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Address: Univerzitetski trg 2, 18000 Niš,YU, Tel. +381 18 547-095, Fax: +381 18 547-950
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ACOUSTIC COMFORT OPTIMIZATION OF INDUSTRIAL HALE USING INTELLIGENT TECHNOLOGY

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Dragan Cvetković, Miloš Manić,
Momir Praščević, Slobodan Milutinović

University of Niš, Faculty of Occupational Safety, Čarnojevića 10a,
18000 Niš, Serbia, Yugoslavia, e-mail: misko@ieee.org

Abstract. *The problem of acoustic comfort optimization has been resolved in traditional manner by classical numerical methods, so far. The authors of this paper have proposed a new method introducing intelligent methodologies, namely fuzzy logic. Proposed method consists of a fuzzy extension of Saaty's AHP multiple criteria optimization, is applied on an optimization of acoustic comfort of an industrial hall. Test example is illustrated by diagrams and tables, which are obtained by the authors software.*

Key words: *fuzzy logic, acoustic comfort, industrial hale*

1. INTRODUCTION

Prior to any construction activities, it is necessary to perform appropriate actions, such as investigation and research, in order to obtain optimal solution for the acoustic comfort of industrial hall. Optimization of acoustic comfort understands the choice among alternatives in respect to some predefined criteria.

Decision making often refers to a complex problem as a result of existance of concurrent and conflict criteria among available alternatives. **AHP** (**A**nalytical **H**ierarchy **P**rocess) has been developed and introduced by Tomas **SAATY** in seventies, in order to resolve mentioned decision problems, which include larger number of decision makers, criteria and multiple intervals of time [1].

The advantage of the method refers to an adaptivity to a decision maker's capabilities, meaning, number of factors (criteria and alternatives) which are simultaneously being involved in decision making process by natural, hierarchical decomposition of an general problem. The main advantage of the method is the possibility of quantitative as also as

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qualitative description of data (criteria).

Fuzzy extension of this method consists yet in linguistically, fuzzy depiction of criteria, according to appropriate alternatives are compared i.e. ranked [2,3,].

Fuzzy logic, one of the leading concepts among intelligent technologies, is experiencing growing popularity in industrial and commercial approximate reasoning systems, decision making systems, optimization, control, etc. This is the reason for growing need for qualitatively depicted attributes multiple criteria decision making (ranking) [5].

2. Analytic hierarchy process

This multiple criteria optimization method is based on the concept of relative significance determination of relevant attributes set (criteria, alternatives) that refers to a certain decision making problem.

This complex problem of multiple criteria, decision intervals, and decision makers is decomposed into a certain number of hierarchy levels. The whole process can be described by four main steps:

a) Hierarchical decomposition of a problem i.e. natural, logical rationalization of a problem into a levels starting from global objective towards to the criteria i.e. subcriteria and eventually ending in possible alternatives that are going to be evaluated. This is how decomposition (structuring) of attribute interdependencies in different hierarchical levels is enabled.

b) The next step refers to an attribute pairwise comparison on every level, regarding to every higher level attribute. Experimentally determined nine point scale is used for relative estimations determination, that consists the comparison matrix.

c) The third phase considers priority vectors (weights) generated by an eigenvector (values) method for every level regarding to a every higher level element. Normalized and unique weight vectors for all attributes on every hierarchy level are obtained.

For every A_i attribute (i = 1,...,n) and appropriate weight w_i, a following matrix is formed:

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \cdots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \tag{1}$$

Normalized weight vector $w = [w_1, w_2, ..., w_n,]^T$ is obtained by eigenvector method:

$$A\,w = n\,w \tag{2}$$

Matrix **A** has all positive elements, is reciprocal ($a_{ij} = 1/a_{ji}$) and consistent ($a_{ik} = a_{ij}a_{jk}$, i, j, k, = 1,...,n).

Instead of eigenvector technique an approximate method is often used. Matrix consistency is determined by so called consistency index.

d) **Final step** considers overall, global priority vector determination by a linear, additive synthesis function of vectors as:

$$W_i = \sum_{j=1}^{n} c_j w_{ij} \ , \ \forall i = 1,...,m. \quad (3)$$

where W_i is weight (priority of an alternative **i**), c_j is criterion **j** weight (j = 1,...,n), w_{ij} is an alternative **i** weight regarding to criterion **j**, **m** - number of alternatives, **n** - number of criteria.

It is important to note that the AHP does not require decision makers to be consistent but, rather, provides a measure of inconsistency as well as a method to reduce this measure if it is deemed to be too high.

3. FUZZY EXTENSION OF AN AHP METHOD

Fuzzy extension of AHP method proposed in this paper refers to a qualitatively (linguistically) described criteria and alternatives. In order to pairwise comparison of linguistic terms of such depicted criteria, an original software for fuzzy numbers (and fuzzy values those are not necessarily normal, convex and continual fuzzy sets) ranking is exploited.

Ranking is carried out by fuzzy preference relation that is based on a fuzzy satisfaction function [6,7].

As a result of such ranking, normalized preference values of two fuzzy numbers are obtained. These values ought to be incorporated into a well known nine points scale, in order to use further the preference matrix. Mapping is carried out by subsegments mapping (16 of them) to a discrete scale set (17 points) while 1 (equally important, 9-th point) corresponds to a 0.5 preference relation value. As for 0 (absolutely preferred) 1 preference corresponds and for 1/9 corresponds 0 preference. For other preference intensities, mapping is carried out with rounding (for example: to a 0.6930 preference value corresponds a point 5). Following steps are conducted according to a classical AHP method.

3.1. Fuzzy preference relation

Fuzzy preference structure on a set of alternatives A is a triplet $\Pi_\varnothing = (P, I, R)$ that can be characterized by means of a unique binary relation S in A, called characteristic preference relation $S(a,b)$ which represents the degree in which alternative **a** is at least as good as alternative b.

If $\mathsf{A} = \{A_1, A_2, ..., A_n\}$ is taken to be a set of fuzzy numbers, those can be the evaluation for the competing alternatives, then a fuzzy preference relation R_S, with respect to the satisfaction function S_γ, can be defined as follows:

$$R_s : \mathsf{A} \times \mathsf{A} \rightarrow [0,1] \quad (4)$$

The value fuzzy preference relation $R_S(A_i,A_j)$ indicates the degree to which fuzzy number A_i dominates to fuzzy number A_j.

Different approaches to fuzzy preference relation construction can be found in literature [10, 11]. One of the earliest, used for further developing of other approaches, is Orlovsky's fuzzy preference relation [12]:

$$R_s(A_i, A_j) = \begin{cases} S_\gamma(A_i > A_j) - & \text{when } S_\gamma(A_i > A_j) \geq \\ -S_\gamma(A_j > A_i), & \geq S_\gamma(A_j > A_i) \\ & \text{otherwise} \\ 0, & \end{cases} \quad (5)$$

Lee with associates [13] has proposed fuzzy preference relation:

$$R_s(A_i, A_j) = S_\gamma(A_i > A_j) + \tfrac{1}{2} S_\gamma(A_i = A_j) \quad (6)$$

They have also proved the following two frequently used properties of fuzzy preference relations:

$$R_s(A_i, A_j) + R_s(A_j, A_i) = 1, \quad \forall A_i, A_j \in \mathrm{A} \quad (7)$$

$$R_s(A_i, A_i) = 0.5, \quad \forall A_i \in \mathrm{A} \quad (8)$$

3.2. Fuzzy satisfaction function

The satisfaction degree of an arithmetic comparison relation of two fuzzy numbers is exploited in constructing of fuzzy preference relation. This degree is calculated by using a fuzzy satisfaction function [11].

In order to find satisfaction degree, it is essential to discrete fuzzy alternative's performances expressed by fuzzy numbers. Fuzzy number A is a fuzzy set defined in the real domain R and its membership function has to fulfill conditions of convexity, normality and continuity on the universes of discourse. In this paper, performances of alternatives are considered to be in a continual form.

The γ resolution set $D_\gamma(A)$ is defined as follows:

$$D_\gamma(A) = \{x \mid x = n\gamma,\ n \in N\} \quad (9)$$

and plays the role of mapping a continuous real domain into a discrete domain whose elements are at g distance intervals (precision).

Discretization is performed on both fuzzy numbers by the same discretization interval for both considered alternatives. This means that different number of intervals is possible for fuzzy numbers depending on their overlap factor and shape.

The values in which is $\mu(x) = 0$ are not excluded (in mapping (Eq. 9), x doesn't belong to a support set of A) as it is done in Lee's work [11]. Therefore the information about left (right) edge of a fuzzy number is preserved and taken into a consideration in below calculation.

The satisfaction degree $\wp(A \Re B)$ for relation $\Re$ (arithmetic comparison relation such as <, >, ≤,...) of fuzzy numbers A and B denotes the degree to which the proposition $A \Re B$ is true:

$$\wp(A \Re B) \in [0,1] \quad (10)$$

(1 represents the full satisfaction (truth), while the degree 0 represents the dissatisfaction (falsity)).

For the purpose of estimating the satisfaction degree, a so-called the satisfaction function is proposed. It represents the ratio of the aggregation of membership degrees of actual values for the region satisfying the comparison relation to the aggregation of membership degrees of actual values for the whole region.

The satisfaction function $S_\gamma(A_i < A_j)$ for the comparison $A_i < A_j$, at g-resolution set is defined as follows ($x \in D_\gamma(A_i)$, $y \in D_\gamma(A_j)$, $D_\gamma(A_i) \neq \phi$, $D_\gamma(A_j) \neq \phi$):

If a fuzzy value A_k is defined in the discrete domain, we take $D_\gamma(A_k) = Supp(A_k)$, regardless of the γ value, and when only one fuzzy value A_k is defined in the discrete domain, we take for the other fuzzy value A_l γ-resolution set $D_\gamma(A_l)$ such that:

$$Supp(A_k \cap A_l) \subseteq D_\gamma(A_l) \tag{11}$$

so the $S_\gamma(A_i < A_j)$ is:

$$S_\gamma(A_i < A_j) = \frac{\sum_{x=I_{\min}}^{I_{\max}} \sum_{y=J_{\min}}^{\min\{x-\gamma, J_{\max}\}} \mu_{A_i}(x) \Theta \mu_{A_j}(y)}{\sum_{x=I_{\min}}^{I_{\max}} \sum_{y=J_{\min}}^{J_{\max}} \mu_{A_i}(x) \Theta \mu_{A_j}(y)} \tag{12}$$

where $I_{\min} = \min D_\gamma(A_i)$, $I_{\max} = \max D_\gamma(A_i)$, holding the condition that $a\Theta b > 0$ if $a > 0$ and $b > 0$ (Θ denotes one of possible different operators on fuzzy sets).

The satisfaction function $S_\gamma(A_i > A_j)$ is defined in similar way, while the equality comparison $S_\gamma(A_i = A_j)$ has the following form:

$$S_\gamma(A_i = A_j) = \frac{\sum_{x=\max\{I_{\min}, J_{\min}\}}^{\min\{I_{\max}, J_{\max}\}} \mu_{Ai}(x) \Theta \mu_{A_j}(y)}{\sum_{x=I_{\min}}^{I_{\max}} \sum_{y=J_{\min}}^{J_{\max}} \mu_{A_i}(x) \Theta \mu_{A_j}(y)} \tag{13}$$

The satisfaction function S_γ has the following properties:

1. $S_\gamma(A_i = A_j) + S_\gamma(A_i < A_j) + S_\gamma(A_i > A_j) = 1$
2. If max $\{D_\gamma(A_i)\}$ < min $\{D_\gamma(A_i)\}$, then $S_\gamma(A_i < A_j) = 1$
3. If $A_i \equiv A_j$, then $S_\gamma(A_i < A_j) = S_\gamma(A_i > A_j)$
4. For any two fuzzy numbers A_i and A_j $0 \leq S_\gamma(A_i < A_j) \leq 1$

($A_i \equiv A_j$) means that the shapes of two fuzzy values are the same (i.e. $\mu_{Ai} = \mu_{Aj}$), while in formula $S_\gamma(A_i = A_j)$ symbol = means that two fuzzy values represent the same actual value i.e. $av(A_i) = av(A_j)$).

From the above, it is clear that the less two fuzzy values are overlapped by each other, the closer the satisfaction degree to 1 or 0.

4. ILLUSTRATION OF FUZZY EXTENSION

The application of an extended AHP method, in this paper, will be presented through the selection of optimum solution for investing in specific alternative (industrial hall), in respect to its acoustic comfort.

Test example consists of a choice of alternatives – industrial halls. Each of them are linguistically expressed, according to the four selected criteria: **1) reverberation time** of industrial hall, **2) permissible noise level** depending on occupational activity, **3) possibility of direct communication** and **4) possibility of indirect communication**.

Hierarchical decomposition of the example is presented on Fig. 1.

Four criteria are linguistically depicted by Fig. 2-5. The shape and position of linguistically terms are chosen in order to illustrate the fuzzy extension of the method.

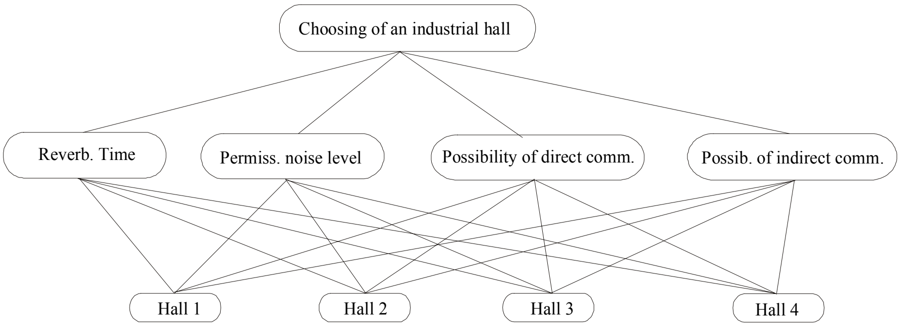

Fig. 1. Hierarchical decomposition of the example

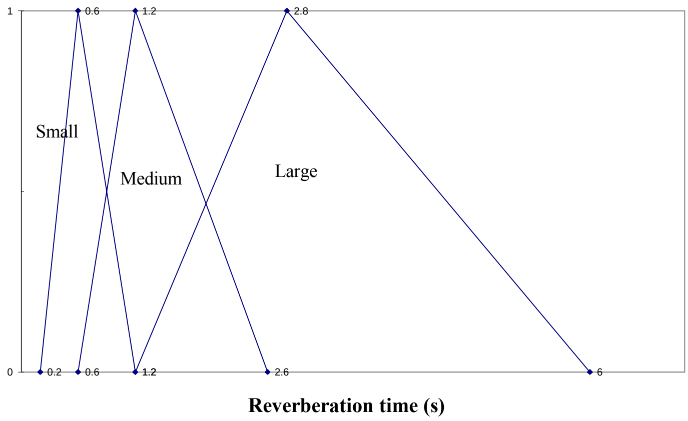

Fig. 2. Reverberation time (s)

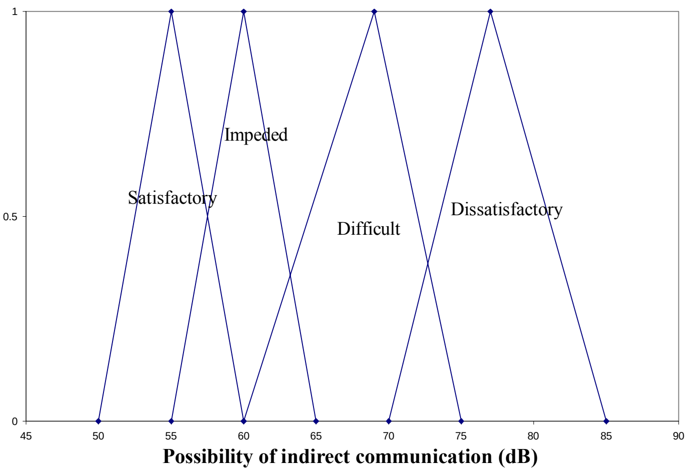

Fig. 3. Possibility of indirect communication (dB)

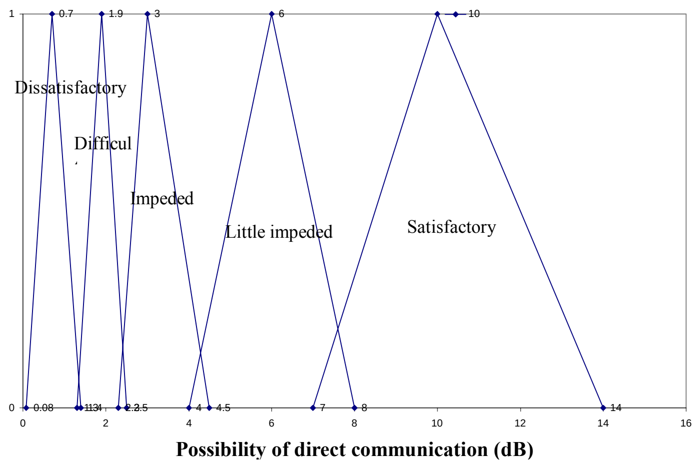

Fig. 4. Possibility of direct communication (dB)

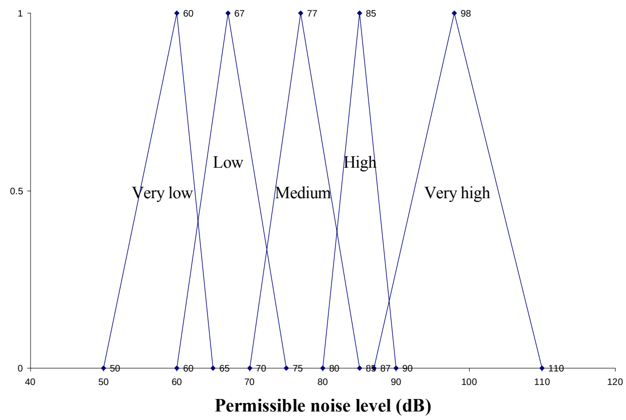

Fig. 5. Permissible noise level (dB)

For all considered alternatives, adequate descriptive marks, according to the accepted criteria, are given in Table 1. Here, a qualitative evaluations of the alternatives in respect to every criterion, individually are given.

Table 1. Qualitative alternative evaluation

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Hall 1	Small	Impeded	Satisfactory	Low
Hall 2	Medium	Difficult	Impeded	Medium
Hall 3	Medium	Dissatisfactory	Dissatisfactory	High
Hall 4	Large	Dissatisfactory	Dissatisfactory	Very high

Mutual criteria evaluation by Saaty's nine points scale is presented by Table 2.

Table 2. Mutual criteria evaluation by Saaty's nine points scale

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Criterion 1	1.000	0.500	0.333	0.250
Criterion 2		1.000	0.500	0.333
Criterion 3			1.000	0.500
Criterion 4				1.000

Fig. 6 shows diagrams of alternative's preference degrees for every criterion. When system parameters are determined, results are obtained by application of extended AHP method. As the optimal solution the alternative **Hall 1** is obtained.

Fig. 6. Results of the calculation

Diagram of alternative's preference degree for criterion 1:
Reverberation time

==================================

A 1 (Hall 1): * .0332
A 2 (Hall 2): ****** .1416
A 3 (Hall 3): ****** .1416
A 4 (Hall 4): ************************* .6834
Diagram of alternative's preference degree for criterion 2:
Permissible noise level depending on occupational activity

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A 1 (Hall 1): * .0311
A 2 (Hall 2): **** .1099
A 3 (Hall 3): ********* .2359
A 4 (Hall 4): ************************* .6228
Diagram of alternative's preference degree for criterion 3:
Possibility of direct communication

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A 1 (Hall 1): * .0325
A 2 (Hall 2): ****** .1433
A 3 (Hall 3): ****** .1433
A 4 (Hall 4): ************************ .6807
Diagram of alternative's preference degree for criterion 4:
Possibility of indirect communication

==================================

A 1 (Hall 1): ****************** .4455
A 2 (Hall 2): ****************** .4557
A 3 (Hall 3): ** .0493
A 4 (Hall 4): ** .0493
Diagram of alternatives preference degree for the global objective
of an overall system

==================================

A 1 (Hall 1): ****** .1464
A 2 (Hall 2): ********* .2142
A 3 (Hall 3): ****** .1602
A 4 (Hall 4): ******************* .4790

The best alternative is the Hall 1.

5. CONCLUSION

Priority defining among alternatives or criteria when a great number of decision makers are involved along with a huge number of criteria in different periods of time, is successfully accomplished by AHP multiple criteria optimization. Fuzzy extension of this method in a manner of linguistically depicted criteria (and attributes of alternatives) which are ranked by fuzzy preference relation, is given in this paper.

The advantage of this method lies in an adaptability to a decision maker in a sense of number of criteria and actions that are simultaneously investigated by a natural, hierarchical decomposition of an overall problem and comparison scale. The possibility of either quantitative or qualitative description of data (criteria) is exploited in this paper. The proposed fuzzy extension is consisted of specific fuzzy depiction of criteria, according to which appropriate alternatives are compared, i.e. ranked.

Experts' estimation of linguistic terms of certain criteria is crucial. More objective way of doing so (knowledge mining, rule discovery and membership functions determination) would probably have an influence on robustness of a system.

Possible further work would consider aggregating of overlapping linguistic terms for certain linguistic variable.

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OPTIMIZACIJA AKUSTIČKOG KOMFORA INDUSTRIJSKE HALE PRIMENOM INTELIGENTNIH TEHNOLOGIJA

Dragan Cvetković, Miloš Manić,
Momir Praščević, Slobodan Milutinović

Problemu optimizacije akustičkog komfora do sada je pristupano na tradicionalan način putem klasičnih numeričkih metoda. Autori ovoga rada predložili su novi metod, uvodeći inteligetne tehnologije, konkretno fazi logiku. Predloženi metod zasniva se na fazi proširenju Saatyjevog AHP višekriterijumske optimizacije, i primenjen je na optimizaciju akustičkog komfora industrijske hale. Test primer ilustrovan je dijagramima i tabelama, dobijenih na osnovu softvera autora.