The sensitivity estimation in simulation modeling by changing the "diffuse reflection coefficient" input

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Summary

The output data sensitivity referred to the input variation in a calculation code developed for the Room Acoustics analysis is the main goal of the paper; in particular for this study CATT-Acoustic commercial software is used.
The paper is focused on the variation of the sound perception connected to the reverberation time output data by changing the diffuse reflection coefficient input data and the degree of model geometric discretization of its volume.
Consequence is the identification of a trend to estimate the output variation in relation with the diffuse reflection coefficient values. It represents a support in the analysis of the acoustic response of confined spaces, especially in the concept phase, when the real space doesn't exist yet, and there is no possibility to carry out measurements on site to compare with the simulation model results.

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1. Introduction[1]

The sensitivity of the software to the variation of the input data Diffuse Reflection Coefficient is analyzed for 6 case studies: Ristori Theatre (Verona It), Astana Opera Theatre (Astana Kk), Milan Auditorium (Milan It), Auditorium Sant'Antonio and Santa Marta (Morbegno It), San Massimilian Chearch (Bergamo It), Foligno Auditorium (Foligno It). The paper focuses on the Reverberation Time output as the main indicator for the acoustics quality of confined spaces.
Two indicators are defined: the Sensitivity and the Deviation related to the jnd (Just Noticeable Difference), together with a new factor, the so called Diffuse Reflection Factor, FRD.
This last factor indicates the "weight" of the sound-reflecting surfaces characterized by sound diffusion in comparison with the total surfaces of the room space, to which the sensitivity of the output is correlated.
For every case study 7 simulations are reported.

1.1. Sensitivity and Deviation

The sensitivity is defined as follows:

$$Se = \Delta output / \Delta input \qquad (1)$$

it evaluates if the system amplifies (Se> 1) or dampens (Se <1) by changing an input; it estimates if a system is explosive or implosive.
The Deviation is referred to the following equation:

$$Sc = \frac{Output_i - Outp_{ref}}{Output_{ref}} \qquad (2)$$

The subscript ref indicates the reference value. The equation indicates the relative offset of a quantity according to the reference one, it quantifies the output variation without highlighting what is caused by it.
Within this discussion an important reference are the jnd explained in the ISO 3382 standard [1]. The jnd or the Just Noticeable Difference represent the minimum difference perceptible to the human ear at the central frequencies 500-1000 Hz. The norm provides a table to identify them. For the parameter Reverberation Time T_{30}, one JND is equal to 5%.
In this case studies the Sensitivity is defined by the Reverberation Time parameter as output and by the Diffuse Reflection Coefficient as input:

$$Se = \frac{|T_{Li} - T_{Lprogetto}|}{L_i - L_{10\%}} \quad (3)$$

The Deviation is defined by the difference between the Reverberation Time referred to a diffusive coefficient L_i (T_{Li}) and the Reverberation Time referred to the possible real project input ($T_{Lprogetto}$),

$$Sc = \frac{T_{Li} - T_{Lprogetto}}{TL_{progetto}} \quad (4)$$

As better specified in the following paragraphs.

1.2. The Diffuse Reflection Factor

The Diffuse Reflection Factor, DRF is defined as:

$$DRF = \frac{\sum reflecting\ surfaces\, with\, diffusion}{S_{tot}} \quad (5)$$

It indicates the "weight" of the sound-reflecting surfaces characterized by diffuse sound reflection (curved surfaces or corrugated profiles) on the total surfaces of the room space to which the sensitivity of the output is correlated.
A Discretization Index is also defined:

$$I_D = \frac{n\_planes}{Vtot} \quad (6)$$

Where n is the number of planes utilized to discretize the room surfaces and V_{tot} is the volume of the room.

2. Prediction analysis

In the Prediction analysis, 7 simulations are proposed for every case study.

Table I. Diffuse reflection coefficient referred to simulation from 1 to 7

Sim	1	2	3	4	5	6	7	
% L	$L_{progetto}$	10	20	30	45	60	125 Hz	20
							250 Hz	30
							500 Hz	30
							1 kHz	45
							2 kHz	45
							4 kHz	60

In the simulation n°1 ($T_{Lprogetto}$) the sound absorption coefficients and the diffuse reflection coefficients are chosen from the literature, with reference to the surface materials of the room, represent the input data (where L it is not specified the software default value of 10% is introduced).
The main absorption coefficients and diffuse reflection coefficients proposed by the literature [2], with reference to the surface materials of the different halls are reported in the following table [3]:

Table II. absorption coefficients and diffuse reflection coefficients with reference to the main surface materials of the different halls

	ABSORPTION COEFFICIENT and DIFFUSE REFLECTION COEFFIENT L					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Audience: moderately upholsterd chairs	55 L 30	86 L 40	83 L 50	87 L 60	90 L 70	87 L 70
Slightly vibrating walls *	2 L 10	3 L 10	3 L 20	4 L 25	4 L 30	5 L 30
Ceiling: Hard surfaces	2	2	3	3	4	5
Floor made of wood on studs	28	21	1 5	12	11	11
polyester fibreboard panels,	20	30	80	98	98	98
*L is applied to curved surfaces						

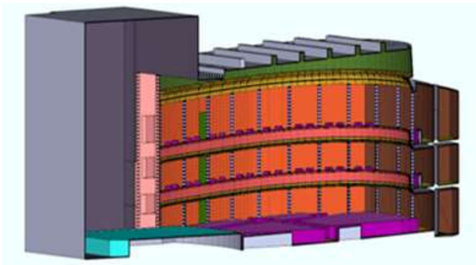
In the simulation from 2 to the 6 the audience input doesn't change as well as the other input absorption coefficients while the other diffuse reflection coefficients increase from a simulation to the other. In simulation 7 the diffuse reflection coefficients differ by octave band, from lower to higher values.

2.1. The simulation models

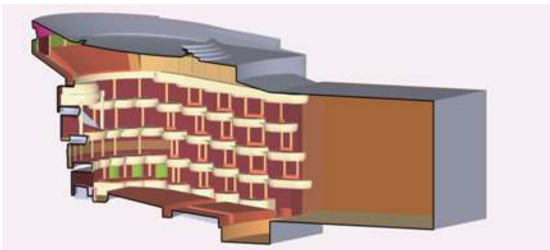
Two models with different Discretization Index are studied for each Theater, a so called "simplified model" and a "detailed model" [4].
Only one model is analyzed for the other case studies [5].

Table III. Simulation models

Ristori Theater
Volume: 7559 m^3; Seats number: 600
Simplified model:
N° discretization Surfaces: 3698
I_D = 0,49; DRF = 0,21
Detailed model:
N° discretization Surfaces: 8296
I_D = 1,09; DRF = 0,19

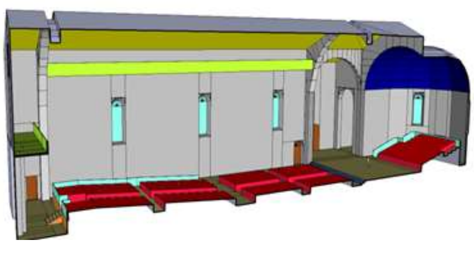


Astana Opera House
Volume: 15.345 m^3, Seats number: 1500
Simplified model:
N° discretization Surfaces: 4983
I_D = 0,32; DRF = 0,38
Detailed model:
N° discretization Surfaces: 17438



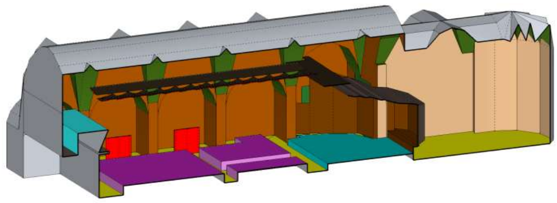
I_D = 1,12; DRF = 0,20

Foligno Auditorium
Volume 18061 m^3, Seats number: 530

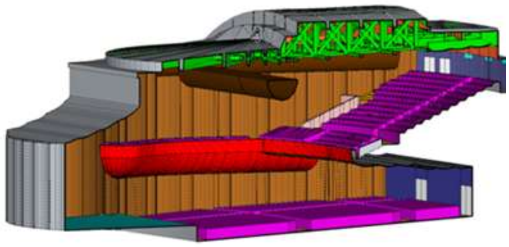


N° discretization Surfaces: 1264
I_D = 0,07; DRF = 0,02

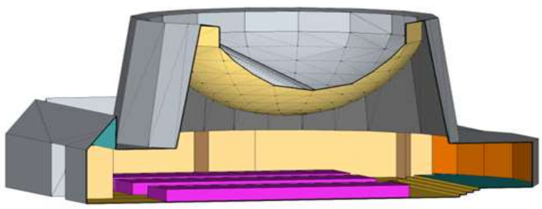
Auditorium Sant'Antonio e Santa Marta
Volume 6617 m^3, Seats number: 400
N° discretization Surfaces: 8956
I_D = 0,09; DRF = 0,08



Auditorium Milano
Volume 8796 m^3, Seats number: 1250
N° discretization Surfaces: 8956
I_D = 1,02; DRF = 0.29



San Massimilian Church
Volume 4785 m^3, Seats number 400
N° discretization Surfaces: 573
ID = 0,12; DRF = 0,28



2.2. Ristori Theatre – simplified model

This case study represents a damping system independently from the value of the diffusion coefficient.
The diffuse reflection coefficient variation doesn't influence the sound perception in the listeners, because it never reaches the value of 1 JND.
The following table shows the Se and Sc values (just for two of the 6 analyzed octave bend from 125 Hz to 4 kHz because of synthesis necessities).
The figures represent the Sc and the T_{30} trend in relation with the different L values.

Table IV. Sensitivity Se and Deviation Sc referred to different diffuse reflection coefficient L

	500 Hz			2 kHz		
%L	T_{30}	Se	Dev	T_{30}	Se	Dev
-	1,45		-	1,37		-
10	1,47	-	1,38	1,38	-	0,73
20	1,45	0,20	0,00	1,35	0,30	1,46
30	1,45	0,10	0,00	1,37	0,05	0,00
45	1,45	0,06	0,00	1,36	0,06	0,73
60	1,46	0,02	0,69	1,35	0,06	1,46

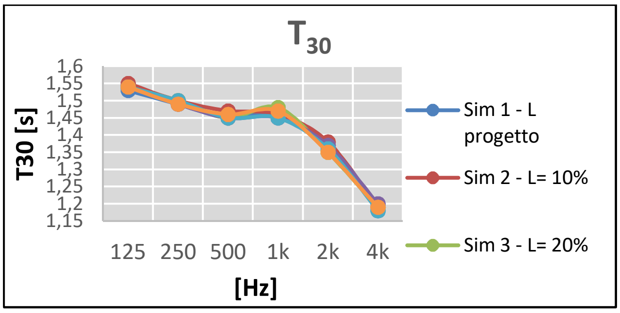


Figure 1. T_{30} trend from sim. 1 to sim. 7

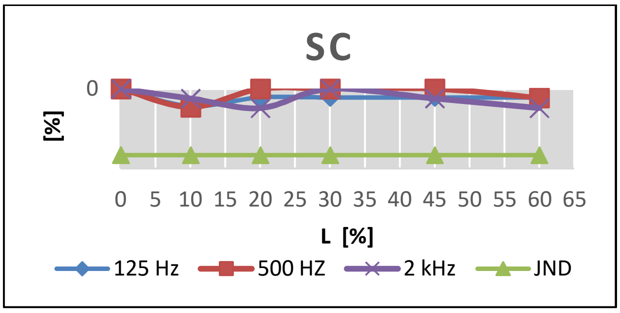


Figure 2. T_{30} Deviation

2.3. Ristori Theatre – detailed model

In this case study, compared to the previous one, a greater sensitivity to the variation of the diffuse reflection coefficient appears, and a greater deviation of the T_{30}, especially at high frequencies. The system is implosive.

Table V. Sensitivity Se and Deviation Sc referred to different diffuse reflection coefficient L

	500 Hz			2 kHz		
%L	T_{30}	Se	Sc	T_{30}	Se	Sc
p	1,47		-	1,35		-
10	1,52	-	3,40	1,4	-	3,70
20	1,49	0,30	1,36	1,39	0,10	2,96
30	1,47	0,25	0,00	1,38	0,10	2,22
45	1,45	0,20	1,36	1,38	0,06	2,22
60	1,45	0,14	1,36	1,37	0,06	1,48

From Figure 4 it is possible to see how, even for this case study, with the varying of the diffuse reflection coefficients, the sound perception does not change. With a diffuse reflection coefficient equal to 10%, a maximum deviation is obtained at medium and high frequencies and a minimum one at low frequencies.

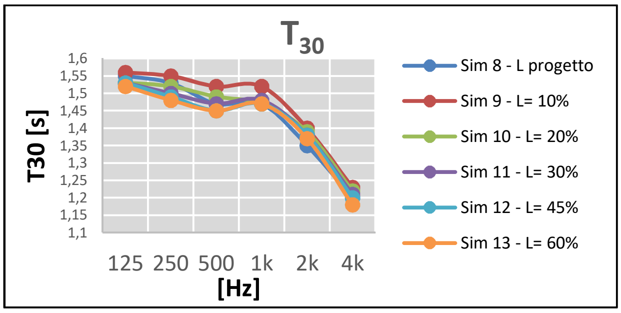


Figure 3. T_{30} trend from sim.1 to sim. 7

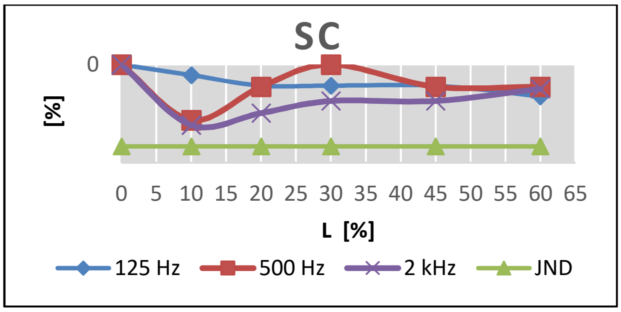


Figure 1. T_{30} Deviation

2.4. Astana Opera House – simplified model

In the following table VI, the model shows a high deviation at medium and high frequencies referred to low diffuse reflection coefficients, and a high sensitivity (the system becomes explosive).

This behavior is due to the numerous curved surfaces to which a diffuse reflection coefficient is assigned.

Table VI. Sensitivity Se and Deviation Sc referred to different diffuse reflection coefficient L

	500 Hz			2 kHz		
% L	T_{30}	Se	Sc	T_{30}	Se	Sc
p	1,64		-	1,59		-
10	1,79	-	9,15	1,75	-	10,06
20	1,76	0,30	7,32	1,61	1,40	1,26
30	1,66	0,65	1,22	1,58	0,85	0,63
45	1,64	0,43	0,00	1,53	0,63	3,77
60	1,58	0,42	3,66	1,53	0,44	3,77

It is noted the sound perception varies, going beyond a jnd by setting a reflection coefficient between 5% and about 23%.

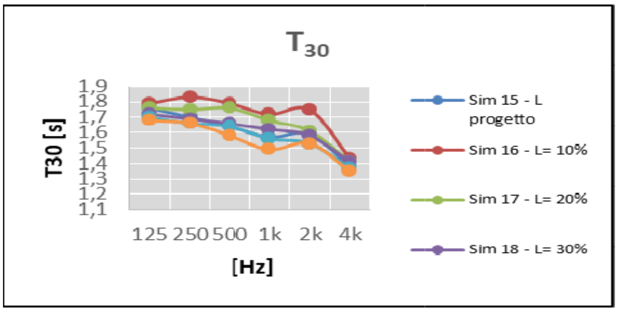


Figure 5.T_{30} trend from sim.1 to sim. 7

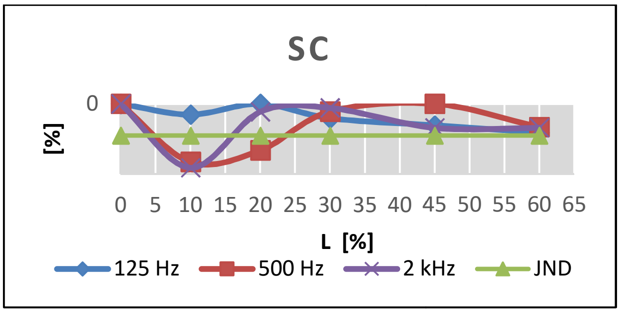


Figure 6. T_{30} Deviation

It will be seen later how much the sensitivity and the variation of diffuse reflection depends on the ratio between the number of curvilinear and scabrous surfaces and the total surfaces used to define the room model and the corresponding degree of discretization, ie the FRD factor and the ID index defined above.

2.5. Astana Theatre – detailed model

It is confirmed a deviation at high frequencies due to low diffuse reflection coefficients. Deviation appears also at the central frequencies for high diffuse reflection coefficients, in which the system is implosive.
From the figures below it is noticed how a variation of the diffused reflection coefficient does not cause a variation in the perception of the sound in the listener.

Table VII. Sensitivity Se and Deviation Sc referred to different diffuse reflection coefficient L

	500 Hz			2 kHz		
% L	T_{30}	Se	Sc	T_{30}	Se	Sc
-	1,71		-	1,6		-
10	1,72	-	0,58	1,64	-	2,50
20	1,7	0,20	0,58	1,67	0,30	4,37
30	1,67	0,25	2,34	1,57	0,35	1,88
45	1,64	0,23	4,09	1,59	0,14	0,63
60	1,64	0,16	4,09	1,58	0,12	1,25

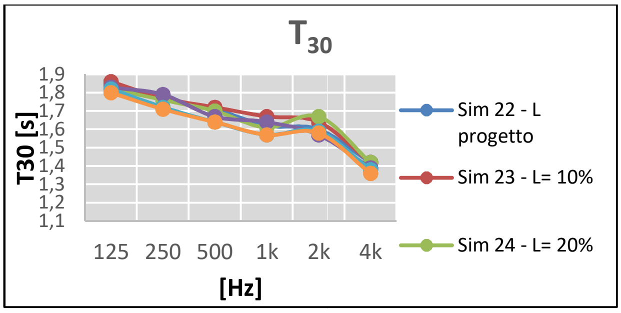


Figure 7. T_{30} trend from sim.1 to sim. 7

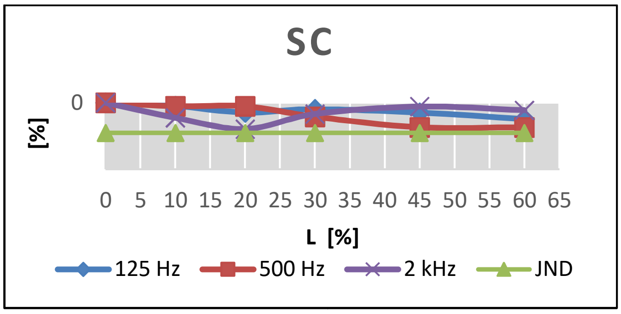


Figure 8. T_{30} Deviation

From the figures below it is noticed how a variation of the diffused reflection coefficient does not cause a variation in the perception of the sound in the listener.

2.6. Auditorium Milano

This case study is more sensitive to the diffuse reflection coefficient' variations than the previous cases.

Table VIII. Sensitivity Se and Deviation Sc referred to different diffuse reflection coefficient L

	500 Hz			2 kHz		
% L	T_{30}	Se	Sc	T_{30}	Se	Sc
-	1,68		-	1,7		-
10	1,65	-	1,79	1,67	-	1,76
20	1,61	0,40	4,17	1,63	0,40	4,12
30	1,69	0,20	0,60	1,64	0,15	3,53
45	1,66	0,03	1,19	1,66	0,03	2,35
60	1,71	0,12	1,79	1,65	0,04	2,94

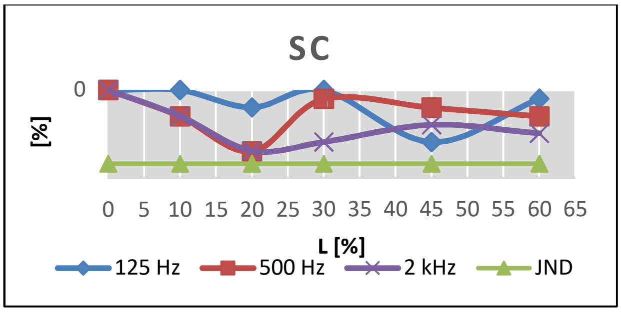


Figure 9. T_{30} Deviation

The deviation is high at high frequencies. At medium and low frequencies it fluctuates considerably. At low frequencies the deviation is bigger for high diffuse reflection coefficients, while at the middle frequencies the opposite occurs.
From the figure 9 it is noted how the variation of the reflection coefficient does not produce a variation of perception for the listener.

2.7. The other case studies

For the other models just the analysis response is reported.
In Auditorium di Sant'Antonio e Santa Marta in Morbegno, at the central frequency of 500 Hz a fluctuating deviation appears when the diffusion coefficient value increases. At high frequencies the deviation is greater for low diffuse reflection coefficients. The value of the T_{30} at low frequencies remains almost constant. In this case it is confirmed there is no change in the sound perception. It means it is independent form the diffuse reflection coefficients change.
In the Auditorium in Foligno the deviation trend is similar for all the analyzed frequencies: the greater the diffuse reflection coefficient the greater the deviation from the design value. This trend is plausible because the number of reflecting surfaces is relatively low. Also in this case the sound perception is not linked to the diffuse reflection coefficients.
The San Massimiliano Kolbe Church is a case study different from the others. A considerable deviation is noted for low diffuse reflection coefficients at all the frequencies considered. The greater the diffuse reflection coefficient, the lower the T_{30} deviation from the design value. The high FRD is noted compared to the other case studies examined. The system becomes explosive, therefore less stable, at low frequencies.

3. Conclusions

In Auditoria and Theaters characterized by the same percentage of diffuse and reflecting surfaces and sound-absorbing materials, varying the diffuse reflection coefficient does not cause a change of sound perception in the listener. In big halls, such as the church of Bergamo, in which many surfaces consist of a predominant diffusing and curvilinear material, diffuse reflection coefficient variations cause significant deviations.

In all the models characterized by the project absorption coefficients as input the T_{30} trend is similar. The T_{30} value decreases with the increase of the diffuse reflection coefficient, and it doesn't varies significantly for coefficient higher than 30 - 45%.

In general for L > 40%, T_{30} remains almost constant. For diffuse reflection coefficient about 40-45% the T_{30} tends asymptotically to a constant value.

It is noted the Sensitivity is greater by setting low diffuse reflection coefficients. The request for greater attention to the choice of lower diffuse reflection coefficients is confirmed.

It is also noted in detailed model the T_{30} values range is bigger by changing the diffuse reflection coefficient.

It is possible to find out also a trend between the DRF, the I_D, the descretizion level and the sensibility of a model.

From the six case studies it seems that, with a DRF <0,25 and a I_D $0.1<I_d<0.3$, lower discretization level models are less sensitive compared with the detailed ones; with the increasing of DRF, a simplified model becomes much more sensitive and a detailed model is much more stable as it is explained in the table below. It would be necessary much more case studies to find out a much more detailed trend[6].

References

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