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RESEARCH ARTICLE Open Access

Assessment of Noise Exposure of Workers in Industrial Environments using the Bowtie and DEA Approach

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Abstract
Sound waves are one of the essential factors of daily life and work activities that can cause environmental pollution in the necessary contact between humans and the surrounding world. Noise pollution is reported to be amongst the leading causes of occupational diseases and the second leading cause of occupational injuries in the workplace. A variety of equipment, machines, and work processes are used in industry that are considered sources of disturbing noise. The aim of this study is to assess the noise exposure of workers in industrial environments using the Bowtie approach and Data Envelope Analysis (DEA). The motivation of the research is the multidimensional nature of the concept of noise exposure from the perspective of the exposure situation and the capability of DEA models to evaluate the efficiency of stations based on multiple inputs and outputs. This study uses a quantitative approach. The research method is descriptive cross-sectional. In this research, a case study was conducted to evaluate 10 stations of a company in the industrial area in the first half of 2023. The Bowtie approach was used to determine the correlation between noise exposure and its consequences. The collection of noise exposure measurement data enables the mathematical modeling of the BCC input based on the DEA approach using the EMS software, where the input of the model is the "equivalent sound level" and the output of the model is the "noise pollution situation". The results show the different efficiencies of the 10 stations investigated and the superiority of station 7 compared to the other stations. In the industrial area studied, 30% of the total measuring stations were located in the risk range. The average sound pressure level was estimated at 101.70 dB. It seems that companies can effectively improve the health of their employees in the workplace by directing their activities within the permissible range of noise exposure. The efficiency of measuring stations plays a constructive role in reducing exposure and improving the health of employees in the workplace.
Keywords: *Noise exposure, Industrial environment, Bowtie approach, DEA*

Introduction

Employees working in different industrial environments are constantly confronted with various environmental factors. Environmental factors such as "heat, vibration, cold, humidity, lighting, noise, etc." are among the biggest threats to employee efficiency and can have a negative impact on employee health and performance. Noise is considered one of the most influential physically harmful factors in work environments, which has become a threat to people's physical and mental health in today's world due to industrial development (Nasiri et al., 2019). Noise pollution is one of the most important environmental problems that endangers human health in various dimensions. This pollution has received more attention in the last three decades. Research shows that in addition to hearing loss, short and long-term exposure to noise pollution causes "increased blood pressure, cardiovascular complaints, irritability, anxiety, sleep disorders, and altered behavioral patterns." Therefore, it is

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necessary to use modern technologies to assess the noise situation. The aim of assessing environmental noise is to improve the way society deals with noise. Properly planned noise management can eliminate this effective component for the health of society (Majidi and Khosravi, 2016). For this reason, this research attempted to evaluate the relative sound level index. The purpose of the assessment is to prevent the harmful effects of noise pollution on workers in the industrial environment.

A lack of risk assessment leads to an increase in the probability of risks occurring, which can lead to irreparable losses (Shafia et al., 2012). Although there are various assessment tools, it is very difficult to find a tool that fully guarantees safety and reliability (Qorbanpour et al., 2018). Assessing the noise exposure of workers requires measuring the sound pressure level and determining the duration of exposure for each worker. Due to the different working conditions based on the exposure method and the type of environmental noise, various executive methods are proposed for measurement and assessment. In most studies, the assessment results are presented on the basis of initial sound level, which makes it difficult to compare the results for the same noise pollution. The DEA model is one of the widely used methods to determine efficiency. In the present study, noise pollution is assessed using the DEA method, and the relative noise pollution rating and the extent of improvement in noise pollution are determined to achieve relative desirability. In addition to identifying efficient units, the results of the DEA assessment are the introduction of reference models to optimize the inputs and outputs of each stage and to determine the path to reach the efficiency boundary.

In order to prevent accidents and their consequences, the Bowtie method correlates the hardware and software system, and the risks and their consequences, and clearly shows how these can be controlled in the safety, health, and environmental management system (Darakhshan Fard and Mohammad Najd, 2018).

As the workforce plays an important role in companies and many people spend more than a third of their lives in hazardous working environments, a risk assessment of employees is very important. The statistics on noise pollution as one of the most important environmental problems and the financial and physical damage it causes show how important it is to pay special attention to the assessment of such occupational hazards. Many studies have been conducted to assess noise pollution, but no study has yet been designed and conducted to assess the relative exposure of workers to noise. As for the importance of conducting this research, we can mention prevention and informing managers with the aim of reducing occupational exposure. In other words, the use of the results of this study and the implementation of intervention programs related to the results obtained can be considered a good step toward controlling and reducing the noise exposure of workers in industrial environments. Therefore, the current study was conducted with the aim of evaluating the noise exposure of workers in industrial environments using the Bowtie and DEA approach, and the practical and ultimate goal of the study is to increase the safety level of workers in the industrial environment. The results of this study will allow managers to optimally allocate resources and evaluate noise exposure prevention programs for industrial workers in a scientific and effective manner.

Literature Review

Noise as an unwanted sound is not a new phenomenon, but in the last century, with the increasing speed of industrialization and the spread of machinery, it has been considered one of the problems of industry and an occupational hazard in a wide range of working environments such as "iron and steel, metal smelting, wood, textile, air, chemical, and many other industries". Noise exposure has direct and indirect effects on the health of employees. Therefore, given the importance of maintaining and promoting the safety and health of workers and the importance of industry in the economic development of the country in various industrial sectors, the evaluation of noise exposure of workers in industry is an issue that requires more studies. In the following, we will describe some of the studies conducted.

Maleki Roshni and Valipour (2023) determine the characteristics of sound pressure during occupational exposure to military frigates. The descriptive-cross-sectional study was conducted on N-class and T-class combat frigates near the city of Mahshahr in 2021. Noise measurement and octaband analysis were carried out using a noise meter and an acoustic calibrator. The results of the present study show that the sound pressure level in the on and rest state does not cause any damage to the hearing of the military personnel, as the sound pressure level is below the standard limits in all measured frequencies.

Akbari et al. (2022) investigated the effects of traumatic noise exposure on the hearing of the armed forces. Based on several studies on the sound pressure level caused by gunfire, they found that this type of noise exposure leads to auditory complications that vary from person to person depending on the amount and intensity of exposure. Background variables and lifestyle are also among the parameters that play a role in the occurrence of noise-induced hearing loss. It is important to note that in order to prevent and manage hearing impairment and hearing loss in military personnel, medical records need to be made focusing on pre-employment hearing monitoring as well as regular examinations of individuals.

Alimoradi et al. (2021) evaluated the effects of occupational noise in steel processing on the psychological and cognitive components of workers in the Isfahan steel industries. For this purpose, the disturbances caused by occupational noise were investigated in 1000 workers in the steel industry of Isfahan in 2020. The standard measurement method 9612 was used to determine the objective noise. From the results, it can be concluded that due to the positive and significant relationship between the sound intensity level and the cognitive and psychological components in the sample group, effective preventive measures must be taken to prevent psychological damage and maintain the health of workers in this industry.

Rank Koi et al. (2021) investigated the effects of noise on blood pressure and hearing loss in workers. This study was conducted on 54 workers in the steel industry. Dosimetry with the TES 1358 noise meter and the Beurer BC16 blood pressure monitor were used to determine noise exposure and blood pressure. The statistical software SPSS 24 with a significance level of 0.05 was used for the statistical analysis. The results of this study show that noise exposure increases blood pressure in humans and that the effects increase with age. To reduce the effects of noise, control measures such as "reduction of sound pressure level, training programs and regular blood pressure screening of workers" are recommended.

Faruhid and Ilkah (2021) analyzed noise pollution in rail transport. A linear regression model was used to model the sound level data of the collected railroad stations. A correlation analysis was used to investigate the influence of various factors on the noise pollution index. The results showed that noise pollution was above the permissible limit at most measurement points so at Sanat Square station, which is the quietest station during train arrivals and departures, an equivalent noise level of 77 decibels was measured, which is above the standard limit.

Pajouhesh Jahani and Siri (2021) investigated the effect of urban vegetation in reducing noise pollution using an artificial neural network. The sound intensity was measured at 100 stations in the parks and streets of districts 2 and 5 of Tehran. The artificial neural network was modeled with 9 vegetation variables 24 neurons in the hidden layer and one output variable. The results of the sensitivity analysis of the model show that the width of the wall, the average height of the trees, and the average crown diameter of the shrubs have the greatest effect in reducing the sound intensity in urban vegetation walls.

Parvizian et al. (2020) created the noise pollution map by spatially modeling the land use map. To investigate the spatial distribution of neighborhoods in land use, the spatial database was used. The distance factor was considered as the main variable of the study and the information was analyzed with the Excel and GIS software. The analysis of the results showed that among the four districts of Yasouj city, "District two had the most pollution and District four had the least pollution".

Tekyekhah and Katorani (2018) studied noise pollution from urban traffic and its impact on the anxiety level of the citizens of Sanandaj city. In this study, 50 stations with residential, commercial, residential-commercial, and green areas were selected and the sound equivalent level was measured using a sound meter. The results showed that noise pollution was highest in commercial use and then in residential and commercial use, which was higher than the standard limit set by the Iranian Department of Environment. Furthermore, the results showed that people's anxiety levels increased due to traffic.

Rahimi et al. (2018) evaluated noise pollution in district 16 of Tehran. In this study, noise pollution in the 16th district of Tehran, one of the densely populated areas of Tehran, was zoned and modeled using the kriging interpolation method. In this study, 8 stations were first selected for a preliminary study. Then, 46 stations were selected in three time periods (morning, noon, and night) to determine the sound intensity level. The results showed that at all stations where noise measurements were carried out, particularly in the road network, the average sound equivalent level measured was above the limit value permitted in Iran.

Khosravi et al. (2018) evaluated user exposure to vibration and noise generated by a rototiller. Hand and arm vibrations were measured according to the ISO 5349 standard and the sound level for the operator and people around him was measured according to the ISO 7216 and ISO 5131 standards and in three different working modes. The results show that the vibration exposure of the hand and arm is above the standards and leads to discomfort and vibration-induced muscle disorders. The highest vibration exposure was found in plow mode and in the direction of the palm to the back of the hand, more than in the other two directions, i.e. in the width of the hand and in the extension of the hand length.

Yari et al. (2016) evaluated noise pollution from traffic in the city of Qom and offered solutions to control it. The sound level equivalent to 15 minutes of passing cars was measured with a noise meter according to the ISO 1996 standard for 7 days and 27 times per day. The results of the studies showed that the average equivalent noise level at all measured stations was above the permissible limit. Noise pollution was higher in the evening and lower in the morning. There was also a significant correlation between the density of motor vehicles and the equivalent sound level.

Majidi and Khosravi (2016) assessed noise pollution in the central part of the city of Zanjan using a geographic information system. For this purpose, the equivalent sound level in "day, night, evening-night, noise pollution index, and traffic noise index" was measured at 20 stations in two periods in winter 2010 and spring 2011. The measurements were carried out in the main streets of this area using the guidelines recommended by AEP and the results were finally analyzed. The results showed that noise pollution occurs at most stations and at most times.

Extensive studies in this field have proposed different operational methods to measure and evaluate the noise exposure of workers, taking into account the different working conditions depending on the exposure method and the type of environmental noise. The results of most studies are based on the difference in sound level, which makes it difficult to compare the results for the same levels of noise pollution. In this context, it is necessary to use today's technologies to assess noise exposure. The present study allows the comparative assessment of workers' noise exposure using the Bowtie and DEA approaches.

Theoretical Background

-Noise pollution

Noise pollution can be considered an unwanted sound that disturbs people's rest during recreation or their concentration at work. Sound is measured in decibels (dB) and is based on the change in air pressure. Its value is specified between zero decibels (hearing threshold) and 130 decibels (deafness threshold). The human ear does not perceive the same volume at different frequencies. Accordingly, a filter is built into noise measuring devices (A-weighted filter) so that the measuring range corresponds to what is heard. The unit of sound level is written as dB(A).

One of the biggest causes of anxiety in people is noise. High noise exposure in the industry leads to anger and irritation in the reaction of the individual. It is believed that noise is one of the direct causes of mental illness and can increase the speed or severity of the development of a mental disorder. In most countries, special attention has been paid to the problem of noise and the pollution it causes, which has led to the development of regulations and the implementation of specific laws to deal with noise pollution. In Iran, measures have been introduced to deal with this environmental pollutant. In order to create optimal conditions and to evaluate and assess the effects of noise, two types of standards have been established (Takiehkhah and Katorani, 2019):

- The standard is the acceptable limit for various urban environments. If a person, be it a passer-by, a resident, or an employee in a commercial or industrial area, complies with the permissible limit values, they will not be disturbed by noise.
- The emission standard can be used to compare and evaluate the emission levels of noise sources. In order to ensure people's comfort and peace and quiet, the limit values of the environmental standards must be defined.

The exact determination of these standards depends on "the type of behavior, culture, customs and finally the physical structure of the cities". For this reason, there are differences in setting these types of standards in different countries. The environmental standard in Iran is set by the Department of Environment. The permissible limit for outdoor noise pollution in Iran is shown in Table (1).

Table 1.
Outdoor noise limit in Iran.

Area type	Day from 7:00 to 22:00 dB(A)	Night from 22:00 to 07:00 dB(A)
Residential	55	45
Commercial-residential	60	50
Commercial	65	55
Residential-industrial	70	60
Industrial	75	65

- BOW Tie method

The Bowtie diagram is an attractive tool for risk identification and qualitative risk analysis, which not only shows the possible paths between hazards and incidents but also makes the distinction between preventive and mitigating barriers clear.

Risk assessment with the Bowtie method takes place in several stages. In the first stage, the event that causes the risk is determined. In the next step, the factors and activities that could potentially pose a threat to the affected environment are identified. The possible consequences of the main event are also presented. The next step is to identify effective factors that can prevent or reduce the risk posed by each of the threatening factors. In the final stage, effective solutions to control and reduce the severity of the consequences of the event and necessary measures to control the failure of obstacles are presented.

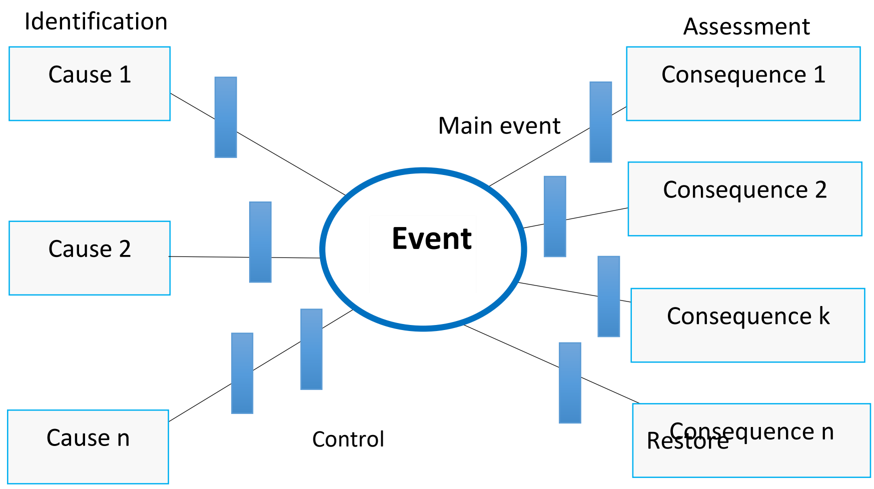

Figure 1. *The structure and components of the bowtie model*

In this method, the necessary documentation is carried out by creating a Bowtie structure for a specific process. This process must be carried out continuously.

Methodology

The research method of this study is cross-sectional descriptive and it is practical and developmental in terms of purpose. The input is the equivalent sound level and the output is the state of noise pollution. The present study evaluates the noise exposure of workers in the industrial environment using Bowtie and DEA approaches. The input-based BCC model is proposed to determine the highest efficiency and to incorporate the inputs and outputs of other decision units in determining the optimal weights for the unit under study. Since secondary models can determine the optimal improvement rate (reference set) of inefficient inputs and outputs, the input-based BCC model is used in this study. Model (1) The basic model of the input-based BCC model is proposed to evaluate the noise exposure of employees in the industry with Bowtie and DEA approaches.

$$\text{Min } \theta \quad (1)$$

S.t.:

$$\theta\, x_{io} - \sum_{i=1}^{n} \lambda_j x_{ij} \geq 0\,,\, i = 1, \dots, m$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro}\ ,\ r=1,\dots,s$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0, \forall_j$$

Since the secondary model is input-based, the objective function tries to reduce the level of inputs (θ) by keeping the level of outputs constant. θ is a real decision variable and λ is a non-negative vector of decision variables, which in this model creates an upper bound for the outputs and a lower bound for the DMU_0 data by choosing any allowable vector λ_j. Given these constraints, θ combined with $\lambda \geq 0$ provides a better option than min $\theta = \theta^*$. This makes θ^* the target pattern for other inefficient units to express the optimal improvement rate.

Definition 4.1. In model (1), a decision unit is effective if $\theta^*=1$.

Results

The risk of noise pollution from the factors of the "cutting process, casting process, material handling process" was considered the main risk factor for environmental pollution in this study, which is shown in Table (2). Table (3) also shows the result of noise exposure.

Table 2.

Hazards of noise pollution to workers in the studied industrial environment.

Risk factor	Controls
Cutting process Casting process Material handling process	Implementation of technical and engineering controls, such as the construction of an acoustic quiet rest room for employees Modification of control rooms and reduction of unnecessary employee exposure

Table 3.

Consequences of noise exposure for workers in the industrial environment studied.

Risk factor	Controls
Cutting process Casting process Material handling process	Hearing damage Health and physiological effects such as neurological effects, gastrointestinal and immunological effects, fatigue, headaches and irritability, and increased risk of accidents. Effects on blood pressure

Figure (2) shows the structure and components of the Bowtie model. In this method, all identified factors are listed on the left side of the model and the identified consequences are listed on the right side.

Ergonomic hazards are introduced as the main event in the bowtie diagram. According to Figure (2), three factors "cutting process, casting process, material transfer process" played a threatening role. In addition, "hearing loss, health and physiological effects, effects on blood pressure" were identified as consequences of the main event. Obstacles were proposed as preventive measures for the threats and various improvement measures for the consequences.

Figure (3) shows the location of the industrial area under investigation and the distribution of the sound level measurement stations. Since the employees were exposed to a uniform noise level during the test, the measurement was repeated three times at the investigated locations and the sound pressure level exposure of the employees was recorded. Table (4) shows the noise exposure levels at the stations in the industrial area studied.

Table 4.

The average sound equivalent level at the noise measurement stations in three daily periods in the industrial hall under investigation.

Station code	Sound equivalent level (dB)			Sound equivalent level range
	Morning	Midday	Evening	
1	72.9	70.2	74.33	2
2	78.3	75.3	79.6	1
3	68.7	70.2	71.3	2
4	78.3	78.3	77.6	1
5	65.2	68.7	68.7	2
6	66.6	69.4	69.4	2
7	60.2	58.3	52.4	3
8	78.9	82.4	81.3	1
9	51.9	65.4	65.4	2
10	66	67.4	70.4	2

The results show that the average equivalent sound level at all measured stations is 70.101 dB, which is within the permissible limit of the equivalent sound level in the industrial area based on the standard of the Iranian Department of Environment (75 dB). The maximum sound pressure level at station 8 is 82.4 dB and the minimum sound pressure level at station 9 is 51.9 dB.

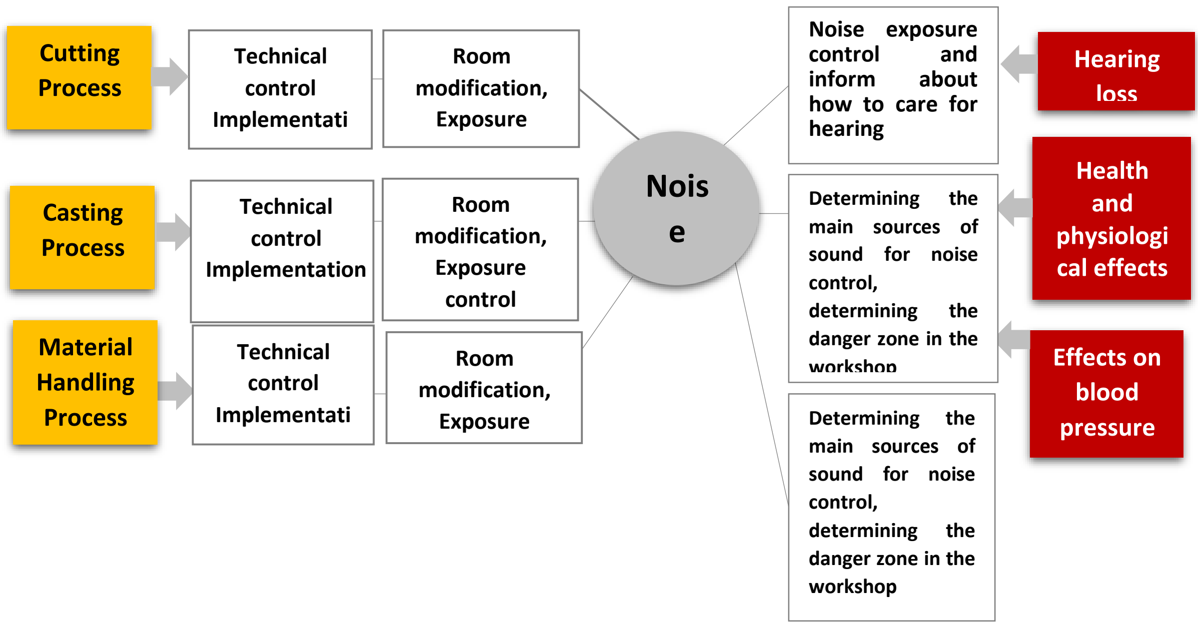

Figure 2. *Bowtie diagram of the noise exposure of workers in the industrial environment studied.*

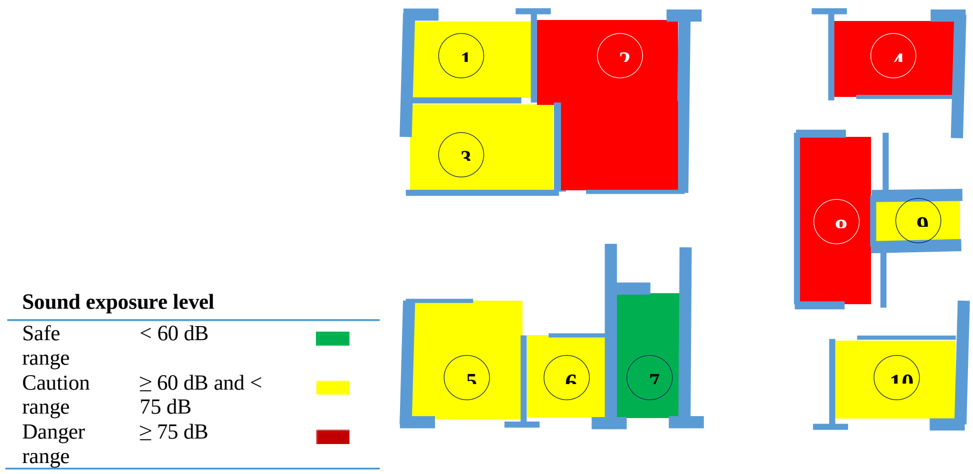

Figure 3.*Location of the selected measuring stations for noise pollution in the industrial area studied.*

In addition, the noise pollution at the stations is higher in the evening. According to the results of dosimetry and the evaluation of sound criteria from the estimation of intensity and noise pollution in the working environment, there is a need to provide basic technical-managerial solutions to reduce the exposure of the employees of sections 2, 4, and 8 and to reduce the ambient noise to reduce the exposure of the employees of these stations.

Model (1) has been implemented in the EMS software and the status of the obtained efficiency of the stations (decision units) is shown in Table (5). As can be seen, out of the ten decision units, unit number 7 is efficient and the other units are inefficient.

In this way, station 7 is within the safe range has an efficiency of 100%, and is considered a reference for other organizational units. The other stations that were examined during this period are in the caution and risk range. Meanwhile, station 8 has performed very poorly in terms of efficiency. The results of the assessed efficiency show that the majority of employees in the organizational units are exposed to noise exposure.

Table 5
Calculated efficiency with the EMS software according to model (1).

	Efficiency	The reference organizational unit and the amount of change in inputs according to the inputs of the reference unit
DMU_1	0.786000	7 (1)
DMU_2	0.732847	7 (1)
DMU_3	0.813035	7 (1)
DMU_4	0.729718	7 (1)
DMU_5	0.843534	7 (1)
DMU_6	0.832035	7 (1)
DMU_7	1	7 (1)
DMU_8	0.704452	7 (1)
DMU_9	0.935413	7 (1)
DMU_{10}	0.838567	7 (1)

To improve the noise exposure of workers in the industrial environment, "noise-reducing technical works and the use of active and passive hearing protection equipment" are among the measures that can reduce the intensity of exposure and the harmful effects on the hearing organ. It is important to note that to prevent and manage hearing damage and loss in workers in the industrial environment, it is recommended to "establish a medical file focused on pre-employment hearing monitoring and regular examinations of workers". Figure (4) shows the scatter plot of the calculated efficiency of noise exposure of workers in industrial environments.

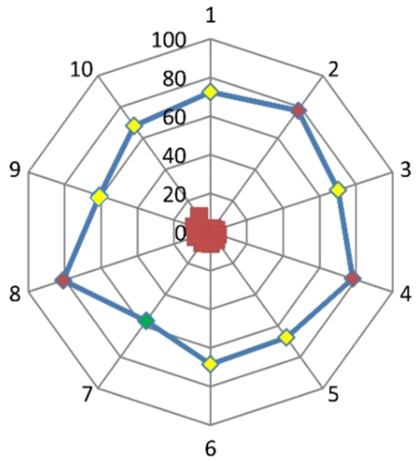

Figure 4.*The radar (spider) diagram of the dispersion of the calculated noise exposure efficiency of the workers in the studied industrial environment.*

Conclusion

In the present study, the noise exposure of workers in industry was assessed using the Bowtie and DEA approaches. The input-based BCC model was proposed to determine the highest efficiency ratio and to incorporate the inputs and outputs of other decision units in determining the optimal weights for the unit under study. The results of the study show that the exposure of employees in most of the monitoring stations is within the permissible range and the average noise exposure of employees in all the studied stations is 101.70 decibels. Of the ten stations studied using the DEA approach, one station is efficient and the other stations are inefficient. To reduce the potential impact of the unfavorable organizational performance of other organizational units in inefficient stations, the noise exposure of employees should be improved:

-To improve the noise exposure of industrial workers, "noise-reducing technical measures and the use of active and passive hearing protection equipment" are among the measures that can reduce the intensity of exposure and the harmful effects on the hearing organ.

-For the prevention and management of hearing impairment and hearing loss in industrial workers, it is recommended to "establish a medical file focusing on pre-employment hearing monitoring and regular examinations of workers".

-In general, three solutions have been proposed for noise control: "noise control at the production source, control in the sound transmission path, and individual control". In most industries, it is not possible to implement the first and second solutions for technical and economic reasons. Therefore, the use of personal protective equipment is the best solution. Types of earplugs and earmuffs are used in various industries. Earplugs are inserted into the external ear canal in various shapes and sizes and are widely used due to their low cost and small size. Earmuffs completely cover the outer ear and are larger, heavier, and more expensive than earplugs. When used correctly, they offer better protection against noise.

-Noise exposure can be reduced by factors such as "training and making employees aware of noise exposure".

Finally, it is recommended:

The DEA model should be carried out regularly at different times.

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