ACOUSTICS OF TEATRO DEGLI ARCIMBOLDI IN MILANO DESIGN, COMPUTER AND SCALE MODELS, DETAILS, RESULTS

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1 INTRODUCTION

To design a second opera house in Milano, not too far from the famous Teatro alla Scala, is an extraordinary challenge.

Whether or not it is completely justified today, the acoustics of Teatro alla Scala has become a myth and a model for many opera house designers: it is of course very favourable to the voice, the male voice in particular, in spite of the fact that, over the years, the introduction of excessive amounts of absorbing surfaces has somehow diminished its musical qualities. It is of course not quite suitable for symphony or even for chamber music.

The first question that arose was the following: should the acoustics of the new theatre match the acoustics of the older theatre. Since the new theatre, with its capacity of 2385 seats is much larger than Teatro alla Scala, in its present condition, and since the hall must also accommodate symphonic concerts, it is obvious that it should sound very differently.

As one knows today quite well, it is very difficult to come up with a design that is at the same time musical, that is favourable to instrumental music, and clear, meaning favourable to the human voice. With the exceptions of the Bayerische Staatsoper, of Teatro Colon in Buenos Aires and of the Metropolitan Opera in New York, there is hardly any example of an excellent opera house with a capacity of more than 2000-seats.

The counter-example of the Opera Bastille in Paris is now well known. Even though Professor Cremer declared, at the preliminary design stage, that the design would fail, his advice was not heard. This costly lesson has influenced more recent designs.

As always, the design process of Teatro degli Arcimboldi was long and fraught with incidents, from beginning to end. In an attempt to propose a “normal” project and an “economical” project, two designs were proposed: the first was a classical design with boxes all around, the second, more modern, was moderately fan-shaped, like the Bayreuth Festpielhaus, with superposed balconies. The first was initially selected and a detailed design was produced. It was later abandoned, because the leadership of the City had changed, and the second version was actually developed and built.

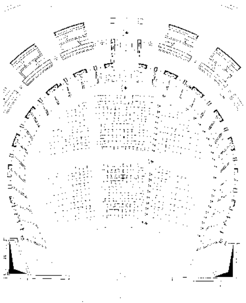
2 THE ACOUSTICAL DESIGN OF TEATRO DEGLI ARCIMBOLDI

2.1 The first version

The first design was presented at the 1996 Torino meeting on Opera Acoustics[1]. This version was a classical cylindrical room. The objective was to obtain an adequate volume for an audience of around 2400, to shorten as much as possible the distance between audience and stage and to provide a considerable amount of diffusion. This design is a contemporary interpretation of the classical opera house, a model of which is the Staatsoper in Munich, which is also, with its orchestra shell, a genuine concert hall.

With this type of shape, the listeners, including those in the stalls, benefit from early reflections that are an essential ingredient for opera. The side boxes give an opportunity to create a lot of diffusion.

This first design was tested in detail using computer models and a 1/16th scale model to determine whether the response was adequate throughout the hall and that the distribution of the sound was as even as possible.






The figures above show the model, its quasi-omnidirectional source, the orchestra shell, and the plan and front and side views.

For political reasons, this version of the project was abandoned. A few weeks later, detailed studies of a second version that had been developed in parallel to investigate whether a more economical type of hall could be considered started. Of course, a lot of the elements defined for the first one could be used again or slightly modified.

2.2 The second and final design: a cylinder in a narrow triangle

The second version was originally conceived to determine whether, with very similar specifications and content, a more economical design could be developed. It turned out that the difference in predicted cost between the two versions was less than 10%, mainly because of the use of cheap materials on the outside for the second version.

This second version, with a moderate fan shape, was finally selected and built. It is a large reverberant volume with various diffusing devices distributed on the walls and the ceiling and around the audience, as the following plans and sections show.

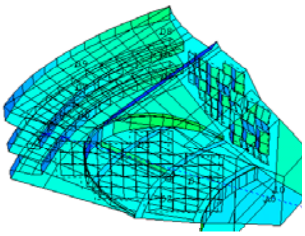
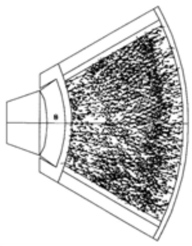
The design is quite compact since the maximum distance between the edge of the stage and a spectator is 34-m. It is interesting to compare the plans of the “new” and of the old Scala (Teatro Piermarini): one observes that, in spite of a much larger capacity, only a few spectators are actually sitting outside of the virtual Scala volume.

The major risk of such a design is well known: a fan shape hall generates efficient lateral reflections for the back of the hall and, usually, poor lateral reflections for the stalls. The quality criteria for the second and final version, the one that was actually to be built, was the same as those of the first version. However, its geometry was vastly different and, because of its shape in plan, a great deal of modelling was needed to ascertain that it would work.

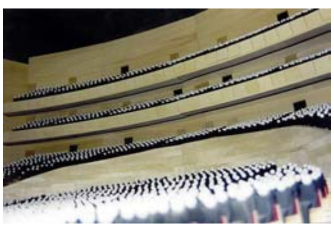
In summary, the principles that were applied in the acoustical design are the following:

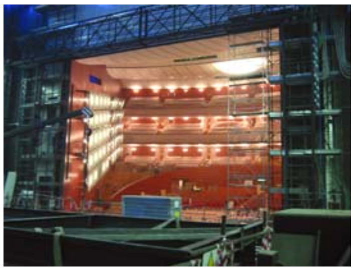
- Bring the people as close as possible to the stage in spite of the size of the audience. The moderate fan shape of this very large hall has been chosen to maximise intimacy.
- Design a relatively large volume so that music can develop freely and envelop the listeners.
- Achieve a relatively long response corresponding to a relatively long reverberation time, without excess since the main function of the hall is opera. From this standpoint, Arcimboldi is quite different from the Teatro alla Scala.
- Provide for everyone lateral reflections that contribute to the clarity of music and to the intelligibility of lyrics. In particular, the sidewalls and the back of the orchestra level, among other elements, distribute the sound to the whole audience and, more specifically, to the center of the hall.
- Create diffusion on the sidewalls. The large glass panels, later replaced by wood panels, are tuned carefully to optimise sound distribution and sound diffusion.
- The design of the orchestra pit, and of the elements surrounding it, is such that sound is correctly distributed to the audience and to the stage but also to the musicians. A resonant cavity has actually been designed and built but it is not operational. Another device fulfils the role of providing an adequate resonance of the pit.
- The “musical” response of the hall is of course essential: this is achieved mostly through the choice of decorative components that, even though they appear from the outside to be all identical, are in fact quite different from one another. The wood panels of the walls are in fact designed in such a way that they have different acoustic responses, thus smoothing the overall response of the hall.
- Install a high performance orchestra shell, made of light contemporary materials that have an acoustic response that is very similar to ancient wood concert halls. Of course, it is designed in such a way that the musicians playing under it will be able to hear themselves and one another correctly: this is an essential factor in music making. At this point the construction of this shell has not been completed.

The acoustical design and the architectural design were co-ordinated and simultaneous from the onset. The following pictures illustrate the computer and scale model used to verify that the acoustical criteria are met.

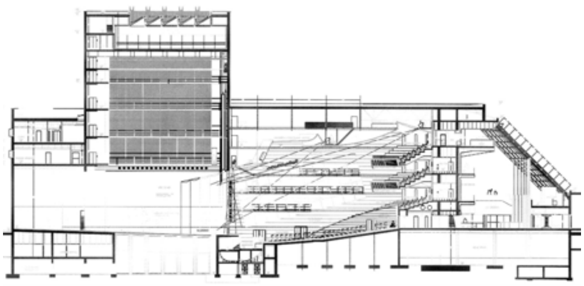
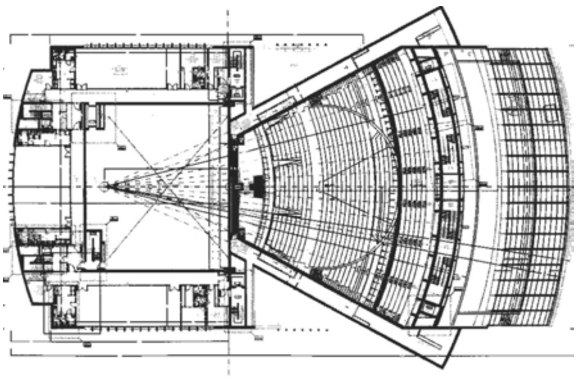







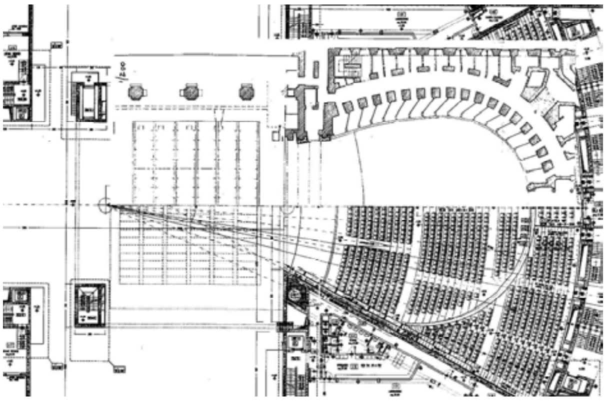


2.2.1 Comparing Arcimboldi and Scala

It is interesting to compare the sizes of Teatro degli Arcimboldi and of Teatro alla Scala: in spite of a very big difference in capacity, the two plans can almost be superposed. It is obvious that Arcimboldi is very compact because of the superposition of balconies. From the point of view of acoustics this is a key factor because it prevents excessive attenuation of the sound and it contributes to creating intimacy. The figure below shows the distribution of sound in the stalls and the first gallery between 50 ms and 80 ms after the emission of the sound.

The figure below shows in plan half of Teatro alla Scala, on top, and half Teatro degli Arcimboldi, at the bottom. It shows that only the extreme seats of the gallery are outside of the 'volume' of la Scala in spite of the larger capacity of the new theatre.



3 SOME SPECIFIC CONSTRUCTION FEATURES

3.1 Diffusing in the stalls

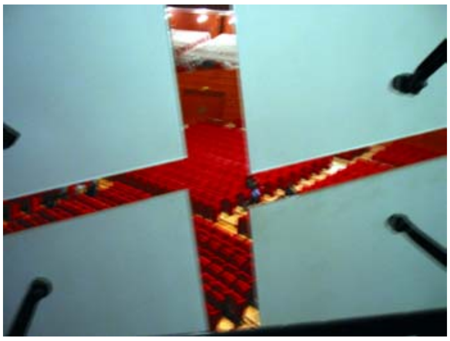
The shape in plan that has been selected requires a solution to distribute the lateral energy towards the center of the room. As can be observed in the pictures below, the stalls are enclosed in a high cylindrical wall. Of course, to avoid focalisation, it is leaning towards the stalls and it is diffusive. For obvious architectural reasons, this diffusive surface, rigid wood elements in front of a well damped space, must be quite discrete meaning that the irregularities must be as thin as possible. The 1/16th scale model demonstrated the capacity of this wall to diffuse the sound adequately.

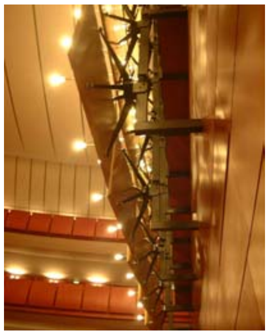
3.2 Lateral diffusion from glass or wood panels

Diffusion is also provided by 90 large panels that also provide lateral reflections towards the pit, the stalls and the balconies.

Glass panels were initially investigated, with great caution. A damped glass sandwich was selected and three types of panels, with different characteristics and responses, wee actually built and installed. They appear on the pictures taken in the hall immediately after it opened.



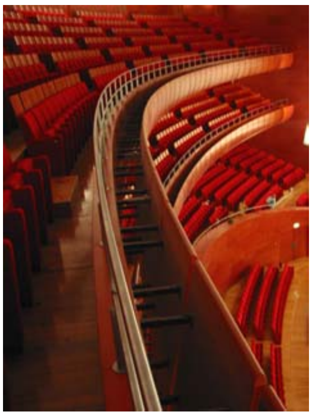


The results were satisfactory as the measurement results given below and by subjective evaluations.

A few days after the inauguration, one of the glass panels was broken by a violent shock. This incident triggered the replacement of the glass panels by wooden panels (picture on the right), presumably temporarily. Of course, once installed the wood panels, properly designed with varied thickness and damping and with an adequate angle, provided the expected diffusion and reflections.

3.3 Diffusion in the balconies

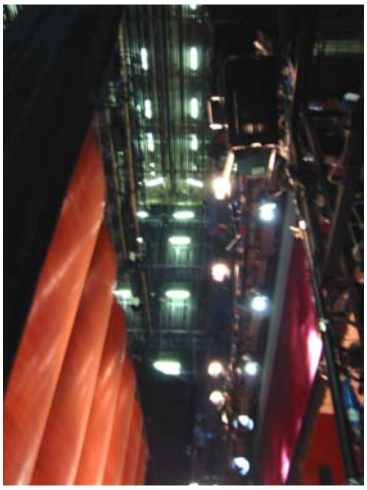
The following pictures show the classical solution to diffuse the sound from the balustrades of the balconies, thus avoiding unwanted echoes on stage and in the pit.




3.4 Orchestra shell

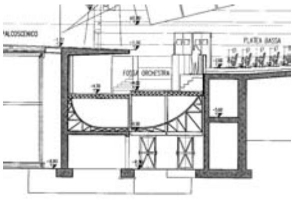
In the concert configuration, the use of an efficient orchestra shell is planed. It will be a light orchestra shell, with a weight of about 5kg/m², using the technology developed for Opéra Garnier, the Staatsoper in Munich and other similar projects.

Its construction has been postponed and, for the first concert, a makeshift shell used in the Piermarini has been installed on stage. Of course, as the pictures below show, it is not completely functional since it makes use of curtains and since the coupling with the stage tower is not prevented.



3.5 The orchestra pit

The orchestra pit, which is of course an important element in this house, is designed to almost match the dimensions of the pit of Teatro alla Scala. It is built over a large resonant cavity, in an attempt to revive thus a technique that had been used in almost all opera houses until the end of



the nineteenth century. This design was actually built but failed acoustically because of a decision of the Fire Department to require a thick thermally insulated floor.

Another simple solution was implemented: a resonant wood cavity was built above the fireproof floor and provided an adequate response to the musicians and to the stalls in particular.

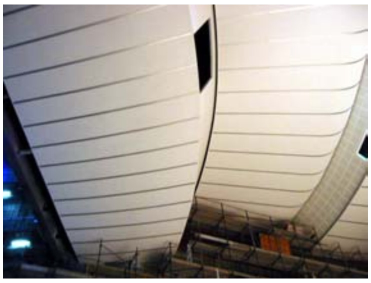
Other details, suggested by the musicians, are of interest: a curved wood panel can be installed in the pit in front of the diffusive back wall. Also, the “wall” separating the public and the musicians contains a louver that guarantees good communication between the instruments and the audience. Of course, a good portion of the top of this “wall” is continuous to ensure good communication between the pit and the stage.

3.6 Ceilings

As the pictures below show, the shape of the ceiling has followed strictly the recommended acoustical characteristics. It was originally planned to build it in plaster. A proposal of the construction company to build it with three plasterboard layers was accepted under condition that the boards be bent, glued together and damped. The weight of the ceiling is over 100 tons.



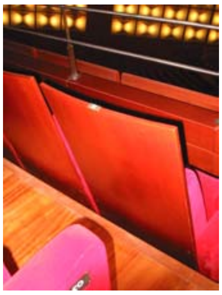


3.7 The floor

In a concert hall or in an opera house, the floor plays an acoustical role that seems to have been underestimated in the XXth century by most acoustical designers. Frequently, a very hard wooden floor, bonded to the concrete slab is built; the motivation is to limit as much as possible low frequency absorption, thus avoiding hurting the low frequency response of the hall, a very critical parameter. If this technique is used, it is sometimes necessary to compensate by adding low frequency resonators in the ceiling.

In Teatro degli Arcimboldi, as in all the projects of the acoustical consultants involved, the floor is made of wooden parquet installed on a relatively high damped space. The pictures below show some of the details.

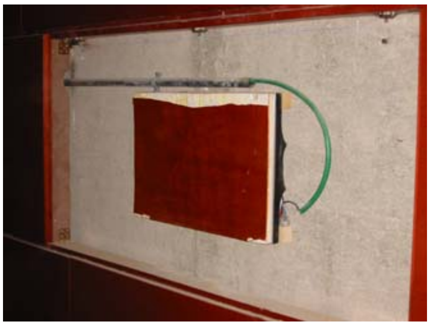

3.8 Seats

For the seats, the composition that has now become the norm in concert halls has been adopted: a thick wooden back, a thick perforated wooden bottom, upholstered seat and back and for some areas a high wooden back to provide additional back-reflections. The seats were tested in the laboratory for the occupied and unoccupied configurations.

The result is satisfactory; there is only a minor difference in the response of the hall empty and full.

3.9 Sound system

Even tough the room is not supposed to be used for overamplified music, an invisible sound system has been installed in the room mostly for special effects. It is composed of a cluster hidden behind an acoustically transparent cloth in the ceiling and of a set of flat omnidirectional loudspeakers installed in the sidewalls and in the ceilings of the balconies.



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5 THE ORCHESTRA REHEARSAL ROOM

Since the budget for rooms other that the main hall was extremely limited, a very simple rehearsal room has been designed with a partially diffusive and absorptive ceiling and very classical reversible wall panels with a reflective side and an absorptive side.

6 TRAM VIBRATIONS

A new tramway line has been built a few meters from the theatre's side. The track has been installed on resilient pads and the rails are elastically mounted.

7 COSTS AND TIMING

It is often assumed that the construction of a world-class concert hall or opera house costs hundreds of millions of €. This project, which did not include parking and that houses only two main rehearsal rooms and only a few offices, has been built for 44 M€, a budget that excludes the cost of the land. The following chart compares recent buildings of a similar nature.

Place	Project	Duration	Cost in Million €	Number of seats	Cost per seat €
Birmingham, Great Britain	Symphony Hall	4 years 1987 – 1991	206	2200	93600
Bruges, Belgium	Concertgebouw	28 months + 1999-2002	27	1320	20000
Genova, Italy	Carlo Felice	4 years 1987 – 1991	62	2000	31000
Lyon, France	Opera House	7 years 1986 – 1993	72	1300	55400
Milano, Italy	Teatro degli Arcimboldi	27 months 1999 – 2002	44	2385	18500
Paris, France	Opéra Bastille with offices and parking	7 years 1979 – 1989?	1000	2700	370000
Philadelphia, PA	Kimmel Center	? – 2002	428	2500 + 650	136000
Rome, Italy	Auditorium	8 years + 1994 – 2002?	130	4600	28300

8 OBJECTIVE RESULTS

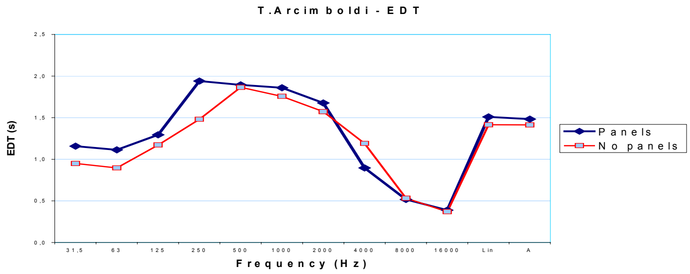
Extensive measurements have been performed after completion of the building in the opera and symphony configurations, with and without audience. The incident leading to the removal of the side panels made it possible to try to assess the role of the side glass and wooden panels. A summary of important results is given below.

8.1 Results with glass panels and without panels

The results below that compare objective results with and without the glass panels have been obtained with a dodecahedral loudspeaker source placed in the central area of orchestra pit, a little out of symmetry. The fire curtain was down the receivers, both B-format and binaural, were distributed at seven positions in the theatre. The data below refer to the omnidirectional W signal. Measurements with wood panels have not been completed at the time of printing; a later publication is expected on the comparison between glass and wood panels.

Early Decay Time

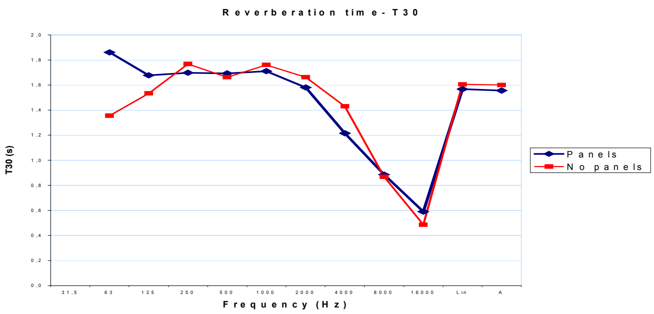
With panels in place, the curve (blue line) shows higher values in the mid-range; those values correspond to the targets of the project. Lower values are measured in the lower range probably



due to early bass absorption of the ceiling and of the lateral walls especially in the configuration without panels. The presence of panels is thus to be preferred.

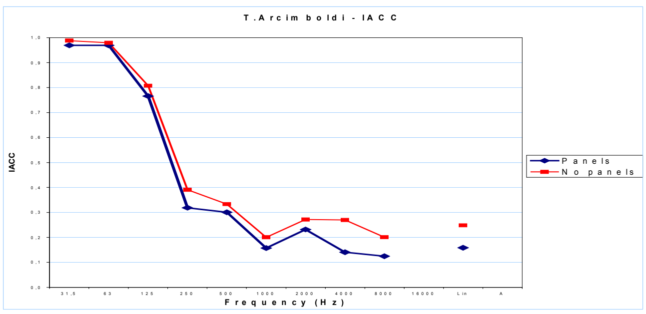
Reverberation time T_{30}

Reverberation time shows quite constant values across the mid- to high frequencies. The values fit



the target and a richer RT is measured in the lower range. It is interesting to note the role of the panels at low frequencies. The configuration with panels is to be preferred since RT without panels is clearly diminished.

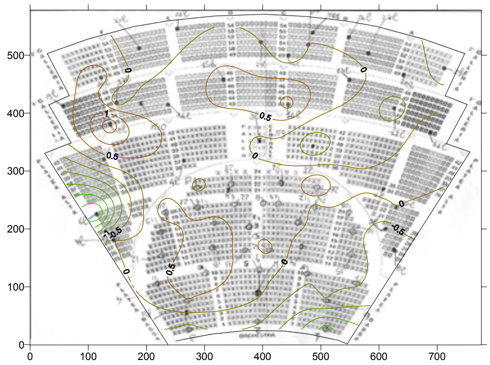
IACC



The values of the parameter are quite appropriate and are in line with expectations. A better diffusion is achieved with the panels, since they add also a certain degree of scattering.

Strength: G difference with and without panels

The results shown here for the difference in strength with and without the glass panels display a better range with the panels in place. This was true even though, for the measurements, the orientation of the panels had not been optimised. In absolute terms, the parameter G covers a range that is consistent with the requirements and with the project targets.

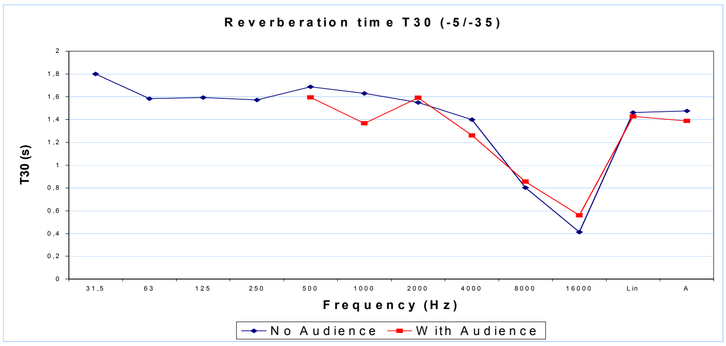


8.2 Results with and without audience

The results refer here to the concert configuration with a temporary orchestra shell in place. In one case, there are no audience or musicians while, in the other, both public and orchestra are present at their respective positions. Only two measurement positions could be used, one in the centre of lower stalls and one in the first gallery.

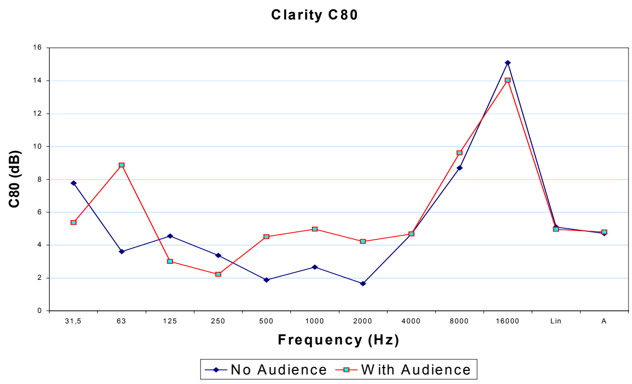
Reverberation time

The parameter shows limited discrepancies between the two conditions. Only in the 1kHz octave band, lower values have been observed with audience. So, the goal, which required a reverberation time independent of the occupancy, seems to have been reached.



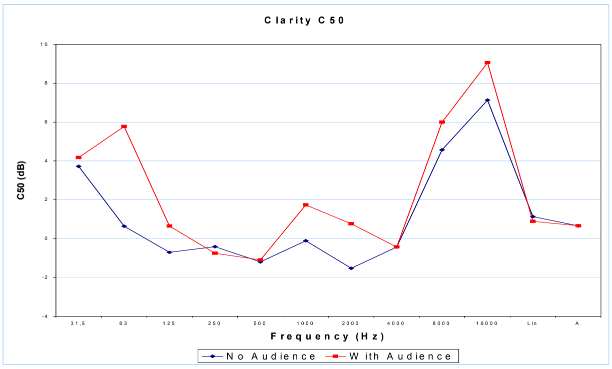
Clarity C80

Clarity can have notable variations from one position to another in an opera house. In this case, measurements for a limited set of positions show that, with audience, clarity shows some variation; it increases significantly in the range of mid-frequencies. Measurements for a large number of positions may clarify this behaviour.



Clarity C50

Similar conclusions apply to C50.



8.3 Comparison between computer model, scale model and actual room

		Goal	Arcimboldi	Arcimboldi	Arcimboldi
Criteria			Measured	computer	1/16 model
Early Decay Time	EDT	1.5 to 2.0 s	1.8 s	1.8 s	
Reverberation Time	RT	1.8 s	1.7 s	1.9 s	1.6 s
Clarity	C80	-2 to +3 dB	0 dB	3.2 dB	5 dB
Clarity	C50	-2 to +3 dB	-3 dB		
Definition	D50	0.34 to 0.60	0.40	0.51	0.51
Central Time	Ts	< 140 ms	100 ms	106 ms	80 ms
Strength	G	- 2 to + 4 dB	- 1 to + 4 dB		- 4 dB
Inter-Aural Cross-Correlation	IACC	0.12 to 0.70	0.19 to 0.31		
Initial Time Delay Gap	ITDG	30 ms	20 ms		

The table above summarises the most important objective results achieved in Teatro degli Arcimboldi. As it can be seen, the targets have been reached. One observes that computer predictions provided some good indications of the overall behaviour.

8.4 Comparison between Teatro degli Arcimboldi and Teatro alla Scala

Criteria		Arcimboldi	Scala
Early Decay Time	EDT	1.8 s	1.2 s
Reverberation Time	RT	1.7 s	1.25 s
Clarity	C80	0 dB	2 to 3.8 dB
Clarity	C50	-3 dB	3 dB
Definition	D50	0.40	0.54
Central Time	Ts	100 ms	70 ms
Strength	G	- 1 to + 4 dB	-0.7 to –3.0 dB
Inter-Aural Cross-Correlation	IACC	0.19 to 0.31	0.48 to 0.54
Initial Time Delay Gap	ITDG	20 ms	38 ms

In the table above, the comparison between Teatro degli Arcimboldi and Teatro alla Scala shows the outstanding differences of the two halls. The former has a higher reverberation time, a lower clarity, stronger sound levels and a better envelopment. In conformity with one of the main objectives of the design, to obtain good conditions for opera and for concerts, without any compromise between concert and opera, it appears that the new theatre is appropriate for both types of performances.

9 CONCLUSION: ACOUSTICS IN TEATRO DEGLI ARCIMBOLDI

The objective and subjective results obtained since Teatro degli Arcimboldi opened on 19 January 2002 seem to indicate that adequate acoustical qualities can be obtained for both concerts and operas in a 2385-seat hall. The geometry and the proper distribution of tuned diffracting elements, mainly around the stalls and on the sides, seem to be the key.

Acknowledgements

As always, it is impossible to thank the many colleagues who contributed to the design of Teatro degli Arcimboldi. However, special thanks are due to Vittorio Gregotti and Giuseppe Donato, Lia Kiladis for contributing to the design of the side panels and of the orchestra shell, Nelida Auletta and Åsa Nystrøm for computer modelling, Roberto Pompoli, Angelo Farina, Patrizio Fausti and Nicola Prodi for scale model measurements.

[1] D. Commins, V. Gregotti, A new house for Teatro alla Scala, Conference on opera house design, Torino, 14-16 October 1996.