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Research Paper

Prediction Models with Multiple Linear Regression for Improving Acoustic Performance of Textile Industry Plants

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In industrial plants noise is a major threat to the mental and physical health of employees. The risk increases more due to the presence of high noise sources and the presence of too many employees in textile industry plants. This paper aims to predict the consequences of variables that may arise in the plants for acoustic improvement in textile industry plants. For this purpose, scenario plants have been created according to architectural properties and source-transmission path-receiver characteristics. The acoustic analyses of the scenario plants were performed in the ODEON Auditorium, and *A*-weighted sound pressure level (LA), noise reduction (NR), and reverberation time (RT) were determined. From the data, prediction equations were created with a multiple linear regression (MLR) model. To test the prediction equations, acoustic measurements were made, and acoustics improvements were carried out at a textile industry plant located in Türkiye. When the obtained results, the success, validity, and reliability of the prediction method are provided. In conclusion, the effect of architectural properties and the surface absorption on acoustic improvements in the textile industry was revealed. It was emphasized that prediction methods can be used to determine the effectiveness of interventions that can be applied in different facilities and can be improved in future studies.

Keywords: industrial noise control; acoustics simulation; multiple linear regression; prediction methods; textile industry; ODEON Auditorium; noise reduction; reverberation time.

1. Introduction

Noise is one of the physical environmental factors that affect our mental and physical health in today's world. Noise is generally defined as unpleasant sounds that disturb people physically and physiologically and cause environmental pollution by disrupting environmental values (Job, 1996; Kurra, 2020; Durán del Amor *et al.*, 2022). Noise has not only physical and psychological effects on individuals but also many negative effects on employee productivity (Reinhold, Tint, 2009; Fredriksson *et al.*, 2015; Baker, 2015). Industrial plants with intensive working areas pose a risk to many employees as areas with high noise levels. By eliminating the risks, the health of the employees should be created by occupational safety (Leather *et al.*, 2003; Themann, Masterson, 2019; Masullo *et al.*, 2022). For this purpose, regulations have been made to limit the noise exposure of industry employees in many countries (Arenas, Suter, 2014). For example, the Occupational Noise Exposure Regulation in the USA states that the noise exposure level of employees should be limited to 90 dB(A) for 8 hours (Occupational Safety and Health Administration, 1995). In Türkiye, in line with the directive of the European Parliament and the Council of the European Union (2003), the exposure limit value is $L_{\mathrm{EX,8\,h}}$ = 87 dB(A); p_{peak} = 200 Pa. The relevant limit values applied by different countries vary.

The textile industry has developed to a great extent with its close to raw materials and high export rates in Türkiye. Recently, thanks to this development and employment opportunities, the number of employees in textile industry plants has been increasing. High noise in textile industry plants affects employees negatively. Research studies on sound pressure level measurements and noise exposure level measurements are carried out in textile industry plants. Abbasi *et al.* (2020) found that in a textile industry plant, 42.1 % (77) of the employees were exposed to noise below the limit value of 85 dB(A), and 57.9 % (106) of them were exposed to noise above 85 dB(A). In the acoustics measurements they made at the textile industry plant, Yaman Turan and Öney (2021) determined that the noise level in the area where the weaving machines are placed varies between 92 dB(A)–97 dB(A), and the noise level in other areas decreases to approximately 82 dB(A). Zaw *et al.* (2020) stated that 66.4 % of the employees in the textile industry plant were exposed to noise above 85 dB(A) and determined the prevalence of hearing loss among the employees as 25.7 % with hearing tests. Atmaca *et al.* (2005) determined that the employees in the textile and cement factory were exposed to very high noise levels with the acoustic measurements they applied in different plants. In particular, they determined that 60 % of those working in the textile industry were exposed to noise at a maximum level of 106 dB(A). Ejigu (2019) determined that the noise exposure level is over 90 dB(A) in the acoustics measurements. Studies have revealed that there are high sound pressure levels in textile industry plants, and this may have negative effects on employees.

Noise, created in textile industry plants, adversely affects the health and task performance of employees. Ali (2011) determined that 47.1 % of the employees of different industrial plants are highly annoyed by noise. It has been determined that there is a significant and positive relationship between noise level and the percentage of employees' noise annoyance. In a study conducted in Pakistan, it was determined that 79 % of textile industry plant employees had hearing loss at levels of 25 dB and above (Shahid *et al.*, 2018). Similarly, in the study, hearing loss in employees exposed to high noise levels increases approximately four times compared to normal conditions. Additionally, it has been determined that hearing loss increases as the noise exposure in the plants increases, and the employment time increases (Shakhatreh *et al.*, 2000). Al-Dosky (2014) determined that textile industry plant employees had a high level of noise annoyance and determined that there was a significant relationship between noise annoyance and employment time. It has been observed in the studies that the employees in the textile industry plants are greatly affected by the noise; and as a result of this, the employees encounter physiological and psychological problems. As a result of the research, it has emerged that the noise problems in the plants should be eliminated, and the appropriate acoustical environments should be created. Various acoustic improvement studies are carried out with computer simulations and models. Monazzam and Nazafat (2007) used acoustic barriers to reduce spinning machine noise, compared the application and mathematical methods, and obtained effective results in noise reduction (NR). They evaluated the results as related to the high internal absorption. Ilgürel (2013) investigated the effect of total absorption on NR in all industrial plants by a simulation method. Jayawardana *et al.* (2014) conducted experimental studies on noise control by constructing a mathematical prediction model of the noise determined by measurements. It has been observed that noise can be reduced at high frequencies as a result of the use of suspended ceilings through simulations. The reliability of the model was determined by comparing the results obtained from simulations and prediction models. Monazzam-Esmaeelpour *et al.* (2014) investigated the effect of the surface absorption on NR by computation in a textile industry plant. Effective results were obtained in NR at high frequencies, and they recommended the use of sound absorption materials with an air gap and increasing the thickness of sound absorption materials for low frequencies. Studies indicate the effective results of noise control measures to reduce noise in textile industry plants.

Reducing noise in textile industry plants is achieved by reducing the sound pressure level and controlling the reverberation time – called RT (Chatillon, 2007). For RTs, analysis was performed especially in the mid-frequency bands, and prediction methods were created on 500 Hz (Bistafa, Bradley, 2000; Yahya *et al.*, 2010; Nowoświat, 2023). Determining the interventions that can be made for this purpose and estimating their effectiveness provides practical convenience. Mathematical models, simulations, and prototypes constitute the prediction methods used for this purpose (Bistafa, Bradley, 2000; Probst, 2012; Fichera, 2020). In this paper, acoustic simulations were applied in various textile industry plant scenarios, and prediction models were created for the analysis of acoustical and non-acoustical parameters (independent variables) using multiple linear regression (MLR) analyses. Prediction models include the testing of interventions and analysis of their effectiveness and offer solutions to reduce noise for employees. It also provides a guide for researchers, acousticians, and employers.

2. Materials and methods

2.1. Acoustics scenarios

Scenario plants were created to make acoustic performance evaluations in textile industry plants and compare the effects of interventions. Scenario plants were designed based on the textile industry plants located in the Republic of Türkiye and identified within the scope of the literature review. Independent variables affecting indoor acoustic performance were created through scenario plants. The independent variables were designed as architectural properties (geometry-width-length-height), source characteristics (number of machines, sound power level, frequency spectrum), transmission path characteristics (wall and ceiling sound absorption materials), and receiver characteristics. As a result of the crossover of the independent variables, 480 different textile industry plants were created. The dependent variables investigated were determined as the indoor *A*-weighted sound pressure level (LA), NR, and RT, which are effective acoustic parameters for NR. For this purpose, the effects of different independent variables on the dependent variables were investigated. The improvement of the acoustic performance approach is primarily based on the implementation of engineering. Engineering controls that can be applied in textile industry plants and can provide high efficiency for the purpose are examined, and the effects of the precautions in a virtual environment (ODEON Acoustics) are investigated.

Different scenario plants were created by crossover architectural properties, source, transmission path, and receiver characteristics to control noise distribution and mitigation in textile industrial plants. Architectural properties (K1–D5), source characteristics (Y1, Y2, F1, F2), transmission path characteristics (S1–S12), and receiver characteristics (A1) components were used in the crossover (independent variables). As a result of the crossovers, a total of 480 (240 square plans / 240 rectangular plans) different simulation outputs were obtained (Fig. 1). The LA, NR values, and RT values (dependent variables) were investigated and analyzed in the scenario plants defined as KX/DXYXFXSXA1.

Scenario plants, which are analyzed through square (1:1) and rectangular plan schemes (2.5:1) as two basic geometry forms, can also be designed as more complex structures. However, square/rectangular main geometries that can be divided into rational units are prioritized in this research. Variables were created to examine the effects of width, length, and height properties in square and rectangular plans. To compare the square and rectangular plans with each other, their areas [m^2] and volumes [m^3] were kept at equal values (Table 1). The plants with square and rectangular plans represent five variable plants each. In the analysis of architectural properties in the created scenario plants, evaluations were made depending on the increase in the main area by taking the height constant (K2-K3-K4/D2-D3-D4); with a similar situation, evaluations were made depending on the increase in height within the same main area (K1-K3-K5/D1-D3-D5).

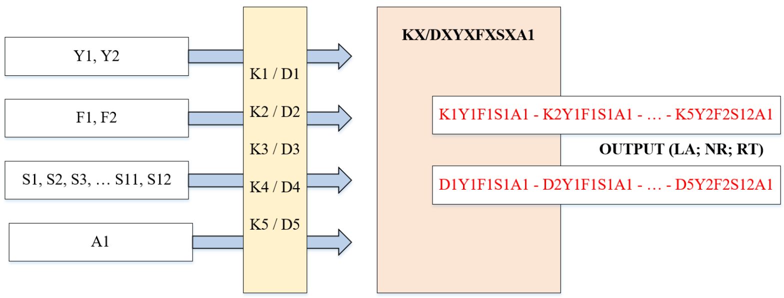

Fig. 1. Formation of different scenario plants.

Table 1. Plan geometries in scenario plants.

Plan geometry code	Length L [m]	Width W [m]	Height h [m]	Area A [m^2]	Volume V [m^3]
K1 (square)	40	40	5	1 600	8 000
K2 (square)	20	20	7	400	2 800
K3 (square)	40	40	7	1 600	11 200
K4 (square)	80	80	7	6 400	44 800
K5 (square)	40	40	9	1 600	14 400
D1 (rectangular)	64	25	5	1 600	8 000
D2 (rectangular)	32	12.5	7	400	2 800
D3 (rectangular)	64	25	7	1 600	11 200
D4 (rectangular)	128	50	7	6 400	44 800
D5 (rectangular)	64	25	9	1 600	14 400

Weaving and spinning machines (open-end and ring spinning) were taken as the basis for examining the acoustic performance in textile industry plants within the scope of source characteristics. Weaving and spinning machines constitute the series of machines that produce the highest noise level in textile industry plants. Two different variables are considered for source characteristics:

– less dense (infrequent) layouts and more dense (frequent) layouts of sources;
– using sources with high frequency and sources with flat frequency distribution in terms of sound power levels.

The layouts of noise sources (more and less dense) in textile industry plants were created based on the number of machines per area of textile industry plants located in the Republic of Türkiye and determined within the scope of the literature review (more dense: approximate values: area/25-frequent placement; less dense: area/50-infrequent placement). From the values, the highest number of machines and the lowest number of machines were analyzed through two variables as machine layout variables (Table 2).

Two different frequency spectrum distributions were accepted in the sound power level distributions of noise sources in scenario plants. These are general hypothetical sound power level spectra obtained from the researched machine catalogues. Two variables were created according to the use of sources with a high frequency spectrum distribution and sources with a flat frequency spectrum distribution (Table 3).

In acoustic performance in textile industry plants, the effect of the surface absorption on dependent variables within the scope of transmission path properties was investigated. In the investigation of the effects of the surface absorption on indoor NR, floor, wall, and ceiling were examined. Due to the industrial floor in the plants, a finish material with high sound reflectivity properties (which cannot be changed) was defined (ODEON Code: 100). A constant sound absorption coefficient was assumed for the floors in all scenario plants (Table 4).

In the analysis of transmission path properties, scenarios allowing the comparison of ceiling and wall were created separately. The effect of sound absorption materials used in the lower (S8) and upper (S9) parts

Table 2. Number of weaving and spinning machines.

Number of sources code	Number of machines			h [m]	A [m^2]	V [m^3]
	Less lense (Y1) – infrequent layout	Mean	More dense (Y2) – frequent layout			
K1, D1	36	50	64	5	1 600	8 000
K2, D2	9	12.5	16	7	400	2 800
K3, D3	36	50	64	7	1 600	11 200
K4, D4	144	192	256	7	6 400	44 800
K5, D5	36	50	64	9	1 600	14 400

Table 3. Frequency distribution of the sound power levels of the sources.

Frequency spectrum code		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	Overall sound power level
$F1$	Flat frequency	93	93	93	93	93	93	93	93	102
$F2$	High frequency	78	81	84	87	90	93	96	99	102

Table 4. Weighted sound absorption coefficients of building components in scenario plants*.

Sound absorption coefficients code	Description	Floor	Walls		Ceiling
			Lower part	Upper part	
S1	Live room (high sound reflection)	0.05	0.1	0.1	0.1
S2	Ceiling with medium absorption	0.05	0.1	0.1	0.5
S3	Ceiling with medium absorption (planar)	0.05	0.1	0.1	0.5
S4	Ceiling with medium absorption (baffle)	0.05	0.1	0.1	0.5
S5	Ceiling with medium absorption (canopi)	0.05	0.1	0.1	0.5
S6	Ceiling with high absorption	0.05	0.1	0.1	0.9
S7	Walls with medium absorption	0.05	0.5	0.5	0.1
S8	Walls with medium absorption (lower)	0.05	0.5	0.1	0.1
S9	Walls with medium absorption (upper)	0.05	0.1	0.5	0.1
S10	Walls with high absorption	0.05	0.9	0.9	0.1
S11	Ceiling and walls with medium absorption	0.05	0.5	0.5	0.5
S12	Dead room (high sound absorption)	0.05	0.9	0.9	0.9

*ODEON codes were used to define the sound absorption coefficients of materials: 10 for 0.1; 50 for 0.5; 90 for 0.9.

of the walls on the indoor acoustic performance was analyzed. Additionally, by using the same amount of materials on the ceiling (planar-S3, baffle-S4, canopy-S5 scenarios), the effect of the differentiation of sound absorption materials due to shaping on the indoor acoustic performance was investigated. The fact that the materials are in the same quantities reveals the effect values of the sound absorption materials on the LA, NR, and RT (dependent variables) according to their formal properties.

In the examination of acoustic performance in the textile industry, a homogeneous layout of receivers within the scope of employee characteristics was taken as a basis. Employees have been assigned to each machine to use the machines specified according to Table 2. Analyses were carried out in the form of point receiver calculations to determine the general distribution within the main area in determining sound pressure level distributions and RTs. In point receiver calculations, 150 cm was taken as the ear height of the standing individuals from the floor. Point receiver calculations were based on the homogeneous distribution (A1) to represent individuals standing at different points.

2.2. Prediction models

The relationships between dependent and independent variables in the scenario plants were investigated by regression analysis. Four different plant types were categorized by crossing the components of square and rectangular plan layouts and machine sound power level frequency distributions. The four different plants selected were created using nominal (categorical) variables. The MLR method was used to explain the effects of independent variables on the dependent variables. With the regression equations created to predict the dependent variables, a prediction model for acoustic performance improvement in textile industry plants was created. The recommendations are based on the principle of obtaining appropriate dependent variables by differentiating the independent variables.

The MLR is a statistical technique that uses several explanatory variables to predict the outcome of a response variable. The purpose of MLR is to model the linear relationship between independent (explanatory) variables and dependent (response) variables. Since MLR models include more than one independent variable, they use the ordinary least squares (OLS) method as a regression extension (McIntosh *et al.*, 2010). Studies on the prediction of variables in acoustic research can be carried out with regression analysis (Kumar, Kumar, 2016; Baffoe, Duker 2018; Tang *et al.*, 2018; Yang, 2019):

$$\gamma = k + aX_1 + bX_2 + cX_3 \ldots + \text{error}, \tag{1}$$

where k is a constant, X_1, X_2, X_3, etc., are the independent variables, a, b, c, etc., are the coefficient of independent variables, and the error term is taken as the difference between the observed and predicted values of the dependent variable (γ). The lower the error term, the lower the difference between the predicted value and the observed value. Depending on the unit of the estimated dependent variable, the error term may have different numerical magnitudes.

Two different analyses were conducted for the square-plan plants, with flat frequency sound power levels and the plants with high frequency sound power levels. In the analyses, the area, the height, the number of machines, the weighted sound absorption coefficient of the walls, and the weighted sound absorption coefficient of the ceiling were found to be effective for the LA; the height, the weighted sound absorption coefficient of the walls, and the weighted sound absorption coefficient of the ceiling were found to be effective for NR; the width, the height, the weighted sound absorption coefficient of the walls, and the weighted sound absorption coefficient of the ceiling were found to be effective for RT. The coefficient of determination (R^2) values equal to the square of the linear correlation coefficient between the dependent variables and the independent variables were determined (Eqs. (2)–(7)).

Plants with a square plan and flat frequency of machine sound power levels-1:

$$\begin{aligned} \mathrm{LA}_1 &= 96.48 - 0.001A - 0.22h + 0.034n \\ &\quad - 3.65w_{\alpha_w} - 4.97c_{\alpha_w}, \\ R^2 &= 0.795 \text{ and } p < 0.01, \end{aligned} \tag{2}$$

$$\begin{aligned} \mathrm{NR}_1 &= 2.36 - 0.12h + 2.66w_{\alpha_w} + 3.98c_{\alpha_w}, \\ R^2 &= 0.871 \text{ and } p < 0.01, \end{aligned} \tag{3}$$

$$\begin{aligned} \mathrm{RT}_{500\,\mathrm{Hz}_1} &= 1.86 + 0.015d + 0.25h - 2.52w_{\alpha_{500\,\mathrm{Hz}}} \\ &\quad - 2.07c_{\alpha_{w500\,\mathrm{Hz}}}, \\ R^2 &= 0.804 \text{ and } p < 0.01. \end{aligned} \tag{4}$$

Plants with a square plan and high frequency of machine sound power levels-2:

$$\begin{aligned} \mathrm{LA}_2 &= 96.78 - 0.001A - 0.21h + 0.034n \\ &\quad - 2.92w_{\alpha_w} - 4.14c_{\alpha_w}, \\ R^2 &= 0.769 \text{ and } p < 0.01, \end{aligned} \tag{5}$$

$$\begin{aligned} \mathrm{NR}_2 &= 2.23 - 0.12h + 2.21w_{\alpha_w} + 3.43c_{\alpha_w}, \\ R^2 &= 0.870 \text{ and } p < 0.01, \end{aligned} \tag{6}$$

$$\begin{aligned} \mathrm{RT}_{500\,\mathrm{Hz}_2} &= 1.83 + 0.015d + 0.25h - 2.52w_{\alpha_{500\,\mathrm{Hz}}} \\ &\quad - 2.07c_{\alpha_{500\,\mathrm{Hz}}}, \\ R^2 &= 0.803 \text{ and } p < 0.01. \end{aligned} \tag{7}$$

LA_X is the A-weighted sound pressure level [dB] of the plant-x characteristics; NR_X is the NR [dB] of the plant-x characteristics; $\mathrm{RT}_{500\mathrm{Hz}_X}$ is the RT [s] of the plant-x characteristics (500 Hz); A is the plan area [m^2]; d is the width/depth length [m]; h is the height [m], n is the number of machines; w_α is the sound absorption coefficient of the walls (500 Hz at RT); c_α is the sound absorption coefficient of the ceiling (500 Hz at RT).

For rectangular plants, machine sound power levels were analyzed in two different analyses, flat distributed and high frequency plants. In the analyses, the area, the height, the number of machines, the weighted sound absorption coefficient of the walls, and the weighted sound absorption coefficient of the ceiling were found to be effective for LA; the height, the weighted sound absorption coefficient of the walls and the weighted sound absorption coefficient of the ceiling were found to be effective for NR; the width, the height, the weighted sound absorption coefficient of the walls, and the weighted sound absorption coefficient of the ceiling were found to be effective for RT. The R^2 values equal to the square of the linear correlation coefficient between the dependent variables and the independent variables were determined (Eqs. (8)–(13)).

Plants with the rectangular plan and flat frequency of machine sound power levels-3:

$$\begin{aligned} \mathrm{LA}_3 &= 94.48 - 0.002A + 0.13d_k - 0.22h + 0.035n \\ &\quad - 3.82w_{\alpha_w} - 4.72c_{\alpha_w}, \\ R^2 &= 0.804 \text{ and } p < 0.01, \end{aligned} \tag{8}$$

$$\begin{aligned} \mathrm{NR}_3 &= 2.36 - 0.12h + 2.84w_{\alpha_w} + 3.74c_{\alpha_w}, \\ R^2 &= 0.884 \text{ and } p < 0.01, \end{aligned} \tag{9}$$

$$\begin{aligned} \mathrm{RT}_{500\,\mathrm{Hz}_3} &= 1.54 + 0.046d_k + 0.21h - 2.52w_{\alpha_{500\,\mathrm{Hz}}} \\ &\quad - 1.95c_{\alpha_{500\,\mathrm{Hz}}}, \\ R^2 &= 0.825 \text{ and } p < 0.01. \end{aligned} \tag{10}$$

Plants with the rectangular plan and high frequency of machine sound power levels-4:

$$\begin{aligned} \mathrm{LA}_4 &= 95.30 - 0.002A + 0.10d_k - 0.22h + 0.035n \\ &\quad - 3.13w_{\alpha_w} - 3.94c_{\alpha_w}, \\ R^2 &= 0.778 \text{ and } p < 0.01, \end{aligned} \tag{11}$$

$$\begin{aligned} \mathrm{NR}_4 &= 2.26 - 0.15h + 2.35w_{\alpha_w} + 3.17c_{\alpha_w}, \\ R^2 &= 0.875 \text{ and } p < 0.01, \end{aligned} \tag{12}$$

$$\begin{aligned} \mathrm{RT}_{500\,\mathrm{Hz}_4} &= 1.52 + 0.046d_k + 0.21h - 2.51w_{\alpha_{500\,\mathrm{Hz}}} \\ &\quad - 1.95c_{\alpha_{500\,\mathrm{Hz}}}, \\ R^2 &= 0.824 \text{ and } p < 0.01, \end{aligned} \tag{13}$$

where d_k is the short side length [m].

The presence of very different production processes in textile industry plants causes very different sound pressure levels in indoor acoustic performance. In this case, it should be known that the constant term in the calculation estimates used to determine the sound pressure levels in regression models can be taken as the sound pressure level of the measured existing situation. In the scenario plants, the LA in the high reflectivity scenarios (KX/DXYXFX'S1'A1) are in line with the sound pressure levels in the textile industry plants before the retrofit. According to the results of MLR analysis, the R^2 ranges between 0.769–0.804 for LA, 0.870–0.884 for NR, and 0.803–0.825 for RT. It is determined that the regression prediction models are at a level that can be applied for the acoustic performance improvement approach in textile industry plants.

3. Case study and test of prediction model

A textile industry plant examined as a case study includes open-end and ring spinning, knitting, and dyed yarn and dyed fabric. The department of open-end yarn spinning has an area of 13 000 m^2 and 12 Schlafhorst (Saurer) open-end machines. The department of ring spinning has 20 Rieter G-33 ring machines in an area of 16 700 m^2. The textile industry plant is planned as the main production areas, storage units, technical rooms, and administrative departments. Production is carried out in the industrial plant with a daily three-shift system. The surface elements of the production area are formed with a lean concrete floor, partition walls made of metal, glass, and brick, and PVC suspended ceiling. It was observed that the finish materials of components were designed with high sound reflectivity properties. This increases the indoor sound pressure level and creates a noisy environment.

3.1. Acoustics measurements

Investigations were carried out to analyze the indoor acoustic performance in the textile industrial plant selected as a case study. The plant process machines in the indoor environment have high levels of sound power levels. Machines with high sound power levels (spinning ring machine – Rieter G-33 – has 103 dB sound power level) and surface elements with low sound absorption coefficients have caused high sound pressure levels. Testo 816-1 sound level meter (IEC 61672-1 Class 2) and occupational health and safety services dosimeters were used for acoustics measurements. Acoustic measurements in accordance with ISO 9612:2009 standard were carried out in the textile industry plant. The measurements revealed varying minimum-maximum sound pressure levels and the equivalent continuous sound level in different sections (Table 5). It was determined that the highest noise level in the plant was in the ring spinning and

Table 5. Acoustic measurements results in textile industry plant.

Measure no.	Acoustic measurements				Departments of the plant
	$L_{\min}$ dB(A)	$L_{\max}$ dB(A)	$L_{C,\text{peak}}$	L_{eq} dB(A)	
1	74.9	90.5	102.7	79.2	Blowroom-carding
2	73.6	85.5	100.3	76.1	Draw frame
3	72.2	82.5	96.0	76.5	Combing
4	76.3	85.8	97.7	80.1	Flyer
5	80.5	91.9	103.8	83.6	Ring yarn
6	77.9	82.3	96.7	79.8	Bobbin
7	71.3	76.2	89.4	74.3	Knitting
8	79.9	91.8	102.9	88.2	Open-end yarn
9	63.4	66.5	81.4	64.6	Sanforizing
10	70.9	80.5	92.3	72.9	Drying
11	71.7	74.1	87.8	72.8	HT 400 Boiler (painting)
12	77.5	84.4	96.8	80.8	Dry reversal
13	76.2	77.7	91.4	77.1	Yarn transfer

open-end spinning production departments. Noise exposure levels were found to be at high levels in parallel with the determined LA. Noise exposure levels in the range of 88.8 dB(A)–90.1 dB(A) ($L_{\text{EX,8h}}$) in the department of ring spinning and 86.9 dB(A)–92.8 dB(A) ($L_{\text{EX,8h}}$) in the department of open-end spinning were calculated.

There are 20 Rieter G-33 ring machines in the ring-spinning section which is accepted as the cross-sectional area. The cross-sectional area is 53.3 m × 44.4 m, and 4 m in height. The section is approximately 10 412 m^3 (Fig. 3). The section has a suspended ceiling covering the air conditioning ducts. Reinforced concrete prefabricated vertical supports divide the working area into two systems. The section area is located after the flyer section. The ring spinning section is separated from the bobbin, knitting, and control rooms by dividing structural elements and operates independently. There are dividing walls (brick and plaster) on the long sides of the production area. Glass partitions separate the production area from the bobbin section (Fig. 2).

The production area was modeled in three dimensions in the SketchUp. Room acoustic modeling requirements were taken as the basis for modeling the in-plant properties. The necessary surface definitions were made in the 3D model, and the acoustic model was transferred to the acoustic computer simulation program (ODEON Auditorium) via the plugin (SU2Odeon). The acoustic performance of the current situation (digital acoustic twin) was created with the model transferred to ODEON Auditorium. The mate-

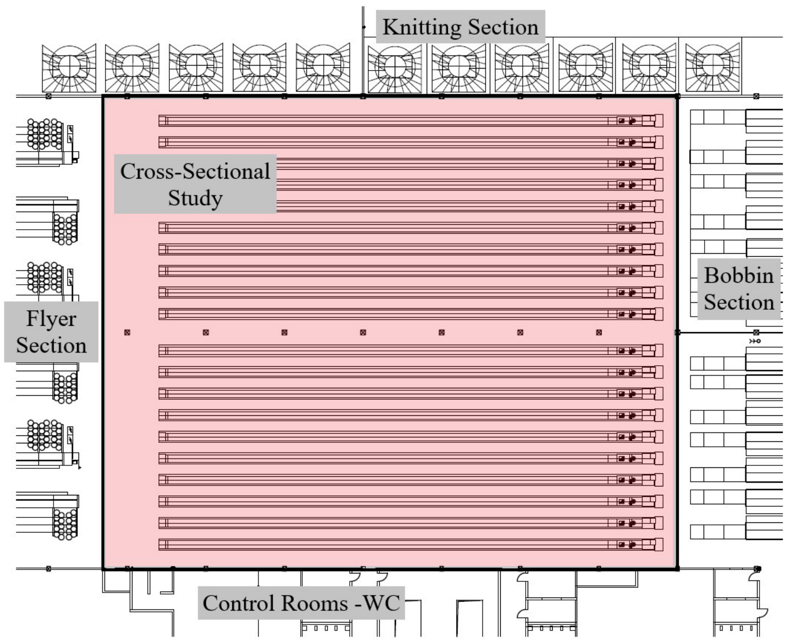

Fig. 2. Ring spinning section of the case study, cross-sectional study.

rials and surface absorptions used in the model were prepared following acoustic measurements. The building component separating the flyer and ring spinning sections obtained by zoning is defined as glass.

While creating the digital acoustic twin of the production area, acoustic calculations made indoors were utilized. The LAs obtained in acoustic measurements were checked, and acoustic performance values were obtained in real situations. In the acoustic measurements, the highest noise level among the ring-spinning machines in the indoor environment was determined as 91.9 dB(A). Digital acoustic twin indoor sound pressure levels were created as a minimum of 91.5 dB(A), maximum of 92.1 dB(A), and average of 91.9 dB(A).

Due to the high levels of noise exposure in the textile industry plant examined, the need for improvement of acoustic performance in the indoor environment has emerged. Indoor LA, NR, and RT were analyzed by changing the parameters affecting indoor acoustic performance on the digital acoustic twin. As a result of the analysis, acoustic improvements that are easy to implement and provide high efficiency were prioritized. The improvements, materials, and applications are presented, and acoustic performance values are determined. In the textile industrial plant, a composite material with a trapezoidal sheet on one side, a perforated sheet on the other side, and a rockwool-filled core (interlayer) was selected for the suspended ceiling. The fact that the composite material is lightweight, applicable, and cheap has proven to be effective. Additionally, the selected material is non-combustible (A2–s1, d0) and resistant to impacts and pressure. The ceiling material was not used in air conditioning duct lines. On the walls, special sound absorption systems consisting of rock wool panels covered with aluminium-vinyl materials were used. The fact that the materials are lightweight, easy to install and have high sound absorption properties has been effective. Additionally, the special sound absorption system is a non-combustible material (A2–s1, d0) and is resistant to impacts and pressure (Table 6).

As a result of acoustic improvements in the ring-spinning section of the textile industry plant as a case study, the indoor minimum LA was determined as 82.7 dB(A), the maximum LA as 83.4 dB(A), and the average sound pressure level as 83.1 dB(A) (Fig. 3). As a result of acoustic improvements, the indoor RT (T30) was calculated as 0.54 s at 500 Hz, and 0.54 s at 1000 Hz (Fig. 3). The difference between the LA (NR) obtained as a result of acoustic improvements and the existing situation in the ring-spinning section selected for the case study was calculated as 8.7 dB. The values were found following the reference values in the regulation.

Table 6. Sound absorption coefficients of materials used in acoustic improvements.

Materials	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	α_w
Floor (industrial floor-concrete)	0.02	0.02	0.03	0.03	0.03	0.04	0.07	0.07	0.05
Vertical structural elements (prefabricate concrete)	0.01	0.01	0.01	0.02	0.02	0.02	0.05	0.05	0.05
Walls* (rockwool panel)	0.12	0.47	0.47	0.85	0.84	0.64	0.62	0.62	0.70
Separators between sections* (rockwool panel)	0.12	0.47	0.47	0.85	0.84	0.64	0.62	0.62	0.70
Zoning – separator* (rockwool panel)	0.12	0.47	0.47	0.85	0.84	0.64	0.62	0.62	0.70
Transition between sections (plastic curtain)	0.8	0.8	0.9	0.9	0.9	0.9	0.1	0.1	0.1
Ceiling* (composite panel)	0.3	0.55	0.8	1	1	0.9	0.9	0.9	1
Ceiling (air conditioner ducts)	0.8	0.8	0.9	0.9	0.9	0.9	0.1	0.1	0.1

*It indicates new materials used in acoustic improvement phase.

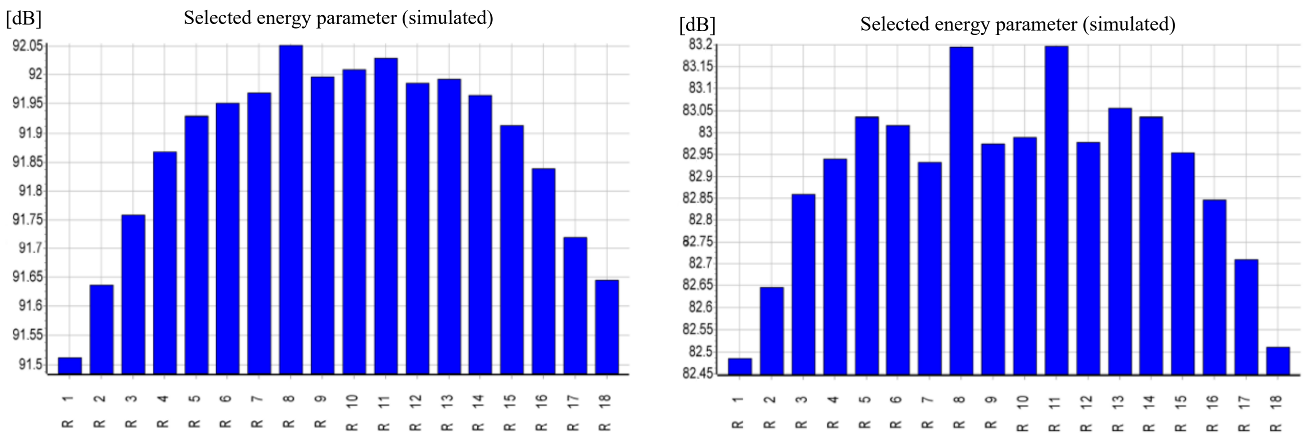

Fig. 3. Average sound pressure level before improvement (left), and after improvement (right).

Table 7. Comparison of acoustic simulation and prediction model results.

Acoustics measurement		Acoustics improvements (acoustics simulation / ODEON)			Acoustics improvements (prediction model)		
Average sound pressure level	Daily noise exposure level	LA	NR	RT (500 Hz)	LA	NR	RT (500 Hz)
LA	$L_{\mathrm{EX,8h}}$	LA	NR	$\mathrm{RT}_{500\,\mathrm{Hz}}$ (T30)	LA_1	NR_1	$\mathrm{RT}_{500\,\mathrm{Hz}_1}$ (T30)
91.9	90.1	83.4	8.7	0.54	82.64	7.05	0.28

To test the validity of the prediction model, comparative research was carried out on the case study used in problem identification. In the comparative research, in the first phase, the existing situation of the plant was calibrated through the simulation program; a digital acoustic twin was created; and then acoustic improvements were made. In the second phase of the comparative research, acoustic improvements were organized in the existing textile industry plant according to the prediction model created (Eqs. (14)–(16)). For both phases, independent variables were investigated in the same method, and dependent variables were transferred. In the acoustic improvements, the limit values determined by the regulation were taken as the basis. In the prediction model, depending on the characteristics of the case study, the equations for square planned plants with flat frequency of machine sound power levels-1 were used (Table 7);

$$\begin{aligned}\mathrm{LA}_1 &= 91.9 - 0.001A - 0.22h + 0.034n\\&\quad - 3.65w_{\alpha_w} - 4.97c_{\alpha_w},\\\mathrm{LA}_1 &= 91.9 - 0.001\cdot 2.389.63 - 0.22\cdot 4\\&\quad + 0.034\cdot 20 - 3.65\cdot 0.6 - 4.97\cdot 0.9,\\\mathrm{LA}_1 &= 82.64\ \mathrm{dB(A)},\end{aligned}\tag{14}$$

$$\begin{aligned}\mathrm{NR}_1 &= 2.36 - 0.12h + 2.66w_{\alpha_w} + 3.98c_{\alpha_w},\\\mathrm{NR}_1 &= 2.36 - 0.12\cdot 4 + 2.66\cdot 0.6 + 3.98\cdot 0.9,\\\mathrm{NR}_1 &= 7.05\ \mathrm{dB},\end{aligned}\tag{15}$$

$$\begin{aligned}\mathrm{RT}_{500\,\mathrm{Hz}_1} &= 1.86 + 0.015d + 0.25h\\&\quad - 2.52w_{\alpha_{500\,\mathrm{Hz}}} - 2.07c_{\alpha_{500\,\mathrm{Hz}}},\\\mathrm{RT}_{500\,\mathrm{Hz}_1} &= 1.86 + 0.015\cdot 53.34 + 0.25\cdot 4\\&\quad - 2.52\cdot 0.6 - 2.07\cdot 0.9,\\\mathrm{RT}_{500\,\mathrm{Hz}_1} &= 0.28\ s.\end{aligned}\tag{16}$$

It was found that the difference between the result values of the prediction model prepared to be applied in the textile industry plants and the result values of the digital acoustic twin is at acceptable levels. The differences can be explained by the fact that for the digital acoustic twin, the data can be entered into the computer simulation program in detail, while in the prediction model setup, descriptive data are obtained by calculations. Additionally, the coefficients of determination (R^2) in the equations used in the calculation estimations for the accepted independent variables also reveal the success of the prediction model. It is envisaged that the prediction model construct can be used in textile industry plants as well as in textile industry plants in the design and planning phase.

4. Results and discussion

In the research, scenario plants were created to analyze acoustic improvements in textile industrial plants. In the scenario plants, architectural properties, and source-transmission path-receiver characteristics were defined as independent variables (input data); LA, NR, and $\mathrm{RT}_{500\ \mathrm{Hz}}$ were defined as dependent variables (output data). As a result of the research, the findings were obtained through MLR models and comparative analyses of the scenario plants for acoustic improvements.

Textile machines with high sound power levels have been identified in textile industry plants. Due to the identification of sound sources, indoor LAs were obtained at high levels (above 85 dB(A)) following real situations. Moreover, the plan geometry (square or rectangular) of the main production area in the scenario plant did not have a decisive influence on the analysis and improvement of the acoustic performance.

The LAs were found to be low in a relatively small area and volumes provided that the number of machines per area [m^2] in the main production areas remained constant. This situation is considered to be related to the reduction of sound sources. For this purpose, it is necessary to make small divisions within the main space for the function of textile industry plants, and then subdivisions/zoning should be created within the divisions. Approximately 2.5 dB NR in sound pressure levels was achieved with each sub-division (1/2 ratio). However, for indoor acoustic performance improvements in textile industry plants, frequency spectrum distributions of sound sources should be determined, and noise control measures should be developed. In the scenario plants, the reverberant sound field is intervened in the NR based on increasing the total absorption of the environment by using the surface absorption, and the A-weighted sound pressure levels of the indoor environment are reduced. In the scenario of textile industry plants, depending on the vari-

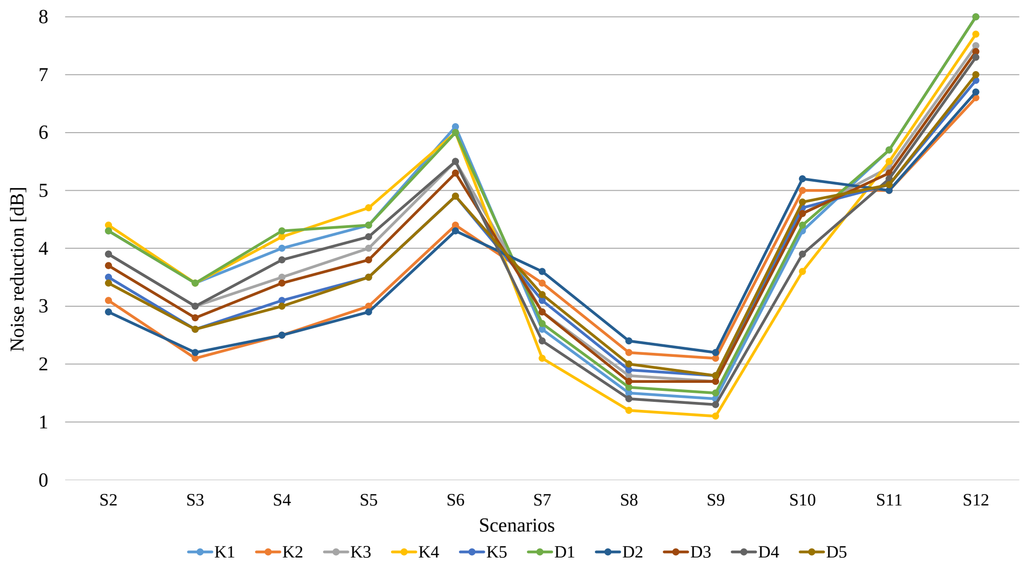

Fig. 4. NR on sound absorption in KX/DXY1F1SXA1 scenarios.

ables, a maximum NR of 8 dB was achieved based on the surface absorption (example of comparative analysis: K1–D5 / difference between S2–S12 and S1 – see Fig. 4).

In NR with the indoor surface absorption, the effect of the ceiling on NR in plants with large areas and volumes is greater than that of the wall (K4–D4 scenarios). In the total absorption, the use of materials with the same weighted sound absorption coefficient in the ceiling (1600 m^2) and walls (total of 2240 m^2) was investigated separately. In the analysis, based on the medium absorption (α_w: 0.5) in the S2–S7 scenarios, absorption values of 800 m^2 Sabine for the ceiling, and 1120 m^2 Sabine for the walls were created separately. As a result of the analysis, it was concluded that the ceiling is more effective in NR than the walls. It was determined that the difference in NR values in the ceiling and walls was between 1.5 dB–2.5 dB (example of comparative analysis: K4/D4Y2F2SXA1 / difference between S2–S12 and S1 – see Fig. 5). While less sound absorptive material was used in the ceiling than in the walls, ceilings were more effective in total NR. In contrast to this situation, in plants with small areas and volumes, the effect of walls in NR is more effective than the ceiling. While fewer sound-absorptive materials were used on the walls than on the ceiling, the walls were more effective in total NR. With the increase in volume, the distances between the sound

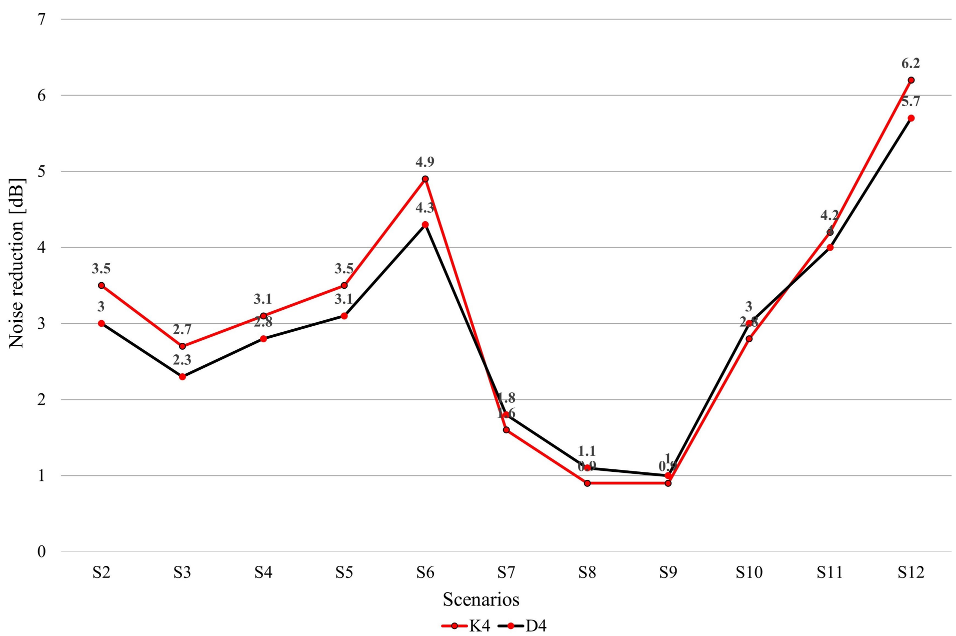

Fig. 5. Effect of ceiling-walls on NR in K4/D4Y2F2SXA1 scenarios.

source and the building components affect the distribution of sound pressure levels and NR. This analysis limits the use of the NR equation based on the sound absorption (Eq. 17):

$$\mathrm{NR} = 10 \log \frac{A_2}{A_1}, \tag{17}$$

where NR is the noise reduction in the room [dB], A_2 is the total volume absorption after improvements (Sabine), and A_1 is the total absorption before improvements (Sabine).

The height as architectural properties in the scenario plants is decisive for the indoor acoustic environment. As the height increases in the plants, indoor LAs decrease. The increase in height allows the sound waves to propagate in a larger area and volume, which leads to a decrease in the sound energy reaching the receiver. Increasing the ceiling height within the scope of acoustic improvements gives effective results in NR. In the scenarios examined (scenarios with medium areas and scenarios with large areas), it was found that the ceiling was more effective than the walls in NR (example of comparative analysis: K1–K3–K5 scenarios / difference between S2–S12 and S1 – see Fig. 6).

In the scenarios examined (scenarios with medium areas and scenarios with large areas), it was found that the ceiling was more effective than the walls in NR. Additionally, the use of canopy absorbers in the ceiling (S4 scenarios) provides the best performance in NR (S3–S5 scenarios). Moreover, the effect of different positioning of sound absorptive materials used in the walls in textile industrial plants (lower-upper section) on LAs and NR was found to be very low.

In the scenario plants, RT analyses were performed at medium frequencies (500 Hz and 1000 Hz). The RT as a property of the interior space does not depend on the sources (more precisely, the sources have a minimal impact due to their sound absorption and as acoustic barriers). In the RT analyses, the live room (S1 – high sound reflection), the scenario with medium absorption of ceiling and walls (S11), and the dead room (S12 – high sound absorption) were evaluated (Table 4). Very high RTs (in the range of 3 s–6 s) were detected in the live room scenarios. In scenarios where the ceiling and wall planes were designed with medium absorption (α_w: 0.5), RTs were calculated at 0.5 s–2 s levels. Low RTs (0.5 s–1 s) were found in dead room scenarios (Fig. 7). The high RTs lead to an increase in sound pressure levels in the plants.

As a result of MLR analyses, the area and height of the plant, the number of machines, and the weighted sound absorption coefficients of the walls and ceilings were effective in determining the indoor LAs. Additionally, the short edge length of the plant was also effective in determining the LA in rectangular plants. The height of the plant and the average wall and ceiling weighted sound absorption coefficients were effective in NR. In RTs, the depth and height of the plant and the average wall and ceiling weighted sound absorption coefficients were effective. The length of the plant refers to the length of one edge in square-planned plants, while it refers to the length of the short edge in rectangular-planned plants. Acoustic improvement prediction models and acoustic simulations were comparatively tested in the case study, and the prediction model was found to be successful.

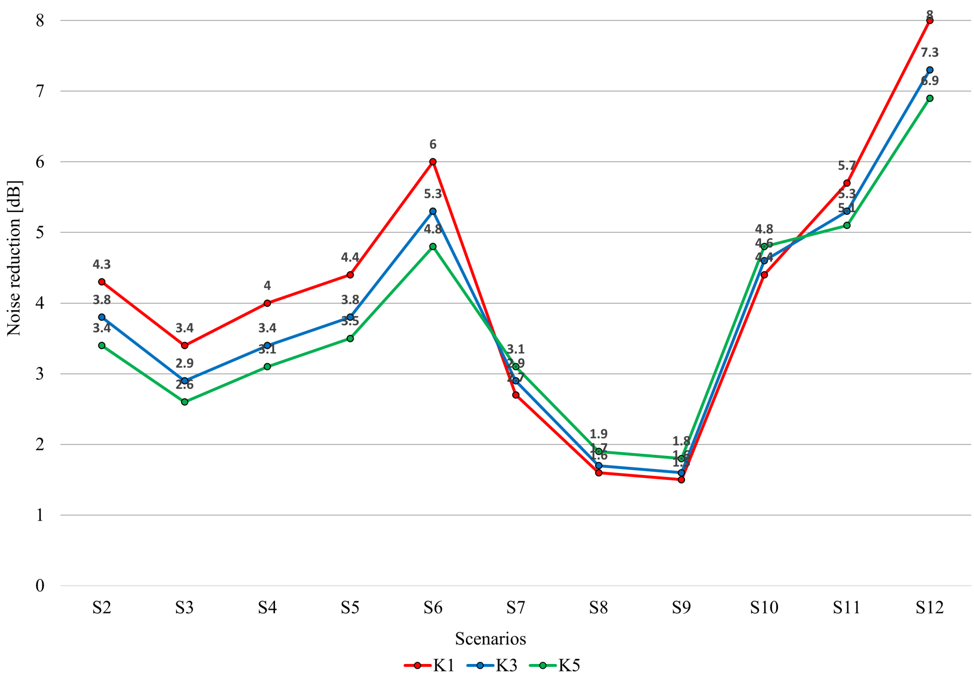

Fig. 6. Effect of height on NR in K1/K3/K5/Y2F2SXA1 scenarios.

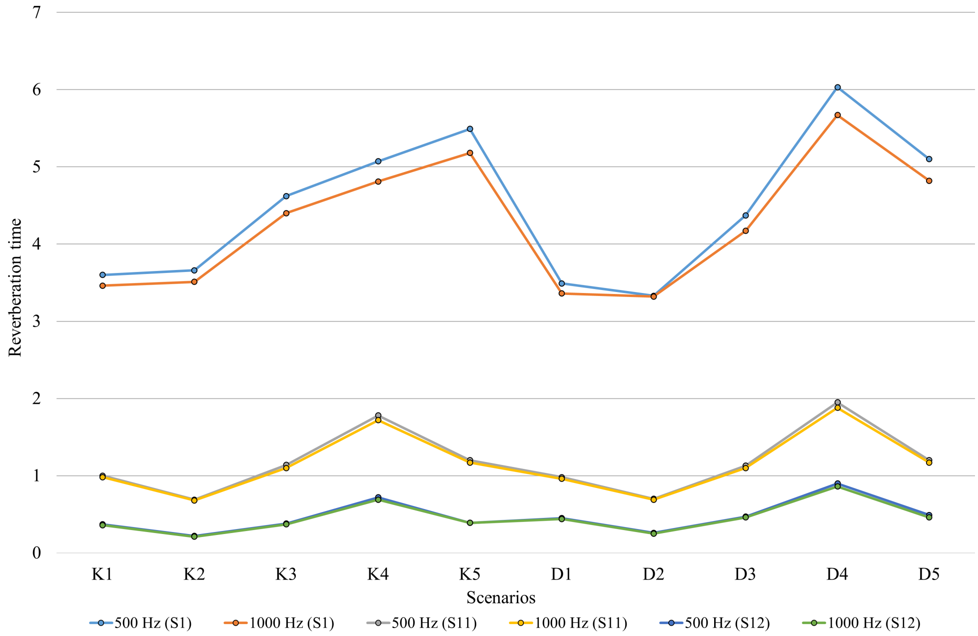

Fig. 7. RT analysis on KX/DXY1F1SXA1 scenarios.

5. Conclusion

This study is part of a wide research involving acoustic improvements for the reduction of high noise levels in textile industry plants. To develop this aim, it should be supported by different noise control mechanisms and detailed with the textile machine design. The study was carried out with scenario plants located in the Republic of Türkiye and determined in the literature review. Different scenario plants created depending on the architecture properties and source-transmission-receiver characteristics were analyzed in the ODEON Auditorium, and LAs, NR, and RTs were analyzed.

In the scenario plant analysis, it has been determined that the plant geometry does not affect *A*-weighted sound pressure levels and NR. Depending on the number of machines per place in the plants, the larger the plant, the more cumulative sound sources, and the higher the indoor sound pressure level. For this purpose, it is necessary to divide the plants into small parts and make zoning. In the acoustic analysis of the plants, a NR of up to 8 dB was achieved by using the surface absorbers. However, the wall and ceiling effectiveness of NR varies. In NR, the ceiling is effective in spaces with a large plan and volume, while the walls are effective in spaces with a relatively small plan and volume. However, as the height increases in the main production area, the decreases are seen in the LA, and as an effect of this situation, effective results are obtained in NR. The lower and upper positioning of the sound absorptive materials used in the walls (facade lighting and ventilation requirement) do not have a decisive variable for the indoor acoustic environment. It is important to control the RT depending on the surface absorption in textile industry plants. However, it was not found appropriate to be evaluated as an acoustic parameter in industrial plants. As a result of the regression analysis, calculation equations were created to predict the LA, NR, and RT at 500 Hz (dependent variables). The prediction model has been comparatively tested with the application of acoustic simulations and calculations over the case study, and its reliability and validity have been provided. In the model, LAs, NR, and RTS can be estimated with the improvements made in textile industry plants and optimum acoustic comfort conditions are created for employees.

This paper represents a starting point for several future works. It would be appropriate to take noise control precautions for machine designs that are not included in the research, construct vibration isolation, and detail the noise control precautions that can be taken at the design phase in future studies to develop the topic. Moreover, preferring different room acoustics simulation programs, using optimization methods and information technologies, and developing methodological tools based on machine learning will also contribute to the research topic.

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