Selection of suitable alternatives to reduce the environmental impact of road traffic noise using a fuzzy multi-criteria decision model

Alejandro Ruiz-Padillo[a,b], Diego P. Ruiz [c], Antonio J. Torija[d], Ángel Ramos-Ridao[b]

[a] Industrial Engineering and Transportation Department, Federal University of Rio Grande do Sul (UFRGS), Av. Osvaldo Aranha, 99 – 5º andar, Porto Alegre - CEP 90.035-190, Rio Grande do Sul, Brazil

[b] Civil Engineering Department, University of Granada. Av. Fuentenueva s/n, 18071 Granada, Spain.

[c] Information Technology and Communication Research Center (CITIC-UGR), Applied Physics Department, University of Granada, Av. Fuentenueva s/n, 18071 Granada, Spain.

[d] ISVR, University of Southampton, Highfield Campus, SO17 1BJ Southampton, UK.

Tel: +34 958 244 161; Fax: +34 958 243 214

E-mail: aruizp@correo.ugr.es, alejandro.ruiz@ufrgs.br (Alejandro Ruiz-Padillo); druiz@ugr.es (Diego P. Ruiz); ajtorija@ugr.es (Antonio J. Torija); ramosr@ugr.es (Ángel Ramos-Ridao).

Abstract

Road traffic noise is one of the most significant environmental impacts generated by transport systems. To this regard, the recent implementation of the European Environmental Noise Directive by Public Administrations of the European Union member countries has led to various noise action plans (NAPs) for reducing the noise exposure of EU inhabitants. Every country or administration is responsible for applying criteria based on their own experience or expert knowledge, but there is no regulated process for the prioritization of technical measures within these plans. This paper proposes a multi-criteria decision methodology for the selection of suitable alternatives against traffic noise in each of the road stretches included in the NAPs. The methodology first defines the main criteria and alternatives to be considered. Secondly, it determines the relative weights for the criteria and sub-criteria using the fuzzy extended analytical hierarchy process as applied to the results from an expert panel, thereby allowing expert knowledge to be captured in an automated way. A final step comprises the use of discrete multi-criteria analysis methods such as weighted sum, ELECTRE and TOPSIS, to rank the alternatives by suitability. To illustrate an application of the proposed methodology, this paper describes its implementation in a complex real case study: the selection of optimal technical solutions against traffic noise in the top priority road stretch included in the revision of the NAP of the regional road network in the province of Almeria (Spain).

Keywords: environmental noise impact; road traffic noise; strategic noise maps; road noise action plans; multi-criteria decision-making; fuzzy analytic hierarchy process.

1. Introduction

Traffic noise has become a major environmental impact in the current global context, largely as a result of the transport infrastructure development. Particularly in Europe, the growing volume of road traffic is generating noteworthy impacts on its infrastructures, environment and resources, in many cases in conflict with the EU's aim to encourage more sustainable modes of transport and to meet certain requirements for reducing greenhouse gases and noise emissions (Mayer et al., 2012). Roughly 65% of the inhabitants of the large European cities are exposed to high noise levels (D'Alessandro and Schiavoni, 2015), and about 80 million people in the EU (around 20% of the population) suffer harmful effects related to excessive noise exposure (Oltean-Dumbrava et al., 2013).

Therefore, in addition to legal, administrative and educational measures to ensure the safeguarding of human health, it is important to come up with technical solutions to address this problem, and abate the noise endured by populations adjacent to roads. In the European context, the application of Directive 2002/49/EC of the European Parliament and of The Council of 25 June 2002, on the assessment and management of environmental noise (commonly called ‘‘European Environmental Noise Directive’’) requires Public Administrations of the EU member countries to generate substantial strategic noise mapping (SNM - a map designed for the assessment of noise exposure in a given area due to the different noise sources) and noise action plans (NAP - plan designed to manage noise issues and its effects, particularly by noise reduction in the exposed area) to cope with this problem (Directive 2002/49/EC, 2002; Garg and Maji, 2014).

At the present stage of the European Environmental Noise Directive, every five years, departments responsible for roads must prepare and publish the SNMs and NAPs corresponding to the major road infrastructures of the network (more than 3 million vehicles a year). When developing noise management action plans, Member States' authorities are required to consult the concerned public (Directive 2002/49/EC, 2002). However, environmental noise due to road traffic continues to increase (Mayer et al., 2012).

Moreover, there are not harmonized methodologies to help in the decision-making of the choice and planning of the solutions against noise when elaborating the NAPs, according to the objective of the Directive. Essentially for this reason and political issues, the NAPs are often not adequately implemented, or the planned measures prove ineffective under some circumstances because the chosen criteria for action prioritization and selection are not the most appropriate from the standpoint of managers (King et al., 2011).

Therefore, it is important to apply appropriate decision methodologies to define necessary actions to be included in the NAPs, as required by the European Environmental Noise Directive. Up to now, each EU member country or administration set their own criteria to identify the most critical areas for action against noise (hot spots) and to select solutions for the problem of road traffic noise. Recently Ruiz-Padillo et al. (2014) proposed a methodology for the prioritization of action with regard to the generation of a NAP for the road stretches identified as troublesome due to traffic noise. According to the present contribution, after sorting out stretches for action based on the "Road Stretch Priority Index" (RSPI) improved in (Ruiz-Padillo et al., 2016), specific measures against noise may be proposed and the most suitable ones selected for each road stretch (or individual case). This suitability includes not only performance for reducing noise, but also other factors such as economic, social, environmental and functional aspects. This second stage effectively completes the overall process of environmental impact assessment (EIA) with the proposal of mitigation measures, which is the aim of the paper. So, this EIA does not derive from the study of the construction of a new infrastructure, as usual, but from the acoustic assessment of the operation of an existing road through noise mapping. Furthermore, the developed methodology may also be useful for the decision-making about the measures to mitigate the impact of the road traffic noise, as result of other environmental assessments.

Studying and making decisions about technical alternatives is a particularly complex issue, involving many factors that may themselves come into conflict, or may depend on uncertain information (Garg and Maji, 2014; Ruiz-Padillo et al., 2016). In this paper a methodology based on multi-criteria decision methods is adopted. In recent years, the use of multi-criteria decision methods in engineering and environmental fields has increased significantly in terms of both the frequency and range of applications. There are studies regarding waste treatment (Soltani et al., 2015), urban sustainability (Egilmez et al., 2015), environmental management and evaluation (Awasthi et al., 2010; Herva and Roca, 2013), air pollution (Vlachokostas et al., 2011), energy production and consumption (Arce et al., 2015; Sun et al, 2015), water pollution (Zhang and Huang, 2011) and linear infrastructure impact assessment (Sayers et al., 2003; Gardziejczyk and Zabicki, 2014; Nogués and González-González, 2014), or specifically traffic noise (Oltean-Dumbrava, 2013; D'Alessandro and Schiavoni, 2015).

The objective of this paper is to achieve a scientific, rigorous and firmly supported approach for the choice of alternatives against road traffic noise, a further step under the prioritization methodology presented in Ruiz-Padillo et al. (2016). In view of the characteristics of the problem mentioned above, a multi-criteria procedure was devised, making it possible to study each particular road stretch in connection with its potential noise control engineering solutions. As a result of this analysis, the proposed methodology allows the decision-maker to identify the best alternative from an ordered list of feasible alternatives for assessment.

Generally, multi-criteria decision problems of this sort call for evaluating alternatives with respect to each criterion involved, the criteria being weighted by a vector that expresses the relative importance among them (Wang et al., 2009). For example, many examples of multi-criteria decision problems related with EIA developed in the area of civil engineering contain a significant shortcoming, which comes from the definition of the weights assigned to the criteria used in the problem (Sayers et al., 2003). Thus, numerous studies apply the chosen method by estimating weights or taking them from earlier cases, without a detailed and specific study of the analyzed problem. Due to this fact, classical multi-criteria analysis methods may not be very effective for complex decision problems. This is, indeed, a key issue —special care must be taken for the selection of weights.

Consequently, this research tries to avoid the arbitrary actions behind selecting weights, applying hybrid methods, yet combining advantages from different methods (Awasthi et al., 2010; Herva and Roca, 2013; Nogués and González-González, 2014; Arce et al., 2015; Soltani et al., 2015; Sun et al., 2015). First, a weighting method based on a fuzzy analytical hierarchy process strictly on preferences from experts is implemented to obtain the weights of the criteria defined for the problem, and then several multi-criteria decision methods are applied to the set of alternatives. In this case, the objective is to provide the decision-maker a complete ranking of the technical solutions according to their suitability for solving the analyzed problem. This procedure can therefore aid practitioners, policy-makers and managers in assessing the impact of action plans, and to make decisions based upon these assessments derived from systematized expert knowledge.

The paper is organized as follows. In Section 2, the elements of the decision-making process are presented, with emphasis on the suitable criteria and the alternatives proposed as technical solutions to the noise control problem. Section 3 presents the weighting and multi-criteria methods used in developing the proposed methodology, and their main features are analyzed and discussed in the context of their application. Section 4 presents the methodology developed for prioritizing alternatives against road traffic noise, and how the data and the weights assigned to the criteria were obtained.. In Section 5, a case study illustrates the application of the methodology: an analysis of alternatives to address the noise problem of a road stretch in the Regional Network of Roads in the province of Almeria, in southern Spain. Finally, in Section 6, some conclusions are drawn and the main results achieved through this research are summarized.

2. Elements of the decision-making process.

The assessment of every decision-making process needs the initial determination of the fundamental elements that define the problem studied. Thus, firstly, the set of feasible alternatives for inclusion in the proposed multi-criteria methodology are defined in the context of noise impact reduction. Secondly, the list of criteria and sub-criteria for the assessment of the alternatives found as relevant for the noise reduction problem are introduced and described.

2.1. Alternatives for noise reduction.

Technical solutions for noise abatement can act (Ruiz-Padillo et al., 2014): (i) by reducing the emission of noise at the source (on the engines and tires of the vehicles; on the traffic behavior, composition or speed; and on the pavements); (ii) on the transmission medium of the noise (by modifying this medium or applying obstacles between the source and the receiver, as acoustics barriers, changing the road design or the land uses and their characteristics); and (iii) directly on the receiver (sound insulation on facades and windows).

In order to ensure the applicability of the methodology presented, the alternatives of difficult or unfeasible implementation should be discarded. This is the case of measures that lie beyond the scope of local authorities responsible for NAP implementation, such as changes on the vehicles type or the land uses and major new constructions. Thus, from an extensive catalog of currently available technical solutions against noise studied in Ruiz-Padillo et al. (2014), as result of a rigorous bibliographic review, five categories of alternatives were pre-selected for the methodology (in addition to the “zero alternative”, i.e. no action is taken at all, which must always be considered in any engineering study

(Ellis et al., 2004)). The set of alternatives pre-selected and their notation (which may be combined) are listed in Table 1:

Table 1: List and description of pre-selected alternatives of the methodology.

A0	Zero alternative		
A1	Noise barriers	A11	Acoustic screens
		A12	Earth berms
A2	Low noise pavements	A21	Bituminous porous asphalts
		A22	Bituminous rubberized mixtures
		A23	Porous concrete
A3	Traffic management	A31	Action on the volume of traffic
		A32	Action on the vehicle speed
		A33	Integral traffic regulation (joint action on the volume of traffic and the vehicle speed)
A4	Building insulation		
A5	Covering the road		

- Alternative 1: noise barriers (A1). The two most representative types of these barriers were considered within the methodology: noise barrier walls or acoustic screens (A11) and earth berms (A12). A mixed combination of both alternatives (A1112) was also considered (Van Renterghem and Botteldooren, 2012).

- Alternative 2: low noise pavements (A2). The most common types used in Europe were selected (Nielsen and Solberg, 1988; Mayer et al., 2012): (i) porous asphalts (A21) and rubberized mixtures (A22) (within the category of pavements with bituminous material); and (ii) porous concrete (A23).

- Alternative 3: traffic management measures (A3). Three actions for traffic management were selected: action on the volume of traffic (A31), on the vehicle speed (A32) or jointly on both variables through an integral road-traffic regulation plan and policies for promoting urban public transport (A33) (Nielsen and Solberg, 1988; Ouis, 2001; Mayer et al., 2012; Fiedler and Zannin, 2015).

- Alternative 4: building insulation (A4). Within this category, actions focused on windows and on facade insulation against noise were considered (Ouis, 2001).

- Alternative 5: undergrounding or covering the road with the design of a false tunnel (A5) (Nielsen and Solberg, 1988).

Each of the pre-selected alternatives has certain pre-requisites that must be evaluated before its implementation. When analyzing a particular road stretch, some alternatives might be ruled out as a result of analysis at the starting step, thus saving both time and economic resources in the decision-making and NAP drafting process. A series of flow charts (Figs. 1 to 4) illustrate the systematic pre-requisite evaluation, considering a number of constraint factors:

- A given road stretch must first be assigned to one of these types: urban road (section running through urban land and only inside the boundaries of an urban agglomeration, being a part of a network of streets with near buildings on both sides); or non-urban section (inter-city road outside the boundaries of urban agglomerations). The process takes place in the following order (Fig. 1):

  Step 1: Firstly, if the road is not an urban section, alternatives A31 and A33 can be discarded, since traffic management measures on traffic volume and integral regulation are not feasible in inter-city stretches (Ouis, 2001).

  Step 2: If it is an urban road (inter-city road crossing a town), the alternatives of full covering (A5) and noise barriers of all classes (A1) can also be discarded, since they are not viable on this type of road stretch. Also, low-noise pavements (A21 and A23) can be ruled out, because low noise pavements are not effective at low speeds (where engine noise is significantly dominant). The option of rubberized thin layers (A22) is considered because they are appropriate in these cases of urban roads (Nielsen and Solberg, 1988).

  Step 3: The process continues by observing whether the road stretch is on a high-speed road. If it is, there is no possibility of implementing vehicle speed traffic management actions and alternative A32 must be ruled out. If it is not, no more alternatives can be discarded.

- If along the road stretch studied there was previous implementation of noise reduction measures, particularly low noise pavement or building insulation, it will be pointless to consider alternatives A2 or A4, respectively, and they can consequently be discarded (Fig. 2).

- The average traffic speed on the road stretch (Fig. 3) should be taken into account. If it is less than 50 km/h, it will make no sense to propose measures for the pavement (A2), (Nielsen and Solberg, 1988; Mayer et al., 2012).

- The necessary sound-level attenuation (ΔL) is based on the comparison between the sound-level recorded (obtained from the SNMs) and the objective noise level, as stablished by the environmental noise regulations applicable to the specific area (Ruiz-Padillo et al., 2014). If it is greater than 5 dB(A), the option of using exclusively alternatives A2 or A3 (i.e., not in combination with other measures) must be ruled out (Fig. 4), since the sole implementation of any of these alternatives will not be able to provide the required sound-level attenuation value (Fiedler and Zannin, 2015).

Having completed this pre-requisite analysis for a given case, the set of feasible alternatives can be defined for their inclusion in the proposed multi-criteria methodology.

2.2. Criteria of the methodology.

Prior to developing the proposed hybrid method, those factors influencing the decision-problem were carefully analyzed. From a comprehensive literature review, but also from the contributions of experts in the related field, the parameters found to be more relevant to the decision-making for road-traffic-noise reduction were selected for inclusion in the set of criteria. The number of criteria selected for the proposed methodology was optimized to a minimum so that the problem would be covered without increasing the model complexity (Keeney and Raiffa, 1993; Awasthi et al., 2010; Achillas et al., 2011; Zhang and Huang, 2011; Gardziejczyk and Zabicki, 2014; Nosal and Solecka, 2014; Sun et al., 2015).

As indicated earlier, there are a number of constraint factors for considering a given technical solution against noise as a feasible alternative, i.e. required sound-level attenuation, average speed of the traffic (Nielsen and Solberg, 1988), physical or technical conditions that might affect the implementation of a given alternative (Ellis et al., 2004), extreme weather conditions that might override any solution (Van Renterghem and Botteldooren, 2012), and the existence of previous measures against noise in the road stretch that were ineffective or that might impede the implementation of other solutions. Because of their relevance in the decision-making process, a pre-requisite evaluation scheme based on these factors was addressed prior to the multi-criteria analysis, allowing the user to rule out unfeasible technical solutions at the earliest stage. Hence, these constraint factors were not included in the multi-criteria assessment methodology.

The different criteria identified as relevant for the noise problem addressed in this work were placed in a hierarchy according to their relationship for further evaluation by

FEAHP (as using AHP) (Herva and Roca, 2013; Arce et al., 2015; Sun et al., 2015). To enhance understanding and implementation by the engineering community, this hierarchy was built on the most important dimensions used in planning studies (technical, economic, social, environmental and functional), which were adapted to the problem studied (Ellis et al., 2004; Oltean-Dumbrava et al., 2013; Gardziejczyk and Zabicki, 2014; Nogués and González-González, 2014; Nosal and Solecka, 2014; Arce et al., 2015; Egilmez et al., 2015; Soltani et al., 2015).

For each criterion, the indicator and units of measurement were defined (Zhang and Huang, 2011; Gardziejczyk and Zabicki, 2014; Sun et al., 2015), as was the nature of its contribution to the objective, i.e. positive (benefit criterion) or negative (cost criterion) (Awasthi et al., 2010; Vlachokostas et al., 2011; Nogués and González-González, 2014; Egilmez et al., 2015).

The list of criteria and sub-criteria proposed for the alternative assessment (see Table 2) are described below.

Table 2: Criteria and sub-criteria, and their indicators and characters for selecting alternatives to road traffic noise.

CRITERIA		**SUB-CRITERIA**		**INDICATORS**	**CHARACTER**
C1	Effect on infrastructure	C11	Territorial permeability	Σdeviation length × no. users (m)	COST
		C12	Driver visibility variation	Visibility distance variation (m)	COST
		C13	Average speed of traffic reduction	Speed reduction (km/h)	COST
C2	Economic	C21	Initial investment	Works budget + expropriations (currency unit)	COST
		C22	Conservation and maintenance	Conservation and maintenance expenses (currency unit/year)	COST
		C23	Operational	Management, water, electricity, gardening… expenses (currency unit/year)	COST
C3	Social	C31	Traffic safety	Accident rate variation (%)	BENEFIT
		C32	Vehicle expenses	Reduction of vehicles expenses (currency unit)	BENEFIT
		C33	Social improvement of the population	Reduction of % of annoyed people by traffic noise (*Eq. 1*)	BENEFIT

		C34	Changes in properties values adjacent to the road	Increase in property values (currency unit)	BENEFIT
C4	Environmental impact	C41	Air quality	Environmental impact evaluation (positive, compatible, moderated, severe, critic: 0, 1, 2, 3, 4)	COST
		C42	Vision and/or lighting quality		
		C43	Landscape quality		
C5	Functional	C51	Corrected area	Σaffected area variation × reduction of L_{den} (km^2×dB(A))	BENEFIT
		C52	No. of corrected dwellings	Σaffected dwellings variation × reduction of L_{den} (dB(A))	BENEFIT
		C53	No. of corrected people	Σaffected people variation × reduction of L_{den} (dB(A))	BENEFIT
		C54	No. of corrected noise sensitive centers	Σaffected sensitive centers variation × reduction of L_{den} (dB(A))	BENEFIT

Criterion C1 - Effect on infrastructure.

This criterion includes the adverse effects caused by the implementation of the anti-noise measure on road users (vehicles and pedestrians). The following sub-criteria were defined:

- Territorial permeability (C11), understood as the effect on the access of the users to the road from the surrounding area (Oltean-Dumbrava et al., 2013; Gardziejczyk and Zabicki, 2014). It is quantified as the sum of the deviation lengths of every user affected by the alternative.

- Driver visibility variation (C12), measured at the most restrictive point in the road stretch.

- Average speed of traffic reduction in the road stretch (C13).

Criterion C2 - Economic.

It includes costs resulting from the implementation of the anti-noise measure. The following sub-criteria were proposed (Oltean-Dumbrava et al., 2013; Gardziejczyk and Zabicki, 2014):

- Initial investment costs (C21).

- Conservation and maintenance costs (C22).

- Operational costs (C23).

The last two sub-criteria must be evaluated annually during the term of the NAP, which is five years according to current legislation (Directive 2002/49/EC, 2002).

Criterion C3 - Social.

This criterion was defined as the sum of the consequences, in addition to noise reduction itself, which the anti-noise measure has on road users and on the surrounding population. It is divided into four sub-criteria (Oltean-Dumbrava et al., 2013; Nosal and Solecka, 2014; Sun et al., 2015):

- Effect on traffic safety in the road stretch where the alternative is implemented (C31). This sub-criterion is measured by accident rates variation in the road stretch considered.

- Vehicle expenses reduction (C32) (i.e. fuel, lubricants, tires, etc.).

- Social improvement of the population affected by road-traffic-noise (C33), measured as the reduction of population annoyed by road-traffic-noise when a given anti-noise alternative is implemented. For long-term exposure, good agreement has been found between the percentage of population annoyed by road-traffic-noise and the sound-level (caused by road-traffic) exposure, expressed in L_{den} (day-evening-night level) (Ouis, 2001). The relationship between the percentage of population annoyed by road-traffic-noise and L_{den} is expressed by Eq. 1 (D'Alessandro and Schiavoni, 2015):

$$\%A = 1{,}795 \cdot 10^{-4} (L_{den} - 37)^3 + 2{,}11 \cdot 10^{-2} (L_{den} - 37)^2 + 0{,}5353 (L_{den} - 37) \qquad (1)$$

where $\%A$ = percentage of people annoyed by road-traffic-noise; and

L_{den} = A-weighted equivalent sound-level integrated over the 24 hour period, in dB(A), with a penalty of +5 and +10 dB for the sound-level integrated in evening and night periods, respectively.

- Changes in value of properties adjacent to the road or affected by it (C34). Depreciation of the property value is estimated in the literature to be around 0.23% for every 1 dB increase in sound-level exposure, or 0.50% per dB above L_{den} values of 50-55 dB(A) (D'Alessandro and Schiavoni, 2015).

Criterion C4 - Environmental impact.

This criterion assesses the significant changes (both positive and negative) in environmental conditions near the road, in addition to noise reduction, generated when the anti-noise alternative is implemented. It is usually determined by an appropriate EIA study using a weighted scale to quantify the impact that the alternative might potentially cause on the environment. However, actions against road-traffic-noise do not usually entail an EIA, on the one hand because European environmental legislation does not require it (Directive 2011/92/EU, 2011), and on the other hand, because these actions are considered to be beneficial for the environment.

In general, EIA are very comprehensive, including a great variety of environmental impacts on the ecosystem: fauna, flora, soil, air, water, etc. (Vlachokostas et al., 2011; Oltean-Dumbrava et al., 2013; Gardziejczyk and Zabicki, 2014; Nosal and Solecka, 2014). However, for the proposed alternatives the following sub-criteria were identified as genuinely influential:

- Effect on air quality (C41).

- Effect on vision and/or lighting quality (C42).

- Effect on landscape quality, both of the road and its surrounding environment (C43).

Criterion C5 - Functionality.

Functional criteria usually consider the compliance with targets set for the infrastructure studied (e.g. in terms of distance and travel time on the marked route, capacity, specific speed, number of beneficiaries) (Gardziejczyk and Zabicki, 2014; Nosal and Solecka, 2014; Fiedler and Zannin, 2015). In the context of the analyzed problem, this criterion was linked to the functional correction between the condition remedied by the alternative implemented and the original condition (characterized by the SNM at different intervals of L_{den}). The sub-criteria are:

- Corrected area (C51).

- Number of corrected dwellings (C52).

- Number of corrected people (C53).

- Number of corrected noise sensitive centers (C54).

The indicators are quantified as the sum of the products obtained by multiplying, in each interval of L_{den} in the SNM, the variation of the corresponding factor (correction) and the reduction of L_{den}.

3. Weighting and multi-criteria decision methods.

In addition of the determination of the sets of alternatives and criteria, there are more three capital issues in every multi-criteria analysis: the weighting of these criteria, the evaluation of the alternatives, and the method of aggregating these evaluations in order to select the most appropriate solution for the problem. Thus, this section presents the main characteristics of the weighting method chosen for assessing the different alternatives (the fuzzy extended analytical hierarchy process), and the multi-criteria decision methods (three of them are selected and proposed for utilization in the methodology).

3.1. Weighting method for assessing different alternatives: fuzzy extended analytical hierarchy process (FEAHP).

The planning process for actions against traffic noise to be incorporated to NAPs is subjected to a high degree of uncertainty, not only owing to the uncertain nature of decision-making in engineering itself, but also to decision-makers' subjectivity and evaluative preferences (Awasthi et al., 2010; Herva and Roca, 2013; Garg and Maji, 2014; Nogués and González-González, 2014; Arce et al., 2015; Egilmez et al., 2015). Information on the various alternatives for a specific problem can be incomplete, vague or imprecise, or even non-existent.

In order to deal with these inexact concepts and subjective judgments more accurately, Zadeh (1965) proposed the fuzzy set theory, which defines the membership of an element of a set in a gradual way. Thus, a fuzzy set establishes partial relations between “completely untrue” {0}, and “entirely true” {1} (in contrast to the classical or “crisp” sets), by using the denominated membership functions. The membership function of a fuzzy set A, $\mu_A(x)$, defines outputs in the interval [0, 1] for every element x contained in the universe X. This degree of membership can be associated with a given linguistic variable to model the inherent characteristics of human opinions (Zadeh, 1965; Wood et al. 2007).

Therefore, a decision-making methodology might be significantly improved with a fuzzy linguistic model, which accounts for subjectivity and assessment preferences better than any conventional model (Awasthi et al., 2010; Garg and Maji, 2014; Egilmez et al., 2015; Arce et al., 2015; Ruiz-Padillo et al., 2016). The criteria-weighting method selected for this study is one of the most powerful ones developed to date: the fuzzy extended analytical hierarchy process (FEAHP), i.e., the methodology of fuzzy AHP (FAHP) based on Chang’s extent analysis (Chang, 1996). FEAHP offers significant advantages over other discrete multi-criteria analysis methods —such as the hierarchy structuration of criteria, the logical process and the efficient management of quantitative and qualitative attribute values, in that it admits an appropriate fuzzy treatment of expert opinions used to assess the relative importance of the criteria (Oltean-Dumbrava et al., 2013).

Essentially, the AHP method consists of constructing a square matrix for criteria comparisons, where each matrix element represents to what extent the row criterion is more important than the column criterion. The eigenvector associated with the dominant eigenvalue of this matrix represents the set of weightings for the criteria in the decision-making problem (Saaty, 1980). A flow chart depicting application of the AHP method can be seen in Figure 5.

In applying the FEAHP method, using linguistic terminology for the criteria comparisons, the matrix elements are triangular fuzzy numbers, a particular type of fuzzy set defined on real numbers by a membership function as expressed in Eq. 2:

$$\mu_A(x)=\begin{cases}\frac{x-a}{b-a}, & if\, a\le x\le b\\ \frac{c-x}{c-b}, & if\, b\le x\le c\\ 0, & otherwise\end{cases} \tag{2}$$

where a, b and c are real numbers.

Therefore, the FEAHP method requires mathematical processing of these fuzzy numbers in order to obtain “crisp” (nonfuzzy) results for the weighting vector. This process is called defuzzification. Chang’s extent analysis (Chang, 1996) is the procedure used; the steps of this algorithm are presented very clearly in (Erensal et al., 2006; Celik et al., 2009; Liao, 2011; Chan et al., 2013; Ruiz-Padillo et al., 2016).

It is important to take into account that FEAHP assumes experts make certain inaccuracies in estimating pairwise criteria comparisons. It is therefore necessary to analyze the consistency of the process by means of the so-called consistency ratio (*CR*). The *CR* is a measure of how accurately the eigenvector estimates the weighting vector. It is obtained by comparing the consistency index (*CI*) with the appropriate average random consistency index (*RI*), derived from a sample of size 500 from a randomly generated reciprocal matrix, using Saaty’s fundamental scale (Saaty, 1980) (Eq. 3):

$$CR = \frac{CI}{RI} \quad (3)$$

Values of the *RI* are obtained according to the size of the pairwise comparisons matrix (Saaty, 1980).

The *CI* of a matrix of comparisons is given by Eq. 4:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

where λ_{max} is the largest or principal eigenvalue of the comparison matrix; and n is the size of the matrix (number of elements of the diagonal).

If *CR* is not less than 10%, it is recommended to re-study the problem and review the judgments. For $n = 3$, the threshold is fixed at 5%, and for $n = 4$ at 8%.

Once the crisp weighting vector is obtained, the calculation of its *CR* will depend on the principal eigenvalue of the comparisons matrix λ_{max} (which should also be defuzzified). In the FEAHP method, defuzzification of the eigenvalue entails choosing the central or modal value of the triangular fuzzy number.

An extensive application of FAHP can be found in the literature: technology management (Erensal et al., 2006), decision-making in ship registration procedures (Celik et al, 2009), evaluation for planning the development of new environmentally-friendly products (Chan et al., 2013) or under-price strategy (Liao, 2011).

3.2. Multi-criteria decision methods.

After examining an extensive number of technical documents dealing with infrastructure planning and design, it was found that public administrations often apply multi-criteria analysis for alternatives comparison. The vast majority of these documents used the weighted sum method (WSM) for ranking alternatives in terms of priority (Ellis et al., 2004). In fact, WSM has been very often used in other environmental studies (Sayers et al., 2003; Gardziejczyk and Zabicki, 2014) and even road traffic noise problems (Oltean-Dumbrava et al., 2013).

The relevant literature includes works where other multi-criteria methods have been implemented for the evaluation and ranking of alternatives in decision-making problems in the environmental and engineering fields, such as ELECTRE (*ELimination Et Choix*

Traduisant REalité) (Achillas et al., 2011; Vlachokostas et al., 2011; Herva and Roca, 2013; Nosal and Solecka, 2014) and TOPSIS (*Technique for Order Preference by Similarity to Ideal Solution*) (Awasthi et al., 2010; Zhang and Huang, 2011; Oltean-Dumbrava et al., 2013; Gardziejczyk and Zabicki, 2014; Arce et al., 2015).

These three multi-criteria decision-making methods were selected for this work, and are briefly introduced in the subsections below. A detailed description of multi-criteria decision-making theory and methods can be found in Barba-Romero and Pomerol (2000).

3.2.1. Weighted sum method.

The WSM is the most classic and widely used discrete multi-criteria analysis methodology because of its easy and intuitive application. It pertains to the American School of multi-criteria methods, characterized by adding the different criteria (with their possible weights) in a single global utility function (Barba-Romero and Pomerol, 2000).

WSM assumes that this function can be taken as a linear additive model, i.e. presented in the form $v = \lambda_1 \cdot v_1 + \lambda_2 \cdot v_2 + ... + \lambda_n \cdot v_n$. Sorting the alternatives by the values of v allows one to establish a priority ranking for all of them. To do this, the criteria (v_i) and weighting (λ_i) values must be standardized.

3.2.2. ELECTRE method.

The ELECTRE method, proposed by Roy (1968), is the most representative multi-criteria method of the European School. It uses outranking relationships and concordance and discordance indices simultaneously to select one solution, which could be considered satisfactory although it might not be optimal. The concordance and discordance indices express to what degree the performances of the alternatives “a” and “b” are in concordance and discordance, respectively, with the assertion “a outranks b”. Thus for example, the concordance index for an alternative i is calculated by the sum of the weightings of the criteria that make this alternative outrank each other alternative (Barba-Romero and Pomerol, 2000; Achillas et al., 2011).

ELECTRE allows for ranking alternatives and selecting the solutions that meet a determined acceptability criterion, defined by a maximum number of alternatives that outrank them. It is thereby possible to reduce the size of the set of efficient solutions. To this end, ELECTRE divides the set of potential alternatives into two subsets: (i) subset with the most favorable alternative for the decision-maker (kernel set N), which is not outranked by any other alternative outside this subset, and (ii) subset containing the least favorable alternatives, outranked by at least one alternative of the kernel set N.

3.2.3. TOPSIS method.

The TOPSIS method also comes from the European School. For the ranking of alternatives, this method calculates the weighted Euclidean distance between each alternative and a previously established positive-ideal and negative-ideal (anti-ideal) solutions. The ideal and anti-ideal solutions are built by taking the best and the worst values of all the alternatives for each criterion, respectively. This method was proposed by Hwang and Yoon (1981).

To combine both the criteria of the shortest distance from the positive-ideal solution and the farthest distance from the negative-ideal solution, TOPSIS uses the so-called similarity ratio (Hwang and Yoon, 1981; Barba-Romero and Pomerol, 2000). The similarity ratio of an alternative *i* is based on the calculated distances from this alternative to the ideal and anti-ideal solutions.

4. Developed methodology for selection of traffic noise reduction alternatives. Alternative assessment and weighting criteria.

In this section the developed methodology is presented. In addition of the alternatives and criteria previously selected to be part of the methodology, another of the main contributions of the present research is the set of weights proposed for assessing the alternatives through the criteria and sub-criteria. The weighting process was performed by the application of the FEAHP to the results from an expert panel, as explained below. The complete procedure ends with the application of any of the multi-criteria decision methods introduced in the preceding section.

4.1. Expert panel method to apply FEAHP.

The expert panel technique has often been used to gather opinions regarding environmental or infrastructure multi-criteria problems/decisions, and especially to facilitate the task of criteria weighting (Awasthi et al., 2010; Zhang and Huang, 2011; Arce et al., 2015; Egilmez et al., 2015; Soltani et al., 2015; Sun et al., 2015).

In order to address the pairwise comparisons by the importance of criteria, necessary for applying FEAHP, an expert panel was organized. A line of communication via e-mail was opened with the expert panel members (Achillas et al., 2011). Using this line of communication, the procedure was explained to the experts and the questionnaires to fill in were sent. The participating experts were given the option to solve any doubt or question about the process before starting filling in the questionnaire, but not about the responses, in order to avoid biased results. The methodology used is described below.

The selection of the group of experts was based on their expertise in activities involved in the planning, evaluation and choice of the best alternatives for road stretches included in a NAP, i.e.:

- Technical staff from Public Administration, responsible for drafting the NAP (Directive 2002/49/EC, 2002). They were chosen from the four current jurisdiction levels for roads in Spain: national, regional, provincial and municipal. Most technicians came from the geographical area of southern Spain. There was one representative of the regional environmental administration, since it handles the final processing of the NAP, in agreement with current Spanish legislation (Spanish Law 37/2003, 2003).

- Technical staff from engineering consulting firms specializing in environmental study drafting and in road projects. The scope of these companies ranged from the small local consultancy-type or firms with mostly regional or national actions, to large consulting firms with an international portfolio.

- Academic experts in research on noise.

A total of 65 questionnaires were answered and processed, according to the distribution by expert groups reflected in Table 3.

Table 3: Data summary of experts participating on the panel for criteria to select alternatives against road traffic noise.

Group of experts	**N. of answered**

			surveys
Public Administration	Regional Road Administration	Central department	3
		Provincial departments	17
	Regional Environmental Administration		1
	Central Government Road Administration		2
	Provincial Road Administration		2
	Local Administration		4
Consulting firms			28
University			8

The linguistic labels offered as possible responses to the experts and their correspondence with the triangular fuzzy numbers in the FEAHP application are shown in Table 4.

Table 4: Linguistic labels used for expert panel and equivalence to fuzzy numbers.

Importance intensity	**Linguistic label**	**Triangular membership function**	**Reciprocal triangular membership function**
	Exactly the same	(1, 1, 1)	(1, 1, 1)
1	Same importance	(1/2, 1, 2)	(1/2, 1, 2)
2	Weak importance	(1, 2, 3)	(1/3, 1/2, 1)
3	Strong importance	(2, 3, 4)	(1/4, 1/3, 1/2)
4	Demonstrated importance	(3, 4, 5)	(1/5, 1/4, 1/3)
5	Absolute importance	(4, 5, 5)	(1/5, 1/5, 1/4)

Accordingly, in the questionnaire, the different groups of criteria and sub-criteria were submitted to the experts with a brief explanation about their meaning and the adopted notation in the questionnaire. They were then asked to sort all the criteria according to their relative importance in the decision-making problem of finding the best alternative for action against traffic noise. The experts were also asked if it was necessary to consider some other criteria in each group in addition to the proposed factors; if so, they were invited to fill in the appropriate field of the questionnaire with the additional criteria and indicators.

It should be noted that the expert panel responses corroborated the convenience of all the criteria and sub-criteria selected for the multi-criteria analysis presented in this paper (detailed in Section 3.2).

Subsequently, each criterion was compared with the other criteria in its group (in accordance with the defined hierarchical structure, detailed in the following subsection), and the experts were asked to answer with the linguistic labels defined in Table 4.

Finally, each expert was thanked for their collaboration and asked to send his/her completed questionnaire back to the authors of the study. The feedback from the experts was appropriately processed by applying the FEAHP method to their answers, and the *CR* index was calculated to ensure the consistency of results.

4.2. Weighting the criteria and sub-criteria using FEAHP.

Once the criteria and sub-criteria had been selected and the possible alternatives defined, a three level hierarchical system was created (Fig. 6). Then, the FEAHP was implemented in order to obtain the weights to be applied to the set of criteria and sub-criteria in the decision-making process approached.

The relative importance among the different criteria (and among sub-criteria within a given criterion) was obtained via the pairwise comparisons conducted by the expert panel (see preceding subsection). Through their responses the experts judged the relative importance among criteria using the scale of linguistic labels, shown in Table 4, that were assigned to the corresponding triangular fuzzy number. All the responses (triangular fuzzy numbers) were aggregated via geometric mean calculation (Liao, 2011; Ruiz-Padillo et al., 2016) to yield the criteria and sub-criteria fuzzy matrices shown in Figs. 7 and 8.

Using the methodology presented in Section 3.1, the defuzzified weighting vectors (criteria and sub-criteria weights) were obtained from the matrices (Figs. 7 and 8). The *CR* calculated for all criteria and sub-criteria weights showed values significantly below the thresholds suggested in the literature. Fig. 6 presents the relative weights (obtained directly from the methodology), the aggregated or total weights of the sub-criteria (calculated simply by multiplying the relative weight by the corresponding weight of the criteria on which the sub-criteria depend), and the *CR* for all the criteria and sub-criteria.

The weights displayed at the sub-criteria level point to the sub-criteria related to the safety of the road users (i.e. road safety and visibility) as the most influential, along with those ones directly measuring the noise exposure and impact (i.e. social improvement of the exposed population, and the number of people and sensitive centers corrected). The corrected area and average speed of traffic were found to be the least influential sub-criteria. After implementing the FEAHP, two sub-criteria (expenses on vehicles and changes in property value) were assigned a weight of zero, and were consequently discarded.

Once the weights of the criteria and sub-criteria have been calculated (using the FEAHP), a multi-criteria analysis must be performed in order to evaluate the possible alternatives. As indicated above, this research employed and tested three multi-criteria assessment methods (WSM, TOPSIS, and ELECTRE). To arrive at a better understanding, the multi-criteria decision-making process for alternative assessment was applied to a case study as shown in the next section.

5. Case study.

To clearly illustrate the different steps and the application of the methodology, a real case study used in a previous publication (Ruiz-Padillo et al., 2016) was chosen, where the NAP of the Andalusian Road Network in the province of Almeria (southern Spain) was reviewed. That analysis determined the road stretch with the highest priority for action against noise: the road stretch named A-1000 which runs from N-340a in ‘‘Huércal de Almería’’ to A-7 in ‘‘Viator’’. It was therefore selected to consider the implementation of noise abatement measures. All the procedures and the characteristics of the road and the data extracted from the SNM corresponding to 2013 (data on population and one school exposed to road noise in the town of Huércal de Almería) can be found in Ruiz-Padillo et al. (2016).

Having selected the road stretch where noise control measures were priority, the methodology developed and proposed in this paper was applied, considering all the possible means of action.

Firstly, a pre-selection of alternatives was performed for this road stretch, following the flow diagrams given in Section 2.1:

- According to Fig. 1: road A-1000 in the analyzed stretch is neither an urban section, nor a high-speed road, so the A31 and A33 alternatives can be discarded.

- According to Fig. 2: since there are no previous measures of sound attenuation implemented in the road stretch, it is not possible to remove any other alternative.

- According to Fig. 3: the average vehicle speed on the road stretch is 55 km/h, thus exceeding 50 km/h, so no other alternative can be ruled out.

- According to Fig. 4: the necessary attenuation in the worst point is higher than 5 dB(A), so alternatives of low noise pavements or traffic management cannot be implemented alone, but may be combined with other measures such as noise barriers or building insulation.

In addition to the above pre-selection, a further refinement of the suitability of the alternatives was made for this case. Since the implementation of a low noise pavement must be done by surface reinforcement, and the existing pavement on the A-1000 road is bituminous, it is not technically appropriate to use concrete only on a relatively short stretch of the road (i.e., where the population is exposed to traffic noise, specifically between kilometer points 0+350 and 0+800). Thus, alternative A23 can be discarded. Moreover, it makes no sense to propose a solution covering the road (alternative A5) because the noise problem is not severe, and such a measure would be very complex and expensive due to the characteristics of the road.

Therefore, after the preselection carried out, the studied alternatives for road stretch A-1000 would be:

- A11: acoustic screen. The solution contemplated is a 444-meter long and 4-meter high noise barrier wall. In the case of a mixed solution with other alternatives, the barrier should consist of a single panel 2 meters high.

- A12: earth berm. A 525-meter long earth berm is proposed, with variable height (up to 9.90 meters, sufficient to interfere with the sound waves at all exposed facades) and coronation by planting a row of trees. If the earth berm were part of a mixed solution with other measures, it would be lower.

- A21: porous bituminous mixture. The spread of a 5-cm-thick layer of drainage asphalt is contemplated.

- A22: rubberized mixtures. This alternative is similar to the above solution, but running a surface reinforcement of a 5-cm-thick bituminous mixture improved with ground-up disused tire rubber.

- A32: action on traffic speed. The installation of a traffic light for speed control to 40 km/h is proposed to achieve an average reduction of about 15 km/h.

- A4: building insulation. This alternative consists of changing windows in homes exposed to noise using two prototypes to add different sound insulations of the windows: more 5 dB and more 10 dB.

Since alternatives of low noise pavements, traffic management and building insulation of more 5 dB alone do not suffice to achieve the necessary attenuation, they were contemplated in combination with one another and with noise barriers. The choice of window insulation of more 10 dB also complemented the alternative A32.

At this point all the feasible and possible efficient alternatives had been defined, and the indicators of the criteria explained in Section 2.2 were evaluated to apply the methodology. Then, they were normalized and weighted with the values obtained from the application of the FEAHP (Fig. 6). Finally, the three multi-criteria decision methods proposed were applied. Table 5 lists the possible alternatives and the results obtained from the multi-criteria decision methods.

Table 5: Results of application of the multi-criteria methods used on case study alternatives.

ALTERNATIVES		**SUMATION VALUE WEIGHTED SUM**	**NO. ALTERNATIVES BY WHICH IT IS OUTRANKED (ELECTRE)**	**SIMILARITY RATIO VALUE (TOPSIS)**
A11	Acoustic screen	5,21	9	0,406
A12	Berm	5,40	9	0,428
A1112	Berm + screen	5,31	10	0,418
A1121	Screen + porous asphalt	7,97	2	0,786
A1221	Berm + porous asphalt	8,03	3	0,758
A1122	Screen + rubberized asphalt	8,84	0	0,859
A1222	Berm + rubberized asphalt	8,19	0	0,809
A1132	Screen + traffic light	4,76	8	0,306
A1232	Berm + traffic light	4,82	10	0,313
A114	Screen + insulation	5,90	6	0,457
A124	Berm + insulation	6,38	4	0,467
A4	Insulation	7,18	6	0,480
A214	Porous asphalt + insulation	7,93	2	0,809
A224	Rubberized asphalt + insulation	9,21	0	0,849
A324	Traffic light + insulation	4,86	7	0,330

A view of this table shows that the kernel set of the ELECTRE method, formed by the non-outranked alternatives (that is, the most suitable ones) are the so-called A1122 (acoustic screen + surface reinforcement with rubberized mixture), A1222 (earth berm + surface reinforcement with rubberized mixture) and A224 (building insulation + surface reinforcement with rubberized mixture). They are also located at the top of the two lists derived from the other methods. In fact, TOPSIS chooses A1122 as the best alternative and places A224 as the second option, whereas WSM chooses A224 and secondly selects A1122.

Therefore, all the methods agree that the final choice should be between A1122 and A224 as alternatives, that is, to reduce the noise in this road stretch it is possible to make the surface reinforcement with a rubberized mixture, and then combine it either with the noise barrier of a lower height on the side of the road or with an additional 5 dB insulation for the house windows. Hence, the best options to mitigate the noise impact according to the NAP can be proposed.

Identifying the best alternatives through the proposed methodology offers another important and practical advantage: they can be implemented in two clearly separate phases, because they involve two independent and inclusive actions. It would seem logical to first implement the low noise surface reinforcement, resulting in a general noise reduction, while further promoting other positive parameters of the road itself (such as surface regularity and visibility of road markings). Then, in a second stage, any of the other actions could be incorporated. It would not even be necessary to make a final decision at this initial moment; the final choice for the second stage could be aided by a more detailed measurement of the noise situation of the road stretch and the exposed dwellings after assessing the benefits of the low noise pavement.

6. Conclusions.

The main administrative tool to reduce the environmental impact of noise on the population are noise action plans (NAPs), which should be developed after the assessment made by strategic noise maps. In Europe, the action plans against road traffic noise published in compliance with the European Directive on the assessment and management of environmental noise reveal a variety of adopted criteria for deciding on the alternatives, depending on the road manager or the specific administration implied in the NAPs. Many of the suggested criteria are moreover unsuitable and would prove ineffective for the noise control problem.

It is therefore highly relevant for policy-makers or managers to rely on a methodology to assess the impact of projects or alternatives and make decisions based upon these assessments. This paper focuses on developing a rigorous means of selecting the best approach to mitigate noise exposure due to road traffic. A useful multi-criteria tool to support decision-making regarding the prioritization of actions in the development of Road Noise Action Plans is proposed. Thanks to its diversified character, the methodology is applicable to any road stretch, and easily adaptable to specific conditions of a road or decision-maker needs.

The suggested procedure starts by selecting the road stretch where noise mitigation measures are to be applied. The manager must then choose the alternatives to be implemented. Appropriate criteria for decision making and different alternatives (not only the commonuse of noise barriers) for the decision-maker are determined and explained in this paper. To aid and guide in the decision process, flowcharts were generated to preselect these alternatives. Then, the use of any of the different multi-criteria analysis methods studied in this paper is suggested, the most appropriate one depending on the analyzed problem and the specific context of use of the methodology. Since the related decisions are highly complex and take place in an environment of uncertainty, the fuzzy extended analytical hierarchy process (FEAHP) is proposed for weighting the criteria. This method is applied to the results obtained from an expert panel, thus capturing their knowledge regarding the problem at hand, but computing the weights in a non-arbitrary way thanks to the FEAHP method. These weights, determined both for criteria and sub-criteria, attain great consistency and logic according to the FEAHP procedure itself. Finally, in terms of the particular decision methods used for the alternatives, three of them are proposed and implemented: the weighted sum, ELECTRE, and TOPSIS.

A real case study served to illustrate the application of the developed methodology for selecting the possible alternatives against noise in a complex situation. It was found that the proposals identified through the sorting and selection process of alternatives proved reasonable and appropriate. In addition, it was possible to verify that different alternatives to the traditional noise barriers come out as more preferable solutions to the noise problem analyzed.

It is remarkable to underline that the use of this methodology provides sound arguments from the standpoint of objectivity and rigor, both for managers responsible for the approval and implementation of a Noise Action Plan, and for the population of affected inhabitants. Therefore, it is an approach based on a very technical support, and other subjective factors are not taken into account in the methodology, as political influences in the decision-making process. However, the methodology does not impose a sole or right solution, but it proposes and sorts by technical suitability the best feasible alternatives.

Moreover, the developed methodology may be also applicable for the decision-making about the measures to mitigate the impact of the traffic noise, as result of the environmental evaluation assessment of the construction of a new road or the improvement of an existing one.

Future research will aim to obtain new results regarding the criteria and their weights that will allow us to corroborate their relative importance in decision problems, considering other real cases. A further systematization for application of the methodology might also be interesting, combining it with other environmental impacts related to road traffic. Similarly, further detailed research on its potential for forthcoming stages of implementation of the European Directive would be pertinent, especially since CNOSSOS-EU will be adopted as the method of generating strategic noise maps from 2017 onward, because the application of the developed methodology is possible regardless of the data noise source or simulation technique used.

Acknowledgments.

This work was supported by the “Ministerio de Economía y Competitividad” of Spain under project TEC2012-38883-C02-02.

This work is also funded by the University of Malaga and the European Commission under the Agreement Grant no. 246550 of the seventh Framework Programme for R & D of the EU, granted within the People Programme, “Co-funding of Regional, National and International Programmes” (COFUND), and “Ministerio de Economía y Competitividad” of Spain (COFUND2013-40259).

The authors wish to thank the “Dirección General de Infraestructuras de la Consejería de Fomento y Vivienda” of the “Junta de Andalucía” (Spain) for facilitating access to the data required for this study.

References.

Achillas, Ch., Vlachokostas, Ch., Moussiopoulos, N., Banias, G., 2011. Prioritize strategies to confront environmental deterioration in urban areas: Multicriteria assessment of public opinion and experts' views. Cities 28, 414–423.

Arce, M.E., Saavedra, Á., Míguez, J.L., Granada, E., 2015. The use of grey-based methods in multi-criteria decision analysis for the evaluation of sustainable energy systems: A review. Renewable and Sustainable Energy Reviews 47, 924–932.

Awasthi, A., Chauhan, S.S., Goyal, S.K., 2010. A fuzzy multicriteria approach for evaluating environmental performance of suppliers. Int. J. Production Economics 126, 370–378.

Barba-Romero, S., Pomerol, J.C., 2000. Multicriterion Decision in Management: principles and practice. Boston: Kluwer Academic Publishers.

Celik, M., Er, I.D., Ozok, A.F., 2009. Application of fuzzy extended AHP methodology on shipping registry selection: The case of Turkish maritime industry. Expert Systems with Applications 36, 190–198.

Chan, H., Wang, X., White, G.R.T., Yip, N., 2013. An Extended Fuzzy-AHP Approach for the Evaluation of Green Product Designs. IEEE Transactions on Engineering Management journal 60(2), 327–339.

Chang, D.-Y., 1996. Applications of the extent analysis method on fuzzy AHP. European Journal of Operational Research 96, 649–655.

D'Alessandro, F., Schiovani, S., 2015. A review and comparative analysis of European priority indices for noise action plans. Science of the Total Environment 518–519, 290–301.

Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise – Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise. Official Journal L 189, 18/07/2002, P. 12–26.

Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment.

Official Journal of the European Union L 26, 28/01/2012, P. 1–21.

Egilmez, G., Gumus, S., Kucukvar, M., 2015. Environmental sustainability benchmarking of the U.S. and Canada metropoles: An expert judgment-based multi-criteria decision making approach. Cities 42, 31–41.

Ellis, J.B., Deutsch, J.-C., Mouchel, J.-M., Scholes, L., Revitt, M.D., 2004. Multicriteria decision approaches to support sustainable drainage options for the treatment of highway and urban runoff. Science of the Total Environment 334–335, 251–260.

Erensal, Y.C., Öncan, T., Demircan, M.L., 2006. Determining key capabilities in technology management using fuzzy analytic hierarchy process: A case study of Turkey. Information Sciences 176, 2755–2770.

Fiedler, P.E.K., Zannin, P.H.T., 2015. Evaluation of noise pollution in urban traffic hubs – Noise maps and measurements. Environmental Impact Assessment Review 51, 1–9.

Gardziejczyk, W., Zabicki, P., 2014. The influence of the scenario and assessment method on the choice of road alignment variants. Transport Policy 36, 294–305.

Garg, N., Maji, S., 2014. A critical review of principal traffic noise models: Strategies and implications. Environmental Impact Assessment Review 46, 68–81.

Herva, M., Roca, E., 2013. Review of combined approaches and multi-criteria analysis for corporate environmental evaluation. Journal of Cleaner Production 39, 355–371.

Hwang, C.L., Yoon, K., 1981. Multiple Attribute Decision Methods and Applications. Springer, Berlin Heidelberg ed.

King, E.A., Murphy, E., Rice, H.J., 2011. Implementation of the EU environmental noise directive: Lessons from the first phase of strategic noise mapping and action planning in Ireland. Journal of Environmental Management 92, 756–764.

Liao, C.-N., 2011. Fuzzy analytical hierarchy process and multi-segment goal programming applied to new product segmented under price strategy. Computers & Industrial Engineering 61, 831–841.

Mayer, R.M., Poulikakos, L.D., Lees, A.R., Heutschi, K., Kalivoda, M.T., Soltic, S., 2012. Reducing the environmental impact of road and rail vehicles. Environmental Impact Assessment Review 32, 25–32.

Nielsen, G., Solberg, S., 1988. Costs and effects of traffic noise abatement measures: basis for a national programme. Applied Acoustics 25, 149–168.

Nogués, S., González-González, E., 2014. Multi-criteria impacts assessment for ranking highway projects in Northwest Spain. Transportation Research Part A 65, 80–91.

Nosal, K., Solecka, K., 2014. Application of AHP method for multi-criteria evaluation of variants of the integration of urban public transport. Transportation Research Procedia 3, 269–278.

Oltean-Dumbrava, C., Watts, G., Miah, A., 2013. Transport infrastructure: making more sustainable decisions for noise reduction. Journal of Cleaner Production 42, 58–68.

Ouis, D., 2001. Annoyance from road traffic noise: a review. Journal of Environmental Psychology 21, 101–120.

Roy, B., 1968. Classement et choix en présence de points de vue multiples, la méthode ELECTRE. R.I.R.O. 2(8), 57–75.

Ruiz-Padillo, A., Torija, A.J., Ramos-Ridao, A.F., Ruiz, D.P., 2014. A methodology for classification by priority for action: selecting road stretches for network noise action plans. Transportation Research Part D 29, 66–78.

Ruiz-Padillo, A., Torija, A.J., Ramos-Riado, A.F., Ruiz, D.P., 2016. Application of the fuzzy analytic hierarchy process in multi-criteria decision in Noise Action Plans: prioritizing road stretches. Environmental Modelling and Software 81, 45-55.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill. New York.

Sayers, T.M., Jessop, A.T., Hills, P.J., 2003. Multi-criteria evaluation of transport options—flexible, transparent and user-friendly? Transport Policy 10, 95–105.

Soltani, A., Hewage, K., Reza, B., Sadiq, R., 2015. Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management: A review. Waste Management 35, 318–328.

Spanish Law on Noise, Official Bulletin of the State of Spain no. 276, 18 November 2003 [Ley 37/2003, de 17 de noviembre, del Ruido. Boletin Oficial del Estado no. 276, de 18 de noviembre de 2003, pp. 40494–40505].

Sun, H., Zhang, Y., Wang, Y., Li, L., Sheng, Y., 2015. A social stakeholder support assessment of low-carbon transport policy based on multi-actor multi-criteria analysis: The case of Tianjin. Transport Policy 41, 103–116.

Van Renterghem, T., Botteldooren, D., 2012. On the choice between walls and berms for road traffic noise shielding including wind effects. Landscape and Urban Planning 105, 199–210.

Vlachokostas, Ch., Achillas, Ch., Moussiopoulos, N., Banias, G., 2011. Multicriteria methodological approach to manage urban air pollution. Atmospheric Environment 45, 4160–4169.

Wood, G., Rodriguez-Bachiller, A., Becker, J., 2007. Fuzzy sets and simulated environmental change: evaluating and communicating impact significance in environmental impact assessment. Environment and Planning A, 39(4), 810-829.

Zadeh, L.A., 1965. Fuzzy sets. Information and Control 8, 338-353.

Zhang, H., Huang, G.H., 2011. Assessment of non-point source pollution using a spatial multicriteria analysis approach. Ecological Modelling 222, 313–321.

Fig. 1: Flow chart: pre-selection of alternatives according to the condition of the road as urban section, urban road or high-speed road.

Fig. 2: Flow chart: pre-selection of alternatives according to the existence of previous measures of acoustic attenuation.

Fig. 3: Flow chart: pre-selection of alternatives according to the average traffic speed.

Fig. 4: Flow chart: pre-selection of alternatives according to the necessary attenuation.

Fig. 5: Flow chart: application of FEAHP weighting method.

Fig. 6: Criteria and sub-criteria weights for selecting alternatives to road traffic noise, and consistency ratios (*CR*).

Fig. 7: Fuzzy pairwise comparison matrix of criteria.

Fig. 8: Fuzzy pairwise comparison matrices of sub-criteria.

Fig. 1:

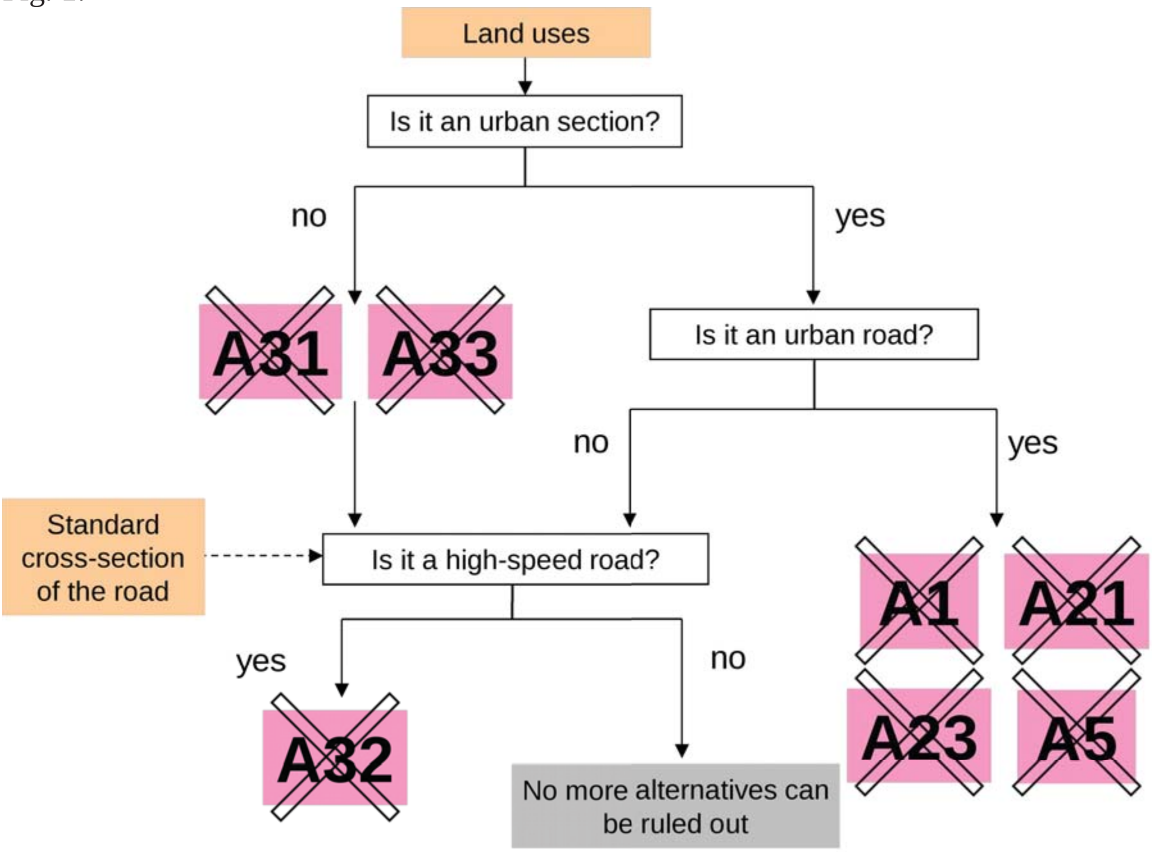
Land uses
Is it an urban section?
no
yes
A31
A33
Is it an urban road?
no
yes
Standard cross-section of the road
Is it a high-speed road?
A1
A21
yes
no
A23
A5
A32
No more alternatives can be ruled out

Fig. 2:

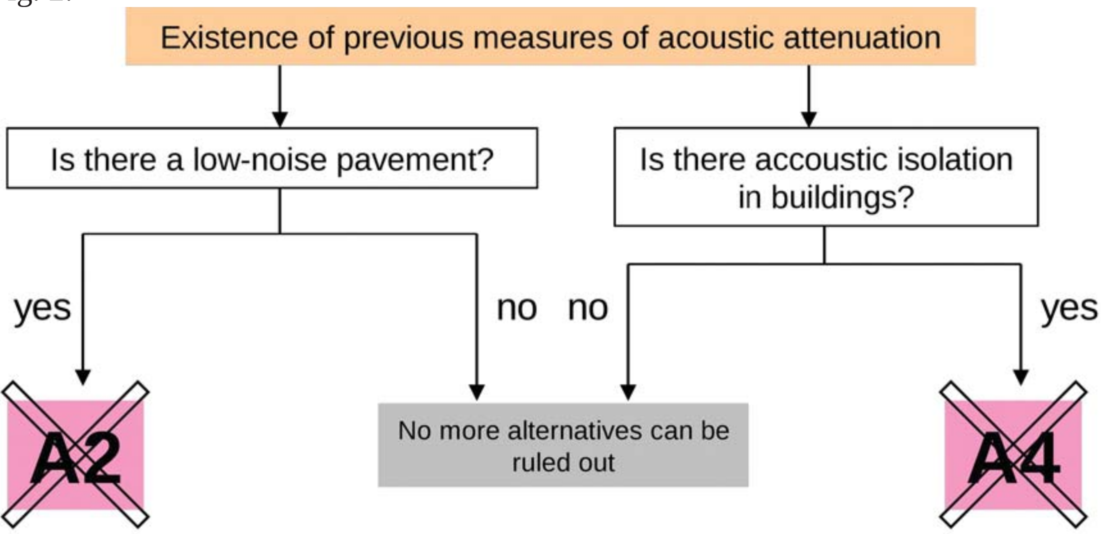
Existence of previous measures of acoustic attenuation
Is there a low-noise pavement?
Is there accoustic isolation in buildings?
yes
no
no
yes
A2
No more alternatives can be ruled out
A4

Fig. 3:

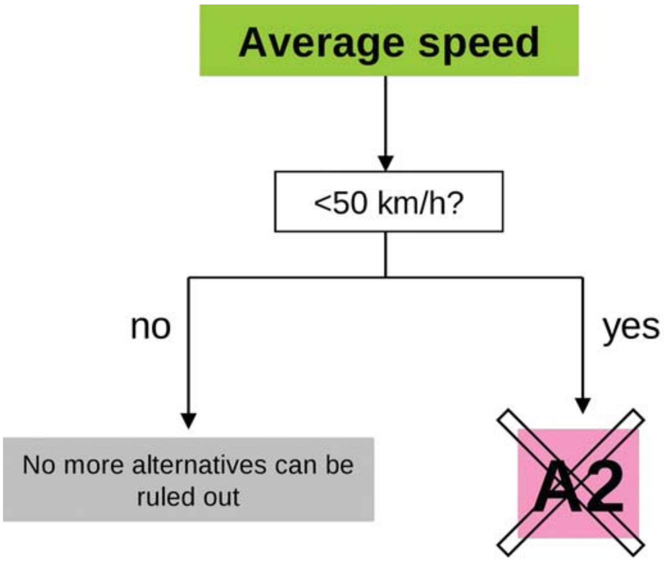
Average speed
<50 km/h?
no
yes
No more alternatives can be ruled out
A2

Fig. 4:

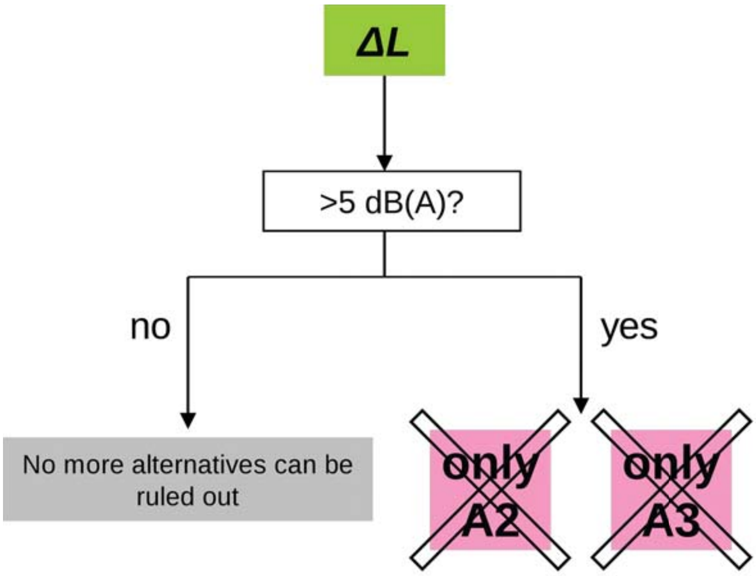
ΔL
>5 dB(A)?
no
yes
No more alternatives can be ruled out
only A2
only A3

Fig. 5:

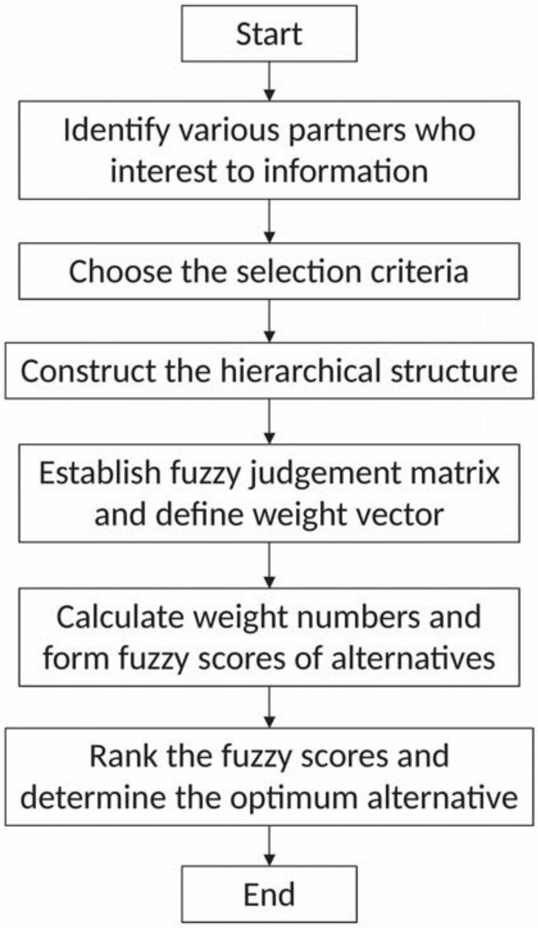
Start
Identify various partners who interest to information
Choose the selection criteria
Construct the hierarchical structure
Establish fuzzy judgement matrix and define weight vector
Calculate weight numbers and form fuzzy scores of alternatives
Rank the fuzzy scores and determine the optimum alternative
End

Fig. 6:

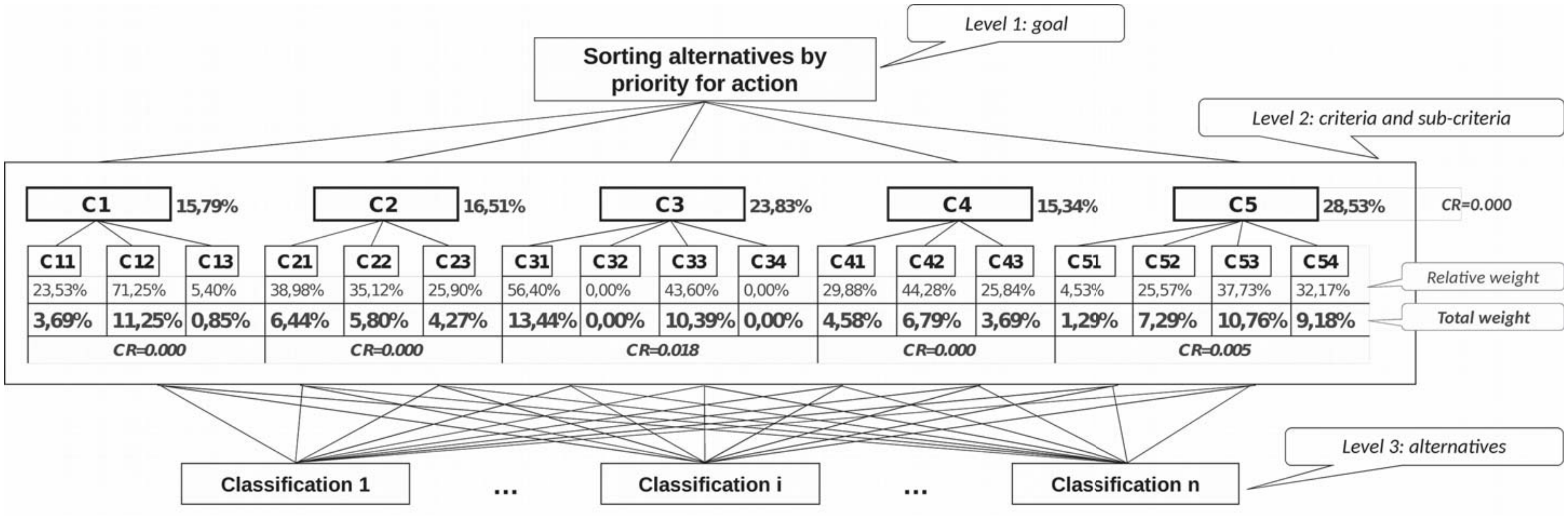
Level 1: goal
Sorting alternatives by priority for action
Level 2: criteria and sub-criteria
C1 15,79%
C2 16,51%
C3 23,83%
C4 15,34%
C5 28,53%
CR=0.000
C11 23,53% 3,69%
C12 71,25% 11,25%
C13 5,40% 0,85%
CR=0.000
C21 38,98% 6,44%
C22 35,12% 5,80%
C23 25,90% 4,27%
CR=0.000
C31 56,40% 13,44%
C32 0,00% 0,00%
C33 43,60% 10,39%
C34 0,00% 0,00%
CR=0.018
C41 29,88% 4,58%
C42 44,28% 6,79%
C43 25,84% 3,69%
CR=0.000
C51 4,53% 1,29%
C52 25,57% 7,29%
C53 37,73% 10,76%
C54 32,17% 9,18%
CR=0.005
Relative weight
Total weight
Level 3: alternatives
Classification 1
...
Classification i
...
Classification n

Fig. 7:

$$
\begin{array}{cc}
 & \begin{array}{ccccc} C1 & C2 & C3 & C4 & C5 \end{array} \\
\begin{array}{c} C1 \\ C2 \\ C3 \\ C4 \\ C5 \end{array} &
\begin{pmatrix}
(1,000,\ 1,000,\ 1,000) & (0,671,\ 0,994,\ 1,487) & (0,489,\ 0,726,\ 1,101) & (0,660,\ 0,971,\ 1,398) & (0,407,\ 0,574,\ 0,858) \\
(0,673,\ 1,006,\ 1,490) & (1,000,\ 1,000,\ 1,000) & (0,547,\ 0,790,\ 1,175) & (0,691,\ 1,020,\ 1,487) & (0,400,\ 0,574,\ 0,899) \\
(0,908,\ 1,378,\ 2,044) & (0,851,\ 1,266,\ 1,829) & (1,000,\ 1,000,\ 1,000) & (1,017,\ 1,662,\ 2,532) & (0,509,\ 0,775,\ 1,227) \\
(0,715,\ 1,030,\ 1,515) & (0,673,\ 0,981,\ 1,446) & (0,395,\ 0,602,\ 0,983) & (1,000,\ 1,000,\ 1,000) & (0,369,\ 0,528,\ 0,816) \\
(1,166,\ 1,741,\ 2,459) & (1,122,\ 1,743,\ 2,502) & (0,815,\ 1,290,\ 1,965) & (1,225,\ 1,894,\ 2,711) & (1,000,\ 1,000,\ 1,000)
\end{pmatrix}
\end{array}
$$

Fig. 8:

$$\begin{array}{cccc} & C11 & C12 & C13 \\ C11 & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}365,\ 0{,}495,\ 0{,}709) & (0{,}848,\ 1{,}290,\ 1{,}891) \\ C12 & (1{,}410,\ 2{,}020,\ 2{,}741) & (1{,}000,\ 1{,}000,\ 1{,}000) & (1{,}773,\ 2{,}617,\ 3{,}529) \\ C13 & (0{,}529,\ 0{,}775,\ 1{,}179) & (0{,}283,\ 0{,}382,\ 0{,}564) & (1{,}000,\ 1{,}000,\ 1{,}000) \end{array}$$

$$\begin{array}{cccc} & C21 & C22 & C23 \\ C21 & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}760,\ 1{,}156,\ 1{,}730) & (0{,}968,\ 1{,}472,\ 2{,}086) \\ C22 & (0{,}578,\ 0{,}865,\ 1{,}315) & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}780,\ 1{,}331,\ 2{,}181) \\ C23 & (0{,}479,\ 0{,}680,\ 1{,}033) & (0{,}459,\ 0{,}751,\ 1{,}283) & (1{,}000,\ 1{,}000,\ 1{,}000) \end{array}$$

$$\begin{array}{ccccc} & C31 & C32 & C33 & C34 \\ C31 & (1{,}000,\ 1{,}000,\ 1{,}000) & (2{,}631,\ 3{,}655,\ 4{,}529) & (1{,}198,\ 1{,}816,\ 2{,}607) & (2{,}510,\ 3{,}383,\ 4{,}040) \\ C32 & (0{,}221,\ 0{,}274,\ 0{,}380) & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}265,\ 0{,}355,\ 0{,}540) & (0{,}913,\ 1{,}443,\ 2{,}126) \\ C33 & (0{,}384,\ 0{,}551,\ 0{,}835) & (1{,}854,\ 2{,}813,\ 3{,}768) & (1{,}000,\ 1{,}000,\ 1{,}000) & (2{,}348,\ 3{,}364,\ 4{,}234) \\ C34 & (0{,}247,\ 0{,}296,\ 0{,}398) & (0{,}470,\ 0{,}693,\ 1{,}095) & (0{,}236,\ 0{,}297,\ 0{,}426) & (1{,}000,\ 1{,}000,\ 1{,}000) \end{array}$$

$$\begin{array}{cccc} & C41 & C42 & C43 \\ C41 & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}457,\ 0{,}667,\ 1{,}029) & (0{,}720,\ 1{,}115,\ 1{,}731) \\ C42 & (0{,}972,\ 1{,}498,\ 2{,}186) & (1{,}000,\ 1{,}000,\ 1{,}000) & (1{,}029,\ 1{,}563,\ 2{,}253) \\ C43 & (0{,}578,\ 0{,}897,\ 1{,}389) & (0{,}444,\ 0{,}640,\ 0{,}971) & (1{,}000,\ 1{,}000,\ 1{,}000) \end{array}$$

$$\begin{array}{ccccc} & C51 & C52 & C53 & C54 \\ C51 & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}353,\ 0{,}485,\ 0{,}721) & (0{,}299,\ 0{,}402,\ 0{,}581) & (0{,}321,\ 0{,}431,\ 0{,}618) \\ C52 & (1{,}388,\ 2{,}061,\ 2{,}834) & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}378,\ 0{,}553,\ 0{,}918) & (0{,}497,\ 0{,}746,\ 1{,}186) \\ C53 & (1{,}721,\ 2{,}486,\ 3{,}345) & (1{,}089,\ 1{,}808,\ 2{,}642) & (1{,}000,\ 1{,}000,\ 1{,}000) & (0{,}772,\ 1{,}294,\ 2{,}046) \\ C54 & (1{,}617,\ 2{,}318,\ 3{,}120) & (0{,}843,\ 1{,}340,\ 2{,}012) & (0{,}489,\ 0{,}773,\ 1{,}296) & (1{,}000,\ 1{,}000,\ 1{,}000) \end{array}$$