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Acoustical Design of Inner Galleries in Heydar Aliyev Center

Zühre Sü-Gül (1) and Mehmet Çalışkan (2)

(1) Department of Architecture, Middle East Technical University, Ankara, Turkey; MEZZO Studio Ltd. Ankara, Turkey
(2) Department of Mechanical Engineering, Middle East Technical University, Ankara, Turkey

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ABSTRACT

Heydar Aliyev Center in Azerbaijan, Baku is an architectural landmark in terms of its symbolic contribution to the city. Contemporary organic architecture of the building, having the signature of the architect Zaha Hadid, ends up with no corners or rectilinear surfaces. Acoustical excitement starts up with the challenge of solving out the acoustical defects related to those mostly curvilinear forms and highly reflective surfaces. Inner galleries having reverberation times up to 10 s are aimed to be taken under within limits of 2.5 s for optimum foyer acoustical characteristics. The challenge starts with the architects no compromise on any architectural design visual alteration. So as to satisfy the sound absorption for desired acoustical performances with architecturally transparent materials that cause the least visual modification, much effort has been spent on the compromise in between materials' visual and acoustical features. Acoustically transparent materials are studied under the consideration of architectural continuum. Acoustically transparent plasters with the least visual dissimilarities in comparison to regular paints or plasters are searched. These materials are used as a finish material over perforated backing. This paper mainly discusses about the acoustical performance of wall construction systems for such a challenging design for both satisfying the energy decay in terms of having the optimum sound pressure levels indicating noise levels, and satisfying sound intelligibility characteristics within given such scheme so as to provide acoustical comfort for the users.

INTRODUCTION

Heydar Aliyev Center is a landmark building for the city of Baku, Azerbaijan. The Cultural Center is designed to house majorly a library, a museum, an auditorium for conference, concert and opera uses, and a multipurpose hall. This paper intends to discuss the acoustical problems and corresponding research on probable acoustical measures and design solutions within the limits of architectural and aesthetic considerations.

Having the signature of Zaha Hadid the proposed design follows a fluid form which emerges by the folding of the landscape's natural topography (e.g. Figure 1). The exterior skin as a single continuous surface wraps around in order to define individual functions of the Center, while providing each element its own identity and privacy.

Source: (Zaha Hadid Architects, 2010)
Figure 1. Heydar Aliyev Center, cultural plaza

The museum faces out into the landscape with its glass facade washing the galleries with natural light (e.g. Figure 2). The ground surface of the museum begins to fold and reaches to the peak by forming a ridge on top of the upper most gallery level. All other mezzanine floors are packed under this primary fold having suspended ceilings above each that provide one major treatment surface for acoustical interventions.

Source: (Zaha Hadid Architects, 2010)
Figure 2. Heydar Aliyev Center, south facade

The other dominating envelope of outer skin forms the library building. This north structure and the glazed facade provide controlled daylight for the reading and archive floors that are stacked on top of each other. As in museum building, library mezzanines have their flat suspended ceilings being potential sound absorption surfaces. The floors connect to each other with ramps creating a continuous path of circulation. The library and the museum are also joined by a ramp that goes through the ground floor of the library to the first floor of the museum (e.g. Figure 3).

Source: (Zaha Hadid Architects, 2010)
Figure 3. Ramp connecting museum to library building

In this former paper inner galleries of library and museum buildings are studied for providing the limits of certain acoustical parameters in relation to functions to be held within those semi-open spaces.

ACOUSTICAL DESIGN

Inner galleries accommodate circulation zones and activity places as of mezzanines within museum and library buildings. The mezzanine floors are connected to each other mainly by ramps ending up in larger halls forming acoustically semi-open spaces under a single continuous shell (e.g. Figure 4). Acoustical design of those interior spaces has two major concerns. First, is the sound isolation of galleries from exterior sources including atmospheric or man-made noises.

Source: (Zaha Hadid Architects, 2010)
Figure 4. Main gallery in library building

The role of sound isolation is mostly taken over by the outer skin namely building shell. As it is hard to state separate exterior walls or roof structures in such a dynamic form, the shell proposed as a glass fiber reinforced concrete in present status together with the inner skin is the single flowing surface that necessitates sound isolation actions.

The outer skin is composed of multiple layers. The glass fiber reinforced concrete (GFRC) exterior shell is attached to the inner skin by a specific space truss system. The material composition or design of inner skin surface has been the key acoustical question. The maximum sound pressure level on the roof is reported as 89 dBA based on a noise mapping study considering the traffic flow projections in previous studies. GFRC is not sufficient to provide sound isolation solely. Besides, the existence of openings on the exterior GFRC skin for water drainage results in poor airborne sound insulation characteristics.

Inner skin material composition is of priority both for isolation considerations and room acoustics. As GFRC does not provide required air borne sound isolation with all mentioned gaps for drainage system, alternative materials for the first layer of inner skin are tested for their acoustical dimensions. Air borne noise insulation characteristics is calculated by INSUL v6.3 [1]. The material data bank of INSUL does not include specific composite materials proposed as alternatives. The closest material in the data bank to a particular alternative is selected in the predictions in reference to density and damping properties.

Three inner skin alternatives are considered in the preliminary study. Assessment is based on airborne sound isolation characteristics of thermal and water insulation layers along with the proposed inner skin alternatives. The isolation characteristics are expressed in terms of airborne noise reduction index, Rw(C; Ctr). The technical data supplied by the manufacturers are used in the predictions.

When the results of predictions for air borne noise insulation are compared, the highest airborne noise reduction index is obtained for two layer gypsum board alternative by the first manufacturer. With a total thickness of 12 mm, this particular alternative results in an airborne noise reduction index value of Rw(C; Ctr) = 31(-2;-5). The second to be the 4,8 mm-thick molded gypsum inner skin alternative proposed by its manufacturer comes next with an airborne sound reduction index of 29(-1;-5). The last place is taken by 5 mm thick laminated glass reinforced gypsum with an airborne sound reduction index value of 28(-1;-4).

The alternatives of inner skin are limited due to the hard workmanship of the curvilinear form. The above mentioned inner skin materials that have proposed to be proper for design and manufacturing are still considered as weak in terms of sound isolation. For that reason no other action that will result in gaps or voids are let through this outer layer of inner skin. The sound isolation details of the shell are studied for minimizing sound leaks from outdoors to the inner galleries.

The second major consideration of the acoustical design is the room acoustics and related comfort parameters. Reverberation time is one major parameter that carries clues on the intelligibility and noise levels due to the suspended sound within enclosed interior spaces. Interior finishing materials, form of gallery facing surfaces, related dimensions and the volume are variables that directly affect the reverberance that occur within galleries. Due to the strict design attitude and attachment to the architectural language of the whole building, no interventions that may lead to possible visual alterations are let through the acoustical design. This results in keeping the surface forms and dimensions, consequently the volume as they are in the concept design. The inner layer of interior skin together with the suspended ceiling flat surfaces have come up to be the major surfaces that sound absorption role could be attributed to.

Source: (Zaha Hadid Architects, 2010)
Figure 5. Inner skin surrounding museum mezzanines

Even before the preliminary simulation studies, it had foreseen that the huge volume and highly reflective fine finish gypsum inner skin surfaces would result in excessive reverberation and related problems if no absorptive material is to be introduced in the interior design. With one basic criterion of not causing any visual modification, inner shell and drop ceiling surfaces have been in the concentration core of acoustical trials. Preserving the white folded curvilinear image of the shell and respecting to the designers approach in keeping the same continuity in flat white suspended ceiling faces, the materials are researched and alternatives are developed with high absorption coefficient and minimum alteration from a white smooth surface as discussed in later sections (e.g. Figure 5).

Together with the treatments on wall/ceiling shell structure and drop ceilings, additional precautions are taken underneath the floor finishes. As of the shell surfaces the floor finishes as well are selected out of highly reflective materials by the design team due to visual and maintenance considerations. For reducing the impact noise that are predicted to be caused mostly by high-heels, a resilient layer of cork or similar material for creating semi-floating floors are proposed to be used underneath natural stone and poured concrete type floor finishes. Besides, for keeping the auxiliary spaces and auditorium away from the noise to be generated in inner galleries resilient wall and ceiling constructions and corresponding details are developed for inner walls and drop ceilings.

The acoustical assessment of galleries in Heydar Aliyev Center are studied for museum and library buildings separately. The 3D model of the complete center is divided into two for the sake of accuracy of acoustical results that might be inversely affected from coupling of big separate volumes. A graphical model for computer simulation is developed by MEZZO Studio for use with ODEON version 10.02 [2]. The models, basically made up of 3-D face elements are obtained after simplifying the graphical model supplied by ZHA Architects and DIA Holding, the main contractor. In this process of modification the geometry and dimensions in the graphical model are preserved in great detail. A series of simulation studies are carried by MEZZO Studio using this new graphical model. Recommended range for acoustical parameters used in the assessment study is listed in Table 1.

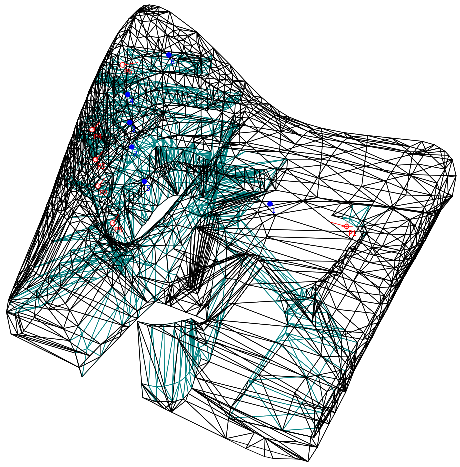
Table 1. Acoustical Parameters and Recommended Ranges

Parameter	*Recommended range*	*Just noticeable difference (JND)*
Mid Frequency Reverberation Time, T30	1.8s to 3.0s	about 0.1s

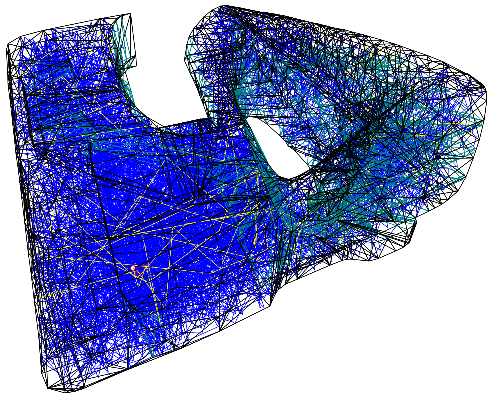
Source: (Çalışkan, 2004) [3]

ANALYSIS OF INNER GALLERIES IN MUSEUM BUILDING

The acoustical model of museum building is comprised of 3233 plane surfaces and the estimated acoustical volume of the building apart from library and auditorium spaces is 57.398 m³. Six sources and corresponding receivers are designated and located in primary zones including mezzanine floors and main gallery hall (e.g. Figure 6). The present condition of the concept design and the proposed alternative acoustical design solutions are discussed in this section. Ray tracing is used in sound path analysis (e.g. Figure 7). Reverberation times are assessed for each configuration. Results are given in the form of global estimate bar graphs and sound distribution maps.



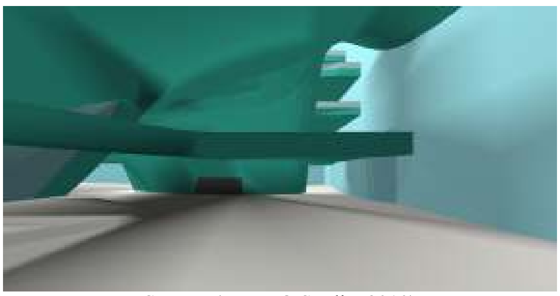
Source: (MEZZO Studio, 2010)
Figure 6. ODEON acoustical model with six source (red) and six receiver (blue) positions, museum building



Source: (MEZZO Studio, 2010)
Figure 7. Ray tracing of ODEON acoustical model, museum building

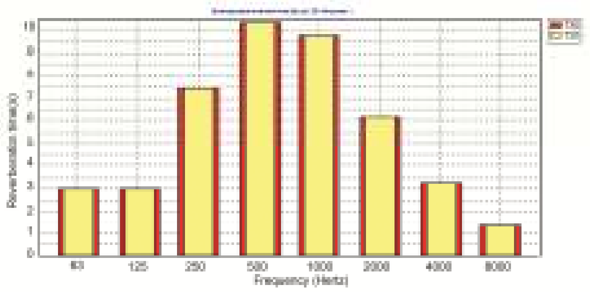
Present condition of museum building

In present condition all surfaces are kept as they are indicated in architectural drawings and 3Dmodels with no additional treatment (e.g. Figure 8). One of the finishing materials - used in spaces as library and museum mezzanines that are acoustically in connection with galleries in the original design - is un-perforated glass reinforced gypsum inner skin shell with an NRC value of 0.16 tested and reported by Chesapeake Acoustics Research Institute. Other key material is presumed to be two layers of gypsum board or similar with an NRC value of 0.11 for drop ceiling surfaces.



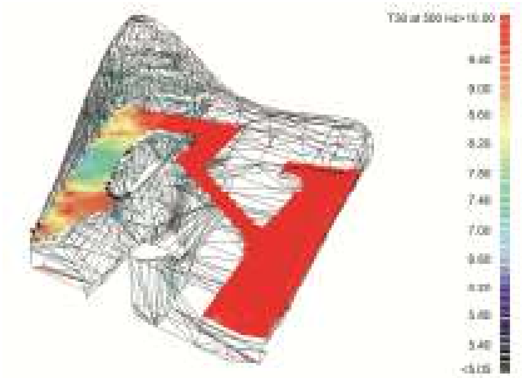
Source: (MEZZO Studio, 2010)
Figure 8. 3D OpenGL view of present condition, museum building

Reverberation times for some sample activity zones in museum building are presented in the form of global estimate results and distribution maps in following (e.g. Figure 9 and 10).



Source: (MEZZO Studio, 2010)

Figure 9. Estimated Global Reverberation Times Bar Graph, for Ground Floor in present condition, museum building



Source: (MEZZO Studio, 2010)

Figure 10. Reverberation Time (T30) distribution map at 500Hz for mezzanine Level 1 in present condition, museum building

The estimated reverberation times in detail for each activity zone corresponding to different mezzanine levels are listed in Table 2 below.

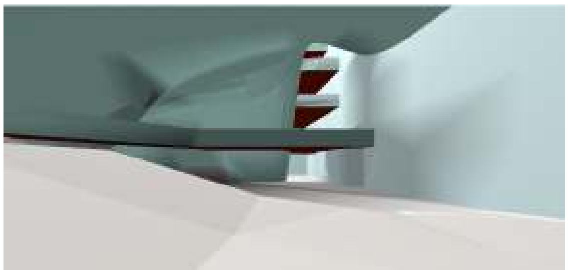
Table 2. Reverberation Time (T30) results for present condition, museum building

	Reverberation time (s)	
Location	*Average low-frequency (125Hz-250Hz)*	*Average mid-frequency (500Hz-1000Hz)*
Ground floor	5.24	10.09
Level 1	4.13	9.09
Level 2	3.80	8.66
Level 4	3.32	7.99
Level 5	3.02	7.42

Source: (MEZZO Studio, 2010)

Alternative design 1 for museum building

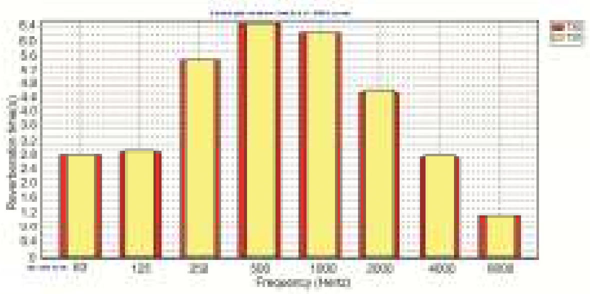
In alternative design 1 for evaluating the maximum effect of mezzanine floor ceilings the absorptive treatment is applied underneath the suspended ceiling surfaces of mezzanine floors (e.g. Figure 11). The absorptive treatment adopted in this alternative is white colored acoustical stretched fabric with rock wool backing as a ceiling surface. Acoustical fabric, with 10cm air gap behind inside filled with 52 kg/m³ density rock wool as measured in METU acoustical labs has an NRC value of 0.86. Apart from that glass reinforced gypsum (GRG) inner shell, interior wall and floor finishing materials are kept as in the original design.



Source: (MEZZO Studio, 2010)

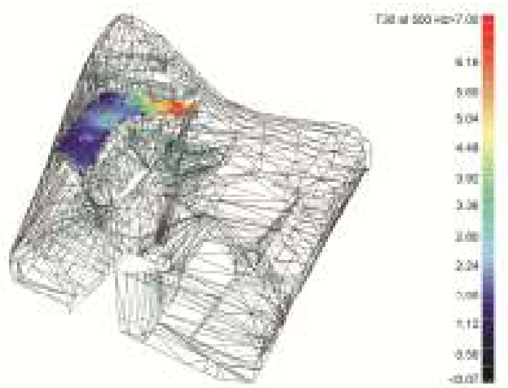
Figure 11. 3D OpenGL view of alternative design 1, museum building

Reverberation times for some sample activity zones in museum building for alternative design 1 are presented in the form of global estimate results and distribution maps in following (e.g. Figure 12 and 13).



Source: (MEZZO Studio, 2010)

Figure 12. Estimated Global Reverberation Times Bar Graph, for Ground Floor in alternative design 1, museum building



Source: (MEZZO Studio, 2010)

Figure 13. Reverberation Time (T30) distribution map at 500Hz, for Level 2 in alternative design 1, museum building

The estimated reverberation times in detail for each activity zone corresponding to different mezzanine levels for alternative design 1 are listed in Table 3 below.

Table 3. Reverberation Time (T30) results for alternative design 1, museum building

	Reverberation time (s)	
Location	*Average low-frequency (125Hz-250Hz)*	*Average mid-frequency (500Hz-1000Hz)*
Ground floor	4.24	6.42
Level 1	2.55	3.94
Level 2	2.40	3.92
Level 4	2.09	3.72
Level 5	2.26	4.25

Source: (MEZZO Studio, 2010)

Alternative design 2 for museum building

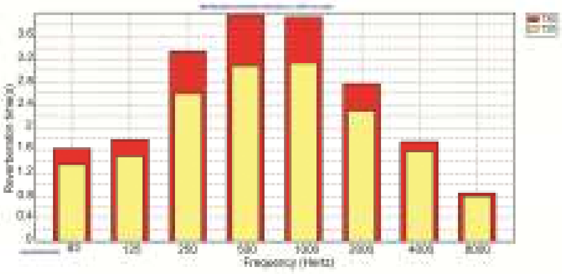
The opposition of the design team on visually distracting seams of acoustical fabric that is manufactured and installed in certain dimensions has lead to further investigations on seamless material alternatives. In alternative design 2, 12,5mm thick perforated gypsum panel with 20mm thick 52 kg/m³ dense rock wool backing in air gap behind is applied in intent of increasing absorptive surfaces to lower the global reverberation times. The NRC value of tested perforated panel with acoustically transparent coating / paint is 0.79 as reported by NEU. The application of sound absorptive material on drop ceiling surfaces only has proved to be insufficient in alternative design 1. A series of acoustical simulations lead to the requirement of sound absorptive perforated panel applications not only on drop ceilings but also in inner layer of interior skin, together with flat fascia and flat interior wall surfaces. All surfaces of drop ceilings are treated with perforated panel type absorbers. Apart from that, necessary areas of absorptive treatment for inner shell, core walls and fascias in square meters over specified surfaces are given in Table 4.

Table 4. Absorptive treatment over specified surfaces, museum building

	Area (m²)	
Location	*Fascias + GRG core walls*	*GRG ceiling surfaces)*
Ground floor	152	-
Level 1	492	-
Level 2	40	-
Level 4	55	-
Level 5	42	-
Museum top ridge	-	365
Main gallery	-	321

Source: (MEZZO Studio, 2010)

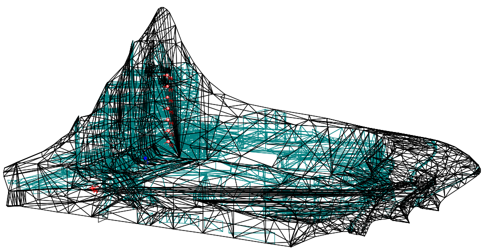
Reverberation times for the most critical zone as to be the ground level for alternative design 2 are presented in the form of global estimate results in following (e.g. Figure 14).



Source: (MEZZO Studio, 2010)

Figure 14. Estimated Global Reverberation Times Bar Graph, for Ground Floor in alternative design 2, museum building

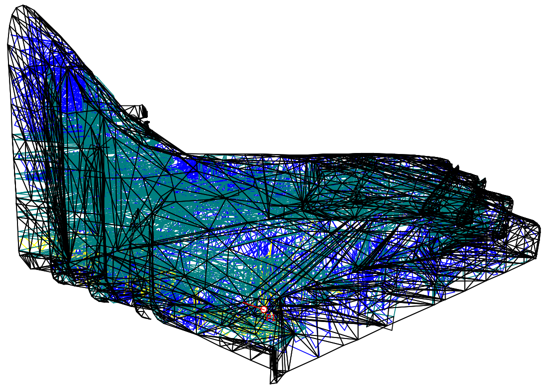
ANALYSIS OF INNER GALLERIES IN LIBRARY BUILDING



Source: (MEZZO Studio, 2010)

Figure 15. ODEON acoustical model with eight source (red) and receiver (blue) positions, library building

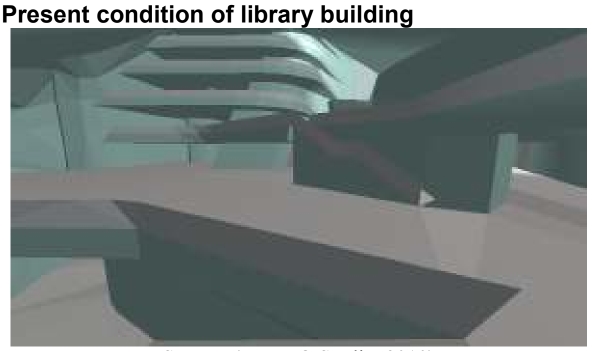
The acoustical model of museum building is comprised of 6494 plane surfaces and the estimated acoustical volume of the building apart from library and auditorium spaces is 154.862 m³. Eight sources and corresponding receivers are defined and located in primary zones including mezzanine floors and main gallery hall (e.g. Figure 15). Ray tracing is used in sound path analysis for the library building as well (e.g. Figure 16). Reverberation times are assessed for each configuration.



Source: (MEZZO Studio, 2010)

Figure 16. Ray tracing of ODEON acoustical model, library building

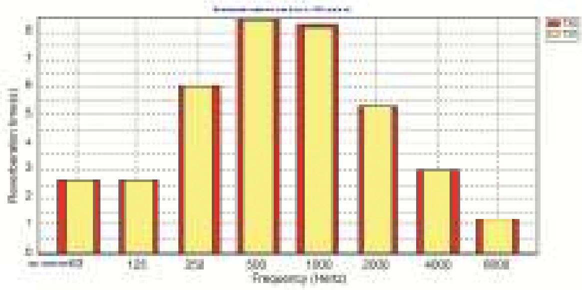
Present condition of library building



Source: (MEZZO Studio, 2010)

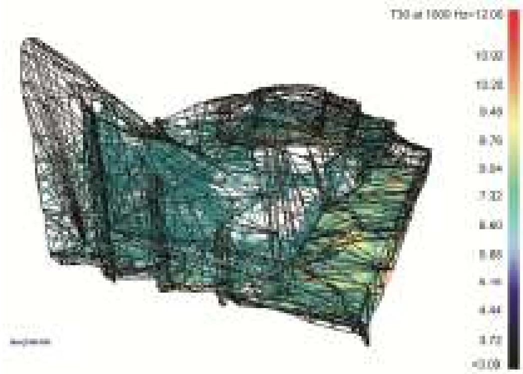
Figure 17. 3D OpenGL view of present condition, library building

In present condition all surfaces are kept as they are indicated in architectural drawings and 3Dmodels with no additional treatment as discussed in museum building (e.g. Figure 17). Reverberation times for some sample activity zones in library building are presented in the form of global estimate results and distribution maps in following (e.g. Figure 18 and 19).



Source: (MEZZO Studio, 2010)

Figure 18. Estimated Global Reverberation Times Bar Graph, for Ground Floor in present condition, library building



Source: (MEZZO Studio, 2010)
Figure 19. Reverberation Time (T30) distribution map at 1000Hz for Ground Floor in present condition, library building

The estimated reverberation times in detail for each activity zone corresponding to different mezzanine levels are listed in Table 5 below.

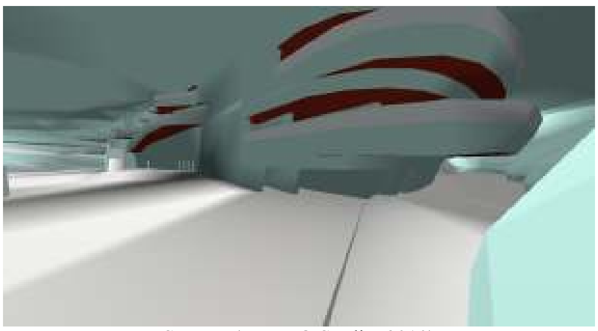
Table 5. Reverberation Time (T30) results for present condition, library building

	Reverberation time (s)	
Location	*Average low-frequency (125Hz-250Hz)*	*Average mid-frequency (500Hz-1000Hz)*
Ground floor	4.33	8.34
Level 1	2.54	5.92
Level 2	2.87	6.34
Level 3	2.71	6.03
Level 4	2.88	6.09
Level 5	2.67	5.93
Level 6	2.70	6.27
Level 7&8	3.19	7.10

Source: (MEZZO Studio, 2010)

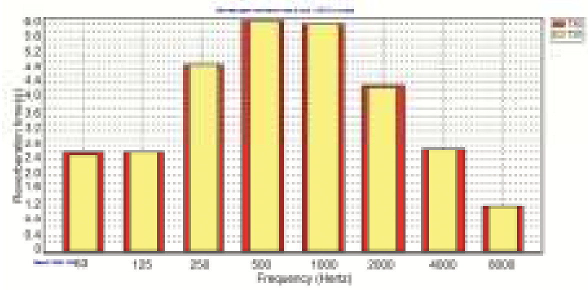
Alternative design 1 for library building

As in the case of museum in alternative design 1 the absorptive treatment is applied underneath the suspended ceiling surfaces of mezzanine floors (e.g. Figure 20), namely acoustical fabric, with 10cm air gap behind inside filled with 52 kg/m³ density rock wool. Glass reinforced gypsum (GRG) inner shell, interior wall and floor finishing materials are kept as in the original design.

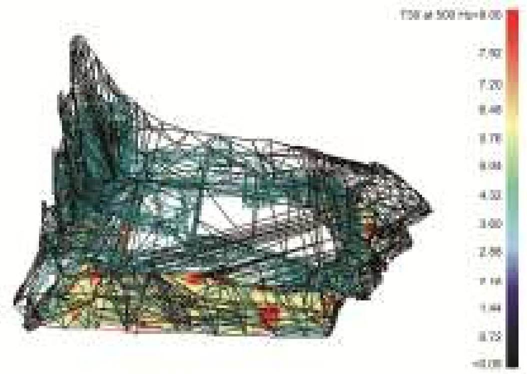


Source: (MEZZO Studio, 2010)
Figure 20. 3D OpenGL view of alternative design 1, library building

Reverberation times for some sample activity zones in library building for alternative design 1 are presented in the form of global estimate results and distribution maps in following (e.g. Figure 21 and 22).



Source: (MEZZO Studio, 2010)
Figure 21. Estimated Global Reverberation Times Bar Graph, for Ground Floor in alternative design 1, library building



Source: (MEZZO Studio, 2010)
Figure 22. Reverberation Time (T30) distribution map at 500Hz, for Ground Floor in alternative design 1, library building

The estimated reverberation times in detail for each activity zone corresponding to different mezzanine levels for alternative design 1 are listed in Table 6 below.

Table 6. Reverberation Time (T30) results for alternative design 1, library building

	Reverberation time (s)	
Location	*Average low-frequency (125Hz-250Hz)*	*Average mid-frequency (500Hz-1000Hz)*
Ground floor	3.77	6.03
Level 1	1.29	1.59
Level 2	1.78	2.38
Level 3	1.60	2.22
Level 4	1.74	2.57
Level 5	1.52	2.11
Level 6	1.64	2.58
Level 7&8	2.88	5.81

Source: (MEZZO Studio, 2010)

Alternative design 2 for library building

As introduced in museum building acoustical design in alternative design 2, 12.5mm thick perforated gypsum panel with 52 kg/m³ dense rock wool backing in air gap behind with acoustically transparent coating / paint is applied in intent of increasing absorptive surfaces to drop the global reverberation times of library building inner galleries.

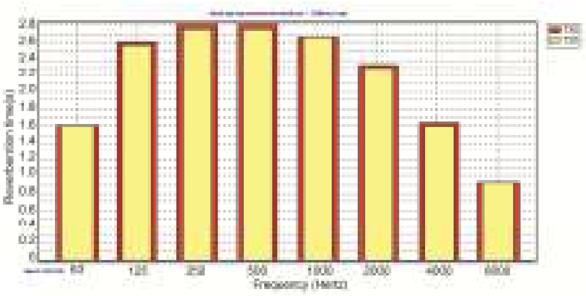
Perforated panel coated with acoustically transparent plaster is applied on all drop ceiling surfaces. Apart from that, necessary areas of absorptive treatment for inner shell, core walls and fascias in square meters over specified surfaces are given in Table 7 below.

Table 7. Absorptive treatment over specified surfaces, library building

Location	*Area (m²)* Fascias + GRG core walls	*Area (m²)* GRG ceiling surfaces)
Ground floor	281	-
Level 1	200	-
Level 2	322	-
Level 3	306	-
Level 4	318	-
Level 5	204	-
Level 6	212	-
Level 7	14	-
Level 8	74	-
Library top	-	360
Auditorium top	-	174
AV top	-	84
Level 8 top	-	183

Source: (MEZZO Studio, 2010)

Reverberation times for the most critical zone as to be the ground level for alternative design 2 for library building are presented in the form of global estimate results in following (e.g. Figure 23).



Source: (MEZZO Studio, 2010)

Figure 23. Estimated Global Reverberation Times Bar Graph, for Ground Floor in alternative design 2, library building

CONCLUDING REMARKS

The targeted reverberation time in preliminary acoustical design as to be 1.8s has been reviewed after initial concept design simulations. With all the constraints imposed by architectural concerns as well as temporal, economic and practical aspects of application, a need for such a revision / relaxation has become a necessity. Spaces facing the same difficulty have been considered in detail. Indoor swimming pools are among such spaces that live up to almost as strict reverberation requirements in reference to speech intelligibility. Such an assessment of speech intelligibility in indoor swimming pools has been made by considering several examples to reach a compromise [4]. With the support of this research on indoor swimming pools the targeted reverberation time limits are revised / relaxed for a compromise as 3s at mid frequencies. This compromise holds only for the condition that all the echo producing areas are treated with absorptive material and an acceptable distribution of reverberation times along frequency is attained. This implies a requirement of target reverberation time of 4 s at 125 Hz.

Within the light of acoustical design targets, present condition simulations test museum and library building with their present conditions with no additional acoustical treatment. Calculated/simulated mid frequency reverberation times around 9s imply that the galleries reverberation characteristics are much above the targeted mid frequency reverberation time limit that is 3s maximum for such spaces.

Alternative design 1 simulations test the efficiency of acoustical treatments on flat suspended ceiling surfaces above mezzanine floors with no intervention on GRG. Two materials have been tested; first perforated gypsum and second acoustical fabric with 10cm thick rock wool backing. The results of fabric use are presented within the scope of this paper. Acoustical fabric is slightly better than perforated gypsum in terms of sound attenuation within the galleries. Acoustical fabric sound absorption characteristics are almost at maximum throughout the frequency bands. The applicable surfaces square meters are crucial in this respect. Any other material that could be proposed instead of acoustical fabric with similar or higher sound absorption characteristics is not expected to make much difference in terms of lowering reverberation times considering that it is applied only on flat ceiling surfaces.

Although acoustical fabric is applied at all flat ceiling surfaces the reverberation times can still not be lowered under limits. Mid frequency reverberation times around 5s in this second simulation is much better than 9s of present condition. However, additional precautions have to be taken on GRG surfaces for acceptable ranges of reverberance together with the application of acoustical fabric or similar materials on flat ceiling surfaces.

In alternative design 2 indicated absorptive treatments for GRG core wall surfaces over floor levels is proposed to be applied in locations closer to main galleries with larger volumes, rather than GRG core walls closer to auxiliary spaces neighboring mezzanine floors. As all suspended/drop ceilings have already been treated with perforated material there is no more need to add absorption on walls closer to those surfaces. This doesn't help to drop RTs in problematic areas, while decreasing RTs of mezzanine floors to unnecessarily low levels. Apart from that this final treatment for both library and museum buildings have proved to be satisfactory in reducing reverberation times below 3s for the majority of activity spaces.

On the other hand, poured concrete as flooring material is found to be much better than the natural stone in acoustical terms. Although the use of poured concrete has a minor effect on sound absorption within the galleries compared to stone flooring, the better performance of that floor finish is crucial when the impact noise, in other words noise generated in the spaces especially by footsteps is of consideration. The findings of this paper and related acoustical precautions are in the process of being incorporated into the ongoing design and construction.

ACKNOWLEDGEMENTS

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