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ESTIMATING THE NOISE-INDUCED HEARING LOSSES UNDER FUZZY ENVIRONMENT

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Open-pit mining,
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Fuzzy inference system

Abstract

Noise causes many negative effects both in our daily life and working life, reduces our quality of life, and affects our mental health directly or indirectly. The most common consequence of noise exposure is especially permanent hearing loss called noise-induced hearing loss (NIHL). NIHL is very prevalent in almost every stage of the mining industry. Therefore, the assessment of noise levels of mining operations and the estimation of NIHLs of employees is an important issue to prevent and minimize them. This study is aimed to the modeling of NIHL prediction at a quarry located in Aksaray, Turkey. Initially, noise levels were measured with a sound level meter for employees working in different positions for the quarry, and daily exposure levels ($L_{ex,8h}$) were determined. Audiometry tests were also performed on all employees and NIHLs were evaluated and determined by an audiometrist. According to the results, 5 employees had NIHL in this enterprise. A fuzzy inference system (FIS)-based NIHL estimating model implemented on fuzzy logic using the Sugeno inference mechanism was developed. The model predicts NIHLs for given occupation, age, experience, and $L_{ex,8h}$ parameters. To determine the accurate prediction ability of the model, field noise measurements and audiometry test results data were used. The obtained results indicated that the model has accurate a prediction ability with a 94% success rate. This study proposes a method with high predictive ability using fuzzy sets theory, and will be a guide for the top management in considering the damage effects of noise in enterprises.

BULANIK ORTAMDA GÜRÜLTÜYE BAĞLI İŞİTME KAYIPLARININ TAHMİN EDİLMESİ

Anahtar Kelimeler

Açık işletme madenciliği,
Gürültüye bağlı işitme kaybı,
Bulanık mantık,
Bulanık çıkarım sistemi

Öz

Gürültü, hem günlük yaşamımızda, hem de çalışma hayatımızda birçok olumsuz etkilere neden olmakta, yaşam kalitemizi düşürmekte ve ruh sağlığımızı doğrudan veya dolaylı yoldan etkilemektedir. Gürültüye maruz kalmanın en yaygın sonucu, özellikle gürültüye bağlı işitme kaybı adı verilen kalıcı işitme kaybıdır. Gürültüye bağlı işitme kaybı madencilik sektörünün hemen her aşamasında çok yaygındır. Bu nedenle, maden işletmelerinde gürültü düzeylerinin değerlendirilmesi ve çalışanların gürültüye bağlı işitme kayıplarının tahmini, bunların önlenmesi ve en aza indirilmesi için önemli bir konudur. Bu çalışma, Türkiye'de Aksaray ilinde bulunan bir taş ocağında gürültüye bağlı işitme kaybının tahmininin modellenmesini amaçlamaktadır. Başlangıçta taş ocağı için farklı pozisyonlarda çalışan işçiler için gürültü ölçüm cihazı ile gürültü ölçümleri yapılmış ve günlük gürültü maruziyetleri ($L_{ex,8h}$) belirlenmiştir. Ayrıca tüm çalışanlara odyometrik testler uygulanmış ve gürültüye bağlı işitme kayıpları bir odyometrist ile birlikte değerlendirilmiş ve belirlenmiştir. Sonuçlara göre, bu işletmede 5 çalışanda gürültüye bağlı işitme kaybı mevcuttur. Sugeno çıkarım mekanizmasıyla bulanık mantık üzerinde uygulanan bir bulanık çıkarım sistemi tabanlı gürültüye bağlı işitme kaybı tahmin modeli geliştirilmiştir. Model, verilen meslek, yaş, deneyim ve $L_{ex,8h}$ parametrelerini kullanarak gürültüye bağlı işitme kayıplarını tahmin etmektedir. Modelin doğru tahmin yeteneğini belirleyebilmek için, sahadaki gürültü ölçümleri ve odyometrik test sonuçları verileri kullanılmıştır. Elde edilen sonuçlar, modelin %94 başarı oranı ile doğru tahmin yeteneğine sahip olduğunu göstermiştir. Bu çalışma, bulanık kümeler teorisini kullanarak doğru tahmin yeteneği yüksek bir yöntem önermektedir ve işletmelerde gürültünün olumsuz etkilerini dikkate almada üst yönetim için bir rehber olacaktır.

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1. Introduction

Nowadays, developing technology has negative aspects compared to many positive developments brought to our lives. One of the most important hazards that exerts occupational disease in the mining industry is noise (Önder, 2018). Large-size mining machines with high technology in opencast coal mines operate with high noise level. This situation can cause a temporary or permanent noise-induced hearing loss (NIHL) on mine employees.

Sound is defined as a physical phenomenon which is the pressure changes that ear can perceive caused by fluctuations in the air pressure of a vibrating source. On the other side, noise is defined as unwanted and unpleasant sounds. NIHL is the most common occupational disease in the EU (EU–OSHA, 2002).

A high level of noise in the working environment prevents communication between mine workers and causes an unfavorable working environment. Noise may also result in different a type of physical, physiological, work-related stress and, psychological effects on the workers. The most common consequence of noise exposure is especially permanent hearing loss called NIHL.

Noise levels that exceeding 89 dB(A) can cause NIHL and also working at high noise levels increase occupational accidents (Picard, Girard, Simard, Larocque, Leroux and Turcotte, 2008; Önder and İbrahimoğlu, 2021).

According to DIRECTIVE 89/391/EEC, noise exposure level $L_{ex,8h}$ defined as a-weighted equivalent sound pressure level for A during a working day. Noise parameters were defined as lower exposure action value $L_{ex,8h}$ (dB(A))=80 dB(A); upper exposure action value $L_{ex,8h}$ (dB(A))=85 dB(A) and exposure limit value $L_{ex,8h}$ (dB(A))=87 dB(A) according to EU-Directive 2003/10/EC. In Turkey, the same lowest, highest exposure action levels and exposure limit levels were accepted considering this directive (Official Gazette, 2013).

Since the reasons of NIHLs of mine employees is a kind of complex and uncertain phenomenon, there is a need flexible and consistent methods to can cope with it. A FIS based fuzzy logic method is one of the most popular artificial intelligence soft computing tools in almost all engineering research areas. This method can give more realistic results easily and with a higher success rate of accurate prediction than other methods including complexity and uncertainty. Thus, a FIS based fuzzy logic method was used to the modeling of NIHL prediction in this study.

2. Literature Review

When the literature is examined, several studies have been done for NIHL in the mining sector. McBride (2004) reviewed current best practices in NIHL prevention and emphasized essential of audiometric monitoring in the working environment of mining. According to this study, the pure tone audio diagram method is still the method of choice and the researcher also made attention to the fact that only a little work has been done about NIHL in the last 10 years. In another study, Sensogut and Cinar (2007) measured in total 95,000 noise levels in different panels of Western Lignite Corporation (WLC), Turkey. The obtained data were used to investigate noise propagation. Onder, Onder and Mutlu (2012) evaluated the factors affecting NIHL by using the hierarchical loglinear technique. The data set was categorized by occupation, age, experience, dB(A) noise level, and having NIHL on miners. According to the noise measurements and hearing tests on employees at a quarry and stone crushing-screening plant in Bilecik-Turkey, drivers in the 46-54 age group have a high probability of exposure to 70-79 dB(A) noise levels, and 4-11 years of experienced crusher employees were more prone to having NIHL due to exposing high noise levels as 90-99 dB(A). Chadambuka, Mususa and Muteti (2013) researched NIHL on employees at a major underground mine located in Zimbabwe-Africa. From the audiometric test results of 169 mine employees, 62 employees of this mine had NIHL. They stated that employees in plant engineering, plant processing, and underground workshop were exposed to hazardous noise level. Cinar and Sensogut (2013) have conducted noise measurements in 4 different mining sites located in Turkey. They also have conducted surveys on a total of 126 employees to define how much they are disturbed by the occupational noise. According to the results of surveys and noise level measurements, employees should be encouraged to use personal protective equipment (PPE) like earmuffs and plugs by researchers. Moroe, Khoza-Shangase, Kanji, and Ntlhakana (2018) investigated trends in the management of occupational NIHL in the African mining industry between 1994 to 2016 years. They emphasized that, need for more studies on the management of NIHL in the mining sector.

The fuzzy logic method is also used in similar studies for predicting and evaluating NIHL in the mining sector up to now. Nanda, Tripathy and Patra (2009) developed FIS-based noise prediction models for predicting far-field noise levels because of the operation of a specific set of mining machinery. Researchers stated that the Sugeno and Kang (TS) fuzzy model gives better results in predicting NIHLs than the Mamdani fuzzy model. Nanda and Tripathy (2007); Nanda, Tripathy and Patra (2008) used Sugeno and Kang (TS) and Mamdani fuzzy models to investigate field surveys of the United States Environmental Protection Agency (EPA) and National Institute for Occupational Safety & Health (NIOSH) results. Researchers predicted almost similar results in both models.

In this study, noise measurements were conducted with MASTECH MS6300 Multi-Functional Sound Level Meter and hearing loss tests were carried out for all employees in the enterprise. The FIS model was used on the fuzzy logic toolbox of the MATLAB environment to achieve the NIHL predicting purpose. The developed NIHL predicting fuzzy model has four inputs as; occupation of employee, age of employee, experience of employee, noise exposure level of employee ($L_{ex,8h}$ (dB(A))); one output as NIHL test result of the employee. The fuzzy model was developed in six steps: (1) identification of input and output variables, (2) determination of the ranges of input and output variables, (3) fuzzing of input and output parameters (selecting the fuzzy class intervals) (4) designing a FIS model, (5) constructing if-then rules (relationships between inputs and output) and (6) choosing a suitable defuzzification procedure. Since this method used in the study used less in literature, this study may also lead to different future studies.

3. Fuzzy Logic Methodology

The fuzzy logic method was designed by Zadeh in 1965, firstly. FIS is a soft computing technique is suitable for subjective judgment and qualitative evaluation in dealing with processes of decision-making problems (Mutlu and Sarı, 2017; Mutlu, 2019). FIS based on digitizing human thoughts and judgments using membership degrees or functions and can be defined as strong tools to simulate nonlinear behaviors by employing linguistic fuzzy rules (Kuşan, Aytekin and Özdemir, 2010; Kurşunoğlu, 2022). FISs are recently more popular tools and have gained popularity for solving engineering issues because of their unique ability to predicting in difficult complex events (Razani, Yazdani-Chamzini and Yakhchali, 2013). In a classical set, an element is expressed as either belonging to a set or does not belong to a set. A third case is impossible, but such situations are often described as a paradox. Zadeh (1965) defined a fuzzy set as a class of objects with degrees of membership in a continuous array. In classical sets, the membership function can take the value 0 or 1, in fuzzy sets, the membership function takes a value in the closed range [0,1]. This case shows its flexibility in linguistic expressions, whereas in the crisp set each element takes a membership value of zero or one ($\mu \in \{0,1\}$) (Yes, No condition), and the μ_F function is expressed by the following equation (Danish and Onder, 2020):

$$\mu_A(x) = \begin{cases} 1 \; if \; x \in F \\ 0 \; if \; x \notin F \end{cases} \tag{1}$$

where A is crisp set and μ_A is membership of an element x in the crisp set A.

$$A = \{x, \mu_A(x) | x \in U\} \tag{2}$$

where U refers to the discourse universe defined for a particular problem; and μ_A is the membership degree of the variable x is described as;

$$x(\mu_A(x) \rightarrow [0,1]) \tag{3}$$

According to the mathematical expression of fuzzy logic (Equation 3), if $\mu_A(x) = 0$, x does not belong to A; otherwise $\mu_A(x) = 0$, Indicates that x is a member of A. $\mu_A(x) = 0.5$ value is the transition point of fuzzy set A. Concluding given values from the classical set is called fuzzification. In fuzzy systems, the decision and conclusion are possible with the if-then rule produced because inputs in fuzzy systems consist of more than two variables. The results obtained in fuzzy systems are interpreted with these rules and reached a new result. So, the construction of if-then rules based on expert knowledge and experience to achieve the purpose is the most important part of designing FIS. Membership degrees at the entrance determine the validity of the results and there is an implication logic in this determination. By combining the results obtained from institutions, aggregation is obtained, this is called the FIS engine. All these operations are shown visually in Figure 1.

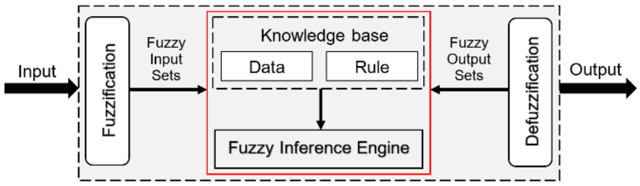

Figure 1. Structure of FIS

In the MATLAB environment, there are many types of membership functions are defined. The form of membership function of fuzzy sets can be linear (triangular or trapezoidal) or various non-linear forms depending on the goal (Acaroglu, Ozdemir and Asbury, 2008). These functions can describe as Equations (4-7) (Nanda et al., 2009). In this study, triangular and sometimes trapezoidal membership function of fuzzy sets were used.

$$Triangular\ (x; a, b, c) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{cases} \tag{4}$$

$$Triangular\ (x; a, b, c) = \left(\max(min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \tag{5}$$

$$Trapezoidal\ (x; a, b, c, d) = \begin{cases} 0, & x \leq a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \dfrac{d-x}{d-c}, & c \leq x \leq d \\ 0, & d \leq x \end{cases} \quad (6)$$

$$Trapezoidal\ (x; a, b, c, d) = max\left(min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right) \quad (7)$$

here a, b, c, d are the parameters of the linguistic value and x is the range of the input parameters. In the applications, there are mainly three applications based on linguistic rules, namely, the Mamdani systems, Sugeno or Takagi, Sugeno and Kang (TS) models, and Tsukamoto models (Mamdani and Assilian, 1975; Takagi and Sugeno, 1985; Sugeno and Kang, 1988). The differences between these FISs are in the consequents of their fuzzy rules, aggregation, and defuzzification. TS model is especially suitable for mathematical analysis, and is the calculation and gives exact numerical results (Takagi and Sugeno, 1985). A typical fuzzy rule is presented in Equation 8. Also, the functioning and mathematical system of the Sugeno inference systems are demonstrated in Figure 2.

$$TS: If\ X_1 is A_{i1} and A_{i2}\ THEN\ Y\ is\ Y = f(a, b) \quad (8)$$

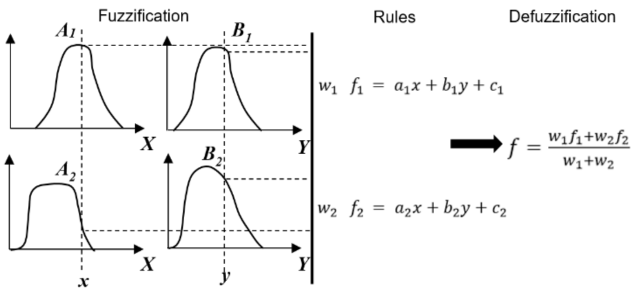

Figure 2. Sugeno FIS System (Jang, 1997)

x and y input values specified in Figure 2 and the sample rule, A and B denote fuzzy sets for x and y inputs. The rules are the coefficient a, b, and c (can be obtained by the least-squares method) and w d the degree of membership. In the defuzzification phase, results are generally obtained by using the weighted average method.

The reason why Sugeno inference system has been preferred in this study is that the structure of the Sugeno inference system is more flexible and against possible future changes in model, the complex defuzzification process in the Mamdani inference system is not present in the Sugeno inference system, and the Sugeno inference system is more suitable for functional analysis than the Mamdani inference system due to its simple rule outputs (Sylaios, Gitsakis, Koutroumanidis, and Tsihrintzis, 2008; Razani et al., 2013). Apart from these reasons, in this study the data type is suitable for Sugeno inference system and also researchers stated that the Sugeno fuzzy inference system gives better results for predicting NIHLs (Nanda et al., 2009).

4. Application Study

The increasing demand for raw materials in the construction and building sector, which is due to the fact that the building stock is not sufficient with the population increase in the cities, this causes the number of stone quarries to increase gradually in parallel with the needs of the sector (Mutlu and Kalkan, 2023). According to the current mine production data of the General Directorate of Mining and Petroleum Affairs (MAPEG), cement and construction raw materials constitute the main minerals needed in the sector (MAPEG, 2022).

The stone quarry (limestone) enterprise selected for the study produces with open-pit production method and is located in the eastern part of Aksaray province in the Central Anatolian Region of Turkey. The location map of the quarry is given in Figure 3. There is also a crushing-screening plant in the enterprise, and the annual production is approximately 550,000 tons. However, this planned production amount may vary depending on the increase or decrease in demand. Production activities is planned for this open-pit mine in the current license area for about 10 years. There are currently 19 employees working in different positions.

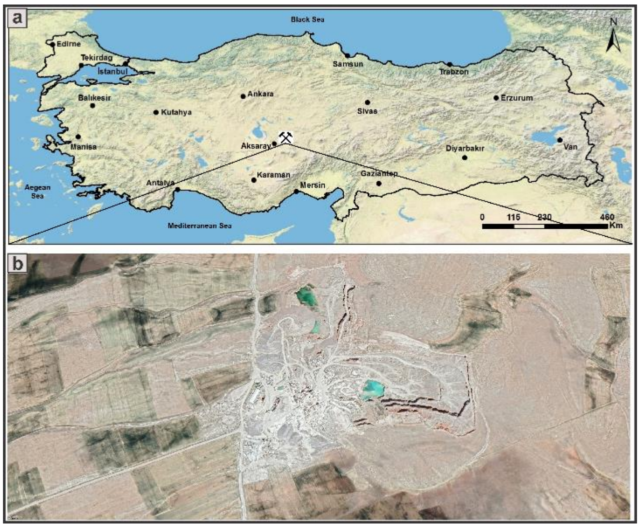

Figure 3. Location Map of the Study Area

The production phase consists of drilling the holes, producing run-of-mine ore by detonating the explosives placed in the drilled holes, in order to reduce run-of-mine ore with crusher excavators, and loading the crushed ore on trucks with excavators and sending it to the crushing-screening plant (Figure 4). Run-of-mine ore feed to the jaw crusher and re-sized in this plant.

While the +22 mm ore crushed in the impact crusher returns to the crusher, the limestone under the screen is classified into 0-4, 4-12 and 12-22 mm dimensions. Sizing process can also change depending to customer demands and supplied to the market.

Figure 4. Production in the Open-Pit Quarry

4.1. Measurement Methodology and Audiometry Tests

Within the occupational health and safety law in Turkey, Regulation on Protection of Employees from Noise-Induced Risks, the determination of noise exposure levels of all employees is a legal requirement (Official Gazette, 2013). In such studies carried out in today's modern world, the trend of a standardization expectation is increasing day by day (Önder and İbrahimoğlu, 2021). TS ISO 1999 standard, which was developed for the estimation of hearing loss caused by noise in the workplace, was also published in 2013 firstly to estimate the probability of employees experiencing hearing loss and it has taken TS 2607 ISO 1999 standard's place in 2020 again.

In order to measure the noise level of the different environments where 19 employees work, noise levels were measured by using "MASTECH MS6300 Multi-Functional Sound Level Meter" (Figure 5(a)). All noise measurements were made according to TS EN ISO 9612 "Measurement of Noise Exposure in Acoustic Working Environment and Principles for Evaluation" standard. Measurements were made based on task as in the TS EN ISO 9612 standard. Each measurement was made for at least 5 minutes. Also it is stated in the standard that at least 3 measurements should be made for each task (Figure 5 (b)) In this study, in order to create a more representative the FIS-based noise prediction model, 6 noise measurements were made for each task.

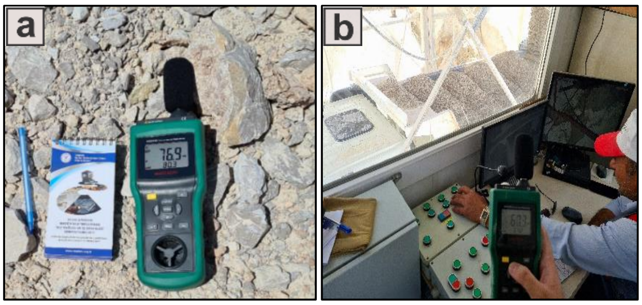

Figure 5. (a) MASTECH MS6300 Multi-Functional Sound Level Meter, (b) Sound Level Measurements in the Quarry Operations

For the accuracy and reliability of the measurements, the days when weather is windless and the temperature is optimum were preferred. There is no electrostatic and magnetic field that might affect the calibration of the device in the working environment. There was no one other than the expert who makes the noise level measurement and the personnel working in the environment. All measurements were made at the operators' and employees in the enterprise at ear position where there is most exposed to noise (Çalış, 2022). Equation 9 is used when converting the measured different noise levels to equivalent noise levels L_{eq} (Pathak, 1996; Şensöğüt and Çınar, 2006; Cinar and Sensogut, 2009).

$$L_{eq} = 10\log\left((1/n)\left(10^{L_1/10} + 10^{L_2/10} + \cdots + 10^{L_n/10}\right)\right) \quad (9)$$

where n means the number of noise measurements in the enterprise, $L_1 - L_n$ means the noise measured values dB(A) and L_{eq} means the measure equivalent noise level dB(A) (the average sound level for a certain period of time) (Cinar and Sensogut, 2013). Daily (8h) exposure noise level ($L_{ex,8h}$ (dB(A))) can be calculate by using Equation 10 (TS 2607 ISO 1999, 2005; Erol, 2022a).

$$L_{ex,8h} = L_{eq} + 10\log\frac{T_e}{T_o} \quad (10)$$

Where L_{eq} means equivalent noise level dB(A), T_e means active exposure on the working day period (hour) and T_o means reference exposure period (=8 hours).

Furthermore, audiometric tests (hearing tests) applied for all employees in the enterprise by hearing test center (Figure 6). Thus, the effect of the noise level in the working environment of the employees hearing functions were investigated.

The pure tone diagram method was used to determine hearing losses for left and right ears (Onder et al., 2012). Measured noise levels and audiometric test results of employees are given together in Table 1.

According to Table 1, 5 employees had NIHL in this enterprise. The average age was computed as 39.11 and the average experience was computed as 11.37 years approximately among employees. On the other hand, these employees commonly over 75.20 dB(A) daily sound level in different working areas.

Figure 6. Application of Audiometry Test for Employees

Table 1. Measured Noise Levels and Audiometric Test Results of Employees

Employee No	Occupation	Age (years)	Experience (years)	L_{eq} (dB(A))	$L_{ex,8h}$ (dB(A))	NIHL (Yes/No)
1	Worksite Chief	28	5	57.7	57.2	No
2	Driver	53	7	81.3	80.7	No
3	Driver	46	10	79.6	79.0	No
4	Driver	45	8	80.8	80.2	No
5	Driver	48	13	82.2	81.6	No
6	Driver	32	11	84.1	83.5	Yes
7	Mining Machine Operator	25	6	74.4	73.9	No
8	Mining Machine Operator	32	8	77.8	77.2	No
9	Mining Machine Operator	51	25	91.6	91.0	Yes
10	Drilling Operator	32	12	87.1	84.1	Yes
11	Crusher Worker	53	24	94.8	94.2	Yes
12	Crusher Worker	47	22	94.8	94.2	Yes
13	Technical Personnel	41	17	76.4	75.2	No
14	Technical Personnel	30	9	76.4	75.2	No
15	Technical Personnel	58	12	76.4	75.2	No
16	Weigher	22	2	59.9	59.4	No
17	Weigher	26	2	59.9	59.4	No
18	Cook	39	15	58.5	57.9	No
19	Office Worker	35	8	50.3	49.7	No

4.2. Designing the Fuzzy Inference System and Predicting Noise-Induced Hearing Losses

To examine the NIHL within the scope of this study by examining previous studies in the literature, the variables were determined such as occupation, age, experience, daily exposure level ($L_{ex,8h}$) (Fişne, 2008; Mutlu, 2010; Onder et al., 2012; Önder, 2018; Erol, 2022b; Onder, Iroz and Onder, 2022;) The main structure of the hearing loss prediction FIS model is established in Figure 7. According to Figure 7, NIHL is a mathematical function of occupation, age, experience, $L_{ex,8h}$ dB(A) in this study. In this model, input variables and output variables are linguistic variables that are described as words or sentences in a natural or synthetic language.

The occupation input variable, and hearing loss prediction output variable are coded to the FIS model. Table 2 presented these linguistic variable descriptions and fuzzy class intervals used in the FIS model. Worksite chief, cook and office worker occupation groups employees were excluded from this model because the measured noise levels in their working environment is very low. And, ranges of input variables have been determined by taking into account the maximum and minimum limits of the measured noise levels. Thus, the first three steps called (1) identification of input and output variables, (2) determination of the ranges of input and output variables and (3) fuzzing of input and output parameters (selecting of the fuzzy class intervals)) of designing the hearing loss prediction FIS model have been completed.

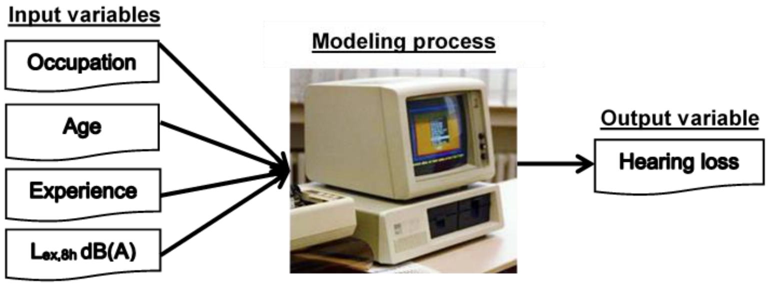

Figure 7. The Main Structure of Hearing Loss Prediction FIS Model

Table 2. Input and Output Linguistic Variables and Fuzzy Class Intervals Used in the FIS Model

Linguistic Variable Type	Linguistic Variable	Linguistic Variable Descriptions	Coding or Description of Linguistic Variable	Fuzzy Class Intervals
Output	NIHL	Noise-Induced Hearing Loss	0 = No 1 = Yes	0 1
Input	$X_{\text{occupation}}$	Occupation	1 = Driver 2= Mining Machine Operator 3 = Drilling Operator 4 = Crusher Worker 5= Technical Personnel 6= Weigher	[1, 1, 2] [1, 2, 3] [2, 3, 4] [3, 4, 5] [4, 5, 6] [5, 6, 6]
	$X_{\text{age(years)}}$	Age (years)	Young Age Middle Age Elderly Age	[22, 22, 30, 34] [30, 34, 44] [34, 44, 58, 58]
	$X_{\text{experience(years)}}$	Experience (years)	Low Medium High	[1, 1, 10, 15] [10, 15, 20] [15, 20, 25, 25]
	$L_{ex,8h}$dB(A)	Daily (8h) Exposure level dB(A)	Low Moderate High	[59.4, 59.4, 70, 80] [70, 80, 85] [80, 85, 94.2, 94.2]

Occupation categories have six categories as driver, mining machine operator, drilling operator, crusher worker, technical personnel and weigher. The age variable has four categories as young age, middle age, and elderly age (EUROSTAT, 2001; Dyussenbayev, 2017). Experience of employees' variable has three categories as low experienced, medium experienced, and high experienced. And lastly, the daily exposure level variable has four categories as low, moderate, and high (Table 2).

In the fourth step of FIS designing, Sugeno fuzzy algorithm was employed in the fuzzing process. In the literature, it was seen that triangular fuzzy sets and sometimes trapezoidal membership functions were chosen as a suitable membership function. According to Table 2, input and output variables have been defined in the FIS-based NIHL prediction model.

Fuzzy modeling was carried out under MATLAB environment. The main structure of the FIS-based NIHL prediction is shown in Figure 7, before. Also, the membership functions for occupation, age, experience, daily exposure level input parameters are shown in Figure 8 respectively. Due to their easy application and simplicity in soft computing, triangular membership functions (TMFs) and trapezoidal shape membership functions are applied in practice extensively.

Finally, in the last two steps of designing the FIS process, the if-then rules stage is the most critical. For this purpose, in total 162 (6x3x3x3) fuzzy if-then rules for predicting NIHL were entered into the model cautiously. Samples of the first 12 if-then rules for the FIS model are illustrated in Figure 9.

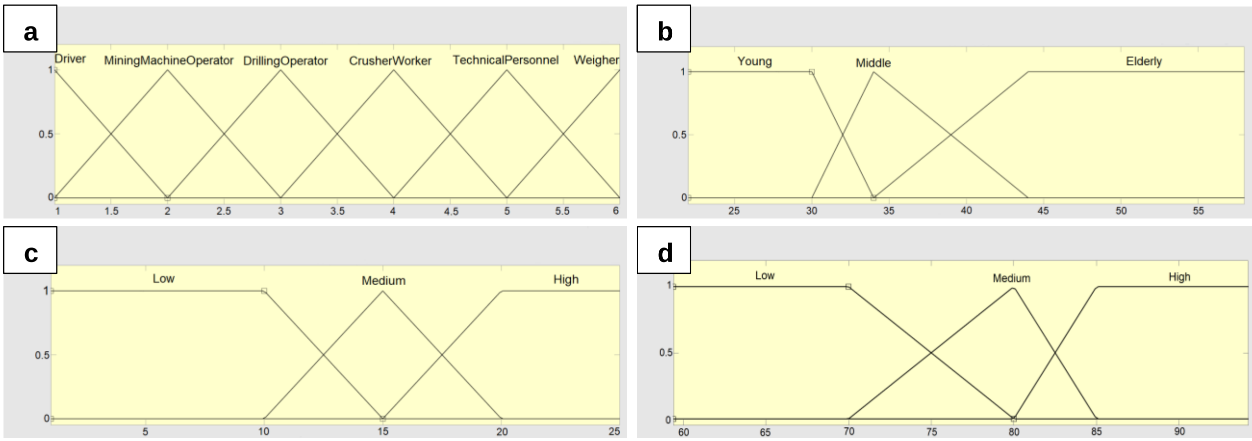

Figure 8. (a) Membership Functions of $X_{occupation}$, (b) Membership Functions of $X_{age(years)}$, (c) Membership Functions of $X_{experience(years)}$, (d) Membership Functions of $X_{Lex,8h}$ dB(A)

After forming the initial FIS structure, the NIHL predicting training step is accomplished, the FIS model was checked with real noise level measurements and audiometric tests results of employees. For employee whose input parameters are as: occupation = 3 (drilling operator), age = 32, experience = 12 years, and $L_{ex,8h}$= 84.1 dB(A); the output predicted as 0.82. For this prediction, this employee will have occupational NIHL (Figure 10).

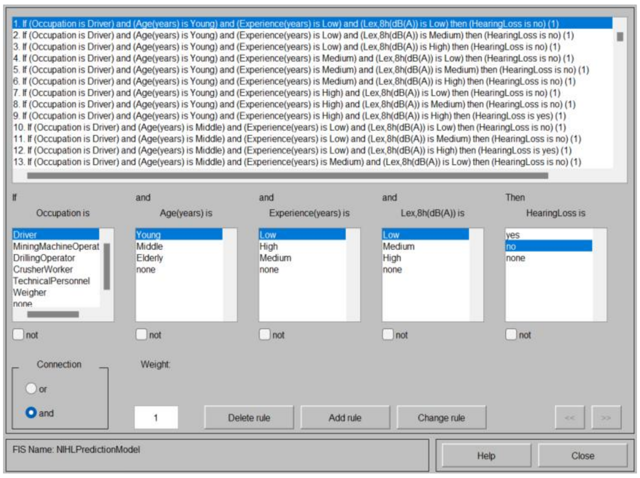

Figure 9. A Sample of If-Then Rules Generated for the FIS Model

Figure 10. Graphical Indication of Fuzzy Reasoning Mechanism for the NIHL Predicting Model

5. Results and Discussion

The interdependency of input and output parameters obtained from the if-then rules are shown by using the control surface plot views are depicted in Figure 11. Figure 11 (a) demonstrates the interdependency of hearing loss on occupation and age, Figure 11 (b) demonstrates the inter dependency of hearing loss on occupation and experience, Figure 11 (c) demonstrates the interdependency of hearing loss on occupation and $L_{ex,8h}$, Figure 11 (d) demonstrates the interdependency of hearing loss on age and experience, Figure 11 (e) demonstrate the interdependency of hearing loss on age and $L_{ex,8h}$, and Figure 11 (f) demonstrate the interdependency of hearing loss on experience and $L_{ex,8h}$. To check performance and effectiveness of the developed FIS based fuzzy logic NIHL prediction model, field noise measurements and audiometry test results of employees were entered to the model. The comparison of real results and predicted fuzzy results were given in Table 3 together.

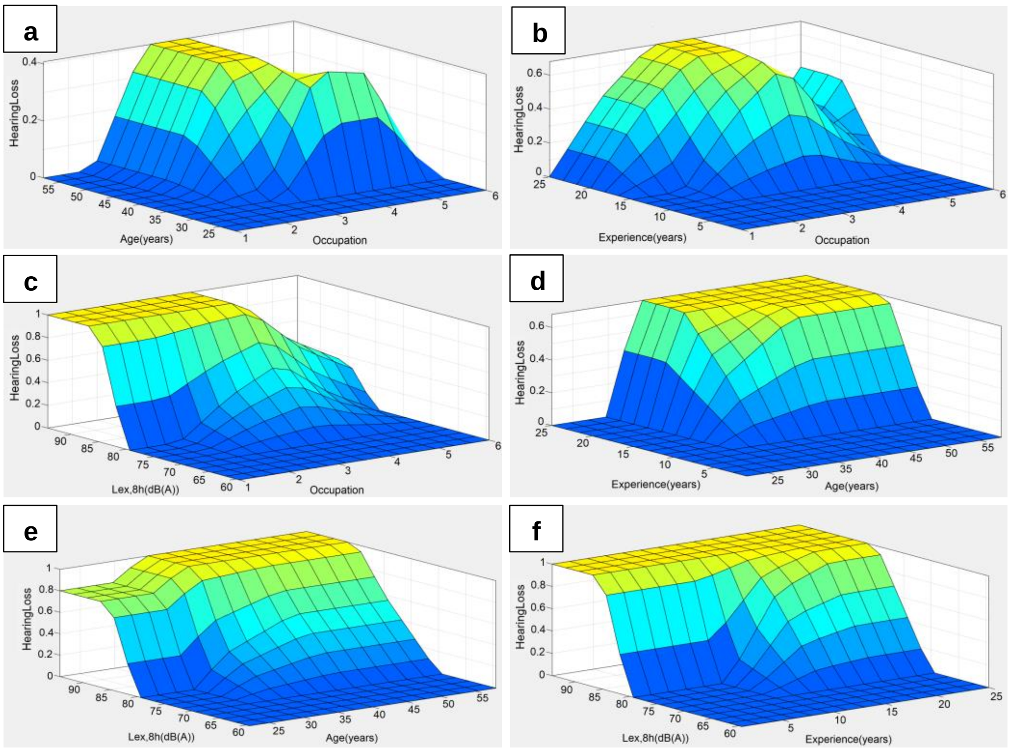

Figure 11. Surface Plot Views of Sugeno for the NIHL Predicting Model

Table 3. Comparison of the Real Audiometric Test Results and Fuzzy Logic Model Predictions

Inputs				Outputs	
Occupation Category Code	Age (years)	Experience (years)	$L_{ex,8h}$ (dB(A))	Audiometric Test Results	Fuzzy Logic Model Predictions
1	53	7	80.7	No	No (0.14)
1	46	10	79.0	No	No (0.00)
1	45	8	80.2	No	No (0.04)
1	48	13	81.6	No	No (0.32)
1	32	11	83.5	Yes	No (0.35)
2	25	6	73.9	No	No (0.00)
2	32	8	77.2	No	No (0.00)
2	51	25	91.0	Yes	Yes (1.00)
3	32	12	84.1	Yes	Yes (0.82)
4	53	24	94.2	Yes	Yes (1.00)
4	47	22	94.2	Yes	Yes (1.00)
5	41	17	75.2	No	No (0.09)
5	30	9	75.2	No	No (0.00)
5	58	12	75.2	No	No (0.00)
6	22	2	59.4	No	No (0.00)
6	26	2	59.4	No	No (0.00)

According to Table 3, the proposed FIS based fuzzy logic NIHL prediction model was used to predict the NIHLs of employees in this enterprise. When the fuzzy logic model prediction result is computed as ≥ 0.5, that employee will likely has NIHL (this result indicated as "Yes"), otherwise not (< 0.5) (this result indicated as "No"). As seen from this table, NIHLs of all employees in this enterprise have been correctly estimated, except for only one employee whose input parameters are as: occupation = 1 (driver), age = 32, experience = 11 years, and $L_{ex,8h}$= 83.5 dB(A). The obtained results indicated that the model has accurate prediction with a 94% success rate. This computed success rate shows that, the constructed FIS based fuzzy logic NIHL prediction model can predict the NIHLs of employees in this enterprise easily and effectively under fuzziness and ambiguity. And this model can be developing by adding new input parameters and chancing the fuzzy class intervals range limits according to working conditions. It can be said that, such soft computing techniques like fuzzy logic has predicting ability in complex phenomena, as in this paper, and can cope with engineering problems in easy way including complexity and uncertainty.

6. Conclusions

This paper describes a method of estimating NIHL of employees using fuzzy sets theory. A FIS-based NIHL estimating model has been considered as a function of occupation, age, experience, and daily exposure level ($L_{ex,8h}$dB(A)) was established.

The developed fuzzy model was constructed based on the Sugeno inference mechanism, and TMFs were usually chosen but sometimes trapezoidal membership functions were also preferred as an appropriate membership function in this study. According to the results, employees in crusher worker, drilling operator and mining machine operator occupational groups are more likely to be exposed to occupational NIHL in this enterprise. Having occupational NIHL age was computed as 43 and the average experience was computed as 18.8 years approximately among employees. On the other hand, these employees commonly over 83.5 dB(A) daily sound level in working areas. To check and validate the accuracy of the NIHL prediction FIS model, real measurement and audiometric tests results of employees were used and NIHLs have been predicted correctly with 94% success rate.

If it is not possible to eliminate, reduce, or control the noise at their source, it is necessary to protect the employees away from noise by encouraging the use of PPEs. Considering the measurement results, it is mandatory to use PPE for employees in the risk group in this enterprise. Employees should be trained and encouraged in the regular use of PPE. Another measure that can be taken against NIHL in the enterprise may be the provision of insulated equipment that will minimize the noise while providing the PPS in the new subcontractor employment contract. With a good work organization, the working hours of the employees can be adjusted according to the noise level in the workplace, and the employees can be prevented from getting temporary or permanent NIHL by taking a break for an appropriate period of time. Also, noise maps drawn according to the measurement results of noise sources should be updated periodically.

The established model can be further enriched by adding the new measurement results over time. The advantage of the fuzzy model is that human judgment and intuition can be effectively used for NIHL predicting, which helps field applications. Using similar methods, enterprises can take important steps toward predicting and reducing the NIHL that may occur in their employees. This study will guide the application of the fuzzy-based system by the company managers and occupational and safety experts and provide new approaches and methodologies as the fuzzy system has enough flexibility in specific cases.

Contribution of Researchers

The author contributed to the publication with the conceptualization, literature review, methodology, field measurements and investigation, software, writing - original draft, writing – review & editing, supervision, formal analysis and visualization.

Conflict of Interest

No conflict of interest was declared by the author. This study complies with scientific research and publication ethics and principles.

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