POLITECNICO DI TORINO
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Master of Science in Architecture Construction City
Honors theses

“Influence of the balconies on the acoustic quality of concert halls”

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To value the acoustic qualities of a concert hall, it’s common use to refer to some acoustic indexes. The ones handled in the thesis are time of first decay (EDT). Clarity (C), direct sounds’ subjective intensity and fraction of first lateral energy. The target in this thesis was to find the best shape for a concert hall and especially the best shape for the balconies, so that those indexes could be optimal.

First of all, it is important to introduce the impulse response: it determines all the acoustic parameters of the room and it is the sound recording in the time of the sound energy that arrives at the receiving point following the issue of a pulse signal from the stage.

As already stated the major objective measures discussed in the thesis are EDT, C80, G and LF.

Reverberation is the most obvious parameter that can be perceived in a closed space. In a closed environment, the sound produced in a point reaches the listener not only in a direct way, but also after reflections on walls and floors.

Wallace, a professor at Harvard University, in 1922 defined the reverberation time as the physical parameter descriptor of the perception of the reverberation sound. It is the quantification of the tail sound. It is defined as the time required for the sound level at a point in the room to decay by 60 dB, the instant of switching off a sound source which emits a stationary signal.

$T = 0{,}161\ (V/A)\ \ (s)$

This parameter therefore depends on the volume of the space V and on the sound absorption characteristics A of the present surfaces.

There are reverberation times relative to decay times, not only referring to 60 dB, but 10 dB (T10), 20 (T20) and 30 dB (T30), etc. However, these values are equivalent to each other because even if they are measured on a shorter decaies, since it is more difficult in normal situations to have a sound decay by 60 dB, they are extrapolated to the corresponding T60. The early decay time (early decay time, EDT or T10) is the time required to obtain a decay of 10 dB of an impulsive signal.

Clarity is the parameter that indicates the ability to hear sounds clearly.

$$C_{80} = 10 \cdot \log \frac{\int_{0}^{80ms} p^2(\tau) d\tau}{\int_{80ms}^{\infty} p^2(\tau) d\tau} \quad [\mathrm{dB}]$$

It is the relationship between the energy directly coupled to the energy of the early reflections and the energy of successive reflections, where we find the numerator of the energy that reaches the ear in the first 80 ms and the denominator of what comes in the following moments (so between the sound that comes from 0 to 80 ms and the sound that comes from 80 ms to infinity).

Stregth or subjective intensity of the direct sound is the parameter that expresses the sound level perceived in relation to its position and the power of the sound source.

$$G = 10 \log \frac{\int_{0ms}^{+\infty} p^2(t) dt}{\int_{0ms}^{+\infty} p_{10m}^2(t) dt} \quad [\mathrm{dB}]$$

Outdoor sound emitted by an orchestra is weaker compared to the same one perceived in a room. The index of strength G is the parameter which describes the perception of the intensity of a sound.
The fraction of the first energy side (LF) is the ratio of the sound energy reflected laterally in a room and the sound energy that comes from all directions, included the sound energy directly from the source. It is a measure for the space of a room.
The fraction of the first lateral energy that comes from a lateral direction within 80 ms can be measured from the impulse response obtained from a microphone shaped like ∞.
It is a parameter that can objectively represent the amplitude of the sound space of perception in which there is a room.
The ratio is expressed as:

$$LF_{early} = \frac{\int_{5}^{80} p_L^2(t) \mathrm{d}t}{\int_{5}^{80} p^2(t) \mathrm{d}t}$$

In the thesis I worked mainly on the balconies. These are often found in concert halls, and allow the development of the hall in vertical and offer advantages especially for those listeners who do not reside directly in them.

The seats under the overhang of the balconies are often disadvantaged both in terms of acoustics that vision. One of the biggest problems of the design of the balconies in the halls is to balance the advantages and disadvantages of the balconies.
To understand the acoustic effect of a balcony, it is useful to consider the early reflections and, separately, those later. Often the reflections are influenced by the presence of a protrusion, such as a balcony. The following reflections are modified significantly by the presence of balconies. In a session away from the balconies, the reverb sound reaches the listener from different directions. Under the balconies the vertical angle from which the sound arrives at the meeting is very small.
The design of the concert hall depends on the definition of the shape, size, materials, and the purpose is to create the best acoustic conditions over the entire area of the pit, to best meet the personal preferences of the listeners.

Concert halls can be classified according to their shape, into four main categories of rooms: shoe box room, fan room, hexagonal and vineyards.
In the second part of the nineteenth century the demand for large concert halls grew, and especially those with rectangular plants prove to be particularly favorable acoustics. The proportions are roughly of a double cube, and are called shoe box.
One of the most important salt shoe box is the Grosser Musikvereinssaal in Vienna, built between 1867 and 1869, by the Dane Ritter Theophil von Hansen (1813-1891) and opened in 1870.
Regarding the balconies the Grosser Musikvereinssaal has a single row of balconies which travels through the four sides of the room, including the side of the organ behind the stage. The balcony is supported at the front by 32 high gilded caryatids and in the back by Ionic columns. The ceiling of the balcony is richly decorated, as well as the fronts of the balconies themselves, so the spread is high: this is a hallmark of the room. When you sit in the balcony side the level of the reflected sound is very high, while the visual quality is much lower in comparison, because you only see half of the orchestra. But this noise level comes at the expense of clarity. A characteristic of almost all the concert halls is the force, strength, of the first lateral reflections. The sound spreads with a sound source far beyond the size of the orchestra; There are two characteristics that increase the effect: the reduced width of the room and the possibility of reflections due to the presence of the balconies.
Another important rectangular room is the Symphony Hall in Boston, designed by architects McKim, Mead and White, with the help of acoustic Sabine.
The sound in the room is clear, warm, bright and strong. The tone of the orchestra is balanced and the overall effect is excellent. Despite this there are a number of negative characteristics. The seats that are at the corners and under the balconies are reached by an unnatural sound due to a shadow area. It 'also an echo effect coming from the rear wall.

There are two levels of balconies that create a "u" profile. The balconies, with the posterior part decorated and gilded, are shallow to avoid sound reflections. In the Symphony Hall in Boston the sound does not get very good listeners under the lower balcony, although the receivers under the highest balcony near the center of the room have relatively good listening conditions. However, the reflected sound from the ceiling does not come very far below both the balconies, and the extreme rear corners of the room beneath the balconies have less than perfect acoustics. The coffered ceiling and the niches in the walls, containing classical statues. The Symphony Hall has a high diffusion due to the presence of a coffered ceiling, and numerous ornaments, such as statues, niches, recesses and decorations on the side walls, and the presence of two levels of balconies, with also the front-rich decorations.

The third of the major European theaters rectangular is the Concertgebouw, designed by AL van Gendt. The room has a volume of 18700 cubic meters, and this causes a great reverberation, and sound waves reflected from the side walls, given the width, they come relatively late to the center of the room. All this gives music a mixed tone, warm, lacks clarity. It has a high and narrow balcony with a very ornated front, which extends along three sides of the room, and it is supported by columns decorated.

The scattering in the room is defined as high, as there are uneven surfaces that lead to the spread of the sound: the coffered ceiling, the presence of the balcony, columns, rich decorations on the walls. Many of the halls of the nineteenth century present this, since they are finely adorned with uneven surfaces.

Worthy of note is the Free Trade Hall. According to the experience of Beranek the sound from the first balcony (on the opposite side of the stage) was very reverberant but lacked in clarity, the plan was not the best and the percussions covered the sound of the strings. The worst part is represented by sessions in the side balconies; in the center of the main floor you clearly hear the instruments . The major defect of the room is the reverb, although it is 1.6, which is not unusual. Barron says that the surprise of the Free Trade Hall is that the drawbacks of the places do not worsen the sound; for example in the back of the main plane the acoustic response is better than the visual's unsatisfactory. The large compensation can be the winding of the sound. The reason is the reverse fan shape at the rear of the main floor and balconies that contribute to each of the lateral reflections to the audience.

The room is composed of two levels of balconies: the first layer runs along the perimeter of the area forming a "u"; the second level is only found in the opinion of the hall and at this point the height of the hall has been erected to accommodate the balcony: it seems to have been added as an appendix to the latter. The room is strongly divided by the presence of its balconies, which prove to be very prominent. The balconies are inclined respecting the vertical plane, to better direct the sound in the central seating.

To assess the best form of the concert hall and in particular its balconies, were used Genetic Algorithms (GA): these have been proposed for the first time in 1975 by John.H. Holland, and were inspired by the principle of Darwinian natural selection and evolution.

In nature, through the process of evolution, survival of the fittest has generated the best species, which can make better use of their attributes in their particular habitat. We can look at evolution as a search process to get to find those qualities which best allow the animals to survive and reproduce. Similarly, survival in a specific environment is the basis of the problem, the animal population is the set of proposed solutions, and natural selection and reproduction are the research processes that will generate the best solutions.

With the use of Genetic Algorithms are created new solutions, with the use of parts taken from the best solutions considered.
How it works: individuals reproduce in nature by mixing their genetic heritage, that is, their chromosomes: the new individuals generated will therefore have a genetic heritage derived in part from the father and partly from the mother. Natural selection (the reuse of good solutions) makes them survive, and then makes reproduce only the stronger individuals, "most suitable", so those with the highest fitness (closest to the excellence); the fitness is the degree of evaluation associated with a solution. The evaluation is based on a designed function specifically said fitness function. The average fitness of the population will tend to increase with the generations, bringing the species to evolve during the iterations.

Genetic Algorithms so far treated were analyzed by a method of finding a single target, but there are also multi-objective AG. The major difference between the two is the number of objectives.

Important is also the Pareto front, which can be explained starting from the concept of non-dominance of an individual. A non dominated individual is not dominated by any other individual of the population. A non dominated individual usually dominates many of the other individuals in the population and is never dominated by others. In order to achieve the parametric model of the concert hall, it was used a script. The script was created with the Python plug-in for Rhinoceros: in this way it was possible to use immediately RhinoScript syntax. In fact, the controls of software modeling have allowed the geometric construction of the concert hall, with its related variables.

After you have defined the function HallGenerator needed to build the geometric model, it has been defined an appropriate range of values within which to vary the shape of the salt to get real cases.
The variables chosen in order that the calculations lead to the best optimization of the hall are:
Balcony Depth: width of the balcony
Delta balcony H: convexity / concavity of the floor of the balcony
Delta balcony depht: convexity / concavity of the front of the balcony
Balcony H: height of the front of the balcony
Alpha: the angle of rotation of the front of the balcony
Three case studies were analyzed:

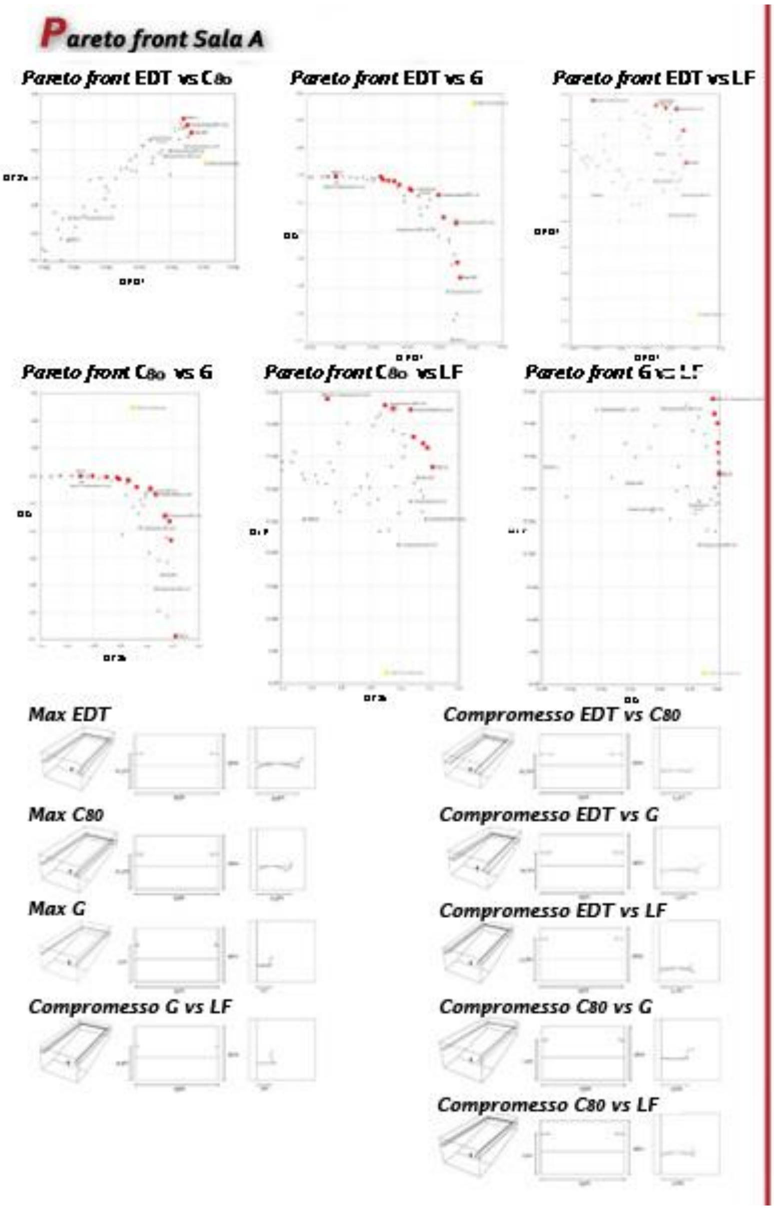
1) The first case study was performed on a shoe box, called Room A, having a row of balconies, with width X height = 25 and Z = 16, with the variables *Depht Balcony*, *balcony Delta H*, *Delta balcony depht*, *Front H*, *Alpha*.
2) The second was carried out on room B, with width X = Z = 35 meters and height 25 meters, with the variables *Depht Balcony*, *balcony Delta H*, *Delta balcony depht*, *Front H*, *Alpha.*
3) The third study was carried out in order to find the best room ever, infact besides the addition to the variables of the previous rooms, are also considered variables width and height.

After defining the range of salt and variables you need to find a combination of variables that can determine the optimum solution: which means finding which dimensions better correspond to the research in question. We speak directly about Fitness Function, as we stand in the field of Genetic Algorithms: each individual of the population is assigned a value, in order to assess its adequacy. A high value of fitness corresponds to a higher probability of choice of the individual for the training of the next generation. The Genetic Algorithm is able to randomly select stronger individuals (high fitness value) and discard the weaker ones (low fitness value). In this perspective we proceed towards the optimization of the population and, therefore, of the solution.
The fitness function is the "goal" that the Genetic Algorithm must maximize or minimize. Everyone will have their own fitness function which will be evaluated through its "goodness."

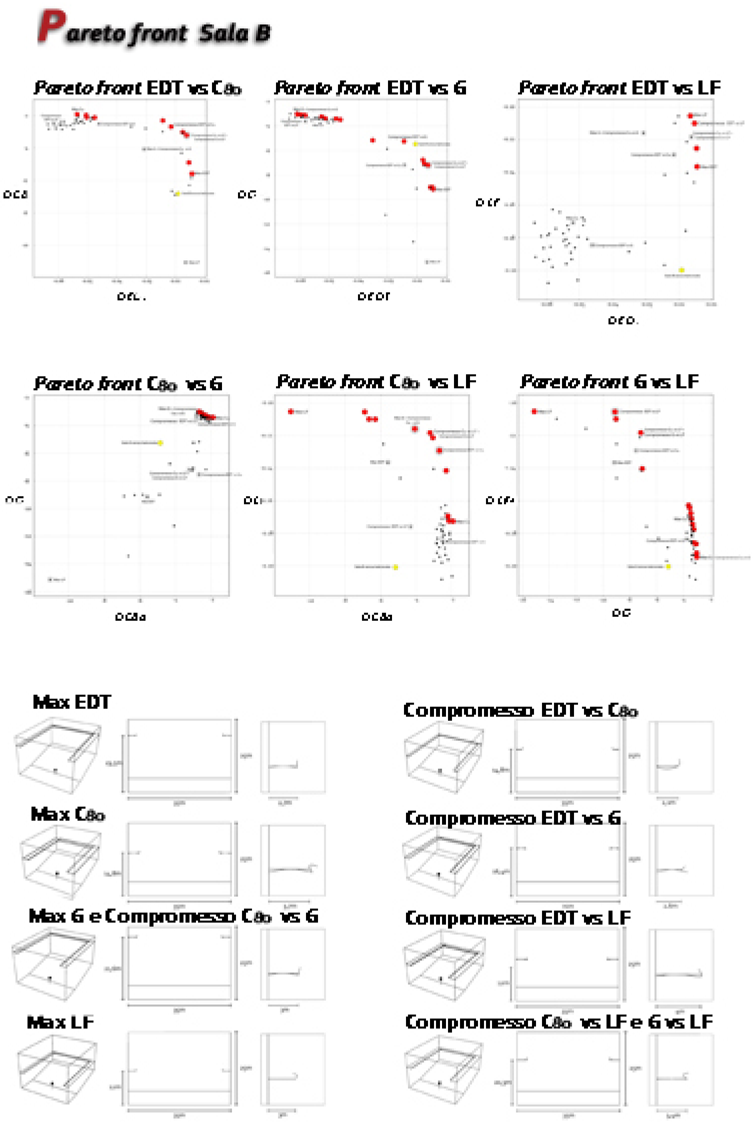
The AG then solve a given problem using a population of solutions which, initially random and therefore with low fitness, are then made to evolve for a certain number of successive generations, until the appearance of at least one solution with high fitness. The study seeks high performance solutions for all different individuals.
As already mentioned, a solution is called non-dominated or Pareto optimal if none of the objective function can be improved in terms of value without degrading some of the other objective values.
And so we come to the results Genetic Algorithm within the domain of the solutions considered: from generation to generation we will get to those results that show which are the best rooms among those analyzed, and in particular which are the best balconies and if these rooms can be considered better or not than the respective shoe box without balconies.

In the results of the first case study (Room A), is analyzed for the generation of the Pareto front of the room number 50 A. The horizontal axis shows the first fitness, D EDT, on the ordinate indicates the second, D C80. The red dots are non-dominated, while blacks are. The diagram is the space goal, and tells the whole story of the Pareto front, until you get the best solutions (red dots). Each point represents a particular room, with its shape of the balcony, and the front of the balcony. The best form of room D EDT will be the one represented by point "Max EDT," while the best way to D C80 will be the point of "Max C80."

The trade-offs between the two can be many, but we will consider only one, and it is called "compromise EDT vs C80." D EDT has a higher value when the halls are short, wide and not too tall. C80 and G are high on salt long, not very wide and high. D LF, in contrast, has a low value since the room is not so narrow and EDT is also inversely proportional to LF.
A corresponding room without the balcony, is better for D EDT compared to the same room with the balcony, but worse for D C80. Best for D EDT as the addition of balconies involves the addition of seats and hence a greater sound absorption of surfaces present. Worst D for C80 because the room with the balcony allows a better distribution of lateral reflections, C80 being the ratio of the energy directly coupled to the energy of early reflections that reach the ear in the first 80 milliseconds, and the energy of successive reflections, which arrive after 80 ms. So, to improve the clarity of the area we must increase the energy, the first one that arrives within 80 ms.

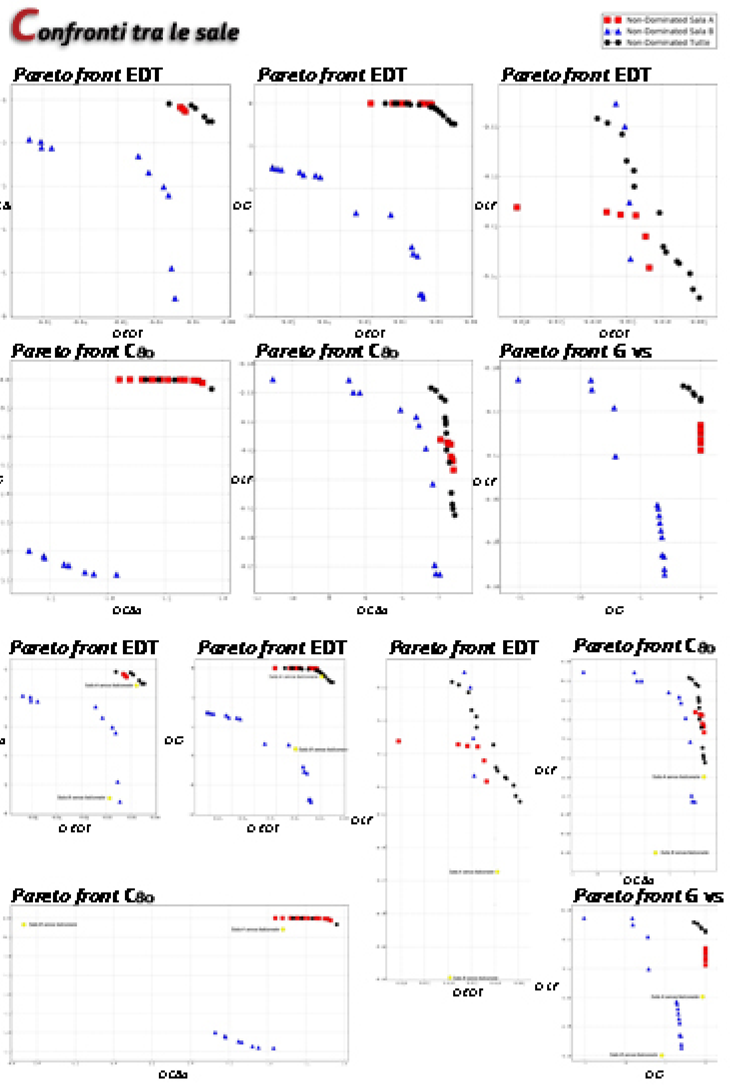


This reasoning is applied for each Pareto front analyzed, and for each case study (also for the Hall B and Hall All Variable), thus arriving to the comparisons between the different results.



For example, after studying all the results obtained, we compare the values of reverberation and clarity for all three case studies: the Pareto front shows the relative comparison between the study room A, room B of the study, and the study of rooms with more variables. We can see that the highest value of D EDT we met it with the third study. This is because the purpose of the introduction of the third calculation is just to find the best room, considering also the variables width and height. Despite this, even the exhibition hall A of the high values of D and D EDT C80. A room has no contrast, so the value of D EDT also corresponds to the proper value of D C80. The first two studies clearly dominate the room B, which shows values of EDT and C80 below. The function is clearly contrasted in room B.

The Hall B is the widest, it measures 35 meters in width and 25 meters in height. We can say that the amplitude of the hall in this case decreases room optimization.
In the Pareto front we can see the smallest comparison between the A and B rooms with balcony and without balcony.
The balconies do not improve the value of EDT in room A, but improve clarity. The Hall B can be improved by the addition of balconies, however, it doesn't get to the level of the others.



The thesis has addressed the problem of improving the acoustic quality of concert halls, through the addition of balconies. The method was proved effective and interesting. The first two case studies were started from salt with fixed variables, so rooms with already studied dimensions . The results obtained by these two rooms allow us to see how the balcony may improve or not the same salt.

The third experiment is a room with variable dimensions, so will always be the best, and always will dominate the other two: as already said more variables are assigned, even for the width and height, Therefore it is logical to say that the result and the shape of the room will be better and more accurate.

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