An Investigation Into The Acoustic Conditions Of An Open Plan Office Located In Ankara

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ABSTRACT

In order to maintain the high productivity in open offices, which are commonly preferred work environments of modern time, acoustic conditions should be optimized. Especially if work carried out within the premises demands full attention of the employees in open offices, ill-conditioned acoustic conditions can result in loss of concentration and hence degradation in the labor productivity. In this study, one of the open plan offices of Middle East Technical University Registrar's Office was investigated in terms of its acoustic properties, according to the standardization document ISO 3382-3 parameters and reverberation time parameter. In order to determine the parameters, the office was analyzed with real-size measurement on site and simulated with Odeon 10.02 software. Measured results were compared with the simulated results and assessed.

Keywords: Open plan offices, room acoustic, speech privacy I-INCE Classification of Subjects Number(s): 51.7

1. INTRODUCTION

While open plan offices commonly preferred in today's world to facilitate the teamwork and the communication between the colleagues, acoustic problems are amongst the disadvantages of such offices. On the condition that acoustic comfort is not provided, problems such as lack of privacy, degradation in the labor productivity and loss of concentration arise.

Especially if the works in open plan offices are based on cognitive sources or require high concentration, intelligible speech often results in distractions or has a negative effect on the labor productivity. Apart from these, speech privacy may not be facilitated in open plan offices. In this case, low speech intelligibility, that is, speech privacy between working units, is desired (1).

2. METHOD

In this study, open plan office of Middle East Technical University Registrar's Office was analyzed with real-size measurement on site and simulated using Odeon 10.02 software. For this purpose, acoustic measurements and simulations are carried out in accordance with room acoustics parameters in ISO 3382-3. The average A-weighted background noise level and reverberation time (T_{30}) of the office are measured. On site sound pressure level measurements were made in order to calculate spatial decay rate of A-weighted SPL of speech ($D_{2,S}$) and A-weighted sound pressure level of speech at a distance of 4 m ($L_{p,A,S,4m}$). Speech transmission index (STI) at the nearest workstation, T_{30} and DL_2 (equivalent of $D_{2,S}$ under ISO 3382-3) were also simulated via Odeon 10.02 simulation software. Simulated results and results of the measurements are comparatively evaluated.

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3. ACOUSTIC ANALYSIS OF OPEN PLAN OFFICE OF MIDDLE EAST TECHNICAL UNIVERSITY REGISTRAR'S OFFICE

The building of Registrar's Office of Middle East Technical University was designed by Behruz Çinici as a whole along with the rectorate building.

3.1 General Information about the Open Plan Office

The office to be analyzed is on the first floor of the building of registrar's office. It has 20.5 meters of length and approximately 6.5 meters of width (Figure 1). The total volume of the office is 320 m³.

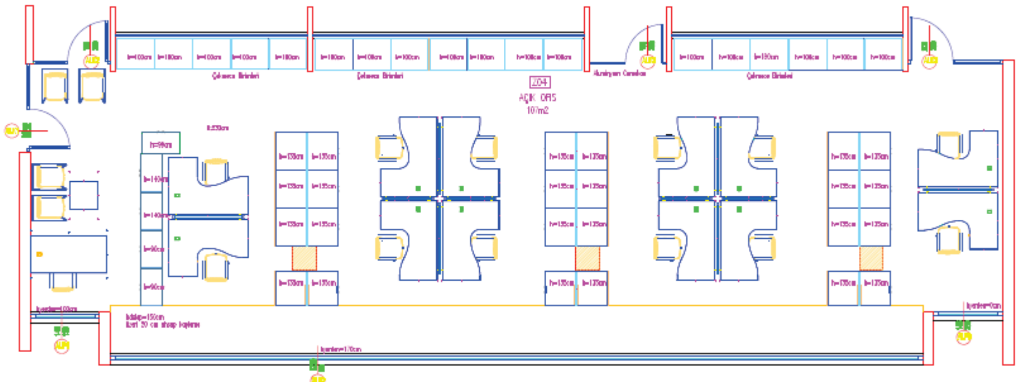

Figure 1. The office in Registrar's Office of Middle East Technical University

The open plan office is furnished intensely and not homogenously. There are 2 working groups of 4 people, 2 working groups of 2 people and a single work table; masking sounds (music sounds) are not used. A total of 13 people work in the office.

3.2 Analysis and Evaluation by means of On Site Measurement Method

3.2.1 Measurement, analysis and evaluation of background noise level ($L_{p,A,B}$):

Measurements of background noise level were made in accordance with ISO 3382-3. Measurements are carried out within working hours when air conditioning was on, and workers were outside the office (11.30-12.00). Measurements were made three times and for 15 seconds for each position (Figure 2). They were made by hand-held sound level meter, Brüel&Kjaer Type 2239B. A-weighted sound pressure level was measured at each measurement position, $L_{p,A,B}$ was determined, and average background noise level was calculated.

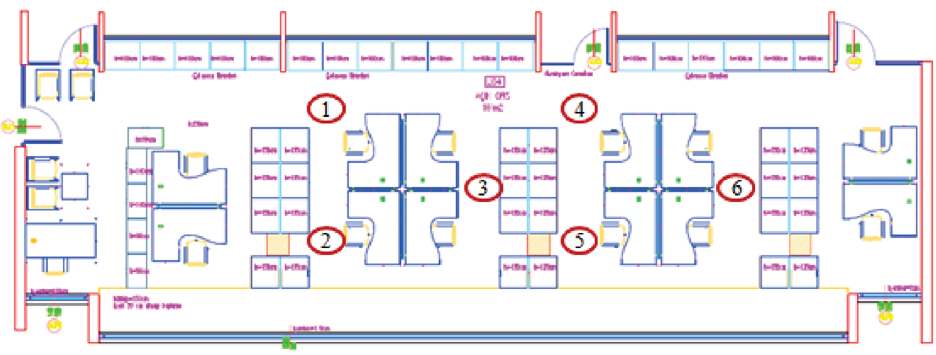

Figure 2. Measurement positions for background noise level

It was found that average A-weighted background noise level for the entire analyzed office ($L_{p,A,B}$) is 36,6 dB(A). It was observed that background noise level is under NC-30 in compliance with the literature (Table 1).

Table 1. NC values and dBA equivalents (2)

Type of Room	Preferred range for noise criterion (NC curve)	Equivalent sound level, dBA
Open plan offices	Between NC-30 and NC-40	38-48

3.2.2 Measurement, analysis and evaluation of sound pressure level for determining spatial decay rate of A-weighted sound pressure level of speech ($D_{2,S}$):

$D_{2,S}$ parameter is the rate of spatial decay of A-weighted sound pressure level of speech per distance doubling in an open plan office (1).

Spatial decay rate of A-weighted sound pressure level of speech is determined when sufficient amount of sound power level arising from sound source per distance doubling is measured in the manner ISO 3382-3 describes at measurement position n. On site measurement results are applied to the equations of the standard and speech spectrum mentioned in the standard is taken into account (1).

As the farthest measurement distance for $D_{2,S}$ parameter depends on the dimensions of the room, it is advisable to obtain the measurement results at a distance between 2 meters and 16 meters. Sound pressure levels in the office were measured at 12.5 m length due to intensive furnishing. An omnidirectional source was used to generate sound. Pink noise is generated for at least 16 non-stop seconds from the source in 1/3 octave bands between 100Hz and 8000 Hz for each receiver position. The source and the receivers were located at 1.2 m height, which equals to the height of a sitting worker's ear. The source and the receivers were located at least 2 meters farther than walls and 0.5 meter farther than tables. Two measurement lines were determined in the office. One source was used for each measurement line and the first measurement position was located at the nearest workstation on the measurement line. As described in ISO 3382-3, measurement lines were set up in the manner that they crossed over each workstation in the office. The sources were located at two opposite endpoints of each measurement line as office layout is on a single line (Figure 3). It was taken into account that it is required to make measurements at least 4 measurement positions for each line. Measurements of sound pressure level were made when the office was unoccupied.

Thereby, all measurement conditions were brought in compliance with the requirements of ISO 3382-3.

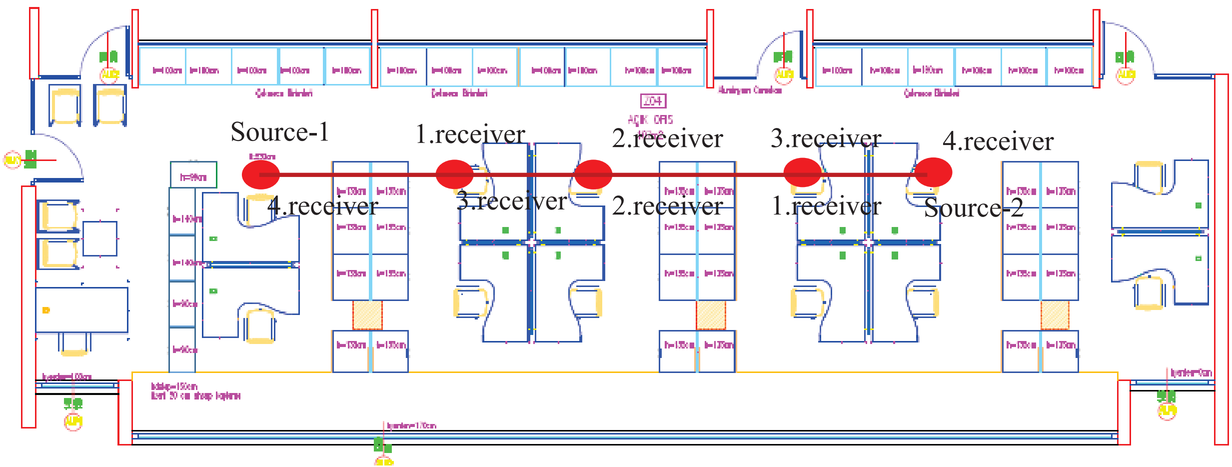

Figure 3. Measurement positions of sound pressure level, for determining $D_{2,S}$ parameter

The measurement was set up in compliance with the standards and by using Brüel&Kjaer equipments;

- Source (122dB-re:1 pW)
- 2734-A Power amplifier (500 W)

- 4192 ½-inch receiver
- 2669-B microphone preamplifier was used.

While the sound power level of the omnidirectional loudspeaker ($L_{w,LS}$) was determined the sound pressure level in each octave band needs to be 6 dB higher than background noise level even at the farthest measurement position in the office (1). To ensure the condition is satisfied, the measured sound pressure levels are compared with the background noise level.

SPL values in octave bands are determined at the receiver locations. As described in ISO 3382-3, the values are used in equations 1-5 by benefiting speech spectrum. The same method was used to calculate DL_2 parameter (equivalent of $D_{2,S}$ under ISO 3382-3), in an article (3) published by Virjonen et al.

The sound pressure levels of speech (average of female and male speech) at a distance of 1 m in free field from the speaker ($L_{p,S,1m,ff}$) and the A-weighted of octave bands depend on the ANSI S 3.5-1997 (R 2007) standard and is shown on Table 2 (1).

Table 2. Values of the sound power levels of speech ($L_{w,S}$) and the sound pressure level of speech at a distance of 1 m in free field from the speaker ($L_{p,S,1m,ff}$) (1).

Band No	Frequency	Sound Power Level $L_{W,S}$	Sound Pressure Level $L_{p,S,1m,ff}$		A-weighting A
			Directional Source	Omnidirectional Source	
i	Hz	dB re 1 pw	dB re 20 µPa	dB re 20 µPa	dB
1	125	60,9	51,2	49,9	-16,1
2	250	65,3	57,2	54,3	-8,6
3	500	69,0	59,8	58,0	-3,2
4	1 000	63,0	53,5	52,0	0,0
5	2 000	55,8	48,8	44,8	1,2
6	4 000	49,8	43,8	38,8	1,0
7	8 000	44,5	38,6	33,5	-1,1
	A-weighed	68,4	59,5	57,4	

In this study, the sound pressure level at a distance of 1 m in free field ($L_{p,Ls,1m,ff}$) from the omnidirectional loudspeaker ($L_{w,Ls}$) was determined using equation 1 (1).

$$L_{p,Ls,1m,ff}i = L_{w,Ls}i + 10\log\frac{1}{4\pi\times1{,}0^2} \approx L_{w,Ls}i - 11\text{dB} \qquad (1)$$

Where
$L_{p,Ls,1m,ff}{}^{i}$ = The sound pressure level at a distance of 1 m from the loudspeaker in free field
$L_{w,Ls}{}^{i}$ = The sound power level of the omnidirectional loudspeaker
^{i} = octave band
ff= free field

The sound power levels of the omnidirectional loudspeaker ($L_{w,Ls}$) are determined through the standards of ISO 3740 series (ISO 3741, ISO 3743-1, ISO 3743-2, ISO 3744 and ISO 3745) by benefiting measurements of sound pressure level (1). The sound power levels of the loudspeaker ($L_{w,Ls}$) were calculated (4) from measurements in the office and were applied to the equation 1.

$$D_n i = L_{p,Ls,1m,ff}\, i - L_{p,Ls,n}\, i \qquad (2)$$

$D_n{}^{i}$= the attenuation at measurement point n
$L_{p,Ls,1m,ff}{}^{i}$ = The sound pressure level at a distance of 1 m from the loudspeaker in a free field
$L_{p,Ls,n}{}^{i}$ = the sound pressure level at measurement point n
^{i} = octave band
ff= free field

Being valid for sound power level of any source, $D_n{}^i$ (the attenuation at measurement point n) is applied to the sound power level of speech ($L_{w,S}$).
Sound pressure level of speech in octave bands ($L_{p,S,n}{}^i$) was determined in equation 3.

$$L_{p,S,n}i = L_{p,S,1m,ff}i - D_n i \quad (3)$$

$L_{p,S,n}{}^i$ = Sound pressure level of normal speech
$L_{p,S,1m,ff}{}^i$ = the sound pressure level of normal speech at a distance of 1 m in free field from the the speaker (The value obtained from table 2)
$D_n{}^i$ = the attenuation at measurement point n
^{i} = 1/1 octave band
ff= free field

Finally, the A-weighted speech level $L_{p,A,S,n}$ was calculated by adding A weight value to each octave band.

$$L_{p,A,S,n} = 10\log\left(\sum_{i=1}^{7} 10^{\frac{L_{p,S,n}i + A^i}{10}}\right) \quad (4)$$

$L_{p,A,S,n}$ = the A-weighted speech level in position n
$L_{p,S,n}{}^i$ = is the sound pressure level of normal speech in position n
A^i = is verified from Table 2.
^{i} = 1/1 octave band

After A-weighted speech level had been determined for measurement positions, equation 5 was applied, and $D_{2,S}$ parameter was determined.

$$D_{2,S} = -\log(2)\frac{N\sum_{n=1}^{N}\left[L_{p,A,S,n}\log\left(\frac{rn}{r0}\right)\right] - \sum_{n=1}^{N} L_{p,A,S,n}\sum_{n=1}^{N}\log\left(\frac{rn}{r0}\right)}{N\sum_{n=1}^{N}\left[\log\left(\frac{rn}{r0}\right)\right]^2 - \left[\sum_{n=1}^{N}\log\left(\frac{rn}{r0}\right)\right]^2} \quad (5)$$

$D_{2,S}$ = spatial decay rate of A-weighted SPL of speech
$L_{p,A,S,n}$ = the A-weighted speech level in position n
n = the index number of the single measurement position
N = the total number of measurement positions
r_n = the distance to measurement position n
r_0 = the reference distance, 1 m

Following the processes, it was found that spatial decay rate of A-weighted SPL of speech ($D_{2,S}$) in the office was 4,98 dB (Table 5). The effect of partition panels in the office is evaluated by means of this parameter (5).
If $D_{2,S} < 5$ dB, an open plan office has poor acoustic conditions; if $D_{2,S} \geq 7$ dB, an open plan office has good acoustic conditions (1). In this context, it could be stated that the open plan office investigated is relatively poor in terms of acoustics. This proves the private speech of the worker sitting on the first table could be heard from the workstation, and the absorption of partition screens in the office is insufficient. The interviews with the workers also verify these results.

3.2.3 Measurement, analysis and evaluation of sound pressure level for determining A-weighted sound pressure level of speech at a distance of 4 m ($L_{p,A,S,4m}$):

A-weighted speech level at a distance of 4 m ($L_{p,A,S,4m}$) is determined if one of the receiver is located at a distance of 4 m from the source (1).
It is shown by means of $L_{p,A,S,4m}$ parameter that how much the source level is influenced by nearby reflecting surfaces (5). In this context, the receiver and the source were located according to ISO 3382-3, and the same conditions as sound pressure levels measurements were maintained to assess $D_{2,S}$.
It was found that A-weighted sound pressure level of speech at a distance of 4 m ($L_{p,A,S,4m}$) was 52,29 dB when the first 4 equations were applied in the case where the parameter for spatial decay rate of A-weighted SPL of speech ($D_{2,S}$) was determined (Table 5).

According to ISO 3382-3, If $L_{p,A,S,4m} > 50$ dB, an open plan office has poor acoustic conditions. If $L_{p,A,S,4m} \leq 48$dB, an open plan office has good acoustic conditions (1). In this context, acoustic comfort is affected negatively by the intensive furnishing of the office, the small distance between the tables and the cabinets, the reflectivity of the close materials and these result in the intelligibility of private speech between the workers from the next table.

3.2.4 Measurement, analysis and evaluation of reverberation time (T_{30}):

Measurements of reverberation time of the office were made according to ISO 3382-2 (1). The omnidirectional source was used in measurements as in the case of other measurements. The number of the sources was predetermined as 1, and that of the receivers was 6. The receivers were located 0.7 m farther from the other reflective surface. They were also located in the manner that they apply to the whole room (Figure 4.)

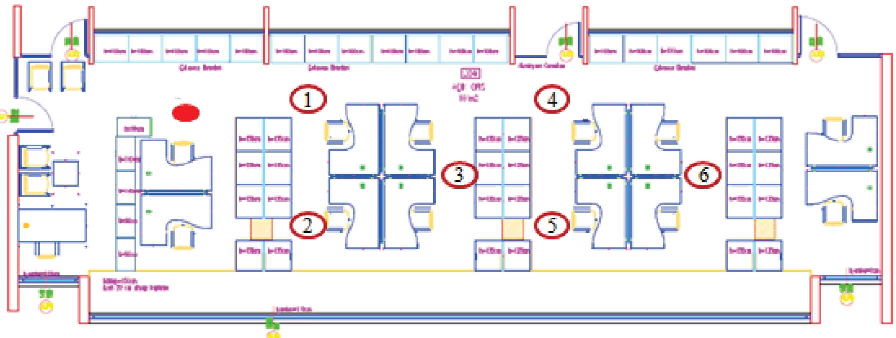

Figure 4. Measurement positions for reverberation time

Reverberation time (T_{30}) values determined in low, medium and high frequencies are demonstrated below in the measurements (Table 3).

Table 3. Measurement results for reverberation time

Results of the measurement	Low Frequencies (125-250 Hz)	Medium Frequencies (500-1000Hz)	High Frequencies (2000-4000Hz)
T_{30}	0.64 s	0.54 s	0.57 s

It was known that reverberation time is applicable between 0.6 s and 1.00 s (6)

Table 4. Values of reverberation time for speech when the rooms are unoccupied (7)

Room Volume (m^3)	Reverberation Time $T_{30\ (500Hz)}$ (s) (For speech)
50	0.4
100	0.5
200	0.6
500	0.7
1000	0.9
2000	1.0

The volume of the investigated office is 320 m^3. In this context, it was proved that reverberation time of the office is not applicable (Table 5).

Although reverberation time of the analyzed office was below the limiting value, it was confirmed by means of the analysis of $D_{2,S}$ parameter that absorbers, shortening the reverberation time of the room, were not neatly placed to maintain the absorption between the tables.

Table 5: Results and assessment of measurements

Criteria for performance	Optimum Values			Findings	Statement
$L_{p,A,B}$, Background noise level	38-48 dBA (2)			36,6 dBA	Convenient
$D_{2,S}$, spatial decay rate of A-weighted SPL of speech	If $D_{2,S}$ < 5 dB, poor office (1)			4,98 dB	Not convenient for speech privacy.
	If $D_{2,S} \geq$ 7 dB, good office (1)				
$L_{P,A,S,4m}$, A-weighted sound pressure level of speech at a distance of 4 m	If $L_{p,A,S,4m}$ > 50 dB poor office (1)			52,29 dB	Not convenient for speech privacy.
	If $L_{p,A,S,4m} \leq$ 48dB good office (1)				
T_{30} (500Hz), Reverberation Time	V	200 m^3	0.6 s (7)	0.53 s (V=320 m^3)	Not convenient
		500 m^3	0.7 s (7)		

3.3. Analysis and Evaluation By Computer Simulation

The investigated office was modelled on SketchUp2014, the model was transferred to the simulation software, Odeon 10.02 (8).

3.3.1. Analysis and evaluation of DL_2 (equivalent of $D_{2,S}$) by means of computer simulation:

DL_2 parameter is the rate of spatial decay of sound pressure level per distance doubling for a given range of distances (9).

When measurement conditions in ISO 14257 Standard were investigated, it was found that DL_2 parameter is similar to $D_{2,S}$ according to the measurement conditions. In this regard, the second sources and receivers were located (10) by copying the simulation file including the first sources and receivers with ODEON 10.02 simulation software, and DL_2 was simulated (Figure 5-6).

It was found that DL_2 parameter is averagely 4,34 dB (Figure 5-6). For this parameter, if DL_2 >4 dB, it means the office has recommended acoustic features. In this context, it was deducted that DL_2 parameter is not applicable for the investigated office because it is too close to the limiting value (Table 6).

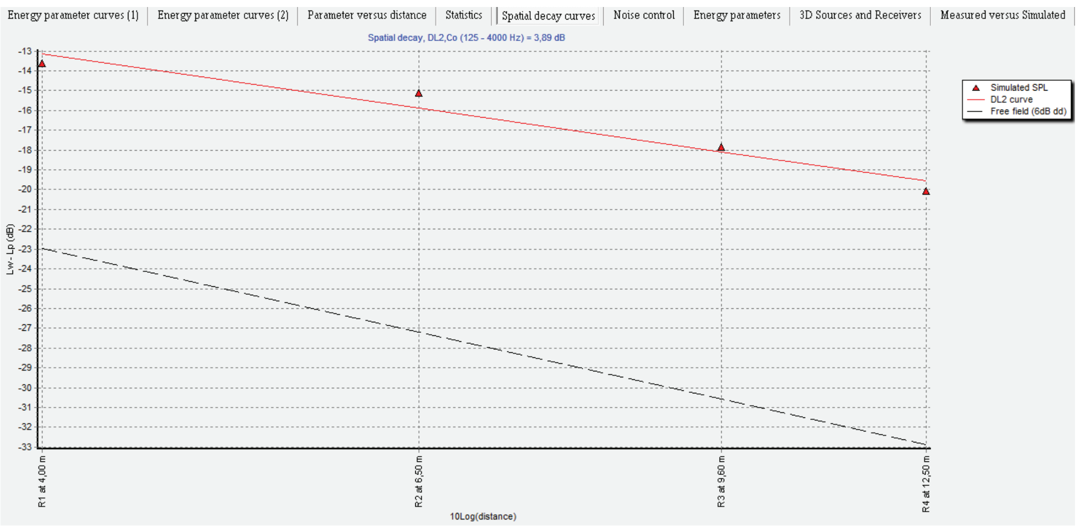

Figure 5. Simulation of the first measurement line for DL_2 parameter

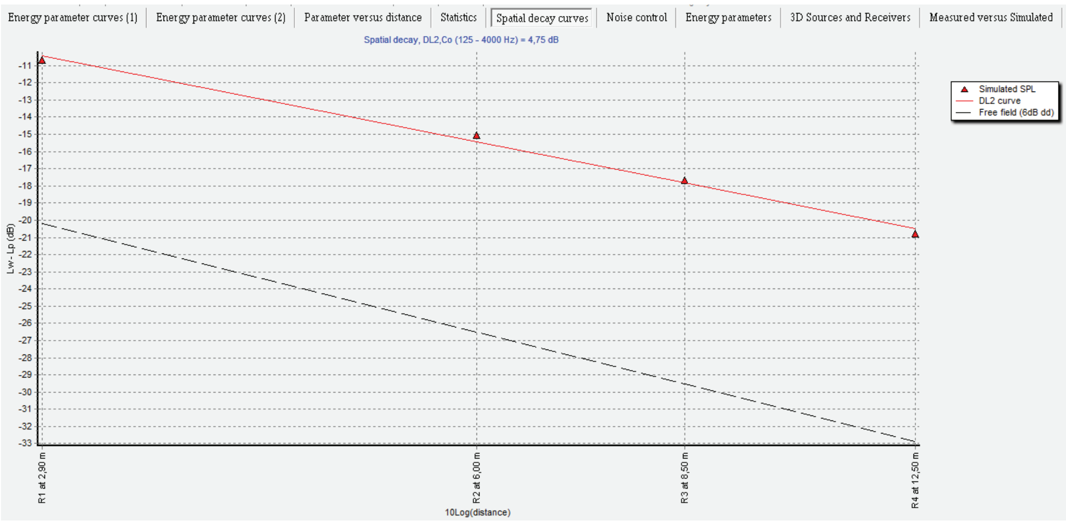

Figure 6. Simulation of the second measurement line for DL_2 parameter

3.3.2. Analysis and evaluation of speech transmission index (STI) parameter by means of computer simulation:

Simulation of room acoustics parameter speech transmission index (STI) developed in order to detect the speech intelligibility, was made in the manner that it maintains measurement conditions in ISO 3382-3 standard.

It was determined that STI parameter is 0,72 at the nearest working position for the first measurement line, and STI is averagely 0,69 (Figure 7).

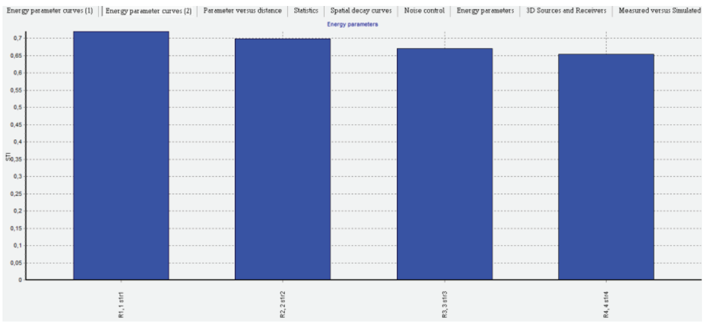

Figure 7. Simulation results of the first measurement line for STI parameter

It was determined that STI parameter is 0,74 at the nearest working position for the second measurement line, and STI is averagely 0,68 (Figure 8).

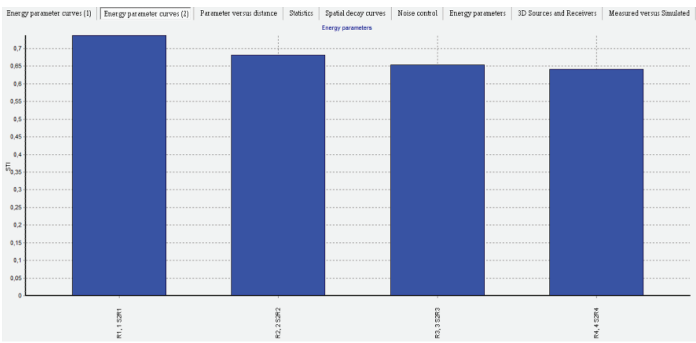

Figure 8. Simulation results of the second measurement line for STI parameter

As the irrelevant speech, which is also intelligible in open plan offices, often arouses interest and distracts attention, which is seen as one of the reasons of the degradation in the labor productivity (1). It is desired that STI go down below 0,50 in the office according to ISO 3382-3. In this context, the office is poor in terms of speech privacy because STI does not go down below 0,50 at any receiver position (Table 6).

3.3.3. Analysis and evaluation of distraction distance (r_D) and privacy distance (r_p) by means of computer simulation:

When speech transmission index (STI) parameter falls below 0,50, the distance between the source and the receiver is r_D. This distance is defined as the distraction distance. When speech transmission index (STI) parameter falls below 0,20, the distance between the source and the receiver is r_P (1).

The value of STI parameter did not fall below 0,50 at any distance (Figure 7-8). According to ISO 3382-3, if $r_D > 10$m the open plan office is acoustically poor. Likewise, if $r_D \leq 5$m, the open plan office is acoustically good. In this context, the distance where STI value falls 0,50, in other words, the value of r_D parameter has to be below 5 m in order to maintain the privacy in an open plan office. However, STI parameter for 2 sources and 2 measurement lines did not fall below 0,50 or 0,20.In these circumstances, r_P parameter could not be presented, and the investigated office is decided to be poor in terms of speech privacy. Likewise, all the irrelevant speech can be understood in the office and result in loss of concentration. The interviews with the workers also verify this case.

3.3.4. Analysis and evaluation of reverberation time (T_{30}) parameter by means of computer simulation:

In this study, the same conditions were maintained for measurement and simulation of analysis of reverberation time (T_{30}) parameter. In this context, it was found that T_{30} parameter is averagely 0.55s at 500 Hz. Simulation results for this parameter verify the findings and are not between limiting values (Table 6).

Table 6. Simulation results and analysis

<table>
<tr><th>Criteria for Performance</th><th colspan="3">Optimum Values</th><th>Findings</th><th>Statement</th></tr>
<tr><td>DL_2 rate of spatial decay of sound pressure levels per distance doubling</td><td colspan="3">If DL_2 >4 dB it is a good office (9).</td><td>4,34 dB</td><td>Being too close to the limiting value, it was deducted to be not applicable.</td></tr>
<tr><td>STI, Speech transmission index (at the nearest workstation)</td><td colspan="3">STI < 0,50 (1).</td><td>0,73</td><td>Not applicable</td></tr>
<tr><td rowspan="2">r_D , distraction distance and r_P, privacy distance</td><td colspan="3">If $r_D > 10$m, poor office (1)</td><td rowspan="2">STI parameter for 2 sources and 2 measurement lines did not fall below 0,50 or 0,20.</td><td rowspan="2">Not applicable</td></tr>
<tr><td colspan="3">If $r_D \leq 5$m, good office (1)</td></tr>
<tr><td rowspan="2">$T_{30\ (500Hz)}$, Reverberation Time</td><td rowspan="2">V</td><td>200 m^3</td><td>0.6 s (7)</td><td rowspan="2">0.55 s</td><td rowspan="2">Not applicable</td></tr>
<tr><td>500 m^3</td><td>0.7 s (7)</td></tr>
</table>

4. CONCLUSIONS

In this study, an open plan office of Middle East Technical University was chosen as an example. The acoustic conditions of the office were investigated according to parameters of ISO 3382-3 standard and reverberation time. In this context, the office was investigated by means of real-size measurement on site and Odeon 10.02 simulation software, and the results are summarized on Table 7.

It was concluded that in the office STI value is high, and the irrelevant speech is intelligible. The intelligible speech of the workers also distracts their attention during working hours. The absorbing materials are not located at the right positions; hence, the speech of the first workstation is intelligible from the other workstations and the speech privacy of the workers is not maintained sufficiently. Finally, because the furnishing is made up of tall metal cabinets with high reflectivity, acoustic comfort is not sufficient as desired in the office.

In order to maintain the acoustic comfort in the office, the early reflections could be prevented by avoiding the use of metal cabinets. In addition, transmission of the speech in the room could be reduced by increasing the absorption of the partition screens. Apart from these, the absorption of the materials in the office should be rearranged. Although reverberation time parameter is lower than the limiting value; it was observed that the absorbing materials are not located at the right positions, and reverberation time parameter in open plan offices is not solely a sufficient measurement parameter. In order to maintain the speech privacy in this open plan office the parameters in the standard (1) should be arranged at proper intervals.

Table 7: Measurement and Simulation Results

	Measurement	**Simulation**	**Assessment**
$T_{30(500Hz)}$ Reverberation Time	0.53 s	0.55 s	Not Applicable
$L_{p,A,B}$, Background noise level	36,6 dBA	-	Applicable
$D_{2,S}$/DL_2	4,98 dB	4,34 dB	Not Applicable
$L_{P,A,S,4m}$ A-weighted sound pressure level of speech at a distance of 4 m (dB)	52,29 dB	-	Not Applicable
STI , Speech transmission index	-	0,73	Not Applicable
r_D	-	It was observed that STI parameter did not fall below 0,50 or 0,20 at any receiver position.	Not Applicable

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ABBREVIATINS AND SYMBOLS

dB	Decibel- Unit of sound pressure level
dBA	Unit of A-weighed sound pressure level
Hz	Hertz
i	Octave band
T_{30}	Reverberation Time
$L_{p,A,B}$	Average A-weighted background noise level
$D_{2,S}$	Spatial decay rate of A-weighted SPL of speech
$L_{P,A,S,4m}$	A-weighted SPL of speech at a distance of 4m
STI	Speech transmission index at the nearest working
r_D	Distraction distance
r_P	Privacy distance
DL_2	Rate of spatial decay of sound pressure levels
ff	Free field
$L_{w,Ls}$	The sound power level of the loudspeaker
$L_{w,S}$	The sound power level of speech
$L_{p,S,1m,ff}$	The sound pressure level of normal speech at a distance of 1 m in free field from the speaker
$L_{p,Ls,1m,ff}\,i$	The sound pressure level at a distance of 1 m in a free field from the loudspeaker in octave bands

$\mathbf{L}_{w,\mathrm{Ls}}i$	The sound power level of the loudspeaker in octave bands
$\mathbf{D}_{\mathbf{n}}i$	Attenuation in octave bands at measurement position n
$\mathbf{L}_{\mathrm{p,Ls,n}}\ i$	The sound pressure level at measurement point n in octave bands
$\mathbf{L}_{p,\mathrm{S,n}}{}^{i}$	The sound pressure level of normal speech in position n in octave bands
$\mathbf{L}_{p,\mathrm{S,1m,ff}}{}^{i}$	the sound pressure level of normal speech at a distance of 1 m in free field from the speaker in octave bands
$\mathbf{L}_{\mathrm{p,A,S,n}}$	The A-weighted speech level in position n
$\mathbf{A}^{i}$	A-weight in octave bands
n	The index number of the single measurement position
N	The total number of measurement positions
$\mathbf{r}_{\mathbf{n}}$	The distance to measurement position n
$\mathbf{r}_{0}$	The reference distance, 1 m

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