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Evaluation of noise control in industrial buildings through simulations

Okan Şimşek[1]✉

[1] *Adana Alparslan Türkeş Science and Technology University, Faculty of Architecture and Design, Department of Architecture, Balcalı Street, South Campus, 01250, Adana, Turkey*

Corresponding author:
Okan Şimşek

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Faculty of Civil Engineering and Architecture Osijek
Josip Juraj Strossmayer University of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA

Abstract:
The most common detrimental effect of noise among workers in industrial facilities is permanent hearing loss. In the literature review, it was found that the combined effect of increasing the total sound absorption and noise barriers on noise control in industrial buildings has not been analysed. The aim of this study is to evaluate the combined effect of these parameters depending on the total sound absorption in the volume, noise barrier and the total absorption of the noise barrier in industrial buildings by comparing the noise reduction levels through acoustic measurements and acoustic simulation results in an existing industrial facility and to provide information that will enable the production of guiding information and method development on the design and applications of related areas. Within the scope of the method applied in the study, acoustic measurements were made in the relevant industrial building and scenarios developed for the industrial building were modelled in computer environment. The results of the study show through tables, graphs and noise maps that it is necessary to develop optimum solutions by analysing the combined effect of these parameters depending on the total sound absorption, the noise barrier and the total sound absorption of the noise barrier.

Keywords:
acoustic simulation; industrial noise; noise map; noise barrier; noise control

1 Introduction

According to a report published by the World Health Organisation (WHO), various environmental elements such as temperature, humidity, wind, precipitation, air pollution, and noise in urban areas affect human well-being and health. The effects of environmental noise, that is, unwanted noise, mainly from road traffic, railway traffic, airports, and industrial plants, on public health are of increasing concern. Among the environmental stressors affecting public health, environmental noise ranked second in six European cities. High noise levels in industrial environments pose significant risks to both employee health and environmental comfort. To improve the health and well-being of employees, the WHO recommends that indoor noise levels should not exceed 75 dB(A). In many countries, occupational health and safety regulations impose a limit of 85 dB(A) in the workplace. Prolonged exposure to noise may cause temporary or permanent hearing loss, sleep disturbances, stress, irritability, and concentration difficulties [1; 2]. Indeed, the WHO has identified noise as the second most significant environmental health risk factor, drawing attention to its cardiovascular, metabolic, and psychological effects [3]. Exposure to high noise levels has been found to have physiological impacts, such as muscle tension, increased blood pressure, changes in heart rate, and sleep disruptions, as well as psychological effects including irritability, anxiety, fatigue, and reduced work performance [4-7].

Field studies have clearly demonstrated these effects. Şerefhanoğlu Sözen and İlgürel (2005) conducted measurements and surveys in various industrial facilities and reported that 55 % of employees were disturbed by noise, with headaches and irritability being the most common complaints. The same study emphasised that, despite noise levels exceeding 85 dB(A) in many workplaces, the usage rate of protective equipment among employees remained low [8]. Similarly, Kara and Ayberk (2021) conducted noise exposure measurements in five different factories and found that exposures exceeding 87 dB(A) led to hearing problems, as well as psychological and cardiovascular issues among workers. This study evaluated the measured values in accordance with occupational health and safety regulations, and emphasised the necessity of engineering and administrative measures against noise exposure. These findings indicated that noise control in industrial facilities is critical not only for environmental noise management but also for employee health and safety [9].

Various methods and strategies for reducing and controlling noise in industrial buildings have been discussed in the literature. Noise control, beginning in the design stage, is one such approach. İlgürel (2009) proposed that the noise factor should be considered in the architectural design process of industrial buildings. This study introduced a principled approach aimed at taking preventive measures against noise through site planning and design decisions, rather than seeking solutions after facilities have become operational. To develop this approach, data obtained using the ODEON acoustic simulation software were utilised, and architectural measures were determined based on the predicted noise levels during the design stage [10].

Bozkurt (2010) conducted an industrial noise mapping study on the DES Industrial Site in Istanbul and identified the distribution of noise generated by industrial sources within the area. Such noise maps are essential for determining affected zones around industrial facilities and identifying the population that is exposed to noise [11]. Similarly, Casas et al. (2014) utilised noise maps to control industrial noise pollution in their study of a metal production facility in Brazil. The measured sound pressure levels around the factory were compared with the calculated map values to identify the contribution of the facility-generated noise relative to external sources [12]. Likewise, Forouharmajd and Shabab (2015) created noise maps for a facility in Iran using Surfer software and compared them with field measurements. This study proposed strategies such as insulating control rooms and improving the performance of existing control systems to prevent unnecessary noise exposure [13]. Bozkurt and Demirkale (2017) addressed industrial noise at the urban scale by preparing a noise map for an industrial area in Istanbul. They demonstrated a strong correlation between the industrial site noise levels and facility usage scenarios. In this study, acoustic barrier scenarios and different door opening conditions in factories were simulated to reduce noise reaching the surrounding residential areas. Ultimately, measurements verified that even operational changes within industrial units significantly affect environmental noise [14].

Jayawardana, Perera, and Wijesena (2014) analysed the distribution of noise within a factory, first predicting indoor noise propagation through a theoretical mathematical model and then validating the model using data collected using standard methods [15]. In this study, low-cost noise control panels were designed and the effectiveness of the proposed design was experimentally demonstrated through a pilot implementation. Similarly, Chen et al. (2014) used the SoundPLAN acoustic software to reduce noise in an electrical transformer substation, creating a sound field model of the facility. Four different control scenarios were tested using this model, and the simulations showed that even with conventional measures, the noise levels at the substation boundary could exceed the standards. However, with appropriate measures identified through modelling, excessive noise could be effectively reduced [16]. Yaman and Kurtay (2024) examined a section of a factory in the automotive sector. The researchers conducted on-site noise measurements in the seat production unit of an automotive factory and transferred the existing conditions into acoustic simulation software [17]. They examined the effects of increasing the sound absorbers and other acoustic improvements on the A-weighted sound pressure levels and mid-frequency reverberation times through various improvement scenarios. The results indicated that the noise levels in the working environment could be reduced by approximately 15 dB through these improvements. At the end of the study, the researchers presented their recommendations for noise control measures for the automotive industry facility and demonstrated the effectiveness of these measures.

Acoustic barriers and sound-absorbing materials have frequently been discussed as noise control elements in literature. Bozkurt (2021) compiled methods for controlling industrial noise at both the building and urban scales in a comprehensive study. By detailing the strategic noise mapping process in line with the European Union Noise Directive, Bozkurt proposed the identification of excessively noisy areas through maps and the development of improvement plans for these areas. The importance of engineering solutions, such as sound-absorbing coatings, vibration dampers, and acoustic barriers, in noise reduction has been emphasised [18]. Similar measures have been implemented in industrial facilities in different countries. Butorina et al. (2022) suggested the use of modern damping materials to reduce vibration-induced noise in steel factories and recommended the installation of barriers to mitigate noise from large machinery and rolling mills [19]. Kim (2021) developed an indoor noise mapping system for the turbine hall at a power plant in South Korea. Using the measured values from selected points, a 3D noise distribution map of the hall was created, enabling the identification of abnormal noise sources within the facility and the planning of proactive maintenance and environmental improvement measures [20].

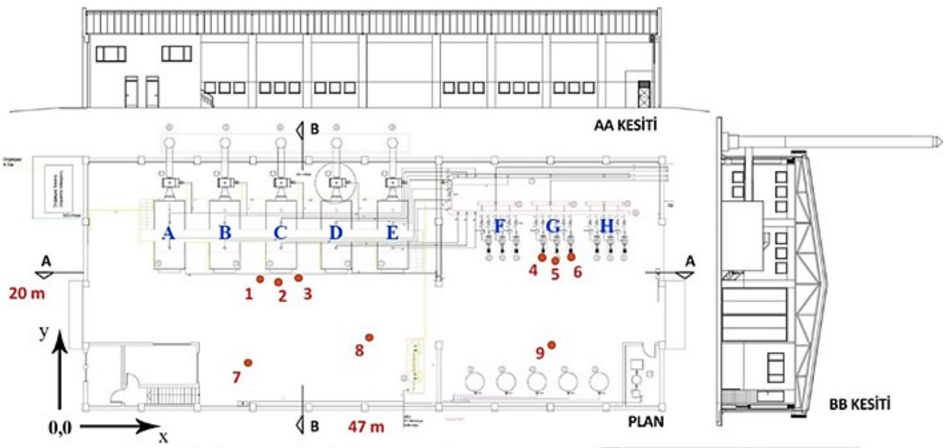
Noise issues in various industrial sectors have also been examined. As opposed to being limited to a single sector, studies on facilities with different production processes provide a general perspective. For example, metal production facilities have been analysed using noise maps and measurements to identify noise sources such as presses and compressors [21], [22]. It has been shown that equipment such as sewing machines and automated cutting machines in textile factories generate high noise levels and impact workers [23]. Diesel generators, turbines, and cooling fans have been identified as significant noise sources in energy production facilities such as thermal power plants [24]. In rubber production factories, processes such as printing, moulding, curing, cutting, and packaging have been reported to generate varying noise levels [25]. Similarly, studies in the automotive sector have demonstrated that noise levels vary according to the processes [17]. Multi-sector evaluations have also been performed. The study by Kara and Ayberk (2021) covered five factories operating in different sectors, including metal, wood, and textiles, and compared the exposure levels in each sector [9]. In addition, Arbaoui et al. reported that rotary machines such as compressors, pumps, and turbines are the primary noise sources in industrial zones in Algeria, and noted that noise levels in some industrial areas of the city reached 95-115 dB(A) [26].

In summary, previous studies have attempted to solve the noise problem in industrial buildings by considering parameters such as noise maps, total absorption enhancements, and noise barriers. In this study, the combined effects of the parameters of the total absorption enhancement, noise barriers, and total absorption of the noise barriers on the noise levels in industrial buildings were investigated. Acoustic measurements were performed in the relevant industrial building, and scenarios developed for the industrial building were modelled. Subsequently, the ODEON (V 14.0 Auditorium) simulation programme, which has frequently been used in the literature with an algorithm known as ray tracing that considers the effects of multiple reflections and first- and second-order diffractions, was calibrated with the acoustic measurements obtained in the volume.

2 Study area

2.1 Characteristics of work facility

In this study, the heat centre serving a large part of Eskişehir Technical University 2 Eylül Campus was considered. This facility meets the heating and domestic hot water requirements of the buildings on the campus. The building in which the study was conducted has a closed area of 940 m^2. The total number of employees is 15. The building has dimensions of 20 × 47 m and a height of 7 m. The roof height is 1 m. The walls are covered with ceramic tiles up to a height of 2,2 m and the remaining parts are plastered. The roof is made of trapezoidal sheet metal, and there are 48 windows of 1 m width and 1 m height on the walls. Natural lighting is provided through the windows. Vehicle entrances to and exits from the industrial building are provided by two metal doors. The doors used for personnel entry and exit are also metal.
There are five burners and three water pumps in the industrial building. Because burners burn natural gas and blow it strongly owing to their working structure, high-level noise is generated. In addition to these five burners, three other pumps are used to pump the heated water to other volumes, generating noise during their operation. The plan of the industrial plant, machine layout, measurement points, and coordinates are shown in Figure 1.



	Coordinates	
	X (m)	Y (m)
A	7	14
B	11.5	14
C	16	14
D	20.5	14
E	25	14
F	34	13
G	38	13
H	42	13

	Coordinates	
	X (m)	Y (m)
1	15	11.6
2	16	10
3	17	11.6
4	37	12.6
5	38	12
6	39	12.6
7	13.5	3.9
8	23	5.4
9	38	4.5

Figure 1. Plan of the industrial plant, machine layout, and measurement points

2.2 Noise level measurements

To determine the sound power levels of the machines by frequency, nine receiver positions were identified for noise level measurements throughout the volume within 1 m of the machines and at three points on each machine to measure the noise exposure of workers working in other parts of the production process and to calibrate the simulations to be performed (Figure 1). The overall sound pressure levels and 16-16000 Hz octave band levels were measured using a precision sound level meter (B&K 2270 Handheld Analyser; Figure 2).

To determine the sound power levels of the machines, the TS EN ISO 3746: Determination of sound power levels and sound energy levels of noise sources using sound pressure - Observation method standard was employed, using a surrounding measuring surface on a reflective plane. This standard covers the methods used for determining the sound power level or sound energy level of a noise source from sound pressure level measurements performed on a surface surrounding the noise source (machine or equipment) in a test environment for which the requirements are specified. The frequency A-weighted sound power level generated by the noise source was calculated using these measurements. In accordance with this standard, microphones were positioned in a semicircle 1 m from the machines and measurements were taken for approximately 1 min at each point. The measurement device was calibrated before each measurement. To determine the sound power levels of the machines, the sound pressure levels from the measurements were obtained using the method in the relevant standard, and the sound powers of the machines were obtained and defined using a simulation programme.

Figure 2. Measurements performed in the volume

Table 1 shows the general sound pressure levels and 16-16000 Hz octave band results of the noise measurements at nine different points in the industrial plant.

Table 1. Results of noise measurements at octave band frequencies

Points	Leq dB(A)	Frequencies										
		16 Hz	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
1	90,0	66,0	74,0	75,0	81,1	89,2	83,6	84,0	84,8	80,0	71,3	59,2
2	90,8	64,5	70,5	77,9	79,3	86,7	84,8	87,8	83,3	79,6	71,8	59,1
3	90,8	63,3	70,2	78,2	78,4	88,5	84,5	86,5	84,5	81,2	73,2	60,1
4	75,2	55,6	60,3	59,1	63,6	65,5	65,5	72,7	66,4	67,4	60,9	51,8
5	74,7	56,2	60,8	59,0	63,3	65,0	66,9	70,9	67,9	66,7	60,8	52,0
6	75,8	58,3	61,2	59,1	66,6	66,5	70,7	72,1	68,3	67,2	61,5	51,8
7	85,5	56,1	66,2	72,1	75,5	79,5	78,4	79,9	80,8	75,7	65,5	52,7
8	84,3	56,3	67,7	75,2	74,4	79,4	78,5	79,5	78,7	74,1	64,7	52,5
9	79,7	56,3	61,5	67,0	67,6	71,9	72,5	74,6	71,6	66,7	56,2	41,1

3 Methodology

To determine the noise environment in the industrial plant, noise maps were prepared, and graphs and tables were used to evaluate the data obtained from the maps. The maps were prepared during the period when all sources were open, and the following steps were followed to prepare the maps.

- A model was created in SketchUp 2017 based on the plans and sections of the industrial plant and then transferred to the ODEON (V 14.0 Auditorium) simulation programme (Figure 3).
- The coating materials used on the surfaces of the industrial plant and the sound absorption coefficients in the 63-8000 Hz octave band frequency range were entered into the simulation programme according to the values listed in Table 2.
- The sound power levels of the sources were defined in the simulation programme by performing calculations based on the sound pressure levels obtained from the measurements using a B&K 2270 Handheld Analyser, a sensitive-type sound level meter, around the relevant machines in the volume (Table 1).
- In-situ measurements throughout the volume were used to calibrate the simulation programme (Figure 3).
- Noise maps were generated using a simulation programme for a height of 1,5 m above the floor, considering that people work while standing up.
- Scenarios were developed to protect the hearing health of workers, according to the Regulation on the Protection of Employees from Noise-Related Risks of the internal noise levels in the industrial facility.
- The simulations were repeated by changing the surface absorptances and modelling noise barrier scenarios with a width of 23 m and height of 3 m at a distance of 1,2 m from the noise sources.
- The results were compared and evaluated.

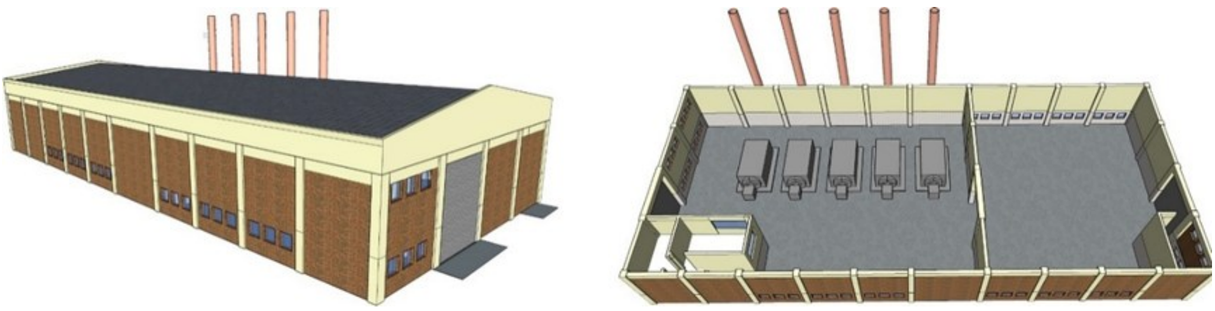


Figure 3. Model created from the plans and sections of the industrial plant

Table 2. Materials used in the interior surfaces of the industrial plant and their sound absorption coefficients

Surface	Material	Surface area (m^2)	Sound absorption coefficients							
			63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Flooring	Smooth unpainted concrete	740	0,01	0,01	0,01	0,02	0,02	0,02	0,05	0,05
Windows	10 mm double glazing with air gap	47	0,10	0,10	0,07	0,05	0,03	0,02	0,02	0,02
Ceramic tiles on the walls: h = 220 cm	Glazed ceramic	475	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02

Doors	Wooden door	48	0,14	0,14	0,10	0,06	0,08	0,10	0,10	0,10
Walls	Painted plaster surface	771	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
Boiler and water pumps	Steel	378	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02
Ceiling	Steel trapezoidal sheet	935	0,40	0,30	0,25	0,20	0,10	0,10	0,15	0,15

This method was implemented according to the aforementioned steps. The developed scenarios were modelled again and analysed using simulation software. The scenarios developed for the existing industrial plants are listed in Table 3.

Table 3. Scenarios developed for the industrial plant

Scenario	Improvements to the industrial facility	Abbreviation of scenario
Scenario 1	High sound absorption on ceiling and wall surfaces	S1
Scenario 2	High sound absorption on all surfaces	S2
Scenario 3	Noise barrier with sound-reflective surface over the existing situation	S3
Scenario 4	Noise barrier with high sound absorption over the existing situation	S4
Scenario 5	High sound absorbing ceiling and wall surfaces and high-sound-absorbing noise barrier	S5 (S1+ S4)

4 Results and discussion

Evaluations were carried out by comparing the sound pressure level values obtained from the measurements carried out in the industrial building and alternatives for increasing the total absorption of the volume created through the calibrated model, noise barrier application, and noise barriers with different absorption values.

According to the Regulation on the Protection of Workers from Noise-Related Risks, to protect the hearing health of workers, interior noise levels specified in national legal regulations should not exceed 85 dB(A). Accordingly, both the 85 dB(A) limit and NR 70 (the Noise Rating (NR) curve determined by ISO 1996) were selected as the evaluation curves because the sum of the octave band levels of the NR 70 curve is very close to 85 dB(A). The NR 70 curve was used as an evaluation criterion in addition to 85 dB(A) for each octave band level to enable a comparison of the noise levels within the volume.

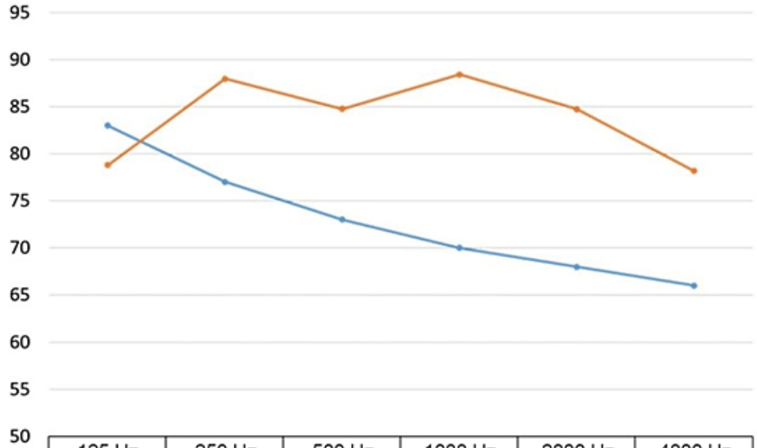
4.1 Acoustic simulations of the current situation

The sound power levels of the sources were defined in the simulation programme based on the measurements performed using a sensitive-type sound level meter around the relevant machines in the volume. It was determined that there was an acceptable difference (1 dB(A)) in Leq (63-8000 Hz) values between the measurement and simulation results for the current situation (Table 4). The smallest difference was obtained in the 63 Hz frequency band (approximately 1 dB), and the largest difference was observed in the 250 Hz frequency band (approximately 3 dB).

Table 4. Measurement and simulation results at the industrial plant

dB(A)	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	Leq (63 Hz-8000 Hz)
Measurement result	72,11	75,51	79,55	78,44	79,96	80,83	75,76	65,5	86,80
ODEON simulation result	71,40	74,40	83,00	79,20	82,30	79,40	73,50	63,00	87,80

A comparison of the volume-wide sound pressure level values obtained from the simulation for the current situation and the NR 70 curve is shown in Figure 4.



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
NR 70	83	77	73	70	68	66
Current situation	78.81	87.96	84.77	88.41	84.73	78.17

Figure 4. Comparison of industrial plant interior noise levels with NR 70 curve

For the current situation, it was observed that the sound pressure levels in the volume were well above the NR 70 curve in all frequency bands, except at 125 Hz. In addition, the sum of the sound pressure levels according to the frequencies in the volume was 93 dB(A), exceeding the value of 85 dB(A), which should not be exceeded according to the Regulation on the Protection of Employees from Noise-Related Risks. The distribution of the sound pressure levels in the volume can be read from the noise map shown in Figure 5.

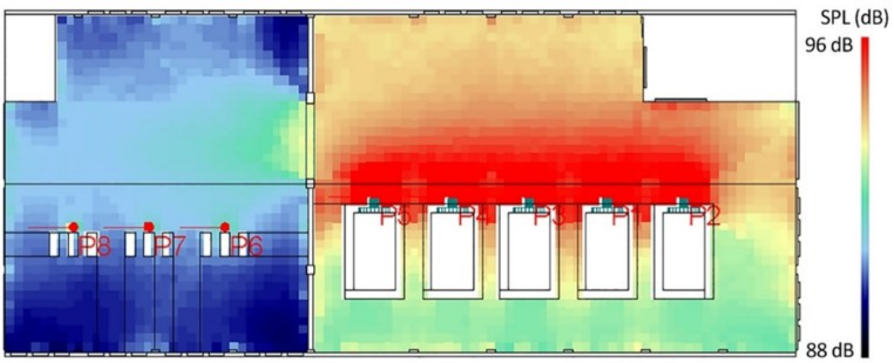


Figure 5. Current situation noise map of the industrial plant

4.2 Scenarios

4.2.1 Scenario 1 (S1): Acoustic simulations of high-sound-absorption configurations of ceiling and wall surfaces of industrial plant

To provide a suitable working environment in the industrial plant and for the health of workers, the internal noise levels should be below the NR 70 curve and 85 dB(A) according to the frequencies. Therefore, in the first stage, it was deemed appropriate to cover the ceiling and wall surfaces of the industrial plant with materials with high absorption values, and the simulations were repeated. The ceramic-coated surfaces of the walls up to 2,2 m were not altered considering the function, safety, and cleaning status of the space and the ceramic-coated surfaces up to the ceiling and entire ceiling were covered with materials with high absorption values. In this context, the proposed and simulated materials and sound absorption coefficient values according to the frequencies are listed in Table 5.

Table 5. Recommended materials for the wall and ceiling surfaces of the industrial plant and their sound absorption coefficients

Surface	Material	Surface area (m²)	Sound absorption coefficients							
			63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Flooring	Smooth unpainted concrete	740	0,01	0,01	0,01	0,02	0,02	0,02	0,05	0,05
Windows	10 mm double glazing with air gap	47	0,10	0,10	0,07	0,05	0,03	0,02	0,02	0,02
Ceramic tiles on the walls: h = 220 cm	Glazed ceramic	475	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02
Doors	Wooden door	48	0,14	0,14	0,10	0,06	0,08	0,10	0,10	0,10
Walls	Acoustic plaster	771	0,15	0,15	0,25	0,40	0,55	0,60	0,60	0,60
Boiler and water pumps	Steel	378	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02
Ceiling	50 mm mineral wool	935	0,15	0,15	0,70	0,60	0,60	0,85	0,90	0,90

From the simulations, it was determined that the noise level in the industrial plant was 88.2 dB(A) if the ceiling and wall surfaces were covered with materials with high-sound-absorption values. In addition, Figure 6 shows that the internal noise levels in the industrial plant covered with absorbing materials were above the NR 70 curve in this frequency band. Although significant improvements were achieved in all frequency bands compared with the current situation, the NR 70 curve and 85 dB(A) value could not be reduced further. Therefore, other scenarios were evaluated.

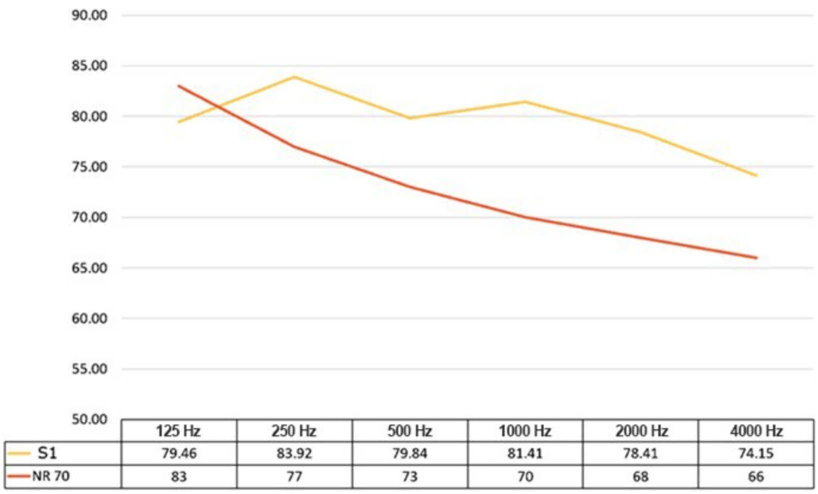
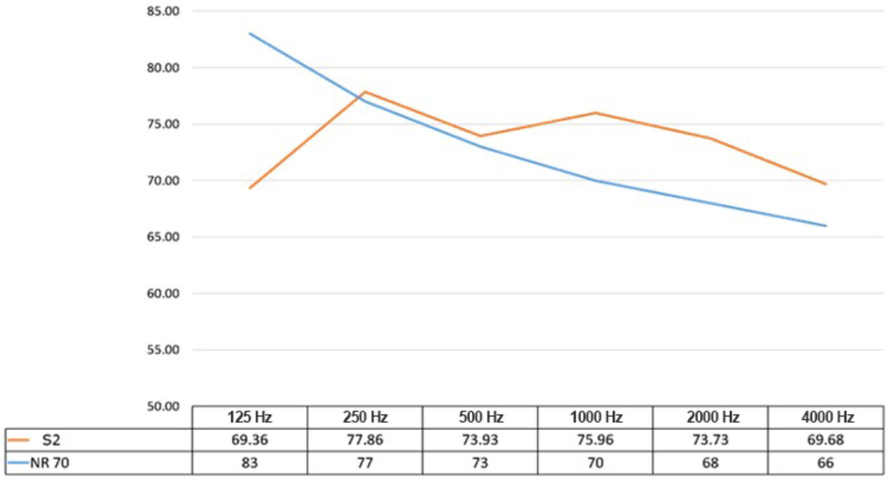


Figure 6. Interior noise levels of the industrial plant when the ceiling and wall surfaces were covered with high-sound-absorption materials

4.2.2 Scenario 2 (S2): Acoustic simulations with high-sound-absorption configurations for all surfaces of the industrial plant

In this scenario, it was deemed appropriate to cover all surfaces of the industrial facility with fully absorbing materials with sound absorption coefficients of 1 in all frequency bands to determine whether the high-level noise in the volume could be controlled only by changing the surface absorption values, and the simulations were repeated. The simulation results in the graph in Figure 7 demonstrate that even if the volume was 100 % sound absorbing, the noise in the volume could not be controlled by surface absorption. This situation can be explained by the fact that although all surfaces in the volume were sound absorbing, the sound emitted from the source, and not the sound reflected from the surfaces, reached the receiver directly without encountering any obstacle in the formation of high-level noise that endangers the health of workers. Noise barrier scenarios have been developed for high interior noise levels that cannot be controlled by surface absorption alone. Figure 7 shows that the internal noise levels in the industrial facility covered with 100 % sound-absorbing materials were above the NR 70 curve in these frequency bands.



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S2	69.36	77.86	73.93	75.96	73.73	69.68
NR 70	83	77	73	70	68	66

Figure 7. Interior noise levels of the industrial plant when it was covered with 100 % sound-absorbing materials

4.2.3 Scenario 3 (S3): Acoustic simulations of noise barrier configurations with sound-reflective surfaces based on the existing condition of the industrial facility

In this scenario, in addition to the existing industrial facility, an obstacle with a width of 23 m, height of 3 m, and thickness of 0,2 m was placed at a distance of 1,2 m from the burners with the highest sound power levels in the volume, and the simulations were repeated (Figure 8). All surfaces of the designed obstacle were made of a ceramic coating, which was used throughout the volume, and the sound absorption coefficient values according to the frequencies are listed in Table 6.

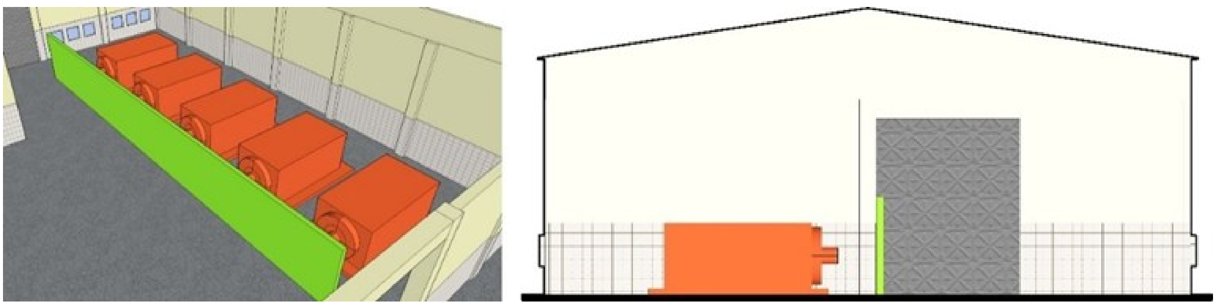


Figure 8. Noise barrier designed for high noise sources in an existing industrial plant

As a result of the simulations, a noise level of 90 dB(A) was obtained within the volume in the case of using a noise barrier with a reflective surface. The noise map obtained from the simulations performed when the noise barrier surface was reflective is shown in Figure 9. This scenario with a noise barrier and only a reflective surface was the least effective and closest to the existing situation (Figure 10). In this scenario, which is similar to the existing situation in all frequency bands, the noise level could not be reduced below the NR 70 curve and 85 dB(A). The fact that the sound pressure level in the frequency bands is very similar to the existing situation can be explained by the fact that the total absorption of the volume was slightly improved, and the noise emitted from the source reached the receivers by reflecting from the reflective surfaces of the volume, especially the noise barrier with a reflective surface.

Table 6. Sound absorption coefficients of the noise barrier in the 63-8000 Hz octave band frequency range in Scenario 3

Surface	Material	Surface area (m²)	Sound absorption coefficients							
			63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Noise barrier	Glazed ceramic	144	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02

4.2.4 Scenario 4 (S4): Acoustic simulations of noise barrier configurations with high sound absorption based on the existing condition of the industrial facility

In this scenario, in which the surface material of the noise barrier was covered with a high-sound-absorbing material, a significant improvement in noise levels was observed compared with the case in which the barrier was ceramic coated. However, it was still not possible for the values to decrease below the NR 70 curve and 85 dB(A), which should not be exceeded according to the Regulation on the Protection of Employees from Noise-Related Risks. The material with high sound absorption values used on all surfaces of the noise barrier was 50 mm mineral wool, whose sound absorption coefficients at the octave band frequencies are listed in Table 7.

Table 7. Sound absorption coefficients of the noise barrier in the 63-8000 Hz octave band frequency range in Scenario 4

Surface	Material	Surface area (m²)	Sound absorption coefficients							
			63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Noise barrier	50 mm mineral wool	144	0,15	0,15	0,70	0,60	0,60	0,85	0,90	0,90

The noise maps obtained from the simulations performed when all surfaces of the noise barrier were covered with sound-reflecting and -absorbing materials are shown in Figure 9. Because the sound emitted from the source was not reflected from any surface within the 1,2 m area between the burners and noise barrier, the effect of the noise barrier surface material was not observed in this area. However, when the noise barrier was covered with sound-absorbing material, the sound pressure levels decreased towards the corner points of the volume (Figure 9). In the simulations using the noise barrier with a sound-reflective surface, a noise level of 90 dB(A) was obtained for the volume, whereas in the simulations using the noise barrier with a sound-absorbing surface, a noise level of 85 dB(A) was obtained for the volume.

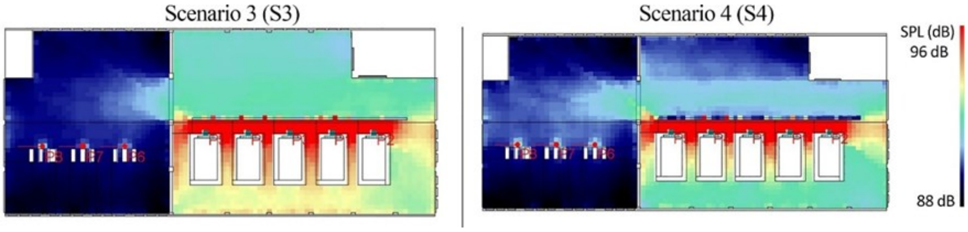


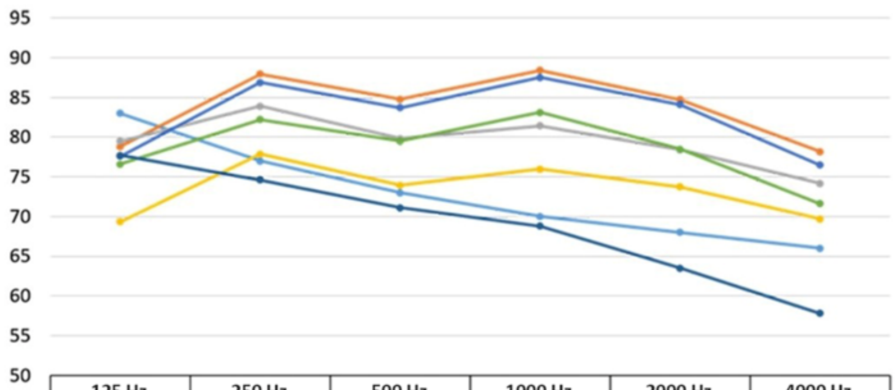
Figure 9. Noise maps obtained from simulations in which the noise barrier surface was covered with sound-reflecting and -absorbing material

4.2.5 *Scenario 5 (S5 (S1+ S4)): Acoustic simulations of high-sound-absorption ceiling and wall surfaces of the industrial facility and noise barrier configurations with high sound absorption*

Based on the current situation in industrial facility, it was determined that the noise level in the volume could not be reduced to below the desired values by using noise barriers covered with sound-reflective and -absorbing materials. Finally, a scenario was developed and simulated based on the combined effect of increasing the sound absorption values of the surface materials throughout the volume and noise barrier application to reduce high-level noise in the volume. In this scenario, the entire ceiling and 2,2 m ceramic coated wall surfaces developed in Scenario 1 were covered with high-sound-absorption materials up to the ceiling without intervention, and the noise barrier application developed in Scenario 4 with all surfaces covered with sound-absorbing materials was also considered (Table 8).

Table 8. Sound absorption coefficients of materials in the 63-8000 Hz octave band frequency range in Scenario 5

Surface	Material	Surface area (m²)	Sound absorption coefficients							
			63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Flooring	Smooth unpainted concrete	740	0,01	0,01	0,01	0,02	0,02	0,02	0,05	0,05
Windows	10 mm double glazing with air gap	47	0,10	0,10	0,07	0,05	0,03	0,02	0,02	0,02
Ceramic tiles on the walls: h = 220 cm	Glazed ceramic	475	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02
Doors	Wooden door	48	0,14	0,14	0,10	0,06	0,08	0,10	0,10	0,10
Walls	Acoustic plaster	771	0,15	0,15	0,25	0,40	0,55	0,60	0,60	0,60
Boiler and water pumps	Steel	378	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,02
Ceiling	50 mm mineral wool	935	0,15	0,15	0,70	0,60	0,60	0,85	0,90	0,90
Noise barrier	50 mm mineral wool	144	0,15	0,15	0,70	0,60	0,60	0,85	0,90	0,90



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
NR 70	83	77	73	70	68	66
Current situation	78.81	87.96	84.77	88.41	84.73	78.17
S1	79.46	83.92	79.84	81.41	78.41	74.15
S2	69.36	77.86	73.93	75.96	73.73	69.68
S3	77.6	86.9	83.7	87.5	84.1	76.5
S4	76.6	82.2	79.5	83.1	78.5	71.6
S5	77.7	74.6	71.1	68.8	63.5	57.8

Figure 10. Existing noise levels of the industrial plant and comparison of all scenarios with the NR 70 curve

Attempts to prevent only the sound emitted from the source from reaching the receiver directly (without any reflection) or to prevent the noise emitted from the source from reaching the receiver by preventing surface reflections by increasing the surface absorption in the volume were insufficient to reduce the noise levels in the volume. The most effective result was obtained using the integrated scenario developed to prevent sound from reaching the receiver points, both directly from the source and through surface reflections. As a result, the noise level within the volume was reduced to 73 dB(A), and all frequency bands were reduced below the NR 70 curve. The current situation of the industrial plant, Scenario 5, and a graph comparing all scenarios with the NR 70 curve are shown in Figure 10.

5 Discussion

The control of indoor noise in industrial facilities is a critical design issue, not only in terms of employee health but also in ensuring compliance with legal regulations and improving the quality of the working environment. In this study, the effects of scenarios combining the total sound absorption capacity of surface materials with the use of noise barriers were analysed through field measurements and acoustic simulations. The results demonstrated that changing only the surface coatings or using only noise barriers does not achieve the desired improvement in industrial spaces with high noise exposure. However, the integrated and holistic application of these two methods provides effective noise control.

In the scenario-based evaluations, the S1 scenario, which involved the application of sound-absorbing materials only to the ceiling and wall surfaces, reduced the noise level from 93 dB(A) to 88.2 dB(A). However, this value remained above the limits specified by current regulations and did not fall below the NR 70 curve. Similarly, in the S2 scenario, even when all surfaces were fully covered with sound-absorbing materials, the desired reduction in noise levels could not be achieved because the direct transmission path of sound from the source to the receiver was not blocked. This finding highlights that surface material improvements alone are insufficient and that direct sound transmission paths must also be addressed.

Scenarios S3 and S4 emphasised the differences in the use of noise barriers. The application of a reflective surface barrier (S3) only reduced the overall noise level to 90 dB(A), failing to achieve the desired effect. However, when a barrier covered with sound-absorbing material (S4) was used, the noise level approached the threshold of 85 dB(A). This clearly demonstrates the impact of barrier material properties on the acoustic performance.

The most significant finding of this study was obtained in scenario S5. The combined use of enhanced sound-absorbing surface materials and a sound-absorbing barrier reduced the indoor sound pressure level to 73 dB(A). Thus, both the NR 70 curve and national regulatory limits were surpassed, providing an environment that is acceptable in terms of employee health and comfort. This finding confirms the practical applicability and effectiveness of the multi-measure approaches frequently recommended in the literature.

Considering the technical and economic feasibility of the proposed solution, the application of sound-absorbing materials on ceiling and wall surfaces is relatively easy for new buildings. However, in existing structures, partial applications may be more realistic owing to structural constraints, equipment layout, and maintenance requirements. Noise barrier implementations can also be integrated into new designs. In existing buildings, proper geometric and spatial planning is required to avoid volume loss. Although surface coatings and barrier systems incur additional costs, their long-term benefits in terms of employee health and regulatory compliance justify these expenses.

The findings of this study can be generalised to other industrial facilities with similar characteristics. Particularly in structures with large volumes and reverberant interiors, such as metal production plants, power plants, automotive factories, and textile workshops, increased surface absorption combined with barrier use offers an effective solution. Moreover, this method is applicable to other large-volume spaces such as sports halls, workshops, and warehouses.

A review of the existing literature reveals that surface treatments, noise barriers, and noise mapping studies are generally considered singular measures. However, this study addressed the combined optimisation of all three methods through field measurements and simulations, thereby filling a significant gap in the literature. Previous studies, such as those of İlgürel (2009), Bozkurt (2010), and Yaman & Kurtay (2024), focused solely on surface treatments, while those by Casas (2014) and Bozkurt & Demirkale (2017) evaluated barrier effects at the environmental scale. In contrast, this study revealed the combined effects of these methods, specifically in indoor spaces.

Challenges that may arise in practice include limitations on barrier applications in existing facilities owing to equipment layouts, the high cost of surface treatments in spaces with high ceilings, and difficulties in maintenance and cleaning. Nevertheless, any intervention that reduces noise exposure provides significant benefits for employee health.

The findings of this study revealed that acoustic planning should be considered in the earliest stages of the design process for new industrial buildings. In existing structures, comprehensive solutions should be developed by combining surface materials and barrier systems.

6 Conclusions

This study investigated the effects of using surface materials with enhanced sound absorption capacities and acoustic barriers, both individually and in combination, to control indoor noise in industrial buildings. The scenarios developed based on measurements conducted in a real industrial facility and acoustic simulations demonstrated that a single-solution approach is insufficient; effective noise control requires the holistic integration of surface absorption and barrier applications.

The most significant finding of this study is that the combined use of enhanced sound-absorbing surface treatments and barriers can reduce indoor noise levels to below legal limits (85 dB(A)) and accepted acoustic criteria (NR 70 curve). It was proven that neither surface material improvements nor noise barriers alone can achieve this goal; however, an optimised combination of both measures provides an effective solution.

These findings highlight the necessity of adopting a multi-parameter approach for noise control in industrial buildings. In existing facilities, partial applications may be recommended, considering practical constraints such as the available space, equipment layout, and costs. In new facilities, it is essential to consider both surface materials and barrier planning together from the design stage onwards.

The contribution of this study to the literature lies in quantitatively demonstrating the combined effects of surface materials and noise barriers through acoustic simulation-based analyses and validating the results with field data. Furthermore, the findings provide industrial facility designers, engineers, and decision-makers with effective, applicable, and measurable solutions for both new projects and existing structures.

Future research could develop new scenarios involving different barrier typologies, dimensions, material combinations, and spatial configurations. Thus, the current findings can be further supported, contributing to the development of more flexible and effective noise control strategies for industrial buildings.

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