with regard to the earthquake hazard criterion. The importance of individual alternatives in relation to the hazard criterion can be determined based on the input data on the earthquake hazard in the territory of each county. When comparing the alternatives, the county in which the hazard is higher, i.e. the potential devastating effects of an earthquake (for example, ground shaking, liquefaction, landslides, tsunami, etc.) are more serious in the observed location, receives higher marks.

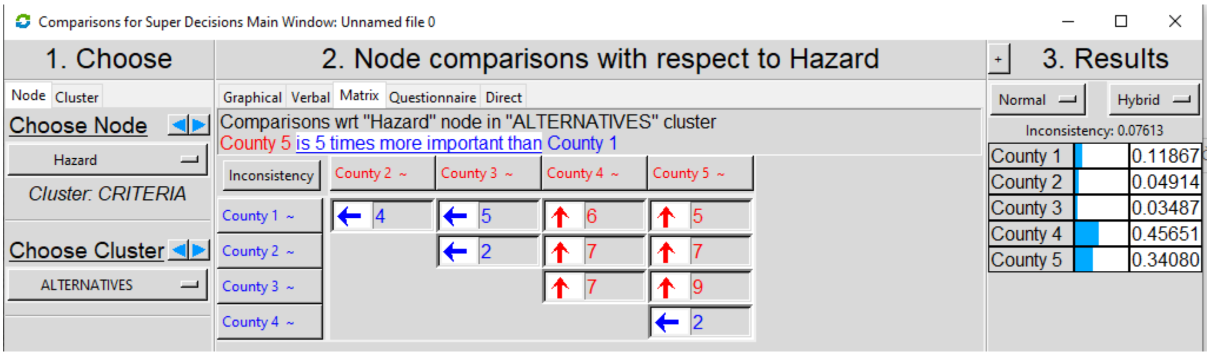
Table 7 – Comparison matrix with respect to level 2 – criterion: hazard

Wrt Hazard	County 1	County 2	County 3	County 4	County 5
County 1	1	4	5	1/6	1/5
County 2	1/4	1	2	1/7	1/7
County 3	1/5	1/2	1	1/7	1/9
County 4	6	7	7	1	2
County 5	5	7	9	1/2	1

As shown in Table 7, in County 5 the earthquake hazard is strongly higher (5) than in County 1. Fig. 5 shows a screenshot from the *Super Decisions*, where the value of the eigenvector W_{a2} and consistency ratio CR_{a2} for level 2 are calculated as:

$W_{a2} = (W_1, W_2, W_3, W_4, W_5)^T = (\mathbf{0.119, 0.049, 0.035, 0.457, 0.341})^T$

$CR_{a2} = \mathbf{0.076} < 0.10$



Comparisons wrt "Hazard" node in "ALTERNATIVES" cluster
County 5 is 5 times more important than County 1

Inconsistency	County 2	County 3	County 4	County 5
County 1	← 4	← 5	↑ 6	↑ 5
County 2		← 2	↑ 7	↑ 7
County 3			↑ 7	↑ 9
County 4				← 2

Inconsistency: 0.07613

County 1	0.11867
County 2	0.04914
County 3	0.03487
County 4	0.45651
County 5	0.34080

Figure 5. Comparison of alternatives in relation to the hazard criterion – *Super Decisions.*

Table 8 shows a comparative matrix with regard to level 2, in which the defined alternatives are compared with each other with regard to the vulnerability criterion. The importance of individual alternatives in relation to the criterion of vulnerability can be determined based on input data on the vulnerability of the built stock of buildings in the territory of each county. When comparing alternatives, the county in whose area the vulnerability of the built environment is higher, i.e. the structural features of the exposed buildings are such that they are more susceptible to the effects of earthquakes (damages), receives higher marks.

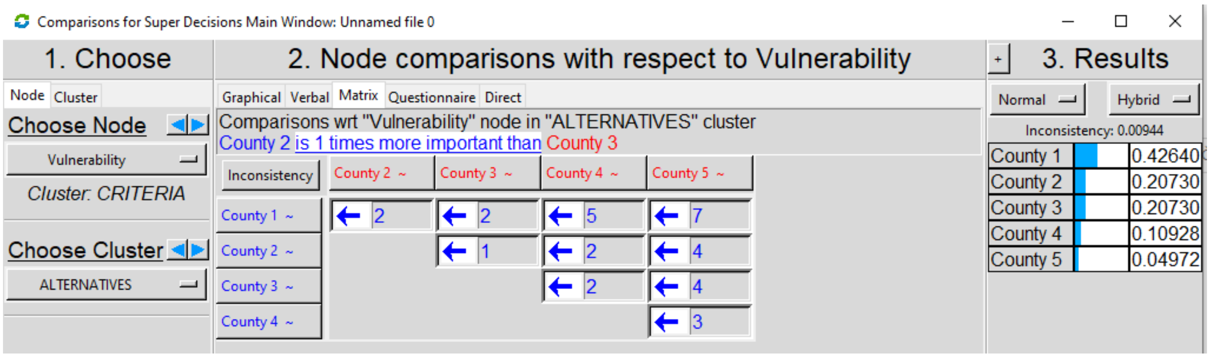
Table 8 – Comparison matrix with respect to level 2 – criterion: vulnerability

Wrt Vulnerability	County 1	County 2	County 3	County 4	County 5
County 1	1	2	2	5	7
County 2	1/2	1	1	2	4
County 3	1/2	1	1	2	4
County 4	1/5	1/2	1/2	1	3
County 5	1/7	1/4	1/4	1/3	1

As shown in Table 8, in County 2 the vulnerability of buildings is the same as in County 3. Fig. 6 shows a screenshot from the *Super Decisions*, where the value of the eigenvector W_{a3} and consistency ratio CR_{a3} for level 2 are calculated as:

$$W_{a3} = (W_1, W_2, W_3, W_4, W_5)^T = (\mathbf{0.426, 0.207, 0.207, 0.109, 0.050})^T$$

$$CR_{a3} = \mathbf{0.009} < 0.10$$



Comparisons wrt "Vulnerability" node in "ALTERNATIVES" cluster
County 2 is 1 times more important than County 3

	County 2	County 3	County 4	County 5
County 1	← 2	← 2	← 5	← 7
County 2		← 1	← 2	← 4
County 3			← 2	← 4
County 4				← 3

Inconsistency: 0.00944

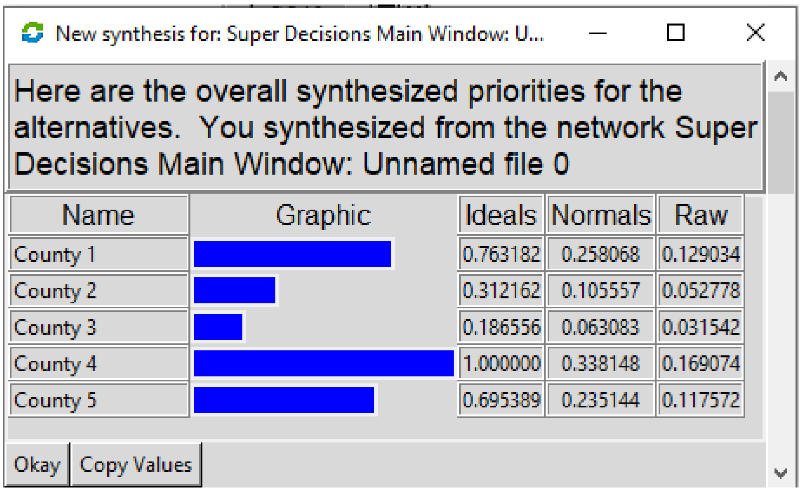
County 1	▮	0.42640
County 2	▮	0.20730
County 3	▮	0.20730
County 4	▮	0.10928
County 5	▮	0.04972

Figure 6. Comparison of alternatives in relation to the vulnerability criterion – *Super Decisions.*

3.3 Synthesis of results

After all comparison matrices are defined, a global eigenvector is calculated, which indicates the weight in prioritizing the alternatives.

Global eigenvector calculation is a simple weighted averaging technique. Eigenvectors of level 1 multiplied by eigenvectors of level 2, and summed for each alternative, give the global eigenvector. The AHP results are shown in Fig. 7, with the global eigenvector shown in the middle column.



Here are the overall synthesized priorities for the alternatives. You synthesized from the network Super Decisions Main Window: Unnamed file 0

Name	Graphic	Ideals	Normals	Raw
County 1		0.763182	0.258068	0.129034
County 2		0.312162	0.105557	0.052778
County 3		0.186556	0.063083	0.031542
County 4		1.000000	0.338148	0.169074
County 5		0.695389	0.235144	0.117572

Figure 7. Results of AHP for earthquake risk of counties.

According to the AHP results, the relative weights of each alternative (W), i.e. their earthquake risk indices, are:

W (County 1) = 0.258

W (County 2) = 0.106

W (County 3) = 0.063

W (County 4) = 0.338

W (County 5) = 0.235

Such results can also be interpreted linguistically, if individual weight values of the alternatives are assigned meanings such as: very low, low, medium, high, very high risk. Therefore, County 4 has a high seismic risk, Counties 1 and 5 have a medium seismic risk, County 2 has a low seismic risk, and County 3 has a very low seismic risk. The same can be interpreted with colours or in any other similar way. The earthquake risk of individual counties can be shown very clearly on the map, which takes into account all elements of earthquake risk.

4. Conclusion

This study presents an example of using the analytical hierarchical process for the assessment of earthquake risk. AHP has proven to be very accurate and suitable for risk assessment, especially in the case when there is not a large enough number of input data, which is the case when dealing with earthquake risk.

The study shows how different elements of earthquake risk, namely hazard, exposure and vulnerability, can be combined by using AHP. By simple comparisons of pairs of model elements, AHP model in this study obtained the weight value of each county (alternative option). The same can be applied at the global, country, city, and municipality level.

The resulting priority list of counties (or other geographical areas) can further be used to produce earthquake risk maps. The information obtained from AHP analysis can also be used by governments or public institutions dealing with disaster management as a useful tool for allocation of mitigation resources and effort.

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