Room Acoustics

Exam Assignments

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1 Acoustic Treatment of a room

1.1 Introduction

The aim of this homework was to select a large environment, determine its dimensions and current Reverberation Time, and then design an acoustic treatment to achieve an ideal reverberation time based on the chosen room.

1.2 Room choice and target time

For this project, we selected a multi-purpose room in the house of one of the group members. The room was chosen because it will be converted into a home studio for recording and mixing. For these applications, we want to keep the reverberation time low enough to ensure accurate monitoring, but not too low, in order to retain some “liveness” when recording acoustic instruments and vocals.

Given these requirements, the target reverberation time was set to $0.3s$.

Additionally, a second room, an event pavilion, will also be analyzed to have reference of a bigger room, and here we will try to reduce the reverberation time to $0.7\,s$, as it was proposed in class.

1.3 Measurements

The room is rectangular, with sides measuring $3m$ and $8m$. It is located directly below a pitched wooden roof, which doesn't significantly affect the reverberation time but helps reduce standing waves in the vertical direction. One of the long walls is completely covered by a bookshelf, which has a large impact on the acoustics by scattering reflections. The only other notable element is an upright piano. The piano can be problematic because a strong impulse may excite its strings and soundboard, causing unwanted resonances.

Measurements were performed using a balloon burst as an impulse source and recorded with a Behringer ECM8000 measurement microphone. Multiple measurements were taken, from which we extracted the T20 and T30 values and averaged them to obtain a final reverberation time of $0.5s$. This represents a good starting point for our purpose.

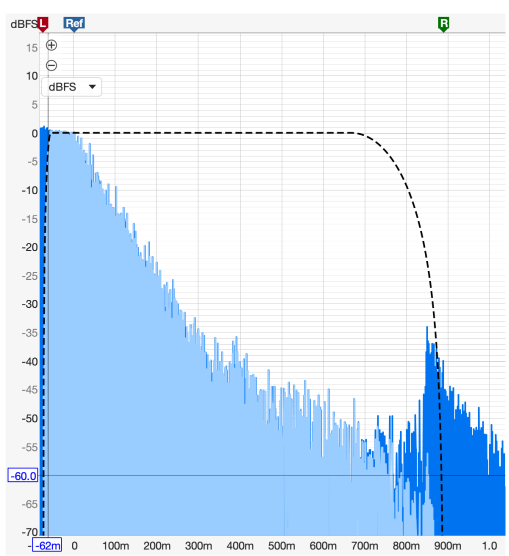


Figure 1: The graph shows the effect of the upright piano on the room. The piano resonance causes a strong peak of about 15dB relative to the noise floor (indicated by the black horizontal line). To reduce the impact of this phenomenon on the measurements, the audio file was windowed (black dotted line)

1.4 Calculations and Results

To obtain a reliable reverberation time value, multiple measurements were performed. Since the assignment specifies using 1 kHz as the reference frequency, a balloon burst was selected as the impulse source.

For each measurement, the T20 and T30 values were extracted and then averaged across all recordings. This yielded a final value of 0.50 s (rounded to two decimal places). The room volume and total surface area were calculated considering the exact geometry, resulting in a volume of 63.60 m^3 and a total surface area of 103.28 m^2.

Using Sabine's formula and these values, the current average room absorption coefficient α was determined to be $\alpha = 0.20$, an expected value for a room in a house. Various acoustic panels were then evaluated by consulting their spec sheets for the 1 kHz absorption coefficient, along with panel surface area and price, to calculate the total cost for each option. Sabine's formula was applied in reverse to determine the required absorption surface area for the target T60. This was divided by the single panel area to find the required number of panels, which was then multiplied by the unit price to obtain the total cost.

As a comparison, the "egg carton" method was also included to assess its viability.

Name	Panel absortion	Panel Surface	Panel price	Required surface	Number of panels	Total price
t.akustik HiLo-N70	0,98	0,50	€ 11,60	17,47	35	€ 406,00
t.akustik PET Wall Absorber 120	1,11	1,2	€ 119,00	14,98	13	€ 1.547,00
Temu Hexagon	0,9	0,696	€ 17,28	19,45	28	€ 483,84
Leroy Merlin	0,96	1,08	€ 39,00	17,92	17	€ 663,00
t.akustik HiLo-N40	0,63	0,5	€ 6,10	31,54	64	€ 390,40
Egg carton	0,63	10,8	€ 20,57	31,54	3	€ 61,71

Figure 2: Side-by-side comparison of treatment options for a target T60 of 0.3 s. Egg cartons are by far the cheapest option, while the other alternatives have similar costs. Note that the most expensive option (PET wall absorber) offers superior low-frequency absorption (50–500 Hz) compared to the alternatives.

To further reduce costs, the target T60 can be increased to 0.4 s. This still provides a good listening experience while enabling more budget-friendly treatments.

Name	Panel absortion	Panel Surface	Panel price	Required surface	Number of panels	Total price
t.akustik HiLo-N70	0,98	0,50	€ 11,60	6,65	14	€ 162,40
t.akustik PET Wall Absorber 120	1,11	1,2	€ 119,00	5,71	5	€ 595,00
Temu Hexagon	0,9	0,696	€ 17,28	7,41	11	€ 190,08
Leroy Merlin	0,96	1,08	€ 39,00	6,83	7	€ 273,00
t.akustik HiLo-N40	0,63	0,5	€ 6,10	12,01	25	€ 152,50
Egg carton	0,63	10,8	€ 20,57	12,01	2	€ 41,14

Figure 3: Side-by-side comparison of treatment options for a target T60 of 0.4 s. Egg cartons remain the cheapest, but the professional options are now significantly more affordable.

1.5 An additional case study

Since the chosen room is a good starting point for the selected target, we decided to expand this assignment by exploring how the treatment would apply to a larger room with a much higher reverberation time.

The selected room measures $20\,m \times 7\,m$ with a height of $4\,m$, having also a stage, bathroom and a small wall for a bar. We expect longer reverberation times due to the size, and also the materials, as floor and walls are all made of concrete.

We measured an average RT at $1\,kHz$ of $0.884\,s$, noting that in the $2-5\,kHz$ range the reverberation time rises to around $1.2\,s$. This gives us $\alpha = 0.19$, which is closer to the previous case that we would expect, but probably due to the presence of curtains, papers in the walls, and multiple objects distributed around. To set a realistic target, we chose $0.7\,s$ to maximize speech intelligibility and comfort without requiring extreme acoustic treatment measures.

Applying the same calculation method described in the previous section, we obtained the following data:

Name	Panel absortion	Panel Surface	Panel price	Required surface	Number of panels	Total price
t.akustik HiLo-N70	0,98	0,50	€ 11,60	22,34	45	€ 522,00
t.akustik PET Wall Absorber 120	1,11	1,2	€ 119,00	19,19	16	€ 1.904,00
Temu Hexagon	0,9	0,696	€ 17,28	24,84	36	€ 622,08
Leroy Merlin	0,96	1,08	€ 39,00	22,92	22	€ 858,00
t.akustik HiLo-N40	0,63	0,5	€ 6,10	39,96	80	€ 488,00
Egg carton	0,63	10,8	€ 20,57	39,9631897	4	€ 82,28

Figure 4: Side-by-side comparison of treatment options for a target T60 of 0.7 s.

As we can see, this room is more challenging to treat effectively. Still, considering the size, it happens to need much less absorbent, but of course, because the demands for a multi-purpose space like this are much lower.

We can't forget also the fact that the reverberation time was higher for frequencies between 2-5 kHz, so this treatment is just a rough estimation. Additionally, the geometry is not optimized for an even distribution, so we see very big differences between the reverberation times depending on where we measure, which is another considerable problem.

1.6 Final considerations and conclusion

The analysis reveals multiple viable options for treating the main room to achieve the target reverberation time.

However, to optimize the room specifically for home studio use, a more comprehensive analysis in the frequency domain is recommended. This should employ appropriate tools such as an omnidirectional speaker and sine sweep measurements. Such a detailed analysis would accurately identify room modes and the overall frequency response, enabling targeted treatment of resonances and selection of panels to flatten the response.

Tuned membrane absorbers represent an effective solution for addressing specific resonances and improving the room response within targeted frequency bands. Diffusers could also be incorporated to mitigate standing waves and comb filtering from early reflections reaching the listening position.

The current analysis nevertheless provides an excellent starting point that can be refined to meet the room's specific acoustic requirements.

As for the second case study, the results highlight how volume, surface materials, and construction choices heavily influence the reverberation time and treatment complexity. Achieving a balanced acoustic environment in large concrete rooms requires more extensive interventions, such as suspended ceiling panels and wall-mounted broadband absorbers, which significantly increase overall costs. This makes the inclusion of acoustic considerations in the design phase highly advisable, as it allows for more efficient and cost-effective solutions.

In conclusion, while egg cartons offer the most economical solution for basic reverberation control, professional acoustic treatments provide superior performance across frequency bands. The chosen approach should balance budget constraints with the studio's long-term acoustic goals, as well as consider the scalability and practicality of the treatment in relation to room size and intended use.

2 ECHO

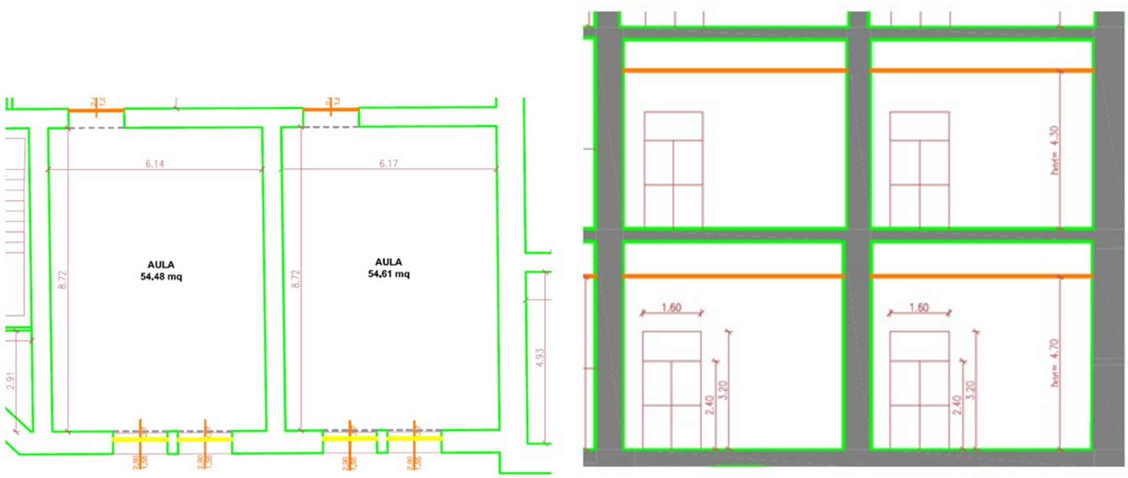
2.1 Introduction

The aim of this project is to study the acoustic conditions of the classrooms of a school, and try to adapt or improve them if they don't meet the regulations. The selected project (Project 4) has 4 rooms of similar dimensions that will be studied.

Everything will be studied with the software ECHO from ANIT (Associazione Nazionale Isolamento Termico e Acustico).

2.2 Case of study

The classrooms of study are, shown in the Figure 1.



(a) Base of the building (b) Section of the building

Figure 1: Blueprint of the building

We can see that there are 4 rooms with the following dimensions:

Room Position	Volume (m^3)	Surface Area (m^2)	Facade Wall (m^2)
Bottom Left	256.06	248.64	19.89
Bottom Right	256.67	249.19	20.01
Top Left	234.26	236.76	17.41
Top Right	234.82	237.27	17.54

Table 1: Relevant dimensions of the classrooms

We will study all of them, but we expect very similar results as the differences are very low (less than 10%).

2.3 Facade isolation (D)

We start by studying the facade, as it's fundamental to isolate the building from the exterior noise. We design our case in ECHO in the *isolamento di facciata* section.

We have to provide the R_w of the different elements of the outer wall and their respective surfaces. The windows are given in the assignment, and we have

$$R_w = 40 \quad S_{window} = 9.99\, m^2$$

For the walls, the surfaces are given in the Table 5, and for the R_w we have to consider that the wall is constituted by different layers.

Figure 2: Composition of the outer wall

We can find a reference for the Poroton of 30 cm from the notes of class (Fig. 3).

CARATTERISTICHE ACUSTICHE[2]	
Indice di valutazione Rw – Parete spessore 20 cm	50 (dB)
Indice di valutazione Rw – Parete spessore 25 cm	52 (dB)
Indice di valutazione Rw – Parete spessore 30 cm	54 (dB)
Indice di valutazione Rw – Parete spessore 38 cm	54 (dB)

Figure 3: R_w of the Poroton

For the *Intonaco interno*, we will neglect it, but for the *Lana di Roccia* and *Intonaco esterno* we will use the integrated tool of ECHO to compute the additional ΔR_w (Fig. 4).

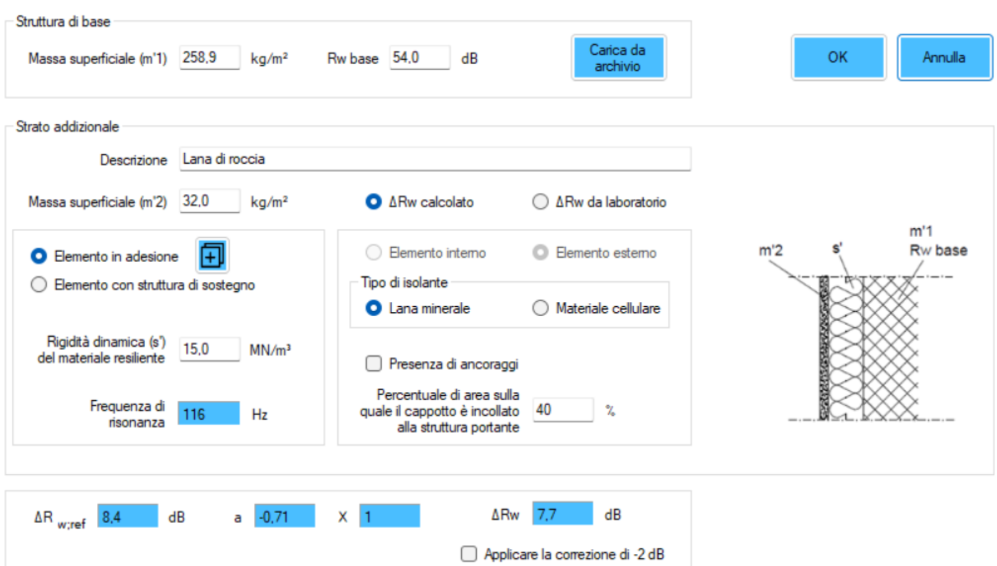


Figure 4: ECHO tool to obtain the ΔR_w due to the insulator

Here we have to put the data of the material we are attaching the insulator to (Poroton), and then the data of the 2 layers of the insulator (*Lana di Roccia* and *Intonaco esterno*). For these values, we use a standard. In both cases (Poroton and *Lana di Roccia*), we are defining these materials and their stratigraphy on ECHO, so it computes the corresponding density and other values.

We obtain that the insulator adds 7.7 dB to the wall.

We input everything into the program as shown in the Figure 5 (for the bottom left room).

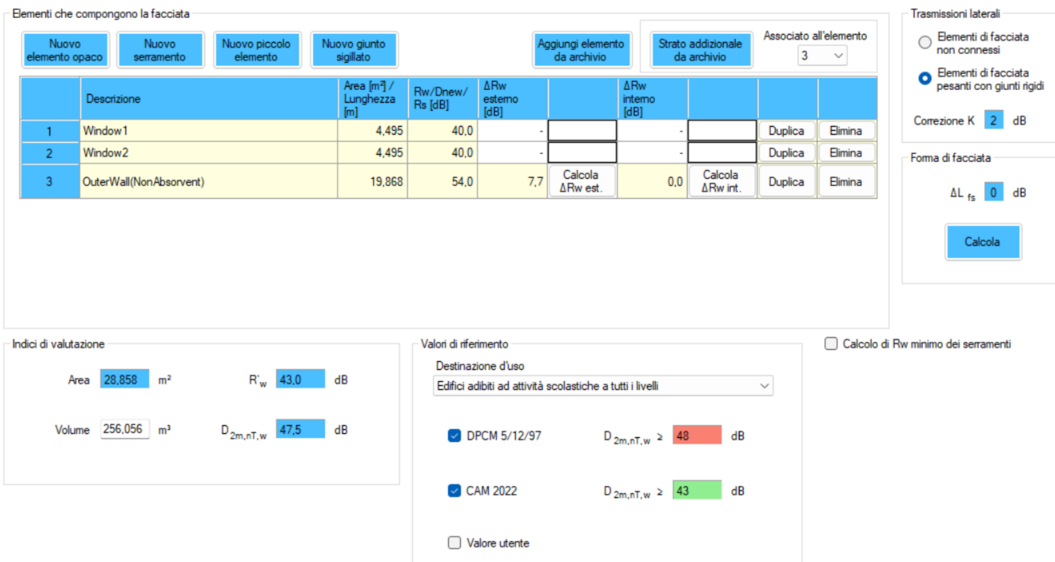


Figure 5: Screenshot of the final solution in ECHO for the bottom left classroom

We obtain that none of the rooms satisfies the criteria, so we will try to modify the properties of the window to achieve the criteria. As we are very close to the $D_w > 48\,dB$, we try to only increase the R_w of the window by 1, which can be easily achieved when choosing the window, as it's a very small increase. The summarized results are:

Room Position	D_w **with** $R_w = 40\,dB$	D_w **with** $R_w = 41\,dB$
Bottom Left	47.5	48.5
Bottom Right	47.5	48.5
Top Left	47.2	48.1
Top Right	47.2	48.1

Table 2: Results of the facade insulation

We can see that $R_w = 41\,dB$ is more than enough to achieve the legal minimum, and even slightly lower values could be enough for the lower rooms. For the top classrooms, the margin is lower, but sufficient.

2.4 Airborne sound insulation (R)

The next step is to check the noise transmitted between rooms that are side by side. To do these, use the *Isolamento pareti* section.

The first step is to define the materials. Now we need to consider all the walls surrounding the room, where we can distinguish: floor, ceiling, interior walls, and exterior walls.

For the floor and the ceiling, we can consider the same material, that we obtain from the ECHO's library. For the exterior wall we will use the poroton previously defined. Finally, for the interior walls that separate rooms, we will define a new material based on the data provided in the assignment ($R_w = 57\,dB$).

Done this, we create the model for both the first and the second floor. This is done by, first, assigning the materials to the respective walls (fig. 6), and second, selecting the type of joints between walls (fig. 7). While considering the joints, we consider that the first floor has a direct floor under but the second has more room over it (as we can deduce from the blueprint). Also, there are small changes in the dimensions.

			Descrizione	ms [kg/m²]	Rw [dB]
S		Inserisci elemento	MidWall	55,0	57,0
1		Inserisci elemento	MidWall	55,0	57,0
2		Inserisci elemento	Floor	360,0	53,9
3		Inserisci elemento	OuterWall(NonAbsorvent)	258,9	54,0
4		Inserisci elemento	Floor	360,0	53,9
5		Inserisci elemento	MidWall	55,0	57,0
6		Inserisci elemento	Floor	360,0	53,9
7		Inserisci elemento	OuterWall(NonAbsorvent)	258,9	54,0
8		Inserisci elemento	Floor	360,0	53,9

Figure 6: Material assigned to the walls (same for first and second floor)

	Lato		Tipo di collegamento	Lunghezza [m]
1-5		Inserisci	A T in laterizio (caso 1)	4,7
2-6		Inserisci	A T in laterizio (caso 1)	8,72
3-7		Inserisci	A T in laterizio (caso 1)	4,7
4-8		Inserisci	A croce in laterizio	8,72

Figure 7: Junctions between walls (first floor)

Having done this, we can just go to the results window and see the results. Both first and second floors achieve the DPCM criteria of $R_w > 50\,dB$, having values of 52.7 and 52.6, respectively.

Still, we do not meet the requirements for the CAM 2022, which requires $R_w > 56\,dB$, a significantly larger value. This is because we consider the condition where rooms are isolated from each other, as it is what we would expect in a classroom where we want the least noise possible to filter from one class to another.

To increase the R_w we first plan to place an insulating panel on both sides of the wall. We start defining the layers with material from ECHO. We add mineral wool and a rigid surface to cover it (Fig. 8). Done this, we use the implemented tool of ECHO to obtain the R_w like we did in Figure 4, but now we consider the other case, a rigid structure with a gap (Fig. 9).

1	LAS	Cartongesso (densità 900 kg/m³)	0,013	900	11,3
2	ISO	Pannelli semirigidi in fibre minerali di rocce feldspatiche	0,040	40	1,6

Figure 8: Definition of the material to insulate the wall

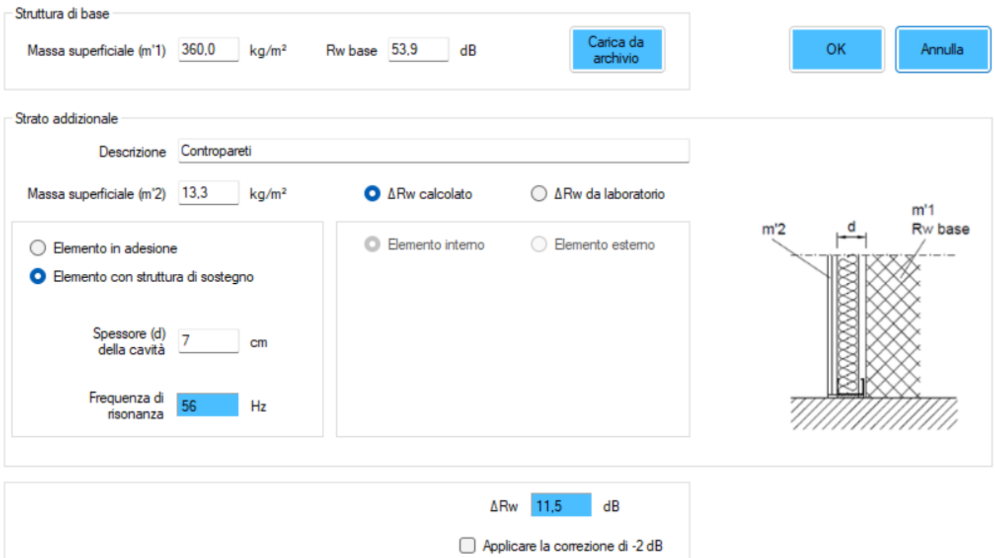
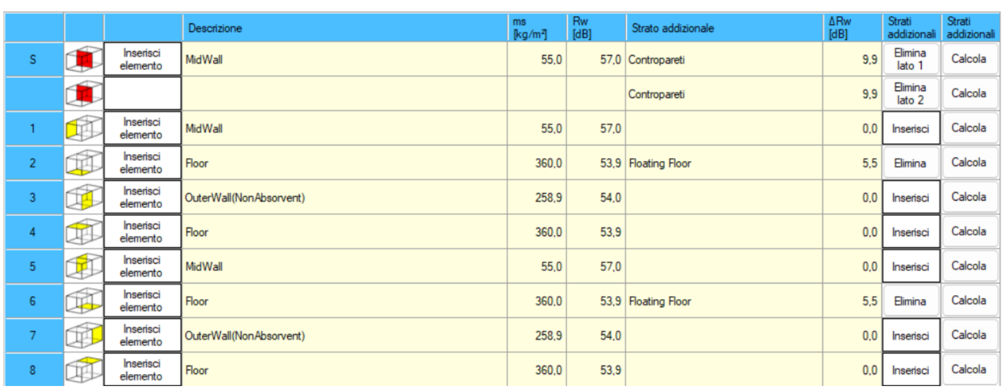


Figure 9: ECHO tool to obtain the ΔR_w due to the insulator

We try this solution on both floors, but we only get up to $R_w = 54.7\,dB$, even if we increase a lot the width of the insulator or the gap. This means the sound is leaking from another point, which very likely will be the floor or the ceiling.

Then, what we do is define a floating floor (*anticalpestio*) and a false ceiling (*controsoffitto*). For the first one, we have to select the material and the original floor, and ECHO will compute the values. For the ceiling, we additionally have to design the stratigraphy first.

We find that the floating floor has $R_w = 5.5\,dB$, but the ceiling has a value of $R_w = 15.4\,dB$. Considering the value for the floor is smaller, we consider placing this one on our system, as shown in Figure 10.



			Descrizione	ms [kg/m²]	Rw [dB]	Strato addizionale	ΔRw [dB]	Strati addizionali	Strati addizionali
S		Inserisci elemento	MidWall	55,0	57,0	Contropareti	9,9	Elimina lato 1	Calcola
						Contropareti	9,9	Elimina lato 2	Calcola
1		Inserisci elemento	MidWall	55,0	57,0		0,0	Inserisci	Calcola
2		Inserisci elemento	Floor	360,0	53,9	Floating Floor	5,5	Elimina	Calcola
3		Inserisci elemento	OuterWall(NonAbsorvent)	258,9	54,0		0,0	Inserisci	Calcola
4		Inserisci elemento	Floor	360,0	53,9		0,0	Inserisci	Calcola
5		Inserisci elemento	MidWall	55,0	57,0		0,0	Inserisci	Calcola
6		Inserisci elemento	Floor	360,0	53,9	Floating Floor	5,5	Elimina	Calcola
7		Inserisci elemento	OuterWall(NonAbsorvent)	258,9	54,0		0,0	Inserisci	Calcola
8		Inserisci elemento	Floor	360,0	53,9		0,0	Inserisci	Calcola

Figure 10: Materials assigned to the walls in the improved case (same for first and second floor)

After considering this, we can finally satisfy the CAM condition, obtaining:

Room Position	R_w **basic elements**	R_w **wall insulation**	R_w **wall insulation and floating floor**
Second floor	52.6	54.7	56.6
First floor	52.7	54.7	56.7

Table 3: Results of airborne sound insulation (R_w)

We don't need to use the false ceiling, but we have now a situation where we can choose if we want to satisfy the soft criteria (DPCM), or add more elements to satisfy the more refined criteria (CAM for different building units).

2.5 Impact sound insulation (L)

We continue studying similarly to how we did before the noise transmitted from top to bottom through the ceiling. To this purpose we use *Livello rumore da calpestio*.

As we already defined all the materials in previous exercises, we only need to input them into the menu as we can see on Figure 11.

			Struttura di base	ms [kg/m²]	Ln,eq,0,w [dB]	Rw [dB]	Strato addizionale	ΔLw [dB]	ΔRw [dB]
S		Inserisci elemento	Floor	360,0	74,5	53,9		0,0	0,0
								0,0	0,0
1		Inserisci elemento	MidWall	55,0					
2		Inserisci elemento	MidWall	55,0					
3		Inserisci elemento	OuterWall(NonAbsorvent)	258,9					
4		Inserisci elemento	MidWall	55,0					
5		Inserisci elemento	MidWall	55,0		57,0			0,0
6		Inserisci elemento	MidWall	55,0		57,0			0,0

Figure 11: Material assigned for the noise transmitted through the floor (not all of them appear)

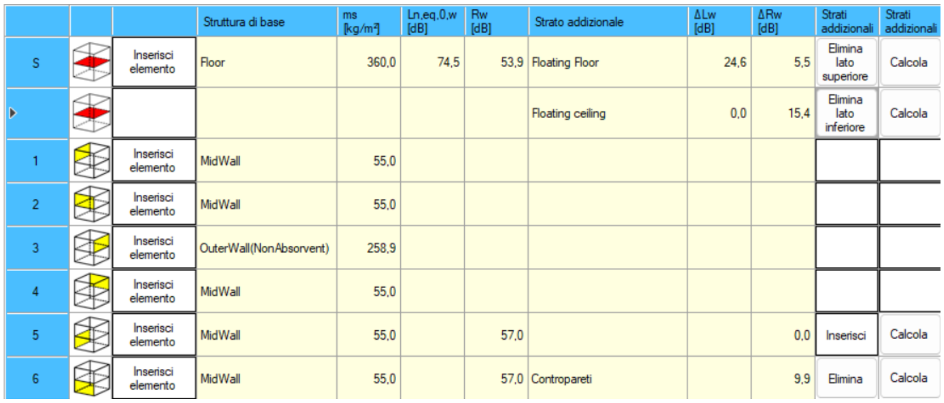
We also have to do the junctions as we did in the previous section (fig. 12). Point out we consider there are more rooms in the building, so we add a cross junction (*croce*).

	Lato		Tipo di collegamento	Lunghezza [m]
S-5		Inserisci	A croce in laterizio	6,14
S-6		Inserisci	A croce in laterizio	8,72
S-7		Inserisci	A T in laterizio (caso 1)	6,14
S-8		Inserisci	A croce in laterizio	8,72

Figure 12: Floor junctions added in ECHO

We check the results and see that they are not sufficient for any of the criteria. This way, we have to consider a correction to decrease the value of L_w. To do this, we will again consider the floating floor we added in the previous section and the floating floor we already designed. We can also attach the insulation to the wall, but we don't expect it to be a major source of noise.

When applying them we realize that only the floating floor has an effect on the L_w, as is the only one with an assigned ΔL_w. We realize that when calculated the parameters with ECHO libraries, the false ceiling doesn't compute ΔL_w because we need to provide the experimental value, and for the wall insulation is not even an existing parameter.



			Struttura di base	ms [kg/m²]	Ln,eq,0,w [dB]	Rw [dB]	Strato addizionale	ΔLw [dB]	ΔRw [dB]	Strati addizionali	Strati addizionali
S		Inserisci elemento	Floor	360,0	74,5	53,9	Floating Floor	24,6	5,5	Elimina lato superiore	Calcola
							Floating ceiling	0,0	15,4	Elimina lato inferiore	Calcola
1		Inserisci elemento	MidWall	55,0							
2		Inserisci elemento	MidWall	55,0							
3		Inserisci elemento	OuterWall(NonAbsorvent)	258,9							
4		Inserisci elemento	MidWall	55,0							
5		Inserisci elemento	MidWall	55,0		57,0			0,0	Inserisci	Calcola
6		Inserisci elemento	MidWall	55,0		57,0	Contropareti		9,9	Elimina	Calcola

Figure 13: Material assigned for the noise transmitted trough floor with corrections.

Despite that, we achieve with only the wall a value that it's good enough to accomplish both laws:

Room Position	L_w **with** $R_w = 40\,dB$	D_w **with** $R_w = 41\,dB$
Left Side	74.6	50
Right Side	74.6	50

Table 4: Results of impact sound insulation ($L_{n,w}$)

What we realize then it's that the false ceiling it's not required to accomplish with the law in any case, that the wall insulation it's useful if we want to achieve a high standard performance, and the false ceiling it's completely unnecessary for our needs.

2.6 Acoustic Comfort

Lastly, once ensured that the classrooms perform good with respect to the neighbouring spaces, we can check how good it's the sound inside the class itself. To do that, we go to the *Comfort Acoustico Ambienti* section.

First, we check the reverberation time. To do so, we have to input all the surfaces of the room with the respective material from the ECHO library. If we consider an empty room with a door and windows, we obtain extremely large reverberation times.

We then consider the insulating panel we added to the wall between classrooms. It significantly decreases the reverberation time to the order of 1 second, but it's still too high for the standards.

That's why we reuse the idea proposed before of the false ceiling. Adding a full ceiling gives us a very low reverberation time, out of the range given by law. The problem is that sizes for the material are fixed in this window, so we don't have the freedom to choose smaller panels to adjust, which is something we could be doing in reality. We summarize all these changes:

Room Position	**T for basic room**	**T with wall insulation**	**T with false ceiling**
Bottom Left	4.58	1.16	0.48
Bottom Right	4.58	1.15	0.47
Top Left	4.40	1.13	0.45
Top Right	4.39	1.13	0.45

Table 5: Reverberation Time (T_{30}) results

What we will do, at least to continue with the calculations, is to choose a set of materials that approximate our proposed case, and can make the time fit into the comfort range defined by law, to be able to work in the next step.

Established the average reverberation time on $0.64\,s$, we go to check the speech transmission index (STI). The idea would be to ensure that the STI is good enough for most o the considitons possible.

The parameters we can study are (fig. 14):

- Speaker. We can choose the gender of the speaker and the effort.
- Sound pressure level of the speaker. Depends on the effort. We will choose the ones given by standard, that are higher for the first floor as the rooms are bigger than $250\,m^3$.
- Directivity of the sound.
- Background noise.

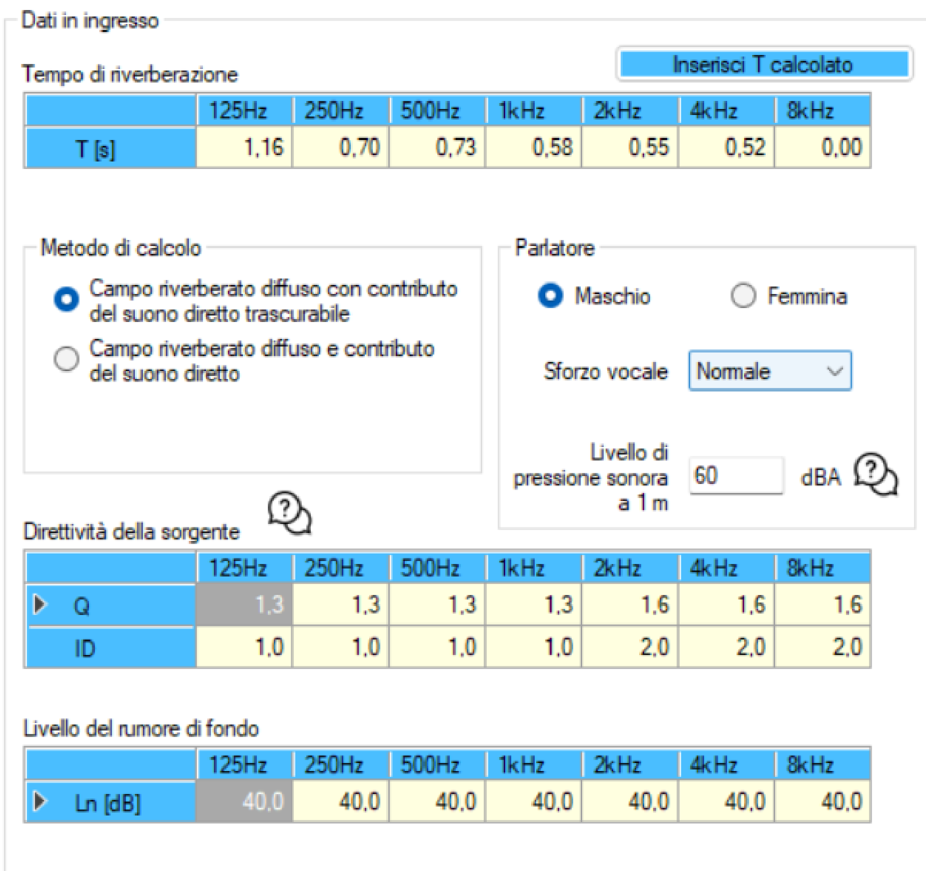


Figure 14: Parameters to adjust in the STI calculation

As there are too many parameters, we are going to study the case of only 1 room, considering the other will have similar parameters, and minor changes might solve the differences. We are going to take the worst case and best case for the directivity given by the standard, and look which values of STI we have for different levels of noise and vocal efforts, obtaining:

Config. (Q + Ln)	**Male**			**Female**		
	Relaxed	**Normal**	**Raised**	**Relaxed**	**Normal**	**Raised**
Worst Dir. + Noise 30dB	**0.50**	**0.56**	**0.59**	**0.46**	**0.53**	**0.57**
Worst Dir. + Noise 35dB	**0.42**	**0.51**	**0.57**	**0.38**	**0.48**	**0.54**
Worst Dir. + Noise 40dB	**0.33**	**0.44**	**0.52**	**0.27**	**0.40**	**0.49**
Best Dir. + Noise 30dB	**0.53**	**0.58**	**0.60**	**0.50**	**0.56**	**0.58**
Best Dir. + Noise 35dB	**0.47**	**0.54**	**0.58**	**0.43**	**0.51**	**0.56**
Best Dir. + Noise 40dB	**0.38**	**0.49**	**0.55**	**0.33**	**0.45**	**0.52**

Table 6: Speech Intelligibility (STI) color-coded by performance thresholds

We can see, that based on the CEI EN60268-16, most of the values we found are acceptable, but not good, finding only 1 good value. Other thing we can notice is that directionality has a considerable influence, but nothing compared to noise, where 10 dB can change the the STI up to 0.19.

This means the main purpose it to ensure the background noise is very low, and this goes beyond the insulation we worked on, because it depends on the location of the school, neighboring areas, noisy devices in the room...

Another thing we notice is that women need to exert greater vocal effort to be understood, although in most cases a normal voice level can be enough to have a good speech transmission.

2.7 Conclusions

Along the project we observe that a building without any acoustic treatment it's not suitable at all for a school. At first, we had to revise the windows to ensure that the facade had a good insulation, even though this was a minor change.

After that, while checking the transmission noise between rooms, we realize the wall itself satisfies the standard law, but in order to satisfy more strict conditions, which should be the case for a school, we need to treat at least both wall and floor.

This treatment in the floor was also good enough for the noise transmitted vertically, but when checking the reverberation time, we realize we need more elements. As for now, only the wall insulation was helping with the reverberation, but all the other elements (floor, wall, windows, ceiling) were acting almost as sound reflectors. That's why we finally decide to put a false ceiling to decrease the reverberation time to proper values for a classroom.

Finally, we study the STI, realizing how important is the background noise to ensure the speech intelligibility, making also important to control the noises inside the room.

In the end, we see for a empty classroom that guarantees good conditions, we need to ensure a very good acoustic treatment, reinforcing walls, windows, floor and ceiling. Of course, many simplifications are taken, but at least we have an idea of the environment, and we can ensure to fulfill the law requirements.