ACOUSTICAL IMPROVEMENT OF TYPICAL SPORT HALLS
FOR MULTI-PURPOSE USE

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ABSTRACT

ACOUSTICAL IMPROVEMENT OF TYPICAL SPORT HALLS FOR MULTI-PURPOSE USE

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In recent years, in addition to the education and sport activities of sport halls, they began to be commonly used for several musical and speech activities, since those structures are available to serve large crowds of people. Most sport halls in Turkey are built as typical projects without considering their potential of use and activity-related acoustical features.

The study was conducted on sport halls, the typical projects designed for the Ministry of Education (Code: MEB 2004.63), with the audience capacity of 70 people. Their acoustical performances are examined by the use of 3-D computer modelling and acoustical simulation methods with the software "*ODEON combined 8.5"*. The examinations were based on the Global Reverberation Time (GRT) at low (125-250Hz), mid (500-1000Hz) and high frequency (2000-4000Hz) ranges andgrid responses analyses. The acoustical parameters used for the grid response analyses wereEDT, STI, SPL(A), T30 and C80with an emphasis on the values at mid-frequency band (500-1000Hz) and their cumulative distribution.

The results have shown that acoustical features of the project are inadequate for education and sport activities, and multi-purpose use.Among the ceiling treatments proposed, baffle suspended ceiling proposals are observed to be the most efficient intervention in terms of acoustical improvement of the hall and material economy. The permanent interventions recommended are:“the use of baffle panelled suspended ceiling”made of 10-cm-thick rock wool panels with 60cm intervals and “the use of sound absorbing perforated metal sheet” covering the parapets between the playfield and the tribune.For the multi purpose use of the sport hall, it is recommended to use sound absorbing curtain modules in front of tribune’s rear wall, side walls, front walls and at the openings between the service and sports areas.The budget needed for a satisfactory remedial work was estimated to vary in the range of 4.5% and 6.9% of the overall construction cost. The results also pointed out the key concerns of the acoustical designparticular tothe sport halls.

Keywords: typical sport hall project (MEB 2004.63), multi-purpose use, 3D acoustical modelling and simulation, room acoustics, sport hall acoustics

ÖZ

ÇOK AMAÇLI KULLANIMLAR İÇİN TİP SPOR SALONLARININ AKUSTİK NİTELİKLERİNİN İYİLEŞTİRİLMESİ

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Son yıllarda spor salonları, eğitim ve spor etkinliklerinin yanı sıra, diploma törenleri, bayram ve/veya festival etkinlikleri, eğitim konferansları ve konserler gibi çeşitli müzikal ve konuşma etkinlikleri için de yaygın olarak kullanılmaya başlamıştır. Bu tür yapılar, çok kişinin bir araya gelebildiği büyük mekânlar olduğundan, çok amaçlı kullanım için tercih edilmektedirler. Oysaki Türkiye'nin birçok yerinde spor salonları tip projeler olarak inşa edilmekte ve olası kullanım potansiyelleri ile etkinliklere bağlı akustik nitelikleri göz ardı edilmektedir.

Bu çalışmada, Milli Eğitim Bakanlığı tarafından tip okul projeleri kapsamında hazırlatılan 70 kişi seyirci kapasiteli, tip spor salonu uygulama projeleri incelenmiştir (Kod: MEB 2004.63). Mekanların akustik performansı, bilgisayar ortamında yapılan üç boyutlu modelleme ve akustik benzetim yöntemleri ile incelenmiş; analizler için "*ODEON combined8.5*" yazılımı kullanılmıştır. Elde edilen veriler, düşük, orta ve yüksek frekans aralığındaki ortamdaki ortalama çınlama süresi değerleri (GRT) ve erken sönümleme süresi (EDT), sesin anlaşılabilirliği indisi (STI), A-ağırlıklı ses düzeyleri (SPL(A)), çınlama süresi (T30) ve berraklık (C80) akustik parametrelerinin orta frekans aralığındaki (500-1000Hz) verilerinin ortamdaki dağılımı dikkate alınarak analiz edilmiştir.

Sonuçlar, mevcut projenin akustik niteliklerinin hem eğitim ve spor etkinlikleri hem de çok amaçlı kullanımlar için yetersiz olduğunu göstermiştir. Önerilen tavan müdahaleleri içinde, düşey ekran asma tavan önerilerinin salonun akustik niteliklerinin iyileştirilmesi ve malzeme ekonomisi yönünden en verimli öneri olduğu görülmüştür. Önerilen kalıcı müdahaleler: 10cm kalınlığında taş yünü panellerin 60cm aralıklarla yerleştirildiği "düşey ekran asma tavan kullanımı" ve spor sahası ve seyirci tribünü arasında bulunan parapet yüzeylerini kaplayan "ses yutucu delikli metal levha kullanımı" olarak belirlenmiştir. Salonun çok amaçlı kullanımı için, tribünün arka duvarında, ön ve yan duvarlarda ve servis ve spor alanları arasında bulunan kapı boşluklarında ses yutucu perdelerin kullanılması önerilmektedir. Yeterli iyileşmeyi sağlayacağı düşünülen öneri için gerekli maliyetin, toplam inşaat maliyetine oranının %4.5-%6.9 aralığında olacağı öngörülmüştür. Bu çalışmanın sonuçları, ayrıca, spor salonlarının akustik tasarımına yönelik temel sorun ve çözümleri ortaya koymaktadır.

Anahtar sözcükler: spor salonu tip projesi(MEB 2004.63), çok amaçlı kullanım, bilgisayar destekli akustik modelleme ve benzetim, hacim akustiği, spor salonu akustiği.

to my beloved parents and brother…

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ABBREVIATIONS

Hz Hertz

dBA Decibel, A-Weighted

α Sound absorption coefficient

GRT Global Reverberation Time

EDT Early Decay Time

STI Speech Transmission Index

SPL(A) A-weighted Sound Pressure Level

T30 Reverberation Time

C80 Clarity

CHAPTER 1

INTRODUCTION

Due to the large audience capacity of sport halls and economical reasons, there is a tendency to use the large spaces designed for sportive activities, such as olympic stadiums, arenas, and sport halls, for multi-purposes including musical and speech activities. Each function loaded to such sport halls requires particular acoustical specifications. This implies that, well-designed acoustical environments should be provided for the sport halls to overcome the acoustical needs for multi-purpose uses. However, acoustical features of many sport halls are not satisfactory to support multi-purpose needs, even far away being enough for sports activities. The study is, therefore, conducted on the adequacy assessment and improvement of acoustical features for sport halls.

In this chapter the argument and objectives of the studyare presented. A brief overview of procedure is followed by the section describing the disposition of the chapters remained.

1.1. ARGUMENT

In Turkey, after the legislation of eight years compulsory education, as a method of rapid building production convenient to the new education program, elementary schools were being constructed with respect to typical or standardized projects (Köse, 2012). In order to minimize mistakes during the planning of schools and provide economy in construction, applications of the typical projects are still on the agenda (Terzioğlu, 2005). Necessities of typical project applications are given by the authorities as (i) speed up the construction, (ii) easing cost preassumptions, (iii) giving the possibility for standardization, (iv) utilization of present resources all across the country equally, (v) providing maximum project service with limited technical team (Gür & Zorlu, 2002). School buildings are commonly constructed with respect to the typical projects due to these reasons. However, convenience of those typical projects is questionable.Major issues in the design of these schools are they need to be designed in order to achieve creative, competitive and productive educational enviroment(Köse, 2010). But, insufficiency of the acoustical ambiencewithin these halls prevents achieving such environment.

Due to the developments in construction technology and changes in the needs of these buildings and socio-economical life, the government of Turkey decided upon a general revision in typical project from the years 1999-2000. These projects were designed mostly by means of architectural competitions and the remaining, by means of private offices or within the municipality(Köse, 2010). Considering this situation, due to commonly existing tendancy, instead of designing new project, revision of already existing project with respect to the needs and requirements was thought to be more feasible solution (Köse, 2010). Within this content, in the year 2004, typical sport hall projects were designed by the Ministry of Education to be constructed in small towns in Turkey.Typical small type sport hall project with 70 people capacity (Code: MEB 2004:63) is mostly constructed in the state schools of those small towns. According to the project investment distribution report of Ministry of Education for 2013-2015 years, out of 69 sport halls, 66 halls constructed/to be constructed to the schools are the small type sport hall project (Ministry of Education, 2013). Although most of these schoolsinclude sports halls, halls for musical activities or congresses are rarely included in these school buildings. Due to limited resources, such uses are planned to take place within these already constructed sports halls.However, their functional and technological features needto be improved. Those structures, therefore, need to be re-evaluated in order to satisfy functional requirements for their complex uses. Well-designed acoustical ambience is essential for the recreational uses of those large spaces in order to establish clear, comfortable conversation for speech activities and satisfactory musical performances. However, the acoustical features of those sport halls are taken into consideration during neither design nor construction periods. Large volume of these halls and sound reflective character of the materials with hard and smooth surfaces such as concrete, glass, steel increase the reverberation and affect the acoustical ambience negatively, regarding the activities taking place in these halls(Yoo, 2001; Bošnjakovic & Tomic, 2007).

Excessive reverberation results in high sound pressure levels and leads to decrease in clarity and intelligibility of speech. For instance, the results of a survey conducted with 3000 thousand students points out that sport halls are the most difficult place for hearing (Conetta, Shield, Cox, Mydlarz, & Dockrell, 2012). These mean that the physical education classes are taking place in a noisy environment with high sound pressure levels which degrade speech intelligibility and obligates the teachers to communicate loudly with the students. Because of this obligation, health problems such as vocal fatigue and dryness in the throat are observed in physical education teachers due to prolonged use during the lectures (Jonsdottir, 2003). Besides, acoustical inefficiency of these halls makes it difficult for the students to hear the teacher which causes the halls to be inefficient core learning spaces. Furthermore, during the sportive activities in these halls, communication in the playfield between the players or the referees is poor because of low intelligibility of sound.In addition to these problems, although such halls are commonly preferred for several musical and speech activities such as graduation ceremonies, student concerts, educational conferences, national festival activities, etc., they cannot be utilized effectively because of the acoustical inefficiency.Therefore, special attention is required for the acoustical improvement of those sports halls.Despite application of well-established regulations and standards defining the acoustical ambience in the sport halls (Department of Education and Skills, 2004), there are not any regulations or standards applied currently in Turkey.

1.2 OBJECTIVES

The main aim of this study is to develop proposals to improve acoustical conditions of existing sports halls for speech and musical performances. Here, sports halls are examined in terms of their existing acoustical features, their improvement to satisfy acoustical requirements expected for their AS-IS use and multi-purpose uses and development of acoustical elements/components for those improvements. It is aimed to point out design principles in order to satisfy the acoustical needs for several functions which might be performed in the sport halls selected.

The specific objectives of the study are:

1. to evaluate the existing situation of the sport halls whether the acoustical requirements are satisfactory or not for their AS-IS use, i.e. physical education (PE) classes and sports games, with the help of the acoustical simulation software, *Odeon 8.5*.
2. to decide on applications and improvements needed for proper/satisfactory acoustical environment for the AS-IS use of the halls.
3. to decide on the possible seating layout for multi-purpose uses of halls.
4. to decide on applications and improvements needed for proper/satisfactory speech and musical performances.
5. to make the acoustical analyses of each proposal by the use of acoustical simulation program, *Odeon 8.5*.
6. to decide the optimum solution in terms of efficiency for the acoustical improvement and the use of material and application cost for feasibility.

Sports hall typical project design by the Ministry of Education (Code: MEB 2004.63), which are constructed in small towns of Turkey, are selected to be studied based on these objectives.

1.3. PROCEDURE

This study is conducted in three phases. First study consists of literature survey conducted on acoustical requirements for sport halls, musical performances and several speech activities.

In the second study, sports hall typical project design by the Ministry of Education (Code: MEB 2004.63) which is constructed in small towns in Turkey is selected to be studied. A design principle suggested to be applied for those sport halls is proposed for achieving acoustically proper environment for their AS-IS uses.

In the third study, with respect to the acoustical requirements of the foreseen additional activities taking place in those halls, a design principle suggested to be applied for those sport halls is proposed in order to establish proper acoustical environment for their multi-purpose use (sportive, speech and musical activities).

After the design principles are determined and the materials to be used are selected with the help of the acoustical computer simulations, the study is finalized with the selection of most feasible proposal.

1.4. DISPOSITION

The study is presented in five chapters. In the first chapter, an introduction to acoustics of sport halls and the extent and objectives of this study is explained.

In the second chapter, a literature survey about the developments and studies made for the improvement of acoustics of sport halls, which are used for other activities as well is reviewed.

The third chapter comprises the methods and their usage in deciding the design principles and materials suggested to be applied for the selected sport halls in order to fulfil different acoustical requirements for sport events, speech activities and musical performances within the same room.

The fourth chapter is presenting the acoustical analyses of the hall selected and results of acoustical simulations. The values of essential acoustical parameters i.e. global reverberation time (GRT), early decay time (EDT), speech transmission index (STI), A-weighted sound pressure level (SPL-A), C80 and T30 are submitted in tables. The data obtained from the acoustical simulations of the AS-IS and Improved cases are given with figures in appendices.

In the fifth chapter, discussion of the results, guiding remarks for the acoustical treatment or design and conclusion are explained.

CHAPTER 2

LITERATURE REVIEW

In this chapter, literature survey about sport hall acoustics, directly or indirectly concerning the study, is presented.

2.1. SPORT HALL DESIGN AND ACOUSTICS IN SPORT HALLS

Typical project design is a concept discussed in the world of architecture considered as a kind of “plagiarism” by the architects; on the other hand, as a mass productionby the users. Typical projects are applied in Turkey as well as in the whole world while that application is argued and reacted (Köse, 2010). In the content of *“Eğitime Fiziksel Katkı Projesi –EFİKAP” (Physical Contribution to Education Project),*supported by the Ministry of Education in Turkey, typical project of educational structureswere designed in the years 2000-2004 (Köse, 2010). In accordance with the requirement program, elementary schools with 240 to 1200 students capacity were designed. In addition to the school building, the requirement program inclueded dormitory, cafeteria, multi-purpose hall, sport hall, kindergarden and supplementary classroom when necessary (Köse, 2010).

Köse (2012) mentions the statement of Özbulut that major function of education, which is considered to be the most significant element of development, is to enable the self-development of people according to their personal skills and, consequently, increasing the creativite power and efficiency of the society. According to the main principle of Ministry of Education regarding the compulsory eight-years education, school buildings need to be planned in order to provide social and personal improvement of the students (Köse, 2012). The limited spatial renovations in the existing schools in order to increase their capacities were not satisfactory for such improvement (Köse, 2012). Köse (2012) refers to Yüksel & Tokay that in order to solve this problem, supplementary spaces such as laboratories, library or sport halls were turned into classrooms. Moreover, sport halls are rented to the teams out of schoolduring vacations to provide income for the schools (Köse, 2010). In the guidebook for elementary schools prepared by the Ministry of Education in 1998, the priorities of the spaces in schools was re-arranged for the design of school buildingsin the future. Among those spaces, the priority of sporth halls was raised from 3rd to 2nddegree (Köse, 2012).

Below are mentioned the architectural requirements followed by the acoustical requirementsfor sport halls.

2.1.1 Architectural Requirements for Sport Halls

Regulations are broght to the sport halls by federations in terms ofplayfield sizes and material spesifications.According to the requirements given by Turkish Volleyball Federations (2014), the playfield should be shaped in a rectangule with 18mx9m sizes surrounded by the 3m free-field in minimum and with a clear height of 7m in minimum. According to the regulations defined by the Turkish Basketball Federation (2014), the playfield size should be shaped in 28mx15m surrounded by 3m free field in minimum and with a clear height of 7m.

2.1.2 Acoustical Requirements for Sport Halls

During the design of sport halls, environmental design requirements including natural ventilation, sufficient daylighting and adequate acoustical environment should be considered (Köse, 2012). Köse (2010) mentions about the statement of Şerefhanoğlu that in addition to the subjective parameters like personal skills and qualifications of the teachers and students, intelligibility of speech in these halls are to have strong relation with room geometry, acoustical characteristics of the finishing materials and furnishing.

For the design of rooms for speech activities, the ability of the listeners to understand speech is very important (Long, 2006). The fundamental acoustical requirements according to Doelle (1972) are mentioned by Long as follows (Long, 2006):

- adequate loudness
- uniform sound level
- appropriate reverberation
- background noise levels low enough not to interfere with the listening environment
- defect-free acoustical environment that eliminate long delayed reflections, flutter echoes, focusing and resonance

Several standards based on the RT in relation to the volume of the space are defined for the acoustical design of the sport halls (Department of Education and Skills, 2004; Wattez, 2012). According to the acoustical standards defined in Building Bulletin 93 (BB-93) prepared by the Department of Education-England in 2004,the reverberation time is required to be below 1.5s at mid-frequency range in unoccupied sport halls of the schools (Department of Education and Skills, 2004). The Dutch questionnaires in mid-sized facilities, such as in a volume of 5000m^3 revealed that the reverberation time should not exceed 1.5s, and that condition could be achieved by the average absorption coefficient,α,of 0.28 at minimum (Rychtáriková, Nijs, Şaher, & Voorden, 2004). The global reverberation time required in classrooms with respect to volume, with or without sound reinforcement systems, was described by Beranek (1993) with the equation 2.1 below:

$$RT = 0.33 logV - 0.15 \qquad (2.1)$$

where:

RT is the global reverberation time in seconds

V is the volume of the hall in cubic meters

The other parameters, such as, the location of these halls in the building, the background noise levels and the features of the mechanical equipment should be considered during the acoustical design of sport halls. Noise control should be provided as much as possible by keeping the background noise level below 40dB(A) according to the Dutch standards (Wattez, 2012) and 55dB(A) according to the Turkish standards, in the sport halls (Ministry of Environment and Forestry, 2010).

During the multi-purpose use of these sport halls, sound reinforcement systems containing microphones, loudspeakers, etc. are also used in order to provide more variability of reverberation time when compared with the passive control elements such as sound absorptive materials. It is stated that the best-rated halls using sound reinforcement systems provided the frequency-independent reverberationtimes in the range of 0.6s to 1.2s for halls in the range of 1000m3and6000 m^3 while the worst rated halls provided significantly long reverberation times especially in the 63Hz and 125Hz frequency bands (Adelman-Larsen, Thompson, & Gade, 2010).

2.2. ARCHITECTURAL FEATURES AFFECTING THE ACOUSTICAL DESIGN OF HALLS

Every building acoustics consideration can be thought of as a system of sources, paths and recievers of sound. The building design is influential on transmission paths of the sound since it determines the sound source and reciever locations and the paths that the sound will travel (Cavanaugh, Tocci, & Wilkes, 2010). Moreover, the materials and construction elements that shape the finished spaces determine how sounds will be percieved in that space (Cavanaugh, Tocci, & Wilkes, 2010). The architectural elements influentialon the acoustical design of halls and design of rooms for multi-purpose use in order to provide variable acoustical environment are explained below.

2.2.1. Architectural Elements in the Acoustical Design of Halls

The architectural components of the halls namely size, shape, surface orientation and materials influence intelligibility of speech (Long, 2006). Basic architectural factors to be considered in the design of hallsgiven asshape, audience absorption and type of chairs, materials for walls, ceiling and stage by Beranek are explained below (Beranek, 2004):

Shape (Geometry): Hall geometry is an important parameter affecting the acoustics of a space. Below mentioned are the most commonly preferred geometrical forms of the hallsand their influence on acoustics of the spaces.

- **Shoebox:** Determined by the interviews of Beranek and questionnaire survey by Haan/Fricketo be “excellent”, of the top 15 halls, two thirds are “shoebox” shaped. Certainly, the shoebox shape, provided the hall is not too wide, is a safe acoustical design. Parallel sidewalls assure early lateral reflections to the audience on the main floor, essential to the desired acoustical attribute “spaciousness”. But as demonstrated in several recent halls, spaciousness can also be achieved by one of three means: (i) some combination of suspended or sidewall-splayed panels and by taking steps to preserve bass energy, (ii) shaping of the sidewalls near the proscenium and the sides of the performing space so as to direct the sound more uniformly to the audience areas, or (iii) interspersing seating areas with “walls” that are located to provide lateral reflections as are found in several “surround” halls. Boston Symphony Hall (Figure 2.1), which has shoe-box form in plan, is mentioned by Beranek (2004) as one of the five highest ranked halls in the world.

Figure 2.1 Boston Symphony Hall- interior view (University of Cambridge, 2013).

- **Fan-shape:** According to the study of Beranek, fan-shaped halls have not been as successful acoustically, although the overall design of the Lenox, Massachusetts, Tanglewood Music Shed (Figure 2.2) has pleased audiences, musicians, and music critics as a place for summer concerts.

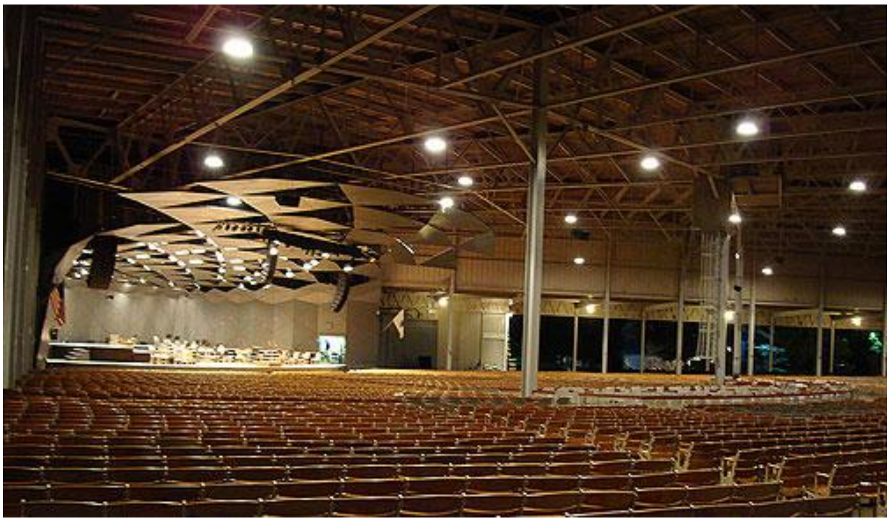


Figure 2.2 Tanglewood Music Shed - interior view (Kwaree, 2013).

- **Vineyard:**In the same study, the author goes on to say that the most successful non-rectangular hall, seating 2325, is the Berlin Philharmonie (Figure 2.3). The orchestra is seated near the centre of the hall, and the audience is situated on 14 “trays”, each at a different level and different in configuration. The acoustical consultant believed it to be important that early reflections come from overhead, so that the ceiling is tent shaped. There are some exposed walls between the trays that reflect early lateral sound to some parts of the audience. An array of panels hangs high above the stage. The musical quality varies from one “tray” to another, as would be expected, because of the directivity f instruments. The architect of the hall said that his goal was to bring the audience into closer relation to the performers than is possible in a shoebox hall. And this fact, too, may add to the hall’s appeal. A number of terraced, surround halls have been built, though none have been as acclaimed as the Berlin Philharmonie.

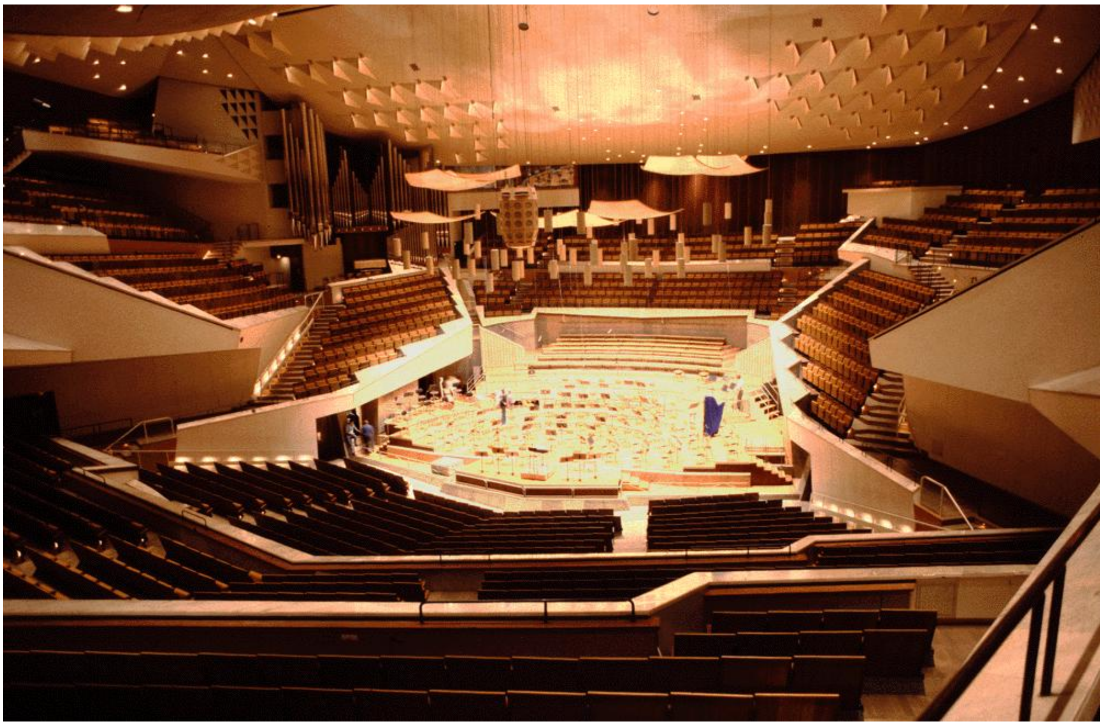


Figure 2.3 Berlin Philharmonie- interior view (Mulyadi, 2013).

Simple plan schemes of the shoe-box, fan-shape and vineyard forms are given in Figure 2.4.

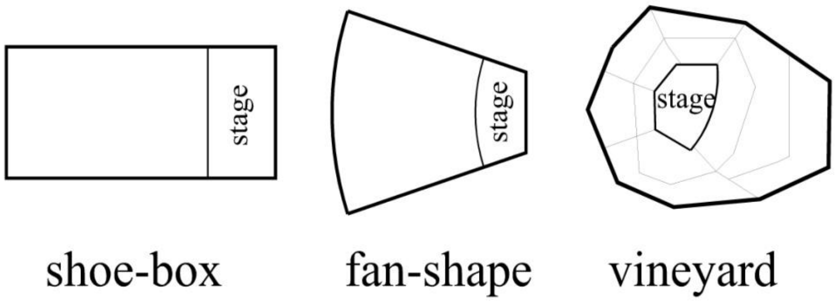


Figure 2.4 Simple plan schemes for shoe-box, fan-shape and vineyard forms.

2.2.2. Audience Absorption and Type of Chairs

In the design of halls audience density, chairs, audience absorption due to the type of chairs and materials for walls, ceiling and stageare described as the architectural elementsaffecting the acoustical environment in a hall (Beranek, 2004).

- **Audience density:** An audience area that is divided into a number of small seating blocks absorbs more sound than if it is comprised only a few blocks. To preserve loudness, the total seating area must not become too large, because to a first approximation, the power available to each person (i.e. per unit area) is equal to the total power radiated by the performing group divided by the total audience area.
- **Chairs:** Widely spaced seats are more luxurious, but they come at the expense of acoustical quality and high building costs in halls with a large seating capacity. If the seats in a large hall are too generously spaced, the architect is likely to design a wide hall in order to obtain the necessary floor area. This causes the back-row listeners to be very far from the stage, thus diminishing the strength of the direct and early sound.

- **Audience Absorption due to Type of Chairs:** People seated in heavily upholstered chairs absorb more sound than those seated in a medium, lightly or non-upholstered chair. The difference is particularly noticeable at bass frequencies. A common cause of bass deficiency in concert halls is overly sound absorbent chairs. It is strongly recommended that a chair be made of molded material, such as plywood, and that the upholstering on the top of the seat bottom be no thicker than 2in. (=5cm), and, on the seat back, no thicker than 1in. (=2.5cm), and, if comfortable, cover only two-thirds of the seat back. Also, the armrest and the rear of the seat back of a chair should not be upholstered. These requirements rule out thick seat bottoms containing springs.
- **Materials for Walls, Ceiling and Stage:** When the audience sits over the raised floor, their weight suppress some of the vibration and the loss of bass is not excessive. In most modern halls where the bass response is good the floors are concrete, covered with either wooden parquet or some synthetic material that is cemented to the concrete, and the walls and ceiling are constructed with materials that have a large weight per square foot.Thin wood paneling strongly absorbs bass energy, where "thin" means 1in. (=2.5cm) or less. For a hall that is lined with wood, it should be as near 2in. (=5cm)in thickness as possible. For the sidewalls of many halls, wood veneer ("wallpaper") on solid (plaster) backing is employed to give the hall a warm, traditional appearance.

2.2.3. Design of Rooms for Multi-Purpose Use

Variable RT is considered to be the most valuable feature for a well-designed auditoria since it may accommadate several types of musical & speech performances and flexible acoustical environments.Acoustic character is more a question of gross shape than small detail which means for variable acoustics, major changes are required. Variable acoustical elements, within this content, are mainly (i) variable auditorium volume, (ii) variable acoustic absorption within the hall (Barron, 1998).

i. Variable Auditorium Volume: There are basically two methods of providing variable volume: by a movable panel/ partition or by a movable shutter system (Barron, 1998).

- The movable panels are to vary the floor area and the seating capacity with it in case used as vertical partitions or as non-vertical surfaces to provide extra volumes with little absorbent materials in them. Suspended ceilings constructed of many independent panels that can be raised or lowered are used as an alternative solution as well.
- The shutter system in which a suspended ceiling can be opened or closed is considered to be another feasible option. For this system to be effective, in the open condition, an open area of 40% is required and the void above the suspended ceiling must be reverberant and behave acoustically as a void. In case the existence of significant acoustically absorbent or diffusing surfaces n the void, the extra volume might not make a worthwhile contribution to the reverberation time.

In addition to the variable volume in halls, *coupled rooms* are also preferred for variable acoustics (Mehta, Johnson, & Rocafort, 1999). *Coupled rooms* are basically two spaces linked to each other through an opening between them. In coupled rooms, sound energy is exchanged between the rooms through the opening. When the sound source is turned off, the sound in both rooms decays at their own individual decay rates and in case the reverberation times of the rooms are not equal, an energy surplus in one room to the other during the decay process which leads to a modification in the reverberation characteristics of rooms (Figure 2.5) (Mehta, Johnson, & Rocafort, 1999).

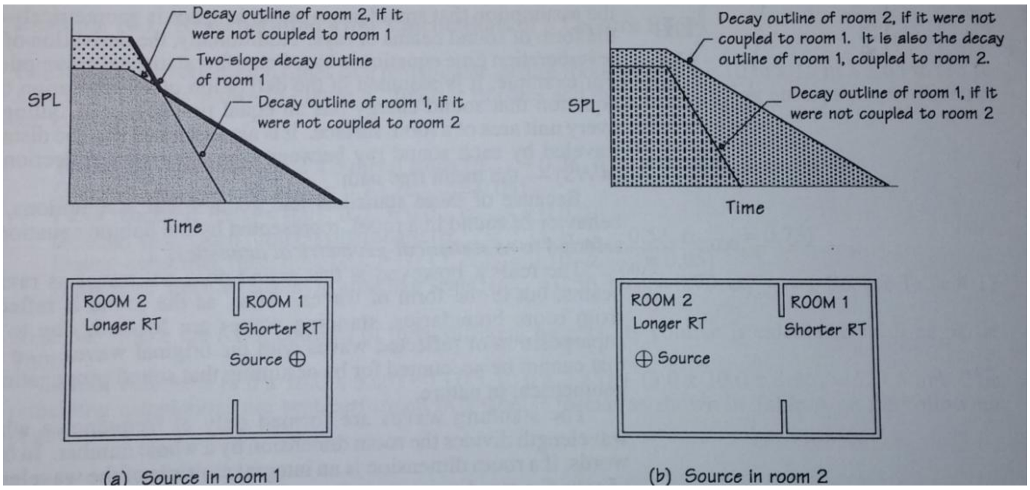


Figure 2.5 Sound decay in coupled rooms. (a) The sound source is in the room 1, (b) The source is in room 2 (Egan, 1988).

ii. Variable Acoustic Absorption: When the reverberation time must be varied to satisfy requirements of different activities in a room, the-sound absorbing treatment can be designed to be adjustable (Egan, 1988). Such treatment can be in terms of:

- Retractable sound-absorbing curtains that can be stored in a recess to expose a sound-reflecting backup surface (Figure2.6).

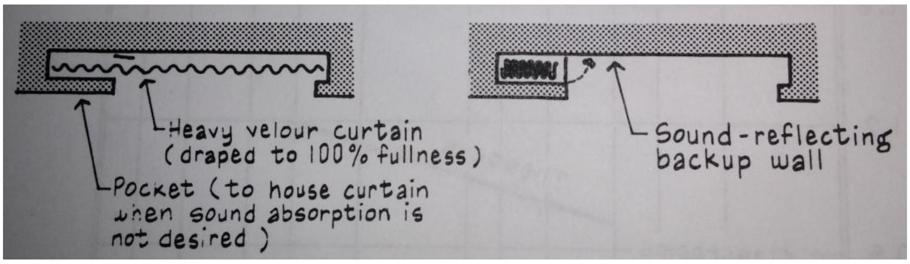


Figure 2.6 Schematic drawings of retractable sound-absorbing curtains (Egan, 1988).

* Sliding facings composed of two panels of perforated material to vary absorption by sliding one panel in front of the other (Figure2.7).

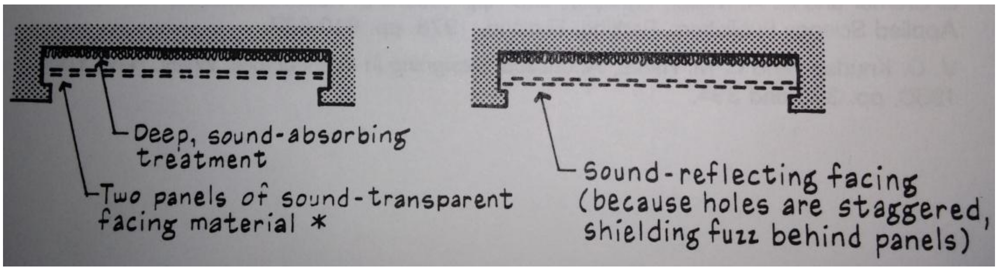


Figure 2.7 Schematic drawings of sliding faces between the surfaces with different sound absorption characteristics (Egan, 1988).

* Hinged panels with sound absorbing material installed on back of sound-reflecting panel that can be swung into position to vary conditions from hard to soft (Figure2.8).

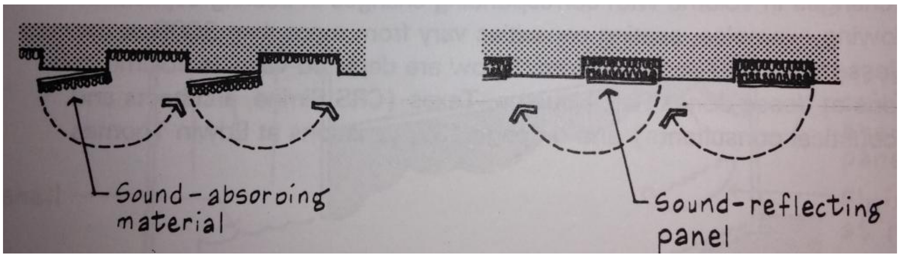


Figure 2.8 Schematic Drawings of Hinged Panels with Sound Absorbing Material (Egan 1988).

- Rotatable elements with 3 different sides of reflecting, absorbing and diffusing surfaces (Figure2.9).

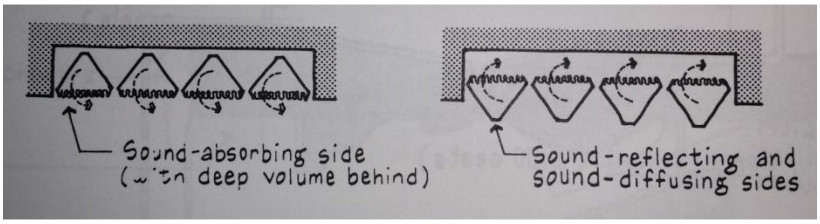


Figure 2.9 Schematic Drawings of Rotatable Elements with Different Acoustical Characteristics of Different Surfaces (Egan, 1988).

2.3. ACOUSTICAL PARAMETERS

Objective acoustical parameters are used to designate the acoustical properties of the halls. These are mainly reverberation time (RT- T10, T20, T30), early decay time (EDT), sound transmission index (STI), A-weighted sound pressure level (SPL(A)).

2.3.1. Reverberation Time (RT)

In an enclosed environment sound can continue to reflect for a period of time after a source has stopped emitting sound. This prolongation of sound is called reverberation. Reverberation time (RT60) is defined as the time required, in seconds, for the average sound in a room to decrease by 60 decibels after a source stops generating sound. Reverberation time (RT), introduced by Wallace Clement Sabine, is considered to be the most significant objective parameter. It is directly proportional to the volume of the hall and inversely proportional to the total absorption in the hall.

$$Global\ Reverberation\ Time\quad RT\ = \frac{0.161\ V}{\Sigma A}\quad (2.1)$$

where:
V is the volume of the hall.
ΣA is total absorption in the hall.

$$\Sigma A = [S1a1 + S2a2 + S3a3 + S4a4 + \cdots] + mV \qquad (2.2)$$

where:
S1 is the surface area of the material
a1 is the sound absorption coefficient with respect to frequency
mV is air absorption

At high frequencies above 1000Hz, the reverberation time inevitably decreases due to air absorption. At low frequencies, the situation can be controlled by the designer. For speech there is good reason to keep the reverberation characteristic constant with frequency; a rise in the bass undermines intelligibility. But for music a bass rise in reverberation time is considered by most people as desirable (Barron, 1998).Optimum reverberation time intervals are given in Figure 2.10.

According to the analyses conducted on eleven concert halls in Europe, from reverberation time, volume and sound-source distance, four out of the five listener aspects Level, Reverberance, Clarity and Listener Envelopment can be predicted (Skålevik, 2010).

Although reverberation time is described as the most important acoustical parameter, further investigations display the fact of existence of other significant parameters (Beranek, 2004).

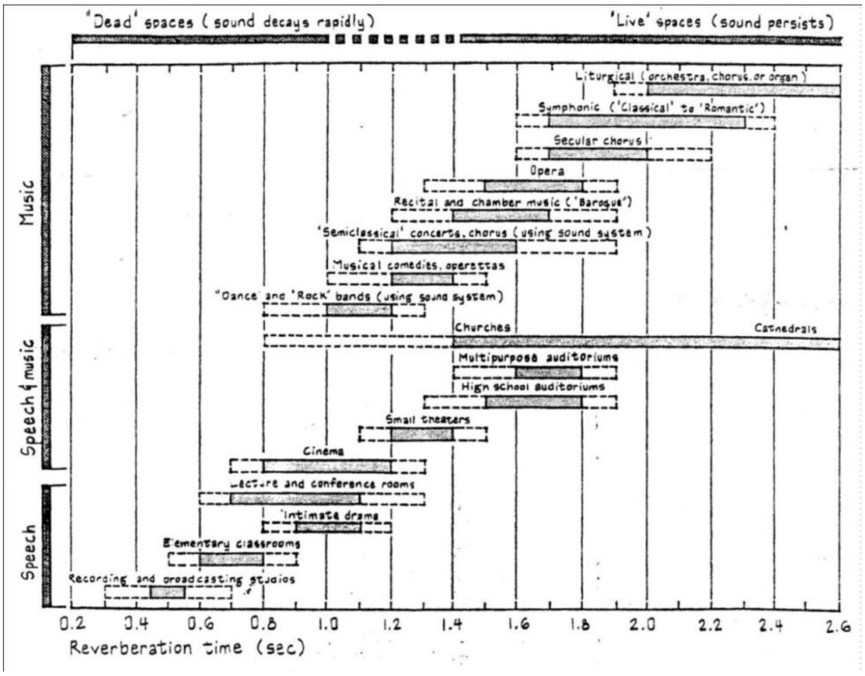


Figure 2.10 Optimum RT values with respect to functions (Egan, 1988)

2.3.2. Early Decay Time (EDT)

The earlier studies of sound decay assumed that the entire 60dB decay of sound is smooth and uniform. Measurements in actual have revealed that the 60dB decay may not be uniform (Mehta, Johnson, & Rocafort, 1999). Experimental investigations have revealed that mainly the initial decay of sound is subjectively significant. The time associated with the early part of the decay process is called the Early Decay Time (EDT). It is described as the time passed during the initial rate of decay of 10dB of the reverberant sound multiplied by six. Early decay time includes more explanatory information than the reverberation time. The multiplication is included to establish a comparison with the global reverberation time (GRT-RT). A shorter EDT provides "clarity" and a long RT provides "liveness" to music (Mehta, Johnson, & Rocafort, 1999). High EDT value indicates that the sound is not intelligible enough but the environment is reverberant.

2.3.3. Speech Transmission Index (STI)

The speech intelligibility of a transmission system, e.g. a telephone line or a room, is usually measured by means of a list of words (or sentences) where the percentage of correctly understood words gives the intelligibility score. The intelligibility depends on the word material (sentences, single words, numbers, etc.), the speaker, the listener, the scoring method and the quality of the transmission system (Jacobsen, Poulsen, Rindel, Gade, & Ohlrich, 2011). The components of speech intelligibility involve only some of several important acoustical qualities of rooms for listening. The concept that early sound reflections are useful and increase the loudness of sounds, thus increasing intelligibility and that sounds from late-arriving reflections, reverberation and background noise in the room decrease intelligibility (Cavanaugh, Tocci, & Wilkes, 2010). Speech transmission index (STI) is determined to be an important acoustical measurement that relates the levels of direct sound and early reflections to the reverberant sounds and background noise for a simulated speech signal. It is thought to account for the relative degradation of speech by the combination of background noise, reverberation and distance in a specific acoustic environment (Cavanaugh, Tocci, & Wilkes, 2010). STI values range from 1.0 (ideal) that refers to the highest to 0.0 refers to the worst (Cavanaugh, Tocci, & Wilkes, 2010) (Figure.2.11).

Rapid Speech Transmission Index, RASTI:The RASTI is a simplified version of the STI and it is used for room acoustics and direct communication situations. It is calculated using only the 500Hz and 2000Hz frequency bands (Larm & Hongisto, 2005). The result is an index which is used in the same way as in STI (Jacobsen, Poulsen, Rindel, Gade, & Ohlrich, 2011).

STI (RASTI)	Description
0.75 – 1.0	Excellent
0.60 – 0.75	Good
0.45 – 0.60	Fair
0.30 – 0.45	Poor

Figure 2.11 STI (RASTI) Value Evaluation Table

2.3.4. A-Weighted Sound Pressure Level (SPL (A)):

Sound pressure level (SPL) or sound level is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibels (dB) above a standard reference level of 20 μPa which is usually considered the threshold of human hearing (at 1000 Hz) (Wikipedia, 2014). The SPL is expressed as the logarithm of the ratio in order to not to deal with a large range of numbers (Mehta, Johnson, & Rocafort, 1999).

$$SPL \quad dB \quad = 10log\frac{I}{Iref} \qquad (2.3)$$

where:
I= sound intensity level of the sound
$I_{ref}= 10^{-12}$ W/m^2

The most common weighting that is used in noise measurement is A-Weighting. Like the human ear, this effectively cuts off the lower and higher frequencies that the average person cannot hear. A-weighted measurements are expressed as dBA or dB(A) (Noise Meters Inc., 2014). Ideal sound pressure level difference in a hall at different seats should not exceed 10 dB(A). The idealSPL(A) difference is 6 dB(A) showing the existence of adequate loudness in the overall hall.Typical sound pressure levels are given in Table 2.1.

Table 2.1 Typical dBA Levels (Sengpielaudio, 2014)

190 dBA	Heavy weapons, 10 m behind the weapon (peak level)
180 dBA	Toy pistol fired close to ear (peak level)
170 dBA	Slap on the ear, fire cracker explodes on shoulder, small arms at a distance of 50 cm (peak level)
160 dBA	Hammer stroke on brass tubing or steel plate at 1 m distance, airbag deployment very close at a distance of 30 cm (peak level)
150 dBA	Hammer stroke in a smithy at 5 m distance (peak level)
130 dBA	Loud hand clapping at 1 m distance (peak level)
120 dBA	Whistle at 1 m distance, test run of a jet at 15 m distance
	Threshold of pain, above this fast-acting hearing damage in short action is possible
115 dBA	Take-off sound of planes at 10 m distance
110 dBA	Siren *) at 10 m distance, frequent sound level in discotheques and close to loudspeakers at rock concerts, violin close to the ear of an orchestra musicians (maximum level)
105 dBA	Chain saw at 1 m distance, banging car door at 1 m distance (maximum level), racing car at 40 m distance, possible level with music head phones
100 dBA	Frequent level with music via head phones, jack hammer at 10 m distance
95 dBA	Loud crying, hand circular saw at 1 m distance
90 dBA	Angle grinder outside at 1 m distance
	Over a duration of 40 hours a week hearing damage is possible
80 dBA	Very loud traffic noise of passing lorries at 7.5 m distance, high traffic on an expressway at 25 m distance
75 dBA	Passing car at 7.5 m distance, un-silenced wood shredder at 10 m distance
70 dBA	Level close to a main road by day, quiet hair dryer at 1 m distance to ear
65 dBA	**Bad risk of heart circulation disease at constant impact is possible**
60 dBA	Noisy lawn mower at 10 m distance
55 dBA	Low volume of radio or TV at 1 m distance, noisy vacuum cleaner at 10 m distance
50 dBA	Refrigerator at 1 m distance, bird twitter outside at 15 m distance
45 dBA	Noise of normal living; talking, or radio in the background
40 dBA	**Distraction when learning or concentration is possible**
35 dBA	Very quiet room fan at low speed at 1 m distance
25 dBA	Sound of breathing at 1 m distance
0 dB	Auditory threshold

2.3.5. Reverberation Time (T30)

T30 is the reverberation time for 60 dB of room decay, based on a straight line curve fit between the time passes for 5 dB drop of the sound and the time passes for 35 dB drop of the sound is doubled to be made consistent with the traditional reverberation time for 60 dB of decay (RT60). The T30 is a measure of the “persistence” of sound in the space.The T30 and EDT provide important information about the way that sound behaves in a room. Both are most applicable when a homogeneous reverberant field exists (i.e. medium to large rooms with low absorption). However, reverberation times are not the same in all parts of a hall and it is necessary to measure it at different seats for averaging (Beranek, 2004).

2.3.6. Clarity (C80)

The usual physical measurement of clarity is the ratio of the energy in the early sound to that in the reverberant sound, a ratio that is expressed in decibels (dB) by C80. The number “80” designates the time considered for the early reflections. Clarity decreases with increased reverberation and *vice versa* (Beranek, 2004).C80 is a widely used parameter for music (Echenagucia & Sassone, 2013). Barron explains that there is negative correlation between EDT and C80. A High C80corresponds to a low EDT and vice versa (Barron, 1995).

2.3.7. Echo

An ***echo***is the distinct repetition of the original sound and is sufficiently loud to be clearly heard above the general reverberation and background noise in a space (Egan, 1988).Echo, typically observed for delays beyond 50 ms and at high reflection levels. If the delay is very long, say 200 ms, then the echo may even be detected at a much lower level (Rossing (Ed.), 2007). In auditoria, sound-reflecting flat or concave rear walls and high or vaulted ceilings are potential echo producers (Egan, 1988). Echoes interfere with speech intelligibility and cause confused perception of music and therefore, must be avoided (Mehta, Johnson, & Rocafort, 1999). Difference between echo and reverberation is echo is a repetition of the original sound that is distinctly perceptible, whereas reverberation is a prolongation of the sound through multiple reflections (Long, 2006).

2.4 3D-ACOUSTICAL MODELLING AND SIMULATION USED FOR THE ASSESSMENT OF ACOUSTICAL PERFORMANCE

Acoustical modeling techniques have been developed to accurately represent the sound fields at individual seating locations in architectural spaces. Resent research and design applications have focused on physical acoustical modeling techniques and computer modeling. Modeling techniques allow basic design approaches to be evaluated in small models that are easy to manipulate during the design process. Using these techniques, it is possible to quickly study the effects of architectural design changes on acoustical measures. This research allows architects and acoustical consultants to “sculpt” the acoustical qualities of rooms as part of their design process. The impulse-response obtained in model studies can be mixed with sound recordings to provide aural simulations of rooms while they are being designed (Cavanaugh, Tocci, & Wilkes, 2010).

Computer models of room acoustics start with s three-dimensional model of a proposed room. Many available software include interfaces so that computer-aided design (CAD) models can be imported into the acoustical program. Sound is propagated from simulated sources on stage into the room. The impulse-response of the room can then be estimated at selected locations in the room. Many of the acoustical measures can also be calculated at specifix locations as well (Cavanaugh, Tocci, & Wilkes, 2010).

Two basic methods are used today in computer models to develop the impulse-response of the room: a ray-tracing method and an image method. The mathematical modeling of ray tracing has undergone rapid development in the last 30 years through the work of computer graphics programmers (Long, 2006). In the ray-tracing method, a selected number of sound rays are propagated from the source into the room. The rays will reflect off surfaces in the room as sound waves would. The amplitude and arrival time of the sound waves will be recorded at selected locations in the model. The room surfaces are assigned absorption coefficients in octave band frequencies. Many current programs can also approximate the diffusion and diffraction of sound that is so important in auditorium acoustics. Some programs provide abbreviated estimation procedures, in which the reverberant energy is approximated by an envelope derived from the reverberation time of the room. This means that the multiple high-order reflections that occur in the reverberant field are not individually calculated. The image method, on the other hand, works backwards. The computer locates all of the surfaces from a given reciever location that can project reflections to it from the source. Rays are then traced from the reciever to the surface on stage (Cavanaugh, Tocci, & Wilkes, 2010).

Computer model studies show the distribution of sound pressure levels in rooms, create ray diagrams of specific sound paths between the source and reciever, estimate the impulse response at specific locations and calculate many acoustical design parameters (Cavanaugh, Tocci, & Wilkes, 2010).

Today’s room acoustical computer models have several advantages compared to scale models. They have become reliable and efficient design tools for the acoustic consultants, and the results of a simulation can be presented not only for the eyes but also for the ears with new techniques for auralisation (Rindel J. H., 2000). It is found quite obvious that a computer model is much more flexible than a scale model because of being easy to modify the geometry of a computer model and the surface materials can easily be changed by changing the absorption coefficients. The advantage of the computer model is not only it is fast, but also the results can be visualised and analysed much better than a scale model because it contains more information than a set of measurements done in a scale model with small microphones (Rindel J. H., 2000). It is also stated that the best programs do neither require extremely long calculation times nor extremely detailed room geometries (Rindel J. H., 2000).

One of the most commonly used acoustical simulation software is *ODEON*. The software is developed for simulating the interior acoustics of buildings. Given the geometry and surface-properties, the acoustics can be predicted, illustrated and listened to. Sound reinforcement is claimed to be easily integrated in the acoustic predictions. *ODEON* uses the image-source method combined with ray tracing (Odeon A/S, 2014). The applications of the software include concert and opera halls, theatres, churches and mosques, open plan offices, foyers, restaurants, music studios, underground and railway stations, airport terminals, industrial environments, outdoor areas with complicated geometry(Odeon A/S, 2014).

With a computer model it is straightforward to calculate the response at a large number of recievers distributed in a grid that covers the audience area. It is stated to be very useful for the acoustic designer to see a mapping of the spatial distribution of acoustical parameters. Uneven sound distribution and acoustically weak spots can easily be localised and appropriate countermeasures can be taken (Rindel J. H., 2000).

Computer techniques for simulation of sound in rooms have improved significantly in recent years (Rindel J. H., 2000). There are several studies on the reliability of these techniques (Rindel J. H., 2000; Rindel & Christensen, 2003; Shiokawa & Rindel, 2007). According to a study conducted on the validation of the quality of room acoustic auralization, comparisons between the auralizations from the computer simulation and dummy head recordings in the same postion in the same room, the differences are claimed to be hardly audible (Rindel & Christensen, 2003). In the content of another study conducted in the search for reliability of the acoustical simulation, comparisons were made between measured room acoustical parameters and those obtained from computer simulations using the software *ODEON v.3.*1on two concert halls (Shiokawa & Rindel, 2007). Comparisons were also made between the results obtained from computer simulations and those from models on both concert halls. According to the results,measured and calculated reverberation times in single positions were found to be in good match (Shiokawa & Rindel, 2007).

CHAPTER 3

MATERIAL & METHOD

Here are presented the material and method of the study. The former describes the architectural features of typical project of small sport halldesigned for the schools. The latter describes the proposals/treatments suggested for the acoustical improvement of the hall. Afterwards, the activities-related scenarios composed of the AS-IS uses of the hall, namely physical education classes and sport games, and multi-purpose use of the hall for speech and musical activities are defined. The methods of 3-D modelling and acoustical simulation methods used for the acoustical assessment of the hall are also explained here in detail.

3.1. SPORT HALL TYPICAL PROJECT DESIGNED FOR STATE SCHOOLS (Code: MEB2004.63)

In this research, typical small sport hall project with 70 audience capacity designed by Ministry of Education as part ofits "Physical Contribution to Education Project - *Eğitime Fiziksel Katkı Projesi (EFİKAP)"*was examined.

Sport hall typical project is designed for physical education (PE) classes and sportive activities such as basketball, volleyball games (Figure 3.1). The design is composed of two parts: first is the "service area" which consists an office, changing rooms, showers and toilets; second is the "sports area" which consists the playfield and the tribune (Figure 3.1).

The service area is carried by reinforced concrete load-bearing system whereas the sports area is carried by the steel truss ceiling on reinforced concrete columns (Figure 3.1, Figure 3.2, Figure 3.3).

The playfield in the sports area is 27 metres in length, 15 metres in width (Figure 3.1). Its clear height is 6.80 metres (Figure 3.2, Figure 3.3).The total volume of the structure is approximately 3200 m^3. Its roof is clad with aluminium sandwich panels; the interior finishing system of the wall is composed of cement plaster, gypsum plaster, satin plaster coating and water-based satin paint layers; concrete floor is clad with polyurethane coating (Polarkon Co. Ltd., 2012).

The acoustical situation in the AS-IS case of the hall was analysed in the content of the study in order to determine the problems and propose solutions for its improvement which are mentioned in the section 3.2.

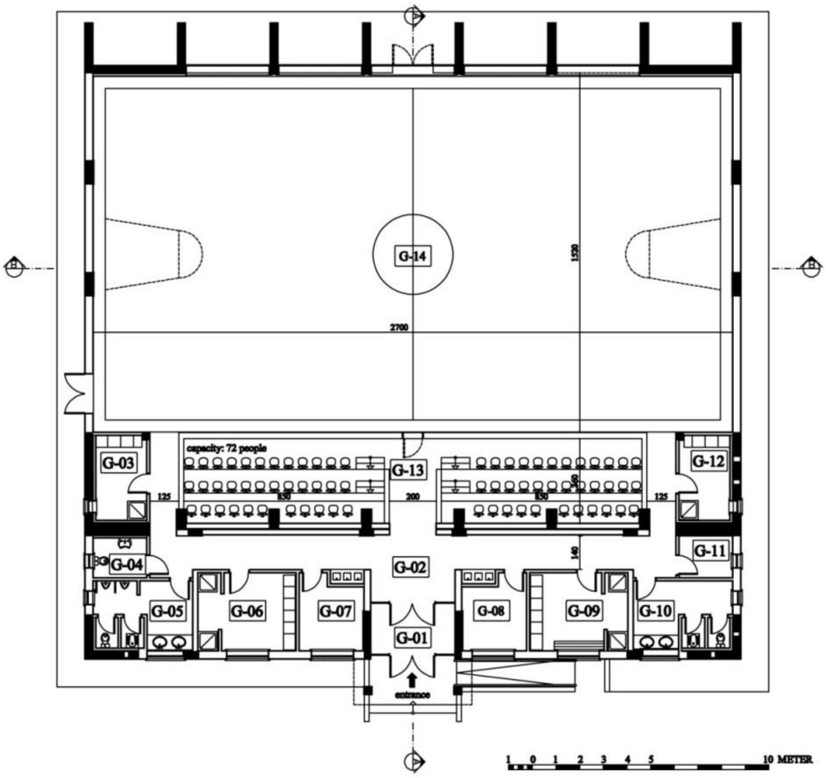


Figure 3.1 Ground floor plan of the sport hall. (Polarkon Co. Ltd., 2012)

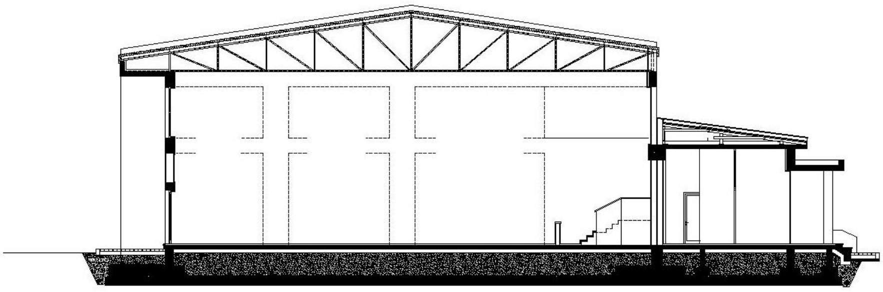


Figure 3.2 Sport hall section AA. (Polarkon Co. Ltd., 2012)

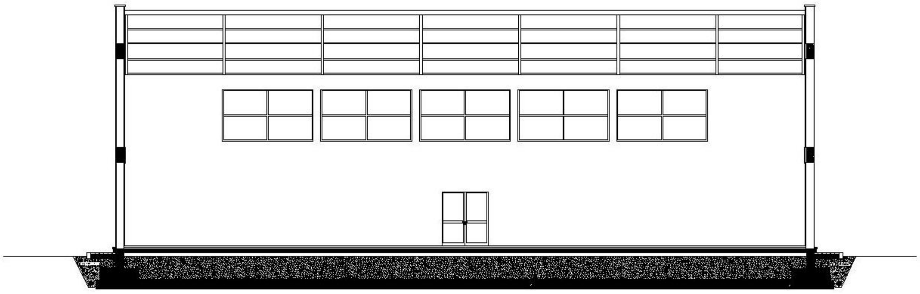


Figure 3.3 Sport hall section BB. (Polarkon Co. Ltd., 2012)

3.2. PROPOSALS INTRODUCED TO THE STRUCTURE FOR ACOUSTICAL IMPROVEMENT

In order to provide a better acoustical environment within the hall, i.e. more intelligible, free from acoustical defects like flutter echoes, etc, a convenient solution was searched.Since thesport halls under study here already been constructed, the solution was needed to be adaptable to the existing structures. For the acoustical improvement of the sport halls, main design principle in this study was respecting the original architectural project and not removing/changing any architectural element within the hall. Within this content, mountable systems and materials were taken into consideration and designed. Furthermore, with the system design proposals and material selections, special care was given to economy, durability, convenience for repairing, maintenance and cleaning, which are the basic principles need to be considered in the design of schools (Karabey, 2003).

In the light of these design principles and the intended uses of the hall, the systems proposed for the design were classified as permanent components and temporary components. The permanent components are the suspended ceiling systems and wall cladding with metal sheets. The temporary components are the suspended curtain modules.

These systems are described in the following sections:

3.2.1. Suspended Ceiling Systems

During the study, one of the primary decisions was clarifying the location and properties of the permanent components. The preliminary aim was to decrease the global reverberation times to the acceptable values in low (125-250 Hz), middle (500-1000 Hz) and high (2000-4000 Hz) frequency ranges.

It was determined that the ceiling is the most appropriate component for permanently mounted systems due to its large amount of surface area that gives the possibility to add large amounts of sound absorbing materials and convenience of its position in terms of damage risk.

In order to achieve required GRT values, designs with variations of 3 different suspended ceiling systems were analyzed. During the study, optimum solution within these variations was searched which were selected as samples.

Flat panelled suspended ceiling system was the first treatment proposed in the study. Acoustical simulations were conducted after adding panelled suspended ceiling system composed of rock wool sound absorbing panels covered with acoustically transparent fabric which were mounted flatly to the trusses at the ceiling, above the playfield, to 6.80 m level (Figure 3.4). During the simulations, first, 5 cm thick rock wool; second, 10 cm thick rock wool was selected as the material.

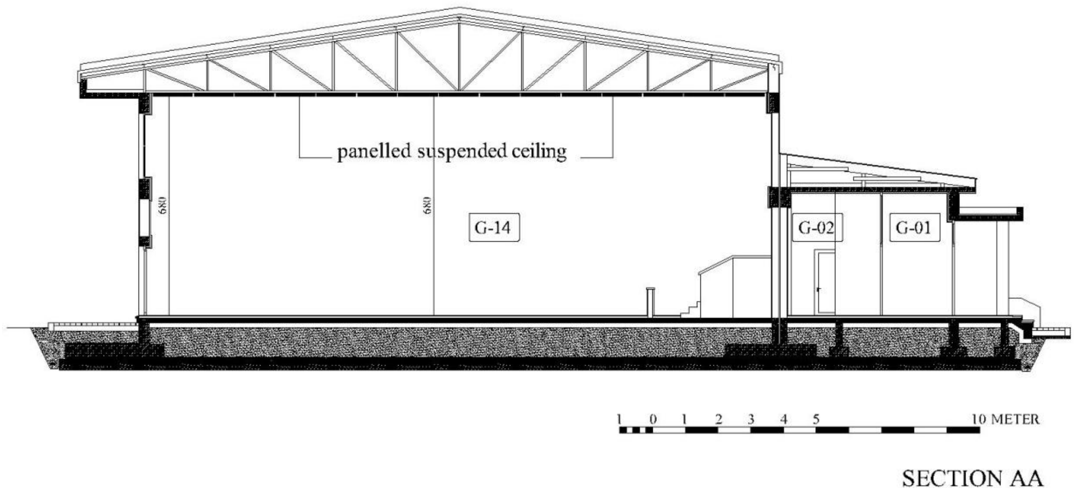


Figure 3.4 Sport hall section AA with paneled suspended ceiling, flatly mounted (Polarkon Co. Ltd., 2012)

Baffle suspended ceiling system was the second treatment proposed in the study. Acoustical simulations were conducted after adding variations of baffle suspended ceiling systems mounted to the trusses, above the playfield. Rectangular sound absorbing modules composed of 60cm wide / 120cm long rock wool panels covered with acoustically transparent fabric with 3cm thick wooden frame (Figure 3.5) were selected to be mounted to the ceiling with the help of steel box profiles. The wooden frame was offered to provide stiffness for the rock wool panels, protect the rock wool from possible ball impacts during sport games and enable the modules to be suspended to the steel frames attached to the steel trusses on the ceiling.

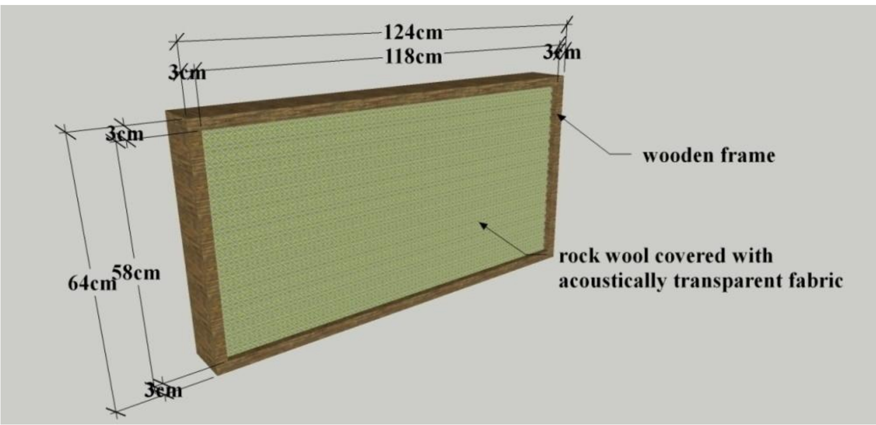


Figure 3.5 3-Dimensional drawing of 1 baffle module.

Acoustical simulations were conducted with several layouts of this system. First, baffles were mounted between the trusses to the 7.40m level. The modules were inserted in the middle of the trusses in order to form grates with the size of 60cmx 360cm. During the simulations, firstly 5cm thick mineral wool was selected for the material. Secondly, 10 cm thick mineral wool was selected. The same procedure was followed with the baffle system forming grates with 30cm x 360cm sizes. Then, baffles were mounted between the trusses at 6.80m level. The modules were inserted in the middle of the trusses in order to form grates with the size of 90cm x 360cm. During the simulations, firstly 5cm thick mineral wool was selected as the material. Secondly, 10 cm thick mineral wool was selected. The same procedure was followed with the baffle system forming grates with 60cm x 360cm sizes (Figure 3.6, Figure 3.7, Figure 3.8). During the simulations, the sound absorption caused by the wooden frame was neglected.

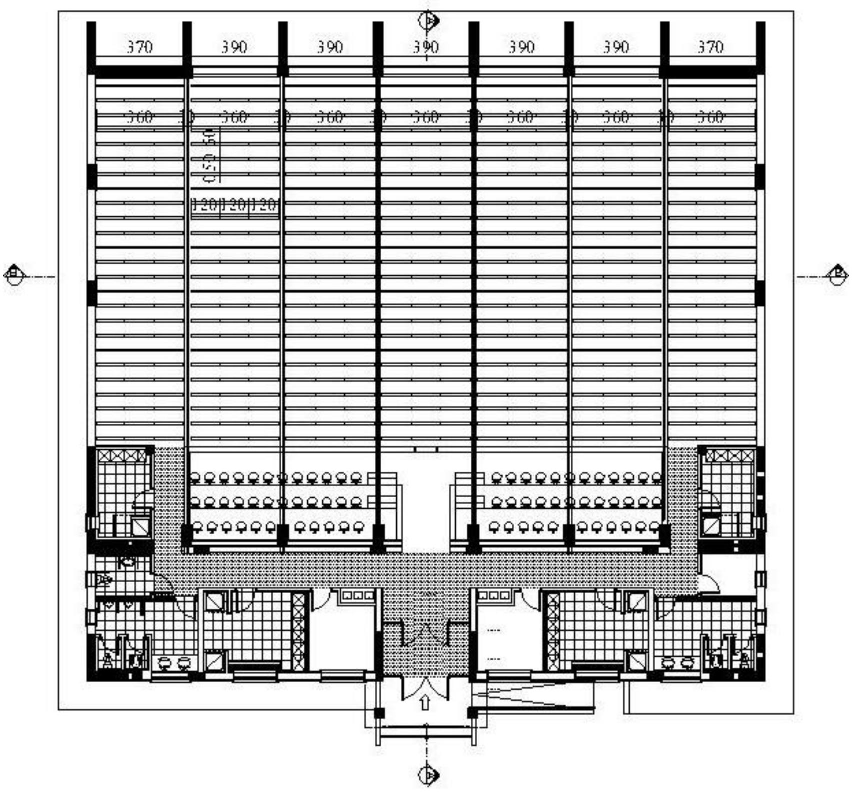


Figure 3.6 Ceiling plan– ceiling configuration of baffles with 60cmx360cm intervals

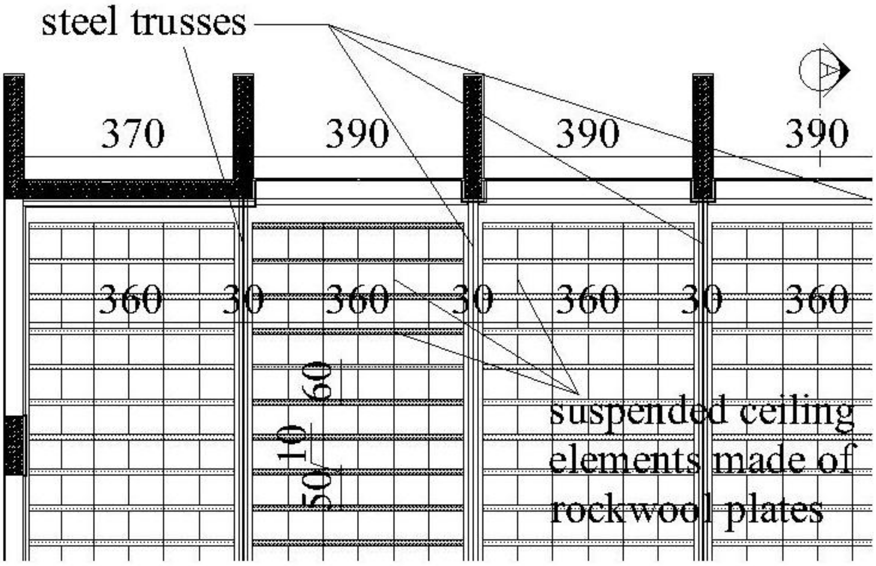


Figure 3.7 Partial ceiling plan above the playfield – ceiling configuration of baffles with 60cmx360cm intervals, 10 cm thick rock wool as material

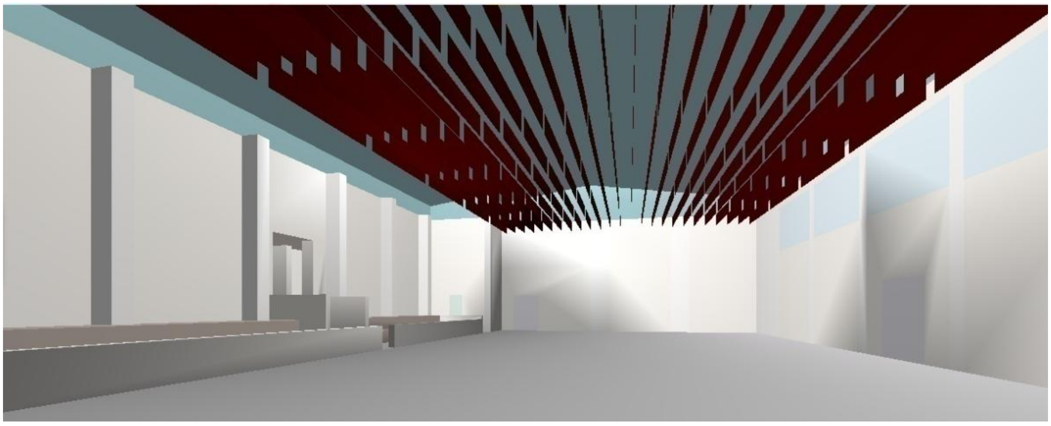


Figure 3.8 Baffles suspended between steel trusses-interior 3-D drawing

Transverse suspended ceiling system was the third treatment proposed in the study. Acoustical simulations were conducted after adding suspended ceiling system above the playfield, where the selected materials were suspended transversely from the trusses (Figure3.9, Figure3.10, Figure 3.11). During the simulations, firstly double layered sound absorbing curtain was selected as the material. Secondly, 10cm thick mineral wool was selected. Thirdly, 5cm thick mineral wool was selected as materials.

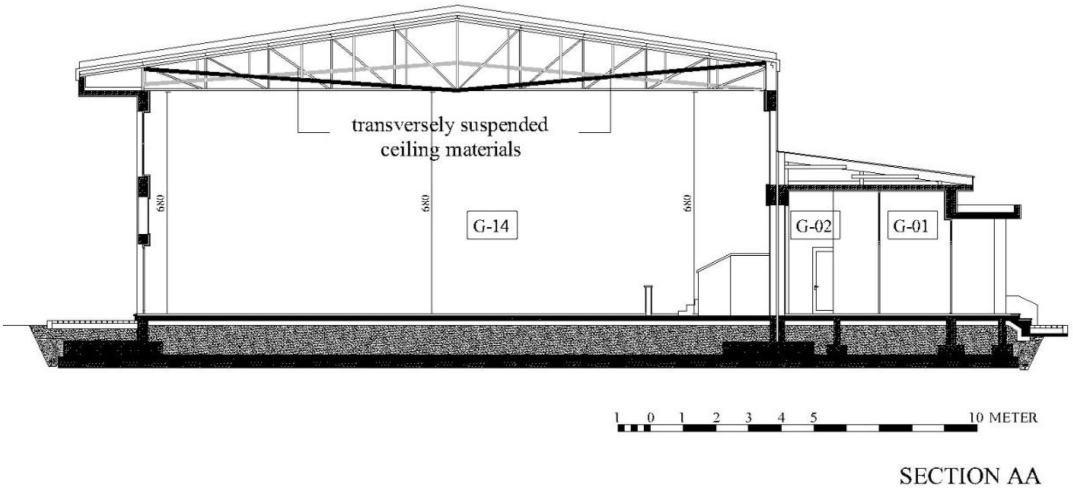


Figure 3.9 Sport hall section AA with suspended ceiling, transversely mounted

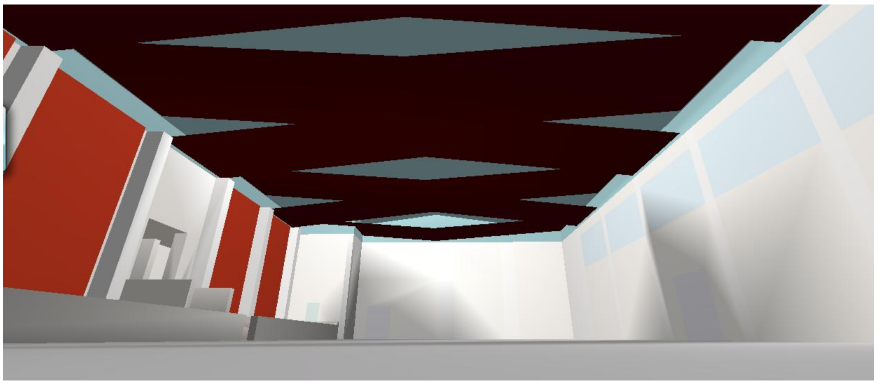


Figure 3.10 Transversely suspended materials to the ceiling between steel trusses above the playfield -interior 3-D drawing

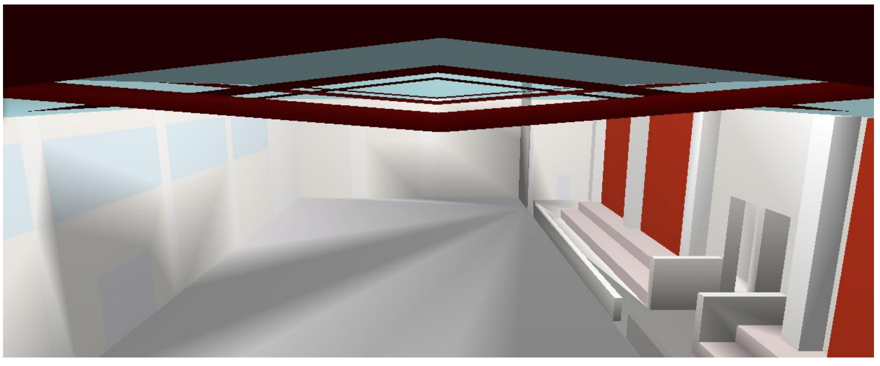


Figure 3.11 Transversely suspended materials between steel trusses above the playfield – 3-D Elevation

According to the simulation results for estimated global RT (GRT-T30) values,the most appropriate T30 values, i.e. closest values to those described in the standards, were obtained with three proposals: (i) baffles suspended below the trusses with 60cm x 360cm grids, (ii) baffles suspended above the trusses with 60cm x 360cm grids, (iii) panels mounted transversely to the trusses and when 10 cm thick mineral wool was used as the material. The amount of the materials used in the suspended ceiling proposal are given in Figure F.1.

3.2.2. Suspended Curtain Modules for Vertical Surfaces

After selection of the most appropriate ceiling system as the permanent implementation, convenient proposal for the temporary implementation was searched in order to achieve variable acoustical environment within the hall and to be used during different activities when necessary. For the temporarily used materials, vertical surfaces of the playfield, i.e. walls, windows, openings, etc., were considered to be the most appropriate location due to its surface area amount and giving possibility to easy access to the materials mounted.

Since the studied halls belong to schools, the procedure for removing when unnecessary / implementing when necessary is going to be conducted by the school janitor, not by specialized operators. Hence, the system proposed needed to be easily operable; requiring as few assisting materials as possible. Additionally, it needed to be economical and easily mountable at the first place. In the light of these principles, instead of automatic system implementation, mechanical system was preferred. Within this content, roller blind curtains were found to be appropriate for the temporary implementation. Double-layered satin curtains with roller blind mechanisms were mounted 15cm from the wall in front of the tribune’s back wall with the height of 5.80m, in front of the side walls and front walls in the playfield with the height of 5.30m and in front of the windows with the height of 2.50m. The amount of the materials used in the wall surfaces are given in Figure F.2.

Simulation results of the proposal revealed the fact that the service area was behaving as a coupled room after the addition of temporary materials. In order to prevent this, namely preventing the late reflections and decrease the T20-T30 difference, the same system was mounted also to the open entrances between the service area and playfield (Figure 3.1).

The study was continued with the acoustical analysesof the selected suspended ceiling system proposals and the joint use of suspended curtain modules when necessary for each activities-related scenario which are explained in the 3rd section of this chapter. The acoustical analyses were (i) ray tracing to find estimated GRT values in low, mid and high frequency ranges, and, (ii) grid response analyses to find the EDT and T30 values at mid-frequencies and ΔSPL(A) values for all of the activities, STI values for speech activities, C80 values at mid-frequencies for musical activities.

3.2.3. Wall Cladding with Sound Absorbing Perforated Metal Sheets

For the improvement of the selected proposals, in order to prevent focusing of the sound in front of the parapet between the playfield and the tribune, sound absorbing material was searched to be mounted permanently to the parapet. The selection criteria were convenience for the implementation to the existing hall,stiffness to the impacts and high-sound absorbing capacity. In the light of these principles, perforated metal sheet on 5cm-thick rock wool was mounted to the parapet.The amount of the materials used on the parapet surfaces are given in Figure F.2.

3.2.4. Abbreviations for Proposals

Each proposal was coded according to thetype suspended ceiling system,thickness of the materials,spacing between the materials (intervals), and placement of the suspended curtain modules in vertical.

The abbreviations used in the codes are listed below:

B: **B**affle Suspended Ceiling

FP: **P**anelled Suspended Ceiling-**F**lat

TP: **P**anelled Suspended Ceiling-**T**ransverse

FT: **F**abric **T**ension Ceiling (suspended fabric on ceiling)

C: Suspended **C**urtain on vertical surfaces

MS: Wall Cladding with **M**etal **S**heets

w: **w**alls – Cw = **c**urtain on **w**alls

r: **r**ear wall – Cr = **c**urtain on **r**ear walls

s: **s**ide walls – Cs = **c**urtain on **s**ide walls

o: **o**penings – Co = **c**urtain on **o**penings

g: **g**lass surfaces (i.e. windows) – Cg = **c**urtain on windows, in front of **g**lasses

a: **a**ll vertical surfaces (i.e. rear wall, side walls, windows)

The nomenclature of the treatmentB10@60(at)+MS+Ca+Co isgiven below:

B10@60(at)+MS+Ca+Co

Baffle suspended ceiling

10cm-thick rock wool panel

Spacing (axial distance) between two neighbouring boards is 60cm……….

Sound absorbing boards positioned **Above Truss level**

Cladding with **perforated Metal Sheet** (on parapet)

Curtain modules mounted in front of **All vertical surfaces** (walls,side walls, rear walls, windows)

Curtain modules that close the **Openings** placed between service and sport area

According to this nomenclature, the treatment is composed of 10cm-thick rock wool boards fixed at 60cm intervals, sound absorbing perforated metal sheet covering the surfaces of parapet located between the tribune and playfield, curtain modules mounted in front of walls, windows and at the entrances/openings between the service area and sport area.

The nomenclature of the treatment FP5+Cr is given below:

FP5+Cr

Flat panelled suspended ceiling …

5cm-thick rock wool panel……………

Curtain modules mounted in front of tribune’s rear wall

According to this nomenclature, the treatment is composed of flat panelled suspended ceiling made of 5cm-thick rockwool boards (mountedin lateral to produce a flatsuspended ceiling)and the curtain modules mounted in front of the tribune’s rear wall.

The nomenclature of the treatment FT+Cg isgiven below:

FT+Cg

Fabric Tension suspended ceiling…..

Curtain modules mounted in front of the windows

According to this nomenclature, the treatment is composed of sound absorbingcurtains/fabrics stretched crosswise between the trusses and the curtain modules mounted in front of the windows.

3.3. ACTIVITIES-RELATED SCENARIOS

In order to examine the halls in terms of their acoustical features, several scenarios with respect to the activities taking/that might take place in the halls were decided. The analyses were based on five different scenarios which are:

Scenario 1: Physical education classes (PEC)

Scenario 2: Sport games activities where the sound source is the players (SG-p)

Scenario 3: Sport games activities where the sound source is the audience (SG-a)

Scenario 4: Multi-purpose use for speech activities (MP-S)

Scenario 5: Multi-purpose use for performance activities (MP-P)

The abbreviations for the scenarios used in this study are listed in Table 3.1 and these scenarios are described in the following sections:

Table 3.1 List of abbreviations for scenarios

Scenario	Abbreviation
Scenario 1: Physical Education Class	PEC
Scenario 2: Sport Games-1: players as the sound source	SG-p
Scenario 3: Sport Games-2: audience as the sound source	SG-a
Scenario 4: Multi-Purpose - Speech Activities	MP-S
Scenario 5: Multi-Purpose - Performance Activities	MP-P

3.3.1. Scenario 1: Physical EducationClass Activities (PEC)

Physical education (PE) class is one of the major aims of designing and constructing a sports hall for a school building. The hall is a core-learning space during this activity. Hence, intelligibility of speech within the hall is important.

According to the activity taking place in this scenario, sound source was the teacher (Table 3.2) and receiver was the students.Since there is no audience apart from the students during this activity, the seating on the tribune is unoccupied. During the activities in this scenario, in order to achieve the required GRT values within the hall, apart from the permanently mounted systems, i.e. suspended ceiling and metal sheet on parapet, suspended curtain modules in front of the rear wall (Figure 3.12) or in front of the windows were also used. Selection criteria for the location of the curtain modules used was thedamage risk. The simulations were conducted with combinations of the selected curtain modules.

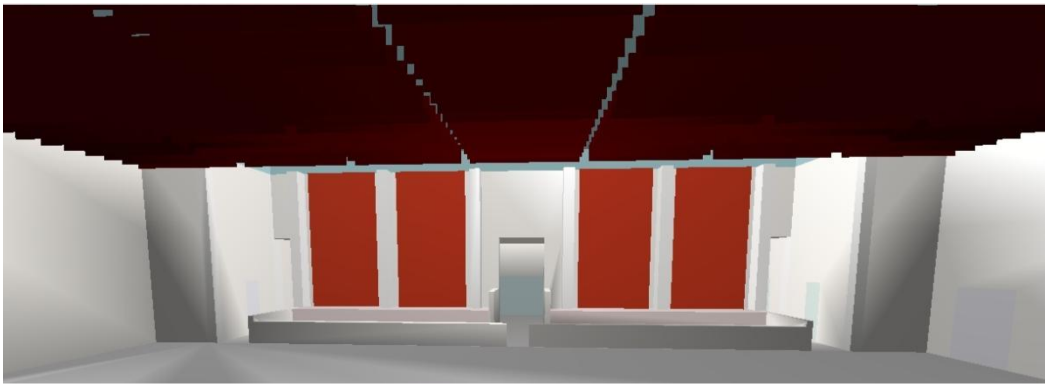


Figure 3.12 Suspended curtain modules in front of the rear wall

3.3.2. Scenario 2/3: Sport Games Activities – Sound Source: Player (SG-p) / Audience (SG-a)

Apart from physical education classes, another major aim of use of the sport halls in schools is the sport games played by the students in the school or teams of the town, since such halls are rented in summer for training or tournaments (Köse, 2012). Scenario 2, where the sound source was the player located in the middle of the playfield,was simulated in order to check communication intelligibility within the playfield between the players.

For the simulations, the seats at the tribune were modelled as occupied seats with 70 audience capacity. Considering the possible damages that might be caused by the spectators, players, etc., it was not possible to use the curtain modules during this

activity. For this reason, only permanent implications were proposed during the simulations.
Considering the purpose of the sport games activity, sensation of the audience during the sport gamesis another important case. For this reason, the simulations were conducted in order to analyse and improve the acoustical conditions within hall from the audience perspectiveto provide sufficient acoustical environment, i.e. suitable aural atmosphere to reflect the enthusiasm during the games. Different from the scenario 2, audience was the sound source during this scenario.

3.3.3.Scenario 4: Multi-Purpose Use: Speech Activities (MP-S)

Another use of the hall is speech activities such as graduation ceremonies, educational conferences where a large performance stage area is not required but a platform for the speakers is enough. So, an additional seating area with 314 people audience capacity and a void was provided to be used as the stage on the playfield. A platform to the stage area is not proposed (Figure 3.13).

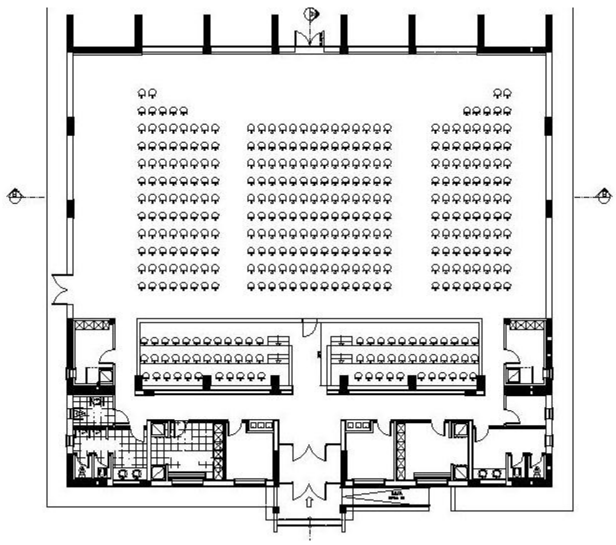


Figure 3.13 Audience seating layout during multi-purpose use for speech activities.

For the multi-purpose use of the hall, in order to provide an adjustable acoustical environment, roller blind curtain modules in front ofthe sidewalls of the playfield,the tribune rear wall and windows were used (Figure 3.14, Figure 3.15). In order to prevent/decrease late reflections from the service area which cause coupling effect, removable curtains were added to the openings separating service area from the sports area (Figure3.14). It was assumed that sound reinforcement systems were going to be used during the activities in this scenario.

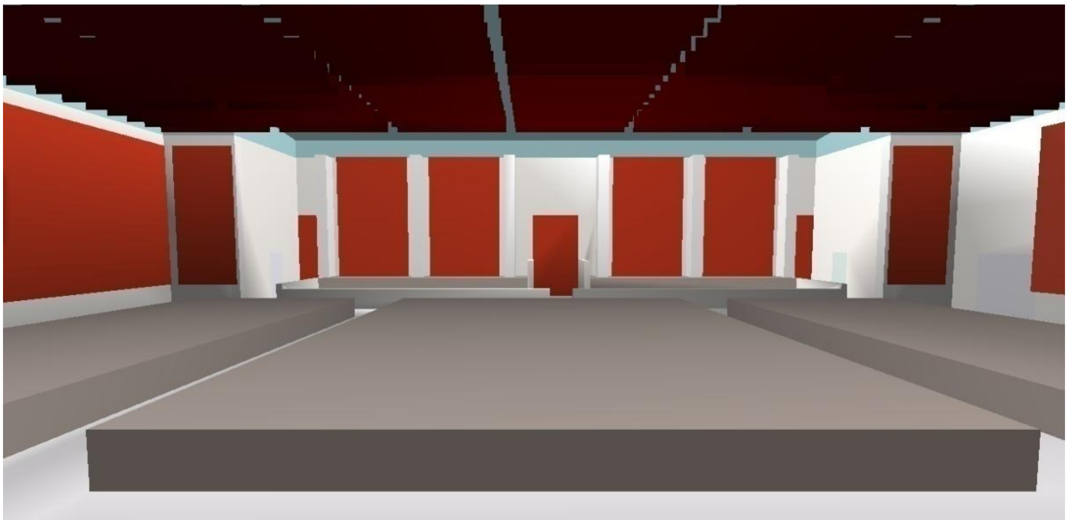


Figure 3.14 Sport hall internal view during multi-purpose use for speech activities.

3.3.4. Scenario 5: Multi-Purpose Use: Performance Activities (MP-P)

Another foreseen use of the hall is for speech and musical activities at the same time such as student concerts, national festival ceremonies where a large performance area is necessary. For the acoustical treatment, same configuration with the multi-purpose use of the hall for speech activities was proposed (Figure 3.15).

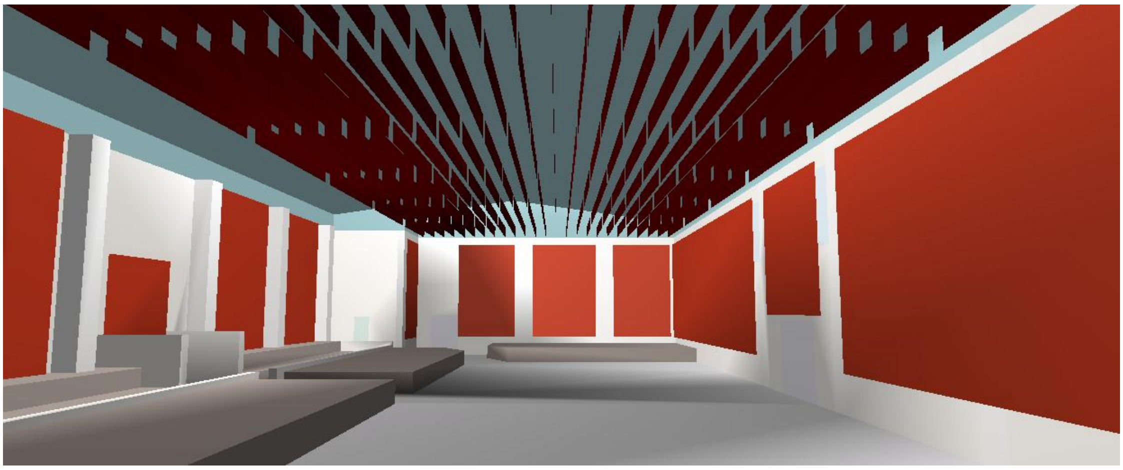


Figure 3.15 Sport hall internal view during multi-purpose use for performance activities.

However, due to need for larger stage area, the seating was planned in order to provide wider performance area to be used as the stage on the playfield. Additional audience seating capacity is 314 people. A platform to the stage area was not proposed (Figure 3.16). It was assumed that sound reinforcement systems were going to be used during the activities in this scenario.

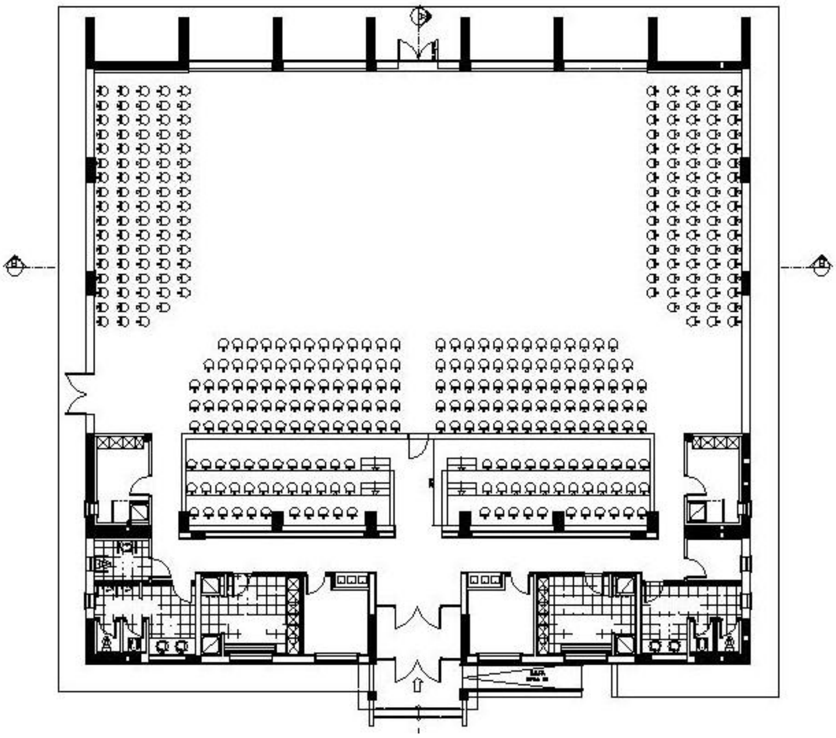


Figure 3.16 Audience seating layout during multi-purpose use for performance activities.

3.4. 3D MODELLING & ACOUSTICAL SIMULATIONS

In the study, the acoustical features of the sport hall for the:

(i) AS-IS case, in other words, the conditions representing the present situation without any intervention, and
(ii) IMPROVED cases, in other words, the case representing the interior ceiling and/or wall surfaces were treated with the sound absorbing suspended ceiling and curtain systems were analysed.

Each scenario was examined by the estimated Global Reverberation Time (GRT) and Grid Response analyses. The 3D computer models of the hall were produced for all the scenarios. The acoustical performance of the AS-IS situation of the hall for its current uses (PEC, SG-p, SG-a) and its IMPROVED situation considering each treatment suggested in the study for multi-purpose uses (PEC, SG-p, SG-a, MP-S, MP-P) were analysed by using these models and acoustical simulation methods. The examinations were done by means of:

- Estimated Global Reverberation Time (GRT) analyses for the frequency range between the 125Hz and 4000Hz in 1/1 octave band;
- Grid Response analyses in terms of acoustical parameters Early Decay Time, (EDT), T30, A-weighted Sound pressure level difference (ΔSPL(A)) for all activities. The Speech Transmission Index (STI)was used in the evaluations for the speech activities and the clarity (C80)was used in the evaluations for musical activities (Table 3.5).Among these parameters, EDT, T30 and C80 values at the mid frequency range (500 and 1000Hz) and STI value were analysed by using their X(50) data presenting the value for the 50% cumulative distribution. The ΔSPL(A) value was obtained by taking the difference between the X(95) and X(5) values of cumulative distribution.The acoustical parameters used to examine the acoustical features for each scenario are listed in Table 3.2. The even distribution of sound was also the other acoustical evaluation criterion for the hall in terms of those acoustical parameters.

Table 3.2 Acoustical parameters used for the examinations for each scenario

scenario	acoustical parameter					
	GRT	EDT	STI	SPL(A)	T30	C80
PEC	+	+	+	+	+	-
SG-p	+	+	+	+	+	-
SG-a	+	+	+	+	+	-
MP-S	+	+	+	+	+	-
MP-P	+	+	-	+	+	+

The acoustical features were determined for the AS-IS case, and then the acoustical performance of each configuration suggested as improvements were analysed by using the software AUTOCAD v.2007, Sketch Up v.7.0 and ODEON v.8.5. The analyses of improved cases were conducted for the individual use of suspended ceiling systems and the joint use of suspended ceiling and curtain module systems. In order to eliminate the sound focusing problem observed in the playfield after the treatments, the use of sound absorptive perforated metal sheets on parapets was suggested as the second permanent treatment, in addition to the suspended ceiling system.

Among the suspended ceiling configurations proposed in the study, the ones that provided the ideal or acceptable estimated GRT values for sportive activities were selected to analyse the scenarios representing the physical education class activities and multi-purpose use of the sport hall for speech and musical activities. Those treatments are namely flat panelled suspended ceiling, baffle suspended ceiling, crosswise (transverse) suspended ceiling. Some of those treatments were supported with the additional use of curtain modules with roller blind mechanism covering the wall surfaces in order to achieve the ideal or acceptable acoustical environment for the physical education class and multi-purpose activities. For physical education class activity, treatments with additional curtain in front of windows or tribune's rear wall were proposed. For the multi-purpose activities, treatments with additional curtain only in front of walls and later in front of walls and at the openings were proposed. The grid response analyses were conducted with the selected configurations for each scenario which are given in the chapter 4. The optimum configurations/treatments providing appropriate/efficient acoustical environment in the sport hall for each scenario were defined in terms of relevant acoustical design requirements (see Section 2.1.2 for the requirements).

Among the simulated proposals, 3 ceiling treatments, namely B10@60 above and below truss level and TP10, were found suitable to be applied to the hall in addition to the metal sheet in front of the parapet. Using curtain modules in front of the tribune's rear wall during the physical education class activity and in front of the all wall surfaces and at the entrances during multi-purpose activities were found to be the most sufficient solutions.

The variations of the proposals for each scenario that the acoustical analyses of the hall were based on, the results from the acoustical simulations and the adequacy of the estimated Global Reverberation Times (GRT-T30) in 125-4000 Hz frequency range in 1/1 octave band, grid responses of EDT, T30 and C80 at 500 and 1000Hz, STI and∆SPL(A) values obtained from simulation results of the proposals for the activities related scenarios are given Chapter 4.

The acoustical model representing the AS-IS situation of the hall was made with respect to the project drawings and material information provided by Polarkon Co. Ltd. During the simulations, scattering coefficient was given to the seats, both while occupied and unoccupied, and to the steel trusses on the ceiling owing to their diffusive character. The absorption caused by the students during the physical education classes, by the players during the games and by the speakers and the performers during the multi-purpose activities was neglected because of the large volume of the hall, lack of sound absorption from the surfaces within the hall in the AS-IS case and little amount of sound absorption in the improved cases. During the simulations, background noise level was taken as 35dB, overall gain within hall was taken as 89dB. The sound source locations decided for the physical education classes, sport games and multi-purpose activities and their directions are indicated on Figure 3.17. Their numerical coordinates in metres (x,y) and the height in metres (z) in the 3D acoustical model are given in Table 3.3.

Table 3.3 Sound source coordinates of the activities-related scenarios

Scenario	Abbreviation	Sound Source Location		
		x (m)	y (m)	z (m)
Physical Education Class	PEC	15	10	1.5
Sport Games 1	SG-p	14	17	1.5
Sport Games 2	SG-a	16	7	1.5
Multi-Purpose Use-Speech	MP-S	14.5	23	1.5
Multi-Purpose-Performance	MP-P	14	19	1.5

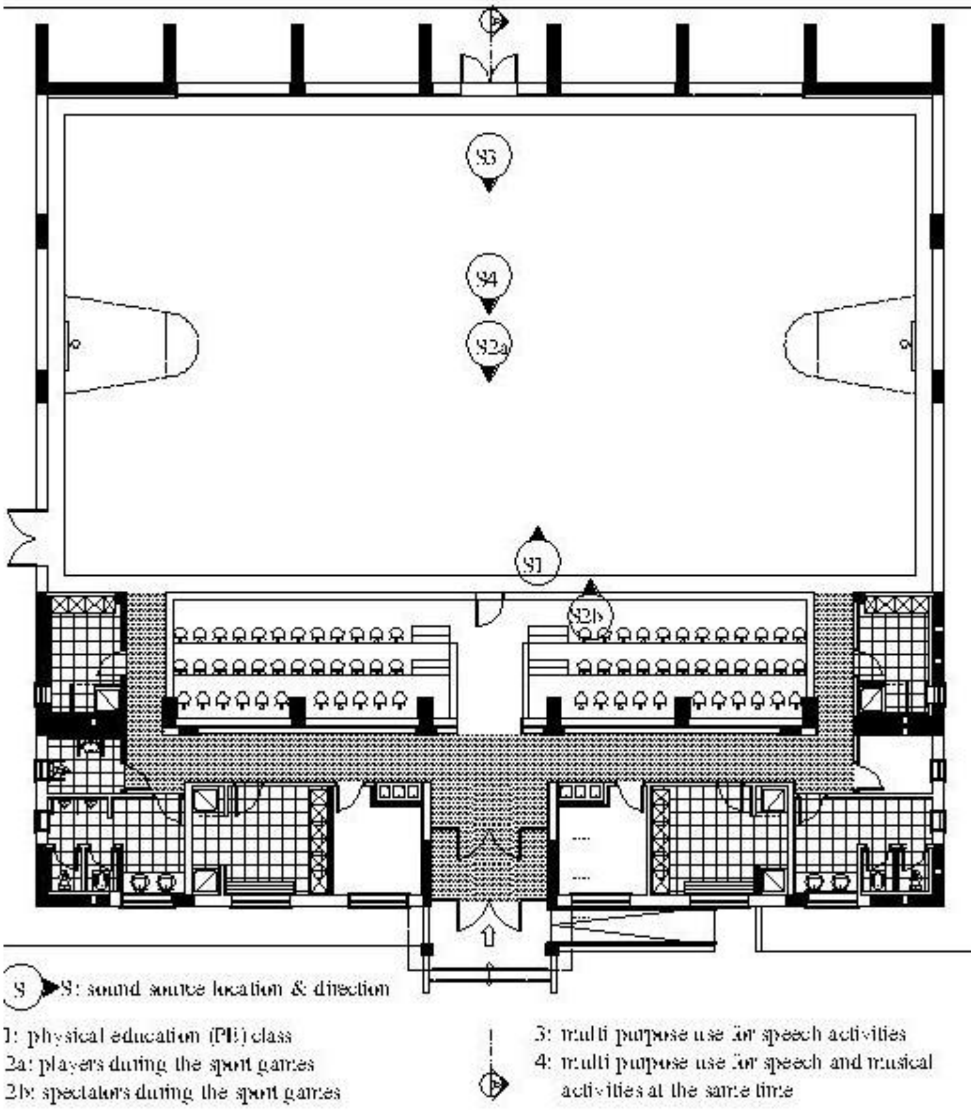


Figure 3.17 Sound source locations and directions according to activities

The surface materials of the AS-IS case,descriptions of the materials and their sound absorption coefficients in 125Hz-4000Hz frequency range in 1/1 octave bandare given in Table 3.4, room finish schedules for the AS-IS case are given in Table 3.5. Descriptions of the materials used in the treatment proposals and their sound absorption coefficients in 125-4000 Hz frequency range in 1/1 octave band are given in Table 3.6.

Table 3.4 Sound absorption coefficients of the floor, wall and ceiling materials and doors and windows used in the AS-IS case of the hall at 125-4000 Hz frequency range in 1/1 octave band (Mezzo Stüdyo Co. Ltd., 2014)

	Material Description - AS-IS Case	Sound Absorption Coefficients					
		125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
floor	1-Plastics, Vinyl tile or linoleum on concrete	0.02	0.3	0.3	0.3	0.3	0.02
	2-Ceramics&Stones, Ceramic tiles with smooth surface	0.01	0.01	0.01	0.02	0.02	0.02
	3-Audience&Seats,Empty plastic or metal chairs	0.07	0.07	0.14	0.14	0.14	0.14
	4-Children, seated in plastic or metal chairs (per child) in m2 units	0.28	0.31	0.33	0.35	0.37	0.37
wall	5-Concrete, Smooth concrete, painted or glazed	0.01	0.01	0.01	0.02	0.02	0.02
	6-Brick, Brick,smooth, plaster finish	0.01	0.02	0.02	0.03	0.04	0.05
ceiling	7-Metals, Steel trapez profile	0.3	0.25	0.2	0.1	0.1	0.15
	8-Concrete on ceiling (poured, rough finish, unpainted)	0.01	0.02	0.04	0.06	0.08	0.1
doors/ windows	9-Doors&Windows, Steel Door	0.05	0.05	0.05	0.06	0.04	0.02
	10-Doors&Windows, Solid timber door	0.14	0.1	0.06	0.08	0.1	0.1
	11-Doors&Windows, Double glazing, 2-3mm glass, 10mm air gap	0.15	0.05	0.03	0.03	0.02	0.02
	12-Doors&Windows, Double Glazing, 2-3 mm glass, 10 mm gap	0.1	0.07	0.05	0.03	0.02	0.02

Table 3.5 Room finish materials of the untreated hall on floor, wall and ceiling surfaces of each room and doors&windows used in each room. (Polarkon Co. Ltd., 2012)

	floor				wall		ceiling		doors & windows			
	1	2	3	4	5	6	7	8	9	10	11	12
G01	-	+	-	-	+	+	-	+	+	-	+	+
G02	-	+	-	-	+	+	-	+	+	-	+	+
G03	-	+	-	-	+	+	-	+	-	+	+	+
G04	-	+	-	-	+	+	-	+	+	+	+	+
G05	-	+	-	-	+	+	-	+	+	+	+	+
G06	-	+	-	-	+	+	-	+	-	+	+	+
G07	-	-	-	-	+	+	-	+	+	-	+	+
G08	-	-	-	-	+	+	-	+	-	+	+	+
G09	-	+	-	-	+	+	-	+	-	+	+	+
G10	-	+	-	-	+	+	-	+	+	+	+	+
G11	-	+	-	-	+	+	-	+	+	-	+	+
G12	-	+	-	-	+	+	-	+	-	+	+	+
G13	-	+	+	+	+	+	+	+	-	+	+	+
G14	+	-	-	-	+	+	+	-	-	-	+	+

Table 3.6 Descriptions of the materials used in the treatment proposals and their sound absorption coefficients at 125-4000Hz frequency range in 1/1 octave band (Mezzo Stüdyo Co. Ltd., 2014)

	Material Description - Proposals	Sound Absorption Coefficients					
		125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
ceiling	Mineral Wool, fibreglass or rockwool, Thickness [cm]=48 kg/m3, 50 mm thick	0.30	0.80	1.00	1.00	1.00	1.00
	Mineral Wool, fibreglass or rockwool, Thickness [cm]=48 kg/m3, 100 mm thick	0.65	1.00	1.00	1.00	1.00	1.00
	Curtains, 0.194psf DbLayer Nomex@30"	0.53	0.57	0.82	1.00	1.00	1.00
wall	Metals, Performated metal (13% open, over 50mm(2") fiberglass)	0.25	0.64	0.99	0.97	0.88	0.92
	Curtains, AV20 double layer satin 550 g/m2 15 cm from wall	0.17	0.45	0.76	0.89	0.91	0.88

3.5. ECHO CONTROL ANALYSES

For the echo analyses within the hall, arrival time difference between the first reflected sound and direct sound was found. During the analyses, reflections from the untreated ceiling and reflections from the untreated wall surfaces were controlled for the AS-IS case. Length difference between the paths travelled by the reflected sound and direct sound was calculated to find out whether echo occurs or not.

For the echo analysis of Scenario 1: Physical Education Class (PEC), sound source and location were explained in section 3.3.1. The receivers are the students who were assumed to be alignedin front of the teacher, in the middle of the playfield. The analyses were conducted (i) in terms of the sound reflections from the ceiling; (ii) in terms of the sound reflections from the front wall that the sound source, namely the teacher, is facing. Three receiver positions were selected: (i) in the middle, (ii) at the right edge (iii) at the left edge of the line (Figure 3.18).

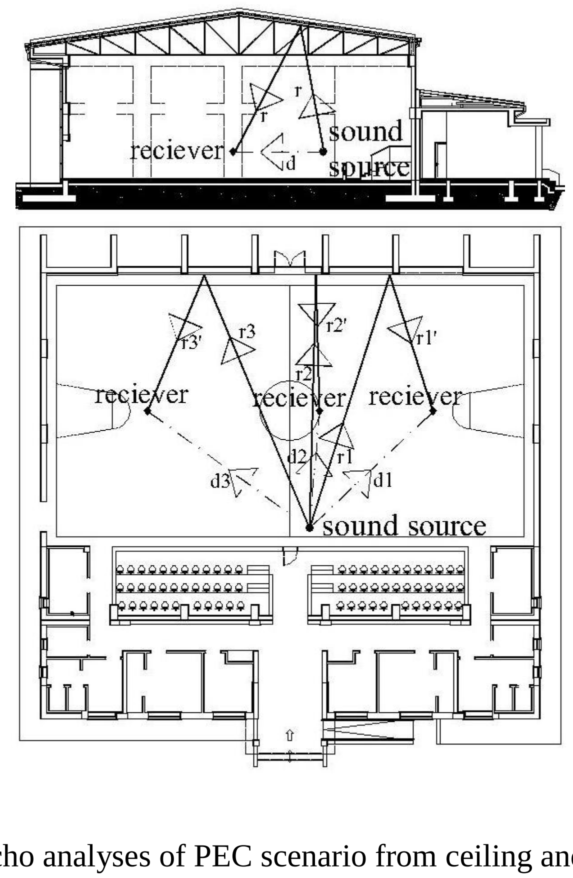


Figure 3.18 Echo analyses of PEC scenario from ceiling and wall surfaces
(r: reflected sound, d: direct sound)

For the echo analysis of Scenario 2: Sport Games-SG-p where the sound source is the players, sound source and location were explained in section 3.3.2. The receivers are the audience on the tribune.The analyses were conducted (i) in terms of the sound reflections from the ceiling; (ii) in terms of the sound reflections from the side wall that the sound source, namely the player, is facing. Selected receiver positions were audience (i) in the middle-right, (ii) at the right edge, (iii) at the left edge, (iv) in the middle-left sides of the tribune (Figure 3.19).

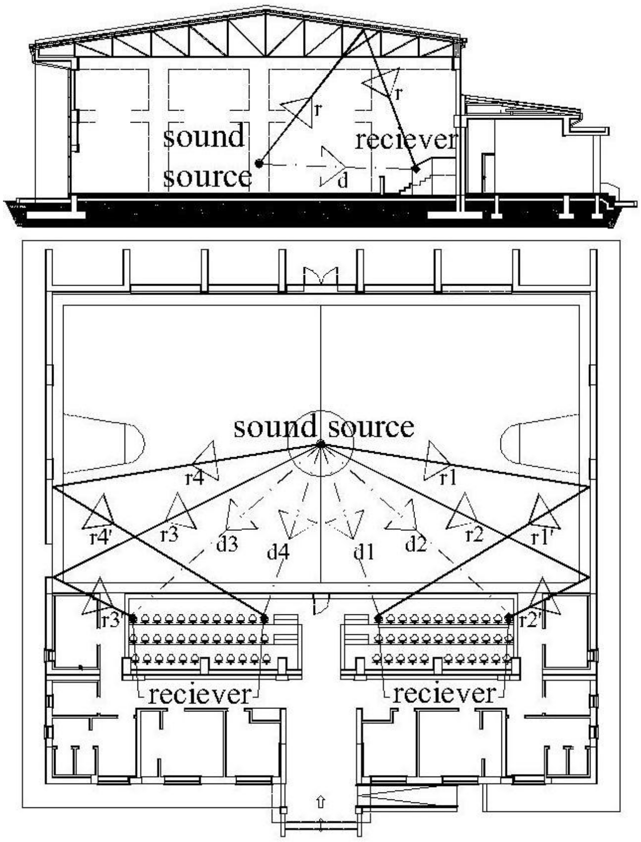


Figure 3.19 Echo analyses of SG-p scenario from ceiling and wall surfaces

(r: reflected sound, d: direct sound)

For the echo analysis of Scenario 3: Sport Games-SG-a where the sound source is the audience (spectators), sound source and location wereexplained in section 3.3.2. The receivers are the players on the playfield.The analyses were conducted (i) in terms of the sound reflections from the ceiling; (ii) in terms of the sound reflections from the front wall that the sound source, namely the audience (spectators), is facing (Figure 3.20).

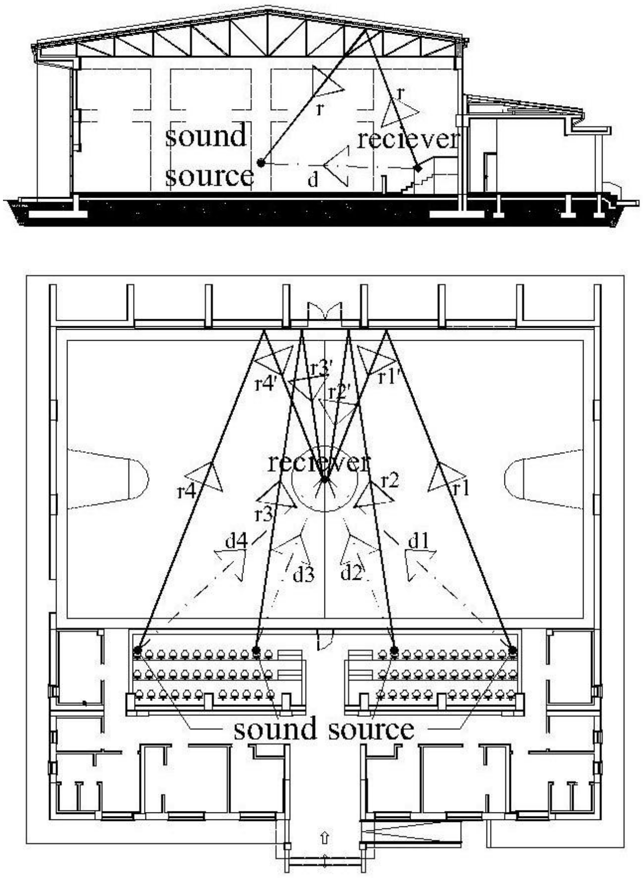


Figure 3.20 Echo analyses of SG-a scenario from ceiling and wall surfaces
(r: reflected sound, d: direct sound)

For the IMPROVED cases of sportive activities (PEC, SG-p, SG-a scenarios), the analyses were not repeated since the procedure is the same with the AS-IS case.For the IMPROVED cases of multi-purpose scenarios (MP-S, MP-P)the analyses were not necessary since ceiling and wall surfaces were treated with sound absorbing materials.

CHAPTER 4

RESULTS

In this chapter, data obtained from the acoustical simulation analyses are summarized to determine the AS-IS acoustical features of the typical small sport hall. Acoustical performances of different types of suspended ceiling systems suggested as improvements, and acoustical features of the typical sport hall for the improved cases based on activities-related scenarios are assessed. Results are presented under respective headings.

4.1. ACOUSTICAL FEATURES OF THE TYPICAL SMALLSPORT HALL FOR THE AS-IS CASE: BASED ON ACTIVITIES-RELATED SCENARIOS

The simulation data obtained for the AS-IS case of the hall based on physical education class and sport games activities are presented in the following sections.

4.1.1. Estimated Global Reverberation Time Values (GRT-Global T30)

The estimated GRT values within the sport hall for the as-is uses of the hall, i.e. PE classes and sportive activitieswere predicted to lie in between 3.06s and 3.47s at low frequencies (125 Hz, 250 Hz), 3.46s and 5.08s at mid frequencies (500 Hz, 1000 Hz), and 2.34s and 4.25s at high frequencies (2000 Hz, 4000 Hz) (Table 4.1, Figure A.1, Figure B.1, Figure C.1). These values obtained from the simulation highly exceed the recommended reverberation time limits for those activities (Department of Education and Skills, 2004; Beranek, Acoustics, 1993).

Table 4.1 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the AS-IS Case: for the scenarios PEC, SG-p, SG-a.

Scenario	Estimated Global T30 values with respect to frequencies (s)					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
PEC	3.47	3.26	3.65	5.08	4.25	2.45
SG-p	3.35	3.08	3.49	4.66	3.92	2.34
SG-a	3.29	3.06	3.46	4.64	3.92	2.34

Considering the distribution of the estimated GRT values within the overall space of the hall, the differences more than 1s, reaching to 2.5s, were determined in GRT values at low, mid and high frequencies. The heterogeneous distribution of GRT valuesat different frequency rangesresults in tonal imbalance, in other words, risk of masking of sounds at certain frequency ranges. The noticeable decrease was also determined in estimated GRT values at 4000Hz that can be attributed to the sound absorption by air in spaces with large volumes (Table 4.1, Figure A.1, Figure B.1, Figure C.1).

4.1.2. Grid Response Analyses

According to the grid response analyses, EDT values were predicted to be evenly distributed in the hall at 500Hzand 1000Hz, individually (Figure A.2, Figure B.2, Figure C.2) while 1.5s difference in EDT values were noticed between 500Hz and 1000Hz, similar to the results of estimated T30 and GRT values (Table 4.2). The T30 values were predicted to be 4.7s average at mid frequency range (Figure A.3, Figure B.3, Figure C.3). The EDT values of 3.5s at 500Hz and 5s at 1000Hz were consistent with the estimated T30 and GRT values. That meant that sound decay occurs uniformly in the whole space. The simulated STI values were predicted to be around 0.35 (Table 4.2) with an even distribution within the hall (Figure A.4, Figure B.4, Figure C.4). That value fell into the poor range of intelligibility. Maximum SPL(A) difference is below 4dB (Table 4.2, Figure A.5, Figure B.5, Figure C.5).

Table 4.2 The results of grid response analyses for the AS-IS case in terms of EDT, T30and STI values (the data X(50) that is the threshold value showing the 50% of cumulative distribution), SPL(A) (the data X(95)-X(5), that is the difference between the SPL values at 95%and 5% of cumulative distribution.

Scenario	Parameter					
	EDT(s)		STI	ΔSPL(A)95%-5% difference (dB)	T30(s)	
	500 Hz	1000 Hz			500 Hz	1000 Hz
PEC	3.74	5.18	0.36	2.6	3.62	5.07
SG-p	3.5	4.76	0.39	3.6	3.49	4.67
SG-a	3.59	4.75	0.39	3.7	3.41	4.64

4.1.3. Echo Control Analyses of the AS-IS Case

For the echo analyses, the path differences between the reflected sound and direct sound reaching to the receivers were calculated. Since the speed of sound is 340m/s, the sound travels 17m in 0.05s. If the difference is equal to or below 17m, it means echo does not occur (Rossing (Ed.), 2007). The distances travelled by the reflected and direct sound from the ceiling and wall surfaces are given below for the scenarios PEC, SG-p and SG-a.

For the**PEC scenario**,the sound source and receiver positions under consideration are given in Figure 3.22. The distances travelled by each sound are given below:

Ceiling:r=7.09m, r'=7.86m,d=4.95m ⇒ r+r'-d=10m

Wall:r1=14.75m,r1'=7.95m,d1=9.45m ⇒ r1+r1'-d1=9.45m

r2=14.06m, r2'=7.57m,d2=6.51m ⇒ r2+r2'-d2=15.12m

r3=15.22m, r3'=8.20m,d3=11.07m ⇒ r3+r3'-d3=12.35m

For the **SG-p scenario**, the sound source and analyzed receiver positions are given in Figure 3.23. The distances travelled by each sound are given below:

Ceiling: r=8.56m,r'=7.32m, d= 7.72m ⇒ r+r'-d=8.16m

Wall:r1=13.65m, r1'=12.43m, d1=9.09m ⇒ r1+r1'-d1=16.99m

r2=15.07m, r2'=4.38m, d2=12.89m ⇒ r2+r2'-d2=6,56m r3=15.07m, r3’=4.38m, d3=12.89m ⇒ r3+r3’-d3=6,56m

r4=13.65m, r4’=12.43m, d4=9.09m ⇒ r4+r4’-d4=16.99m

For the **SG-a scenario**, the sound source and analyzed receiver positions are given in Figure 3.24. The distances travelled by each sound are given below:

Ceiling:r=7.32m, r’=8.56m, d=7.72m ⇒ r+r’-d=8.16m

Wall: r1=17.32m, r1’=8.01m, d1=12.70m ⇒ r1+r1’-d1=12.63m

r2=16.08m, r2’=7.49m, d2=9.14m ⇒ r2+r2’-d2=14.73m

r3=16.08m, r3’=7.49m, d3=9.14m ⇒ r3+r3’-d3=14.73m

r4=17.32m, r4’=8.01m, d4=12.70m ⇒ r4+r4’-d4=12.63m

The path difference between reflected and direct sound from the ceiling and wall surfaces are below 17m for the PEC, SG-p and SG-a scenarios. According to these results, echo does not occur in the hall at the determined sound source and receiver positions in the untreated hall for these activities and in the treated hall for all activities.

4.2. ESTIMATED GRT VALUES OF TYPICAL SPORT HALLS WHEN TREATED WITH DIFFERENT TYPES OF SUSPENDED CEILING SYSTEMS

Considering the PEC scenario, the estimated GRT values obtained for the hall treated with flat panelled, baffle and transverse suspended ceiling systemsare given in relevant tables below. The estimated GRT data achieved was summarized below:

- In the application of flat panelled suspended ceiling mounted immediately below the truss level, the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:
  - 1.82s with the use of 5cm-thick panels (FP5),
  - 1.79s with the use of 10cm-thick panels (FP10) (Table 4.3).

The estimated GRT values at frequencies above 250Hz presented a gradual decrease with the increase in frequency. The GRT values at 125Hz were the longest with 2.63s for the ceiling FP5 and 2.29s for the ceiling FP10.

Table 4.3 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with flat paneled suspended ceiling for PEC scenario.

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
FP5	2.63	2.23	1.93	1.71	1.58	1.26
FP10	2.29	1.87	1.85	1.73	1.58	1.28

- In the application baffle suspended ceiling mounted 60cm above the truss level, the estimated GRT values at mid frequencies were predicted to be:
  - 1.75s with 10cm-thick panels fixed at 60cm intervals (B10@60),
  - 1.72s with 10cm-thick panels fixed at 30cm intervals (B10@30),
  - 1.70s with 5cm-thickpanels fixed at 30cm intervals (B5@30) (Table 4.4).

Similar to the flat panelled suspended ceiling, the baffle system presented the longest GRT values at 125Hz with the values 2.09s, 2.05 and 2.32s, respectively.

Table 4.4 The Estimated Global Reverberation Time (GRT-Global T30) values obtained for the configurations with baffle suspended ceiling–above truss level for Scenario PEC.

configuration	Global T30 values (s)					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B10@60	2.09	1.84	1.82	1.69	1.55	1.22
B10@30	2.05	1.82	1.78	1.66	1.49	1.19
B5@30	2.32	1.87	1.76	1.64	1.49	1.19

- In the application of baffle suspended ceiling mounted immediately below the truss level, the GRT values at mid frequencies were predicted to be:
  - 1.74s with the 10cm-thick panels fixed at 90cm intervals (B10@90),
  - 1.64s with 10cm-thick panels fixed at 60cm intervals (B10@60),
  - 1.66s with the 5cm-thick panelsfixedat 60cm intervals (B5@60).

The longest GRT was observed at 125Hz for the ceiling B5@60 while a certain decrease seemed to be achieved at the other proposals, namely B10@90 and

B10@60, where 10cm-thick panels were used and suspended below the truss level (Table 4.5).

Table 4.5 The Estimated Global Reverberation Time (GRT-Global T30) values obtained for the configurations with baffle suspended ceiling-below truss level for ScenarioPEC.

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B5@60	2.38	1.84	1.73	1.60	1.46	1.19
B10@60	1.98	1.71	1.69	1.60	1.46	1.17
B10@90	1.93	1.8	1.78	1.71	1.57	1.24

- In the application of transverse suspended ceiling, the GRT values at mid frequencies were predicted to be:
  - 1.75s with 10cm-thick panels suspended crosswise between the trusses (Transverse suspended ceiling - TP10),
  - 1.73s with 5cm-thick panels suspended crosswise between the trusses (TP5),
  - 1.82s with sound absorptive fabric stretched crosswise between the trusses (Stretched Fabric suspended ceiling - FT).

Similar to the others, the longest GRT values were observed at 125Hz with the values of 2.14s, 2.84s and 2.29s respectively (Table 4.6).

Table 4.6 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with transverse suspended ceiling for PEC scenario.

configuration	Global T30values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
TP5	2.84	1.93	1.80	1.67	1.57	1.24
TP10	2.14	1.84	1.82	1.69	1.57	1.24
FT	2.29	2.12	1.93	1.71	1.57	1.26

Estimated GRT values within the sport hall for the improved cases regarding sportive activities where the player located in the middle of the playfield is the sound source are given in Table 4.7, Table 4.8, Table 4.9 and Table 4.10.

Considering the SG-p scenario, the estimated GRT values obtained for the hall treated with flat panelled, baffle and transverse suspended ceiling systemsare summarized in relevant tables below. The estimated GRT data was summarized below:

- In the application of flat panelled suspended ceiling mounted immediately below the truss level, the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:
  - 1.85s by the use of 5cm-thick panels (FP5)
  - 1.86s by the use of 10cm-thick panels (FP10) (Table 4.7).

While the GRT values at frequencies above 250Hz presented a gradual decrease with the increase in frequency, the GRT values at 125Hz were the longest with 3.62s for the ceiling FP5 and 2.72s for the ceiling FP10.

Table 4.7 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with flat paneled suspended ceiling for SG-p scenario.

configuration	Global T30 (s) values with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
FP5	3.62	2.30	1.91	1.80	1.66	1.33
FP10	2.72	1.89	1.91	1.82	1.67	1.33

- In the application of baffle suspended ceiling mounted 60cm above the truss level, the GRT values at mid frequencies were predicted to be:
  - 1.71s with 10cm-thick panels fixed at 60cm intervals (B10@60),
  - 1.67s with 10cm-thick panels fixed at 30cm intervals (B10@30)
  - 1.67s with 5cm-thickpanels fixed at 30cm intervals (B5@30) (Table 4.8, Figure B.1).

Similar to the flat panelled suspended ceiling, the baffle system presented the longest GRT values at 125Hz with the values 1.91s, 1.89 and 2.07s, respectively.

Table 4.8 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with baffle suspended ceiling–above truss level for SG-p scenario

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B10@60	1.91	1.78	1.76	1.67	1.53	1.22
B10@30	1.89	1.76	1.73 s	1.62	1.48	1.19
B5@30	2.07	1.76	1.73 s	1.62	1.48	1.19

- In the application of baffle suspended ceiling mounted immediately below the truss level, the GRT values at mid frequencies were predicted to be:
  - 1.70s with the 10cm-thick panels fixed at 90cm intervals (B10@90),
  - 1.62s with 10cm-thick panels fixed at 60cm intervals (B10@60).

The GRT values were the longest at 125Hz for these cases as well, with 1.87s for the ceiling B10@90 and 1.82s for the ceiling B10@60 (Table 4.9, Figure B.1).

Table 4.9 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with Baffle suspended ceiling–below truss level for SG-p scenario

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B10@90	1.87	1.75	1.73	1.67	1.55	1.24
B10@60	1.82	1.69	1.67	1.57	1.46	1.17

- In the application of crosswise suspended ceiling, the GRT values at mid frequencies were predicted to be:
  - 1.70s with 10cm-thick panels suspended crosswise between the trusses (Transverse suspended ceiling - TP10),
  - 1.71s with 5cm-thick panels suspended crosswise between the trusses (TP5),

- 1.77s with sound absorptive fabric stretched crosswise between the trusses (Fabric Tension suspended ceiling - FT).

Similar to the others, the longest GRT values were observed at 125Hz with the values of 2.09s, 2.75s and 2.27s respectively (Table 4.10, Figure B.1).

Table 4.10 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with Transverse suspended ceiling for SG-p scenario

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
TP5	2.75	1.89	1.76	1.67	1.53	1.24
TP10	2.09	1.76	1.75	1.66	1.53	1.24
FT	2.27	2.09	1.89	1.66	1.53	1.24

Considering the SG-a scenario, the estimated GRT values obtained for the hall treated with flat panelled baffle and transverse suspended ceiling systemsare summarized in Table 4.11, Table 4.12, Table 4.13 and Table 4.14. The estimated GRT data was summarized below:

- In the application of flat panelled suspended ceiling mounted immediately below the truss level, the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:
  - 1.92s with the use of 5cm-thick panels (FP5),
  - 1.89s with the use of 10cm-thick panels (FP10) (Table 4.11).

While the GRT values at frequencies above 250Hz presented a gradual decrease with the increase in frequency, the GRT values at 125Hz were the longest with 3.65s for the ceiling FP5 and 2.74s for the ceiling FP10.

Table 4.11 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with flat paneled suspended ceiling for SG-a scenario

configuration	Global T30 (s) values with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
FP5	3.65	2.36	1.98	1.87	1.69	1.35
FP10	2.74	1.93	1.94	1.84	1.69	1.35

- In the application baffle suspended ceiling mounted 60cm above the truss level, the GRT values at mid frequencies were predicted to be:
  - 1.77s with 10cm-thick panels fixed at 60cm intervals (B10@60),
  - 1.73s with 10cm-thick panels fixed at 30cm intervals (B10@30),
  - 1.75s with 5cm-thickpanels fixed at 30cm intervals (B5@30) (Table 4.12, Figure C.1).

The baffle system presented the longest GRT values at 125Hz with the values 2.00s, 1.94s and 2.16s, respectively.

Table 4.12 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with baffle suspended ceiling–above truss level for SG-a scenario

configuration	Global T30 (s) values with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B10@60	2.00	1.87	1.84	1.71	1.57	1.24
B10@30	1.94	1.84	1.80	1.66	1.51	1.22
B5@30	2.16	1.84	1.82	1.69	1.53	1.22

- In the application of baffle suspended ceiling mounted immediately below the truss level, the GRT values at mid frequencies were predicted to be:
  - 1.74s with the 10cm-thick panels fixed at 90cm intervals (B10@90),
  - 1.67s with 10cm-thick panels fixed at 60cm intervals (B10@60).

The GRT values at 125Hz were the longest with 1.94s for the ceiling B10@90 and 1.89s for the ceiling B10@60 (Table 4.13, Figure C.1).

Table 4.13 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with baffle suspended ceiling–below truss level for SG-a scenario

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B10@90	1.94	1.80	1.78	1.71	1.55	1.26
B10@60	1.89	1.76	1.73	1.62	1.49	1.21

In the application of crosswise suspended ceiling, the GRT values at mid frequencies were predicted to be:

- 1.76s with 10cm-thick panels suspended crosswise between the trusses (Transverse suspended ceiling - TP10),
- 1.76s with 5cm-thick panels suspended crosswise between the trusses (TP5),
- 1.82s with sound absorptive fabric stretched crosswise between the trusses (Stretched Fabric suspended ceiling - FT).

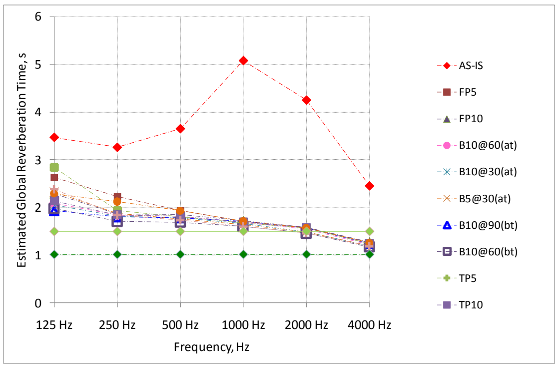
Likewise the other treatments, the longest GRT values were observed at 125Hz with the values of 2.12s, 2.79s and 2.27s respectively (Table 4.14, Figure C.1).

Table 4.14 The Estimated Global Reverberation Time (GRT-Global T30) values obtained from the configurations with transverse suspended ceiling for SG-a scenario

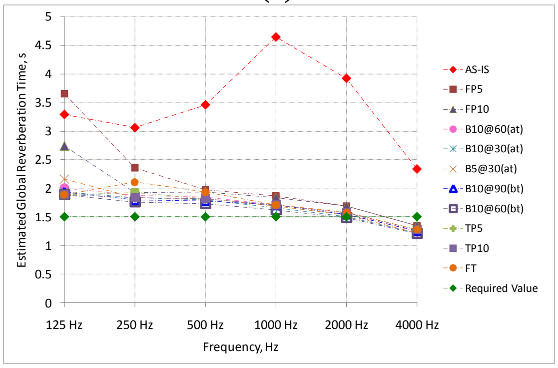
configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
TP5	2.79	1.93	1.82	1.71	1.58	1.28
TP10	2.12	1.84	1.82	1.71	1.58	1.28
FT	2.27	2.11	1.93	1.71	1.58	1.28

Each ceiling treatment proposed in the study provided remarkable decreases in GRT values at high, mid and low frequencies. Among all the proposals,GRT values in the treatments B10@60 – baffles suspended above truss level, B10@60 – baffles suspended below truss level and TP10 were found to be sufficientfor sportive activitiesin all frequency ranges with respect to the specified criterion, 1.5s limit

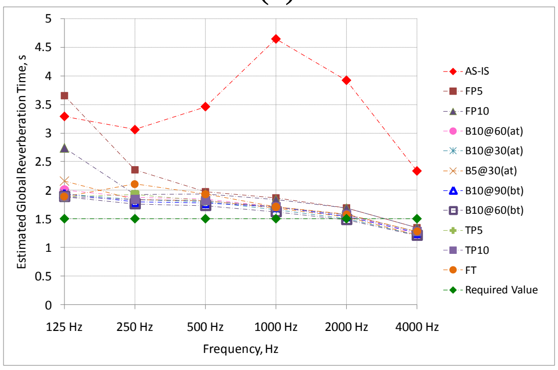
(Department of Education and Skills, 2004). However, for physical education class activity, obtained GRTvalues are estimated to be above the criterion, 1.02s limit (Beranek, 1993) and there was the necessity of additional treatment in order to decrease the estimated GRT values to acceptable values during PEC activity (Figure 4.1).



(a)



(b)



(c)

Figure 4.1 Estimated GRT values for the AS-IS and IMPROVED cases with ceiling treatments in comparison with the required GRT value for sportive activities: (a) PEC, (b) SG-p, (c) SG-a.

Grid response analyses of the hall were conducted for the SG-p and SG-a scenarios with the selected ceiling treatments: baffle (B10@60 above and below truss level) and transversely suspended ceiling (TP10) systems. The data X(50), that is the threshold value showing the 50% of cumulative distribution for the parameters EDT and T30 at 500Hz and 1000Hz, STI and ΔSPL(A),the data X(95)-X(5) that is the difference between the SPL values at 95%and 5% of cumulative distribution, obtained for the hall are given in Table 4.15 and in relevant figures in Appendix B and Appendix C. The grid response analyses were summarized below:

- In the application of baffle suspended ceiling mounted 60cm above the truss level with 10cm-thick panels fixed at 60cm intervals (B10@60), the EDT values were predicted to be 1.29s at 500Hz and 1.28s at 1000Hzfor the SG-p scenario, 1.38s at 500Hz and 1.31s at 1000Hzfor the SG-a scenario (Figure B.2, Figure C.2). These values were below the estimated GRT values which indicate that the sound is intelligible. This is also supported by the STI values of 0.59 for SG-p scenario (Figure B.4) and 0.58 for SG-a scenario (Figure C.4) which signals that in the 50% of the hall, the speech intelligibility is in good range. The estimated T30 values of 1.61s at 500Hz and 1.55s at 1000Hz for SG-p scenario (Figure B.3) and 1.88s at 500Hz and 1.79s at 1000Hz for SG-a scenario (Figure C.3) are close to the estimated GRT values and close to the required ranges of ≤1.5s for both SG-p and SG-a scenarios. Maximum SPL(A) differences were 6.4 dB for SG-p scenario (Figure B.5) and9.2dBfor SG-a scenario (Figure C.5), which is below the required limit of 10dB. According to the grid response analyses results, in both of the scenarios, for all the parameters checked, the sound is evenly distributed within the area with acceptable differences (Appendix B, Appendix C).
- In the application of baffle suspended ceiling mounted immediately below the truss level with 10cm-thick panels fixed at 60cm intervals (B10@60), the EDT values were predicted to be 1.22s at 500Hz and 1.25s at 1000Hzfor the SG-p scenario (Figure B.2), 1.28s at 500Hz and 1.28s at 1000Hz for the SG-a scenario(Figure C.2). Similar to the treatment B10@60 above truss level, these values were below the estimated GRT values which mean that the sound is

intelligible. This is also supported with the STI values of 0.60 for SG-p scenario (Figure B.4) and 0.57 for SG-a scenario (Figure C.4) which signals that in the 50% of the hall, the speech intelligibility is in good range. The estimated T30 values of 1.53s at 500Hz and 1.41s at 1000Hz for SG-p scenario (Figure B.3) and 1.79s at 500Hz and 1.73s at 1000Hz for SG-a scenario (Figure C.3) are close to the estimated GRT values and in required range of≤1.5s for SG-p scenario and close to it for SG-a scenario. Maximum SPL(A) differences were 6.4dB for SG-p scenario (Figure B.5) and 9.2dB for SG-a scenario (Figure C.5), which is below the required limit of 10dB. According to the grid response analyses results, in both of the scenarios, for all the parameters checked, the sound is evenly distributed within the areawith acceptable differences (Appendix B, Appendix C).

- In the application of transversely suspended ceiling with 10cm-thick panels suspended crosswise between the trusses (Transverse suspended ceiling-TP10), the EDT values were predicted to be1.35s at 500Hz and 1.28s at 1000Hz for the SG-p scenario (Figure B.2), 1.50s at 500Hz and 1.46s at 1000Hz for the SG-a scenario (Figure C.2). Similar to the treatment B10@60 above truss level, these values were below the estimated GRT values, but above the values obtained in the treatments with baffles. The STI values were predicted to be 0.62 for SG-p scenario (Figure B.4) and 0.59 for SG-a scenario (Figure C.4) which signals that in the 50% of the hall, the speech intelligibility is in good range. The estimated T30 values of 1.59s at 500Hz and 1.51s at 1000Hz for SG-p scenario are below the estimated GRT values and close the required range of ≤1.5s (Figure B.3). The estimated T30 values of 1.99s at 500Hz and 1.82s at 1000Hz for SG-a scenario (Figure C.3) were above the estimated GRT values and exceed the specified criterion ≤1.5s. Maximum SPL(A) differences were 7.3dB for SG-p scenario (Figure B.5) and 9.8dB for SG-a scenario (Figure C.5), which is below the required limit of 10dB. However, unlike the results in the treatments with baffles, in both of the scenarios, for the parameters EDT at 500Hz and 1000Hz and T30 at 500Hz the sound is not evenly distributed within the hall at different receiver points and significant differences are observed (see relevant figures in Appendix B and Appendix C).

Table 4.15 The results of grid response analysesfor the ceiling treatments B10@60at, B10@60bt, TP10 during the sport games activities: EDT, T30, STI values (the X(50) data which is the threshold value showing the 50% of cumulative distribution), and ΔSPL(A) values (the X(95)-X(5) data which is the difference between the SPL values at 95%and 5% of cumulative distribution).

Scenario	Ceiling treatment	Parameter					
		EDT(s)		STI	ΔSPL(A)95%-5% difference (dB)	T30(s)	
		500 Hz	1 kHz			500 Hz	1 kHz
SG-p	B10@60at	1.29	1.28	0.59	6.4	1.61	1.55
SG-a	B10@60bt	1.38	1.31	0.58	9.2	1.88	1.79
SG-p	B10@60bt	1.22	1.25	0.6	6.5	1.53	1.41
SG-a	B10@60at	1.28	1.28	0.57	9.0	1.79	1.73
SG-p	TP10	1.35	1.28	0.62	7.3	1.59	1.51
SG-a	TP10	1.50	1.46	0.59	9.8	1.99	1.82

4.3 ACOUSTICAL FEATURES OF THE TYPICAL SPORT HALL FOR THE IMPROVED CASES: BASED ON ACTIVITIES-RELATED SCENARIOS

For the improvement of the hall, in addition to the suspended ceiling treatment, curtain modules are attached on the wallsto be temporarily used during physical education class and multi-purpose activities. After the GRT analyses for these activities, simulations are continued with the grid response analyses forall five scenarios individually.

4.3.1. Estimated GRT Values Based on Physical Education Class and Multi-Purpose Activities

Considering the PEC scenario, the estimated GRT values obtained for the hall treated with flat panelled, baffle and transverse suspended ceiling systems with additional curtain modules in front of the tribune’s rear wall or the windows are given in respective tables. The GRT data achieved was summarized below:

- In the application of flat panelled suspended ceiling, mounted immediately below the truss level and curtain modules, with the use of 5cm-thick panels (FP5), the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:
  - 1.56s with the addition of double-layered satin curtain modules in front of the windows,
  - 1.48s with addition of double-layered satin curtain modules in front of the tribune's rear wall;

  With the use of 10cm-thick panels (FP10), the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:
  - 1.57s with addition of the curtain modules in front of the windows,
  - 1.48s with addition of the curtain modules in front of the tribune's rear wall (Table 4.16).

While the GRT values at frequencies above 250Hz presented a gradual decrease with the increase in frequency, the GRT values at 125Hz were the longest with 2.70s for the ceiling FP5 and with curtain in front of the windows and 2.21s for the ceiling FP10with curtain in front of the windows (Table 4.16).

Table 4.16 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the configurations with flat paneled suspended ceiling for PEC scenario

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
FP5+Cg	2.70	1.84	1.64	1.48	1.35	1.10
FP5+Cr	2.65	1.80	1.57	1.40	1.28	1.06
FP10+Cg	2.21	1.73	1.66	1.49	1.35	1.10
FP10+Cr	2.14	1.66	1.57	1.40	1.28	1.06

- In the application of baffle suspended ceiling mounted 60cm above the truss levelwith 10cm-thick panels fixed at 60cm intervals (B10@60)and curtain modules, the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:
  - 1.55s with addition of the curtain modules in front of the windows,

– 1.49swith addition of the curtain modules in front of the tribune’s rear wall (Figure A.1).

For the treatmentwith 10cm-thick panels fixed at 30cm intervals (B10@30) the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:

– 1.48s with addition of the curtain modules in front of the windows,
– 1.44s with addition of the curtain modules in front of the tribune’s rear wall.

For the treatment with 5cm-thickpanels fixed at 30cm intervals (B5@30) the estimated GRT values at mid frequencies (500Hz and 1000Hz) were predicted to be:

– 1.53s with addition of double-layered satin curtain in front of the windows,
– 1.42s with addition of double-layered satin curtain in front of the tribune’s rear wall (Table 4.16).

Similar to the flat panelled suspended ceiling, treatment with the baffle system presented the longest GRT values at 125Hz with the values 2.03s, 1.93s and 2.23s respectively with the joint use of curtainsin front of the windows and 1.98s, 1.94s and 2.2s with the joint use of curtainsin front of the tribune’s rear wall (Table 4.17).

Table 4.17 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the configurations with baffle suspended ceiling–above truss for scenario PEC

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B10@60(at)+Cg	2.03	1.69	1.62	1.49	1.37	1.12
B10@60(at)+Cr	1.98	1.64	1.57	1.42	1.30	1.04
B10@30(at)+Cg	1.93	1.62	1.55	1.42	1.31	1.08
B10@30(at)+Cr	1.94	1.64	1.53	1.35	1.22	0.99
B5@30(at)+Cg	2.23	1.75	1.60	1.46	1.31	1.08
B5@30(at)+Cr	2.20	1.66	1.51	1.33	1.21	0.99

- In the application of baffle suspended ceiling mounted immediately below the truss levelwith the 10cm-thick panels fixed at 60cm intervals (B10@60) and curtain modules, the estimated GRT values at mid frequencies were predicted to be:
  - 1.52s with addition of double-layered satin curtain in front of the windows,
  - 1.44s with addition of double-layered satin curtain in front of the tribune's rear wall (Figure A.1).

The longest GRT values were presented at 125Hz with the values 1.98s with the joint use of curtainsin front of the windows and 1.89s with the joint use of curtainsin front of the tribune's rear wall (Table 4.18).

Table 4.18 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the configurations with baffle suspended ceiling-below truss level for scenario PEC

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B10@60(bt)+Cg	1.98	1.67	1.58	1.46	1.33	1.08
B10@60(bt)+Cr	1.89	1.58	1.51	1.37	1.24	1.03

- In the application of crosswise suspended ceiling with 10cm-thick panels suspended crosswise between the trusses (Transverse suspended ceiling - TP10)the estimated GRT values at mid frequencies were predicted to be:
  - 1.51swith addition of double-layered satin curtain in front of the windows,
  - 1.45swith addition of the curtain modules in front of the tribune's rear wall (Figure A.1).

  In the treatment with 5cm-thick panels suspended crosswise between the trusses (TP5), the estimated GRT values at mid frequencies were predicted to be:
  - 1.55s with addition of double-layered satin curtain in front of the windows
  - 1.47s with addition of the curtain modules in front of the tribune's rear wall.

  In the treatment FT, the estimated GRT values at mid frequencies were predicted to be:

– 1.56s with addition of double-layered satin curtain in front of the windows,

– 1.49s with addition of the curtain modules in front of the tribune's rear wall.

Just like the other treatments, the longest GRT values were observed at 125Hz and presented 2.03s, 2.70s and 2.29s respectivelywith the joint use of curtainsin front of the windows and 2.00s, 2.65s and 2.16s with the joint use of curtainsin front of the tribune's rear wall (Table 4.19).

Table 4.19 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the configurations with transverse suspended ceiling for PEC scenario

configuration	Global T30 values (s) with respect to frequency					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
TP5+Cg	2.70	1.75	1.62	1.48	1.35	1.10
TP5+Cr	2.65	1.69	1.55	1.39	1.28	1.03
TP10+Cg	2.03	1.67	1.58	1.44	1.31	1.10
TP10+Cr	2.00	1.62	1.53	1.37	1.26	1.03
FT+Cg	2.20	1.94	1.67	1.46	1.33	1.12
FT+Cr	2.16	1.85	1.60	1.39	1.28	1.03

Considering the multi-purpose use of the hall for speech and performance activities, the estimated GRT values obtained for the hall treated with the selected baffle and transverse suspended ceiling systems with additional curtain modules in front of the wall surfaces and on the open entrances are given in relevant tables. The GRT data achieved was summarized below:

- In the application of baffle suspended ceiling mounted 60cm above the truss levelwith 10cm-thick panels fixed at 60cm intervals (B10@60) and curtain modules in front of the wall surfaces the estimated GRT values at mid frequencies were predicted to be 0.82s for MP-S scenario (Figure D.1) and 0.89s for MP-P scenario (Figure E.1); with additional curtain modules in front of the wall surfaces and on the openings at the entrances, the estimated GRT values at mid frequencies were predicted to be 0.60s for MP-S scenario (Figure D.2) and 0.67s for MP-P scenario (Figure E.2) (Table 4.20).

Table 4.20 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the configurations composed of Baffle suspended ceiling–above truss level and sound curtain modules for MP-S and MP-P activities

scenario	configuration	Global T30 values with respect to frequency (s)					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
MP-S	B10@60(at)+Ca	1.33	1.01	0.88	0.76	0.68	0.59
	B10@60(at)+Ca+Co	1.15	0.79	0.61	0.59	0.58	0.52
MP-P	B10@60(at)+Ca	1.39	1.06	0.95	0.83	0.76	0.63
	B10@60(at)+Ca+Co	1.19	0.83	0.67	0.68	0.65	0.58

- In the application of baffle suspended ceiling mounted 60cm below the truss levelwith 10cm-thick panels fixed at 60cm intervals (B10@60) and curtain modules in front of the wall surfaces the estimated GRT values at mid frequencies were predicted to be 0.79s for MP-S scenario (Figure D.1) and 0.87s for MP-P scenario (Figure E.1); with additional curtain modules in front of the wall surfaces and on the openings at the entrances, the estimated GRT values at mid frequencies were predicted to be 0.58s for MP-S scenario (Figure D.2) and 0.66s for MP-P scenario (Figure E.2) (Table 4.21).

Table 4.21 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the configurations composed of baffle suspended ceiling–below truss level and sound curtain modules for MP-S and MP-P activities

scenario	configuration	Global T30 values with respect to frequency (s)					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
MP-S	B10@60(bt)+Ca	1.28	0.95	0.85	0.74	0.67	0.58
	B10@60(bt)+Ca+Co	1.10	0.76	0.59	0.58	0.56	0.50
MP-P	B10@60(bt)+Ca	1.33	1.03	0.94	0.81	0.74	0.63
	B10@60(bt)+Ca+Co	1.13	0.77	0.65	0.67	0.65	0.58

- In the application of crosswise suspended ceiling with 10cm-thick panels suspended crosswise between the trusses (Transversely suspended ceiling - TP10) and curtain modules in front of the wall surfaces the estimated GRT values at mid frequencies were predicted to be 0.76s for MP-S scenario (Figure D.1) and 0.80s for MP-P scenario (Figure E.1); with additional curtain modules in front of the wall surfaces and on the openings at the entrances, the estimated GRT values at mid frequencies were predicted to be 0.50s for MP-S scenario (Figure D.2) and 0.51s for MP-P scenario (Figure E.2) (Table 4.22).

Table 4.22 The estimated Global Reverberation Time (GRT- Global T30) values obtained for the configurations composed of transverse suspended ceiling and sound curtain modules for MP-S and MP-P activities

scenario	configuration	Global T30 values with respect to frequency (s)					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
MP-S	TP10+Ca	1.46	0.94	0.83	0.70	0.61	0.52
	TP10+Ca+Co	1.22	0.72	0.52	0.49	0.47	0.43
MP-P	TP10+Ca	1.53	0.99	0.88	0.72	0.63	0.54
	TP10+Ca+Co	1.30	0.74	0.54	0.49	0.47	0.43

With the joint uses of curtain modules on the wall surfaces and the selected suspended ceiling systems, B10@60at, B10@60bt and TP10, for the multi-purpose activities where sound reinforcement systems are used, estimated GRT time values were decreased to the required interval of 0.6.s-1.2s. However, according to the T20-T30 difference on the estimated GRT bar graph, coupling effect phenomenon was observed in all the treatments with curtain modules only in front of the walls (Figure D.1, Figure E.1). According to the estimated GRT bar graphs for all the treatments with curtain modules in front of the walls and at the entrances, coupling effect phenomenon was no longer observed (Figure D.2, Figure E.2).

4.3.2. Grid Response AnalysesBased on Physical Education Class and Multi-Purpose Activities

Grid response analyses of the hall were done for the PEC scenario with the joint use of curtain modules on tribune's rear wall and the selected ceiling treatments; baffle (B10@60 above and below truss level) and transverse suspended ceiling (TP10) systems. The results for the parameters EDT and T30 at 500Hz and 1000Hz, STI and SPL(A) obtained for the hall are analyzed. The data X(50), that is the threshold value showing the 50% of cumulative distribution for the parameters EDT, T30 and C80 at 500Hz and 1000Hz, STI and ΔSPL(A),the data X(95)-X(5) that is the difference between the SPL values at 95%and 5% of cumulative distribution, obtained for the hall are given in Table 4.23, Table 4.24 and Table 4.25 and with respective figures in appendices. The grid response analyses data achieved were summarized below:

- In the application of baffle suspended ceiling mounted 60cm above the truss level with 10cm-thick panels fixed at 60cm intervals (B10@60) with curtain modules in front of tribune's rear wall, EDT values were predicted to be 1.12s at 500Hz and 1.15s at 1000Hz (Figure A.2).These values were below the estimated GRT value which indicates that the sound is intelligible. This is also supported by the STI value of 0.59which signals that in the 50% of the hall, the speech intelligibility is in good range (Figure A.4).The estimated T30 values of 1.47s at 500Hz and 1.29s at 1000Hz are below the estimated GRT values, but still above the required ranges of ≤1.02s (Figure A.3). Maximum SPL(A) difference within the hall is 7.3 dB which is below the required limit of 10dB (Table 4.23, Figure A.5). According to the grid responses analyses results, for all the parameters checked, the sound is evenly distributed within the area at different receiver points with acceptable differences (see relevant figures in Appendix A).
- In the application of baffle suspended ceiling mounted 60cm below the truss level with 10cm-thick panels fixed at 60cm intervals (B10@60) with curtain modules in front of tribune's rear wall, EDT values were predicted to be1.04s at 500Hz and 1.03s at 1000Hz (Figure A.2). These values were below the estimated GRT value which indicates that the sound is intelligible. This is also supported with the STI value of 0.61which signals that in more than the 50% of the hall, the

speech intelligibility is in good range (Figure A.4).The estimated T30 values of 1.73s at 500Hz and 1.63s at 1000Hzare above the estimated GRT values and the required ranges of ≤1.02s (Figure A.3). Maximum SPL(A) difference is 7.5dBwhich is below the specified limit of 10dB (Figure A.5, Table 4.24). According to the grid responses analyses results, for all the parameters checked, the sound is evenly distributed within the area at different receiver points with acceptable differences (see relevant figures in Appendix A).

- In the application of transversely suspended ceiling with 10cm-thick panels suspended crosswise between the trusses (Transverse suspended ceiling - TP10) with curtain modules in front of tribune's rear wall, EDT values were predicted to be 0.88s at 500Hz and 0.86s at 1000Hz (Figure A.2). These values were below the estimated GRT values which indicate that the sound is intelligible. This is also supported by the STI value of 0.63which signals that in more than the 50% of the hall, the speech intelligibility is in good range (Figure A.4).The estimated T30 values of 1.29s at 500Hz and 1.22s at 1000Hzare above to the estimated GRT values and the required ranges of ≤1.02s. Maximum SPL(A) difference is 8.1dBwhich is below the required limit of 10dB (Figure A.3, Table 4.25). However, unlikely the results in the treatments with baffles, similar to the grid response analyses for sport games activities, for the parameters EDT at 500Hz and 1000Hz and T30 at 500Hz the sound is not evenly distributedwithin the hall at the receiver area (Figure A2, Figure A3).

Grid response analyses of the hall were done for the multi-purpose use of the hall for speech and performance activities with the joint use of curtain modules in front of the walls and at the entrances and the selected ceiling treatments, baffle (B10@60 above and below truss level) and transverse suspended ceiling (TP10) systems. The results for the parameters EDT and T30 at 500Hz and 1000Hz and SPL(A) obtained for the hall are analyzed for both of the scenarios, STI for MP-S scenario, C80 at 500Hz and 1000Hz for MP-P scenario. The data X(50), that is the threshold value showing the 50% of cumulative distribution for the parameters EDT, T30 and C80 at 500Hz and 1000Hz,STI and ΔSPL(A), the data X(95)-X(5) that is the difference between the SPL values at 95% and 5% of cumulative distribution, obtained for the hall are given in Table 4.23, Table 4.24, Table 4.25 and with relevant figures in appendices. The grid response analyses data achieved were summarized below:

- In the application of baffle suspended ceiling mounted 60cm above the truss level with 10cm-thick panels fixed at 60cm intervals (B10@60) with curtain modules in front of the walls and at the entrances, EDT values were predicted to be 0.44s at 500Hz and 0.43s at 1000Hz for MP-S scenario (Figure D.3), 0.54s at 500Hz and 1000Hz for MP-P scenario (Figure E.3). These values indicate the good intelligibility of the sound for both scenarios. This is also supported with the STI value of 0.75 for MP-S scenario which signals that in more than 50% of the hall, the speech intelligibility for MP-S scenario is in excellent range (Figure D.5).The estimated T30 values of 0.57s at 500Hz and 1000Hz for MP-S scenario (Figure D.4) and 0.56s at 500Hz and 0.53s at 1000Hz for MP-P scenario (Figure E.4) are close to the estimated GRT values, and almost in the required range of 06.s-1.2s. Maximum SPL(A) difference is 10.2dB for MP-S scenario which is acceptable considering the required limit of 10dB and 6.1dB (Figure D.6) for MP-P scenario which is almost at the ideal limit of 6dB (Table 4.23). The C80 values for MP-P scenario are 8.6dB at 500Hz and 1000Hz (Figure E.5). These values are above the required interval which means this treated hall is suitable for rock, pop or similar music genre where intelligibility of the sound is important; however, not suitable for orchestral music where clarity is required to be in the range of -4dB and +4dB (Noack, 2014). According to the grid responses analyses results, for all the parameters checked, the sound is evenly distributed at different receiver points with acceptable differences (Appendix D, Appendix E).
- In the application of baffle suspended ceiling mounted 60cm below the truss level with 10cm-thick panels fixed at 60cm intervals (B10@60) with curtain modules in front of the walls and at the entrances, EDT values were predicted to be 0.52s at 500Hz and 0.48s at 1000Hz for MP-S scenario (Figure D.3), 0.56s at 500Hz and 0.55s 1000Hz for MP-P scenario (Figure E.3). Similar to the previous treatment, these values indicate the intelligibility of the sound for both scenarios and the STI value of 0.74 for MP-S scenario signals that in the 50% of the hall, the speech intelligibilityis in excellent range (Figure D.5). The estimated T30

values of 0.66s at 500Hz and 0.67s at 1000Hz for MP-S scenario (Figure D.4) and 0.59s at 500Hz and 0.61s at 1000Hz for MP-P scenario (Figure E.4) are close to the estimated GRT values, and in the required range of 06.s-1.2s. Maximum SPL(A) difference is 10.5dB for MP-S scenario that can be acceptable considering the required limit of 10dB (Figure D.6) and 6.7dB for MP-P scenario which is almost at the ideal limit of 6dB (Figure E.6, Table 4.24). The C80 values for MP-P scenario are 8.4dB at 500Hz and 8.6dB at 1000Hz (Figure E.5). Similar to the values in the treatment above truss level, these values are above the required interval and shows that this treated hall is suitable for rock, pop or similar music genre where intelligibility of the sound is important and not suitable for orchestral music due to the required range of -4dB and +4dB for clarity (Noack, 2014). According to the grid responses analyses results, for all the parameters checked, the sound is evenly distributed at different receiver points with acceptable differences for multi-purpose uses of the hall (see relevant figures in Appendix D and Appendix E).

In the application of transverse suspended ceiling (TP10) with curtain modules in front of the walls and at the entrances, EDT values were predicted to be 0.39s at 500Hz and 0.35s at 1000Hz for MP-S scenario (Figure D.3), 0.35s at 500Hz and 0.30s at 1000Hz for MP-P scenario (Figure E.3). The STI value of 0.77 for MP-S scenario signals that in more than 50% of the hall, the speech intelligibility is in excellent range (Figure D.5). The estimated T30 values of 0.49s at 500Hz and 0.42s 1000Hz for MP-S scenario (Figure D.4) and 0.44s at 500Hz and 0.37s at 1000Hz for MP-P scenario (Figure E.4) are below the estimated GRT values, and the required range of 06.s-1.2s. Maximum SPL(A) difference is 10.6dB for MP-S scenario which can be acceptable considering the required limit of 10dB (Figure D.6) and 8dB for MP-P scenario which is below the required limit (Figure E.6, Table 4.25). The C80 values for MP-P scenario are 13dB at 500Hz and 14.2dB at 1000Hz (Figure E.5). These values are highly above the required interval of -4dB and +4dB for clarity for orchestral music (Noack, 2014). According to the grid responses analyses results, the sound is not evenly distributed within the hall which means this treatment is not sufficient for multi-purpose uses of the hall (see relevant figures in Appendix D and Appendix E).

Table 4.23 The results of grid response analyses for all the scenarios with the proposed configurations with baffle suspended ceiling–above truss level in terms of EDT, T30, STI and C80 values (the data X(50) that is the threshold value showing the 50% of cumulative distribution), SPL(A) (the data X(95)-X(5), that is the difference between the SPL values at 95% and 5% of cumulative distribution.

Scenario	Configuration	Parameter							
		EDT		STI	ΔSPL(A)95%-5% difference (dB)	T30		C80	
		500Hz	1kHz			500Hz	1kHz	500Hz	1kHz
PEC	B10@60(at)+Cr	1.12	1.15	0.59	7.3	1.47	1.29	-	-
SG-p	B10@60(at)	1.29	1.28	0.59	6.4	1.61	1.55	-	-
SG-a	B10@60(at)	1.28	1.28	0.57	9.0	1.79	1.73	-	-
MP-S	B10@60(at)+Ca+Co	0.44	0.43	0.75	10.2	0.57	0.57	-	-
MP-P	B10@60(at)+Ca+Co	0.54	0.54	-	6.1	0.56	0.53	8.60	8.60

Table 4.24 The results of grid response analyses for all the scenarios with the proposed configurations with baffle suspended ceiling–below truss level in terms of EDT, T30, STI and C80 values (the data X(50) that is the threshold value showing the 50% of cumulative distribution), SPL(A) (the data X(95)-X(5), that is the difference between the SPL values at 95% and 5% of cumulative distribution.

Scenario	Configuration	Parameter							
		EDT		STI	ΔSPL(A) 95%-5% difference (dB)	T30		C80	
		500Hz	1kHz			500Hz	1kHz	500Hz	1kHz
PEC	B10@60(bt)+Cr	1.04	1.03	0.61	7.5	1.73	1.63	-	-
SG-p	B10@60(bt)	1.22	1.25	0.60	6.5	1.53	1.41	-	-
SG-a	B10@60(bt)	1.38	1.31	0.58	9.2	1.88	1.79	-	-
MP-S	B10@60(bt)+Ca+Co	0.52	0.48	0.74	10.5	0.66	0.67	-	-
MP-P	B10@60(bt)+Ca+Co	0.56	0.55	-	6.7	0.59	0.61	8.40	8.60

Table 4.25 The results of grid response analyses for all the scenarios with the proposed configurations with transverse suspended ceiling in terms of EDT, T30, STI and C80 values (the data X(50) that is the threshold value showing the 50% of cumulative distribution), SPL(A) (the data X(95)-X(5), that is the difference between the SPL values at 95% and 5% of cumulative distribution.

Scenario	Configuration	Parameter							
		EDT		STI	ΔSPL(A) 95%-5% difference (dB)	T30		C80	
		500Hz	1kHz			500Hz	1kHz	500Hz	1kHz
PEC	TP10+Cr	0.88	0.86	0.63	8.1	1.29	1.22	-	-
SG-p	TP10	1.35	1.28	0.62	7.3	1.59	1.51	-	-
SG-a	TP10	1.50	1.46	0.59	9.8	1.99	1.82	-	-
MP-S	TP10+Ca+Co	0.39	0.35	0.77	10.6	0.49	0.42	-	-
MP-P	TP10+Ca+Co	0.35	0.30	-	8.0	0.44	0.37	13	14.2

4.3.3. Estimated GRT Values and Grid Response Analyses with Additional Treatment on Parapet Surfaces Based on Activities-Related Scenarios

In order to remove local T30 increases on the receiver area during the physical education class and sport games activities, parapet surface between the tribune and playfield is covered with sound absorbing perforated metal sheet. Estimated GRT values for the joint uses of the metal sheet, ceiling treatmentB10@60above truss level and respective curtain treatment are given in Table 4.26 and grid response analyses results for each scenarioare given in Table 4.27 and in relevant figures below and in appendices. According to the simulation results, the focusing of the sound disappeared with non-remarkable changes in the values of the parameters and a sufficient variable acoustical environment was provided for different scenarios (Figure 4.2).

Table 4.26 The estimated GRT values obtained for the selected configurations with Baffle suspended ceiling–above truss level for all scenarios

scenario	Configuration	Global T30 values with respect to frequency (s)					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
PEC	B10@60+MS+Cr	1.94	1.62	1.53	1.37	1.24	1.01
SG-p	B10@60+MS	1.89	1.73	1.67	1.58	1.46	1.19
SG-a	B10@60+MS	1.94	1.78	1.73	1.62	1.49	1.21
MP-S	B10@60+MS+Ca+Co	1.13	0.77	0.59	0.59	0.58	0.50
MP-P	B10@60+MS+Ca+Co	1.19	0.81	0.65	0.67	0.65	0.58

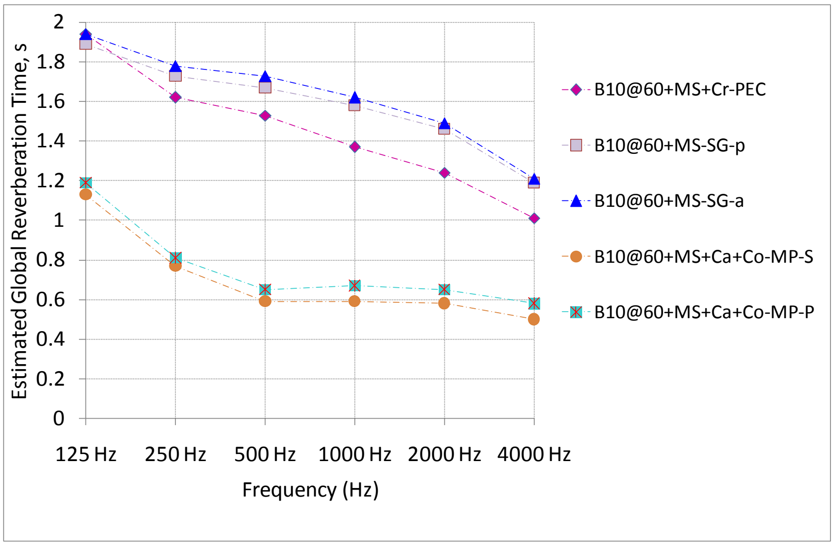


Figure 4.2 Variable GRT provided in the treated hall for all scenarios.

Table 4.27 The results of grid response analyses for all scenarios with the proposed configurations with Baffle suspended ceiling–above truss level in terms of EDT, T30, STI and C80 values (the data X(50) that is the threshold value showing the 50% of cumulative distribution), SPL(A) (the data X(95)-X(5), that is the difference between the SPL values at 95% and 5% of cumulative distribution.

Scenario	Configuration	Parameter							
		EDT		STI	ΔSPL(A) 95%-5% difference (dB)	T30		C80	
		500Hz	1kHz			500Hz	1kHz	500Hz	1kHz
PEC	B10@60+MS+Cr	1.02	1.03	0.61	7.3	1.51	1.32	-	-
SG-p	B10@60+MS	1.19	1.19	0.6	6.6	1.62	1.55	-	-
SG-a	B10@60+MS	1.07	1.11	0.59	8.9	1.65	1.6	-	-
MP-S	B10@60+MS+Ca+Co	0.43	0.42	0.75	10.3	0.54	0.55	-	-
MP-P	B10@60+MS+Ca+Co	0.53	0.51	-	6.2	0.53	0.48	8.9	9.3

In the study, cost analyses was also conducted: the total material and construction cost of the proposal with B10@60(at) and MS as the permanent intervention and Ca+Co as the temporary intervention (Figure G.1). Regarding the analyses, the construction cost of the proposal brings 4.70% - 7.40% increase to the construction cost of the sport hall.

CHAPTER 5

DISCUSSION

In this chapter, the joint interpretation of the data obtained from the simulation analyses are done “to assess the acoustical adequacy of the typical sport hall (Code:MEB-2004.63) in AS-IS case”, “to evaluate the acoustical improvements achieved by the addition of acoustical treatments”. The knowledge achieved from the evaluations is also summarized as “guiding remarks for the acoustical improvement of a typical sport hall for its multi-purpose uses”. The discussions are done under respective subheadings.

5.1 ACOUSTICAL PERFORMANCE ASSESSMENT OF TYPICAL SPORT HALLS FOR THE AS-ISCASE

The estimated data which represented the AS-IS case of the typical sport hall and their interpretation according to the acoustical requirements defined in the standards have shown the insufficient acoustical performance of the hall and their causes.

For the AS-IS case, the simulated GRT data, being in the range of 3.46s and 5.08s at mid-frequency range, were determined to be highly above the required values of 1.02s for PEC and 1.5s for sportive activities(Department of Education and Skills, 2004; Ellison & Schwenke, 2010). Excessive reverberation causes high sound pressure levels and decrease in the clarity and intelligibility of speech. The significant differences were also observed in estimated GRT values at different frequencies. That signalled the presence of tonal imbalance in the space which may cause masking of sounds at certain frequencies resulting in disturbing, noisy and unintelligible acoustical environment. On the other hand, the long GRT values due to the sound reflective envelope seemed to be decreased to some extent by the sound absorption of air in the large volume of the hall, especially at 4000Hz and 8000Hz (Table 4.1, Figure A.1, Figure B.1, Figure C.1).

The data obtained from the grid response analyses also supported the GRT values. For instance, the STI values of 0.36 and 0.39 for the AS-IS case, were determined to be in the poor range and exhibited the poor intelligibility of speech in the hall (Table 4.2, Figure A.4, Figure B.4, Figure C.4). Thedata exhibited the presence of “noisy environment with high sound pressure level” that degrades speech intelligibility during the physical education classes. That is the reason why teachers necessitatecommunicating loudly with the students. Such a troublesome acoustical environment of the hall results in an unintelligible core learning space for the students and poor communication in the playfield between the teachers and students during PE classes as well as among the players or the referees during sport games.

The results also proved that the AS-IS features of the sport hall are not appropriate and sufficient for its multi-purpose use. Multi-purpose activities require the involvement of sound reinforcement systems. Specifically, when the sound reinforcement systems are used, the GRT values are required to be in the range of 0.6s and 1.2s for speech and musical activities (Adelman-Larsen, Thompson, & Gade, 2010) and STI values are required to be equal to or above 0.56 for speech activities (DIN 18041 2004-05, 2004). Due to the GRT values reaching to 5.08s and STI values below 0.4, the acoustical features of the AS-IS case are not appropriate for adapting sound reinforcement systems.

5.2 ACOUSTICAL PERFORMACE ASSESSMENT OF SUSPENDED CEILINGS MADE OF ROCK WOOL PANELS

Here, acoustical performance of the suspended ceiling proposals made of rock wool panels were compared with each other in terms of “amount of materials used” and “the layout of sound absorbing units” in order to determine the optimum solutions. The comparisons were done among:

(i) the different suspended ceiling treatments using almost the same volume of rock wool,

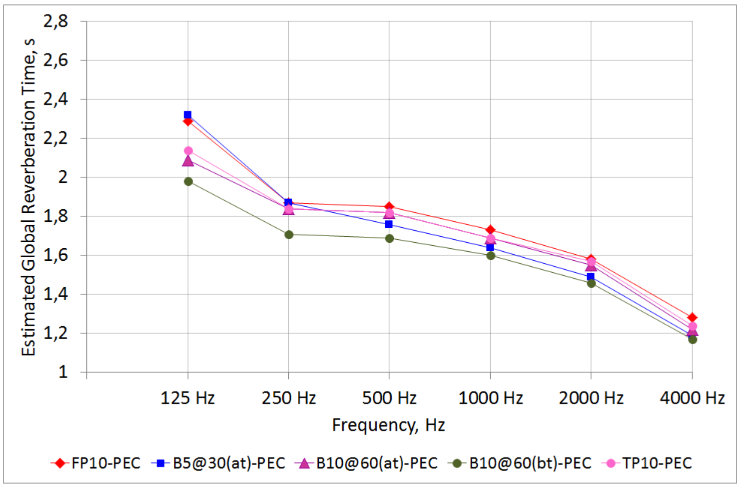
(ii) the same type of suspended ceiling treatments using the same surface area while the thickness of the boards were 5 or 10cm,

(iii) the baffle panelled suspended ceiling treatments with different interval sizes;

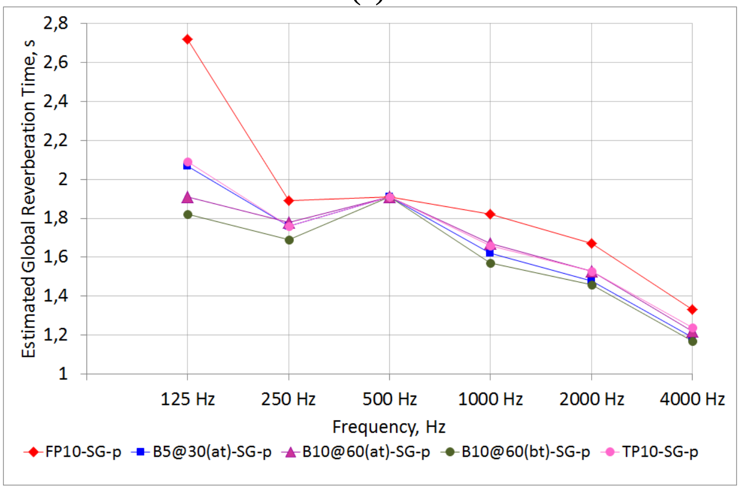
(iv) the baffle and transverse panelled ceilings

The amount of rock wool used in each ceiling treatment are given in Table F1. For the suspended ceiling treatments FP10, B10@60(bt), B10@60(at),B5@30(at), almost the same volume (amount) of rock wool material is used with the total volume of approximately 38m^3 while a total volume of approximately 45m^{3}is used for the treatment TP10. Among them, the treatments B10@60(bt), B10@60(at) and TP10 provided GRT values almost equal to each other while more sound absorbing material was used the treatment TP10 (Figure 5.1). The estimated GRT values of the treatment FP10were above the values obtained from the baffle suspended ceiling treatments.

For the suspended ceiling treatments FP5, B5@60(bt) and TP5, almost the same amount of rock wool panels are used, such as the total volume of approximately 20m^3 for the first two treatments and approximately 22.7m^{3}for the last one, respectively. Although the same amount of rock wool material is used for the flat and baffle suspended ceiling treatments, the baffle suspended ceiling treatment B5@60(bt) provided the lowest GRT values (Figure 5.2). In addition, although more sound absorbing material was used in the proposal TP5, the performance of the treatment B5@60(bt) was found to be better in terms of decreasing the estimated GRT values.



(a)



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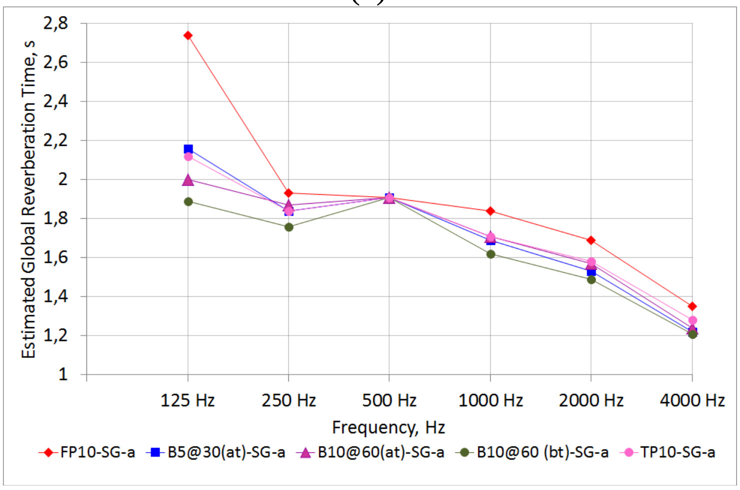


(c)

Figure 5.1 The estimated GRT values obtained for the treatments FP10, B5@30(at), B10@60(at), B10@60(bt) and TP10 for Scenarios of (a) PEC, (b) SG-p, (c) SG-a.

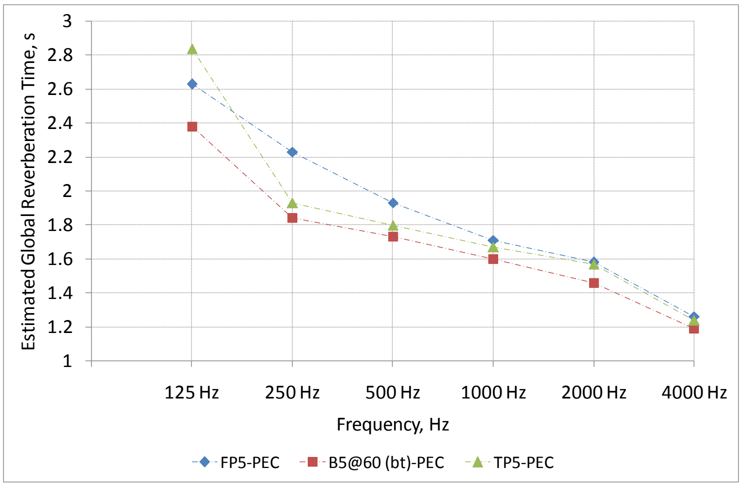


Figure 5.2 Comparison of treatment proposals FP5, B5@60(bt) and TP5 in terms of estimated GRT values for the PEC scenario.

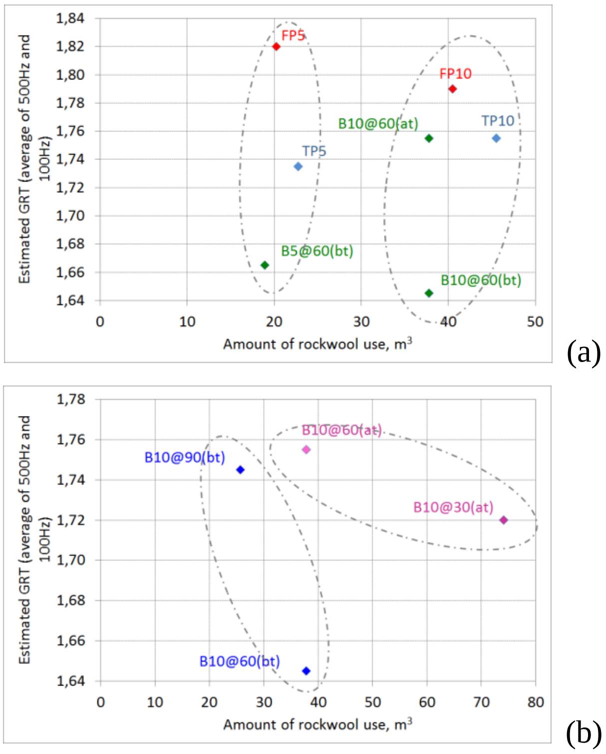


Figure 5.3 The relationship between the amount of rock wool used for the suspended ceiling treatments and their estimated GRT values (average of 500Hz and 1000Hz) for the Scenario PEC.

Despite the use of same amount of material in flat and baffle panelled suspended ceilings,the sound waves hit one side of the panels in flat panelled system while; both sides of the baffle modules were interacting with the sound waves. The increase sound absorbing surface area seemed to provide more absorption of the sound (See groups in circles in Figure 5.3a).

The performance of baffle suspended ceiling systems (B10@60, B5@60) were better than the transverse suspended ceiling systems (TP10, TP5) despite the use of fewer amount of rock wool. This shows that in order to reduce the reverberation time, excessive amount of material is not the only solution, but the configuration of the material and system of the application is effective as well. Moreover, according to the grid response analyses results of the parameters EDT, T30 and C80 at mid frequencies, STI and ΔSPL(A), (See relevant figures in Appendix A, Appendix B, and Appendix C), for evenly distribution of the sound within the hall, due to their diffusive character, proposals B10@60(at) and (bt) were found to be better solutions than the proposal TP10.

Role of thickness for the rock wool boards on the acoustical performance of suspended ceilings is also analysed. According to the comparison of treatments with the same surface area, namely FP5, B5@60(at), TP5 with FP10, B10@60(at), TP10, for PEC, SG-p and SG-a scenarios, treatments with thicker material provided more decrease in estimated GRT value especially at 125Hz.Moreover, In the treatments B10@60(at) and B5@30(at) for the scenarios PEC, SG-p and SG-a, same amount of rock wool was used. According the simulation results, estimated GRT values at mid and high frequencies were almost equal to each other in both proposals. However, at 125Hz, estimated GRT was longer in the proposal B5@30(at) (Table 4.4, Table 4.8, Table 4.12 and Figure 5.4). This was because of sound absorption coefficient (α) difference between 5cm and 10cm thick rock wool at 125Hz (Table 3.4). These results mean that in addition to the amount of the material used, sound absorption characteristics of the material in all frequency ranges (related with the thickness of boards) is also important.

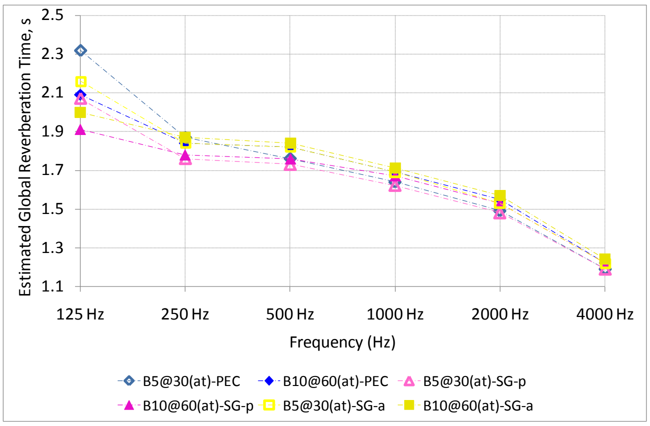


Figure 5.4 Comparison of treatment proposals B5@30(at) and B10@60(at) in terms of estimated GRT values for the PEC, SG-p and SG-a scenarios.

In the treatment proposal B10@30(at), the amount of rock wool used was twice the amount used in B10@60(at) for the scenarios PEC, SG-p and SG-a. However, the decrease in the estimated GRT values in all frequency ranges was not remarkable (around 0.03s) which means doubling the amount of material did not provide a remarkably efficient solution in these cases (Table 4.4, Table 4.8, Table 4.12). The performance comparison of ceiling treatments B10@30(at) and B10@60(at) is given in Figure 5.5.

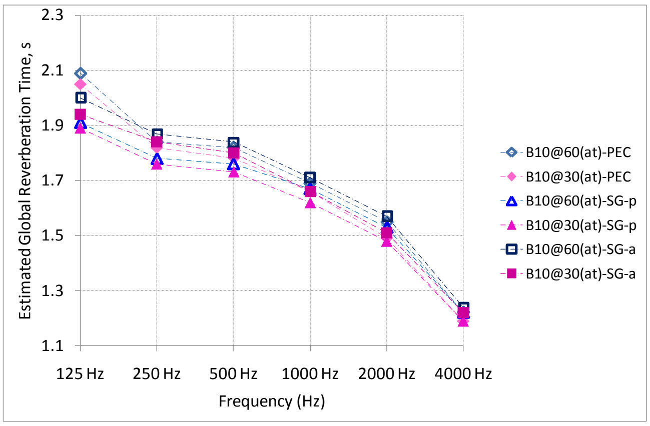


Figure 5.5 Comparison of treatment proposals B10@30(at) and B10@60(at) in terms of estimated GRT values for the PEC, SG-p and SG-a scenarios.

This situation taken into consideration, with the aim of decreasing the material cost, the simulation was repeated with the proposal B10@90(bt) for the PEC, SG-p and SG-a scenarios. In these cases, on the other hand, the estimated GRT values at mid-frequencies were around 0.1s above the values derived with the application of the proposal B10@60(bt) (Table 4.5, Table 4.9, Table 4.13). The performance comparison of ceiling treatments B10@60(bt)and B10@90(bt) is given Figure 5.6.

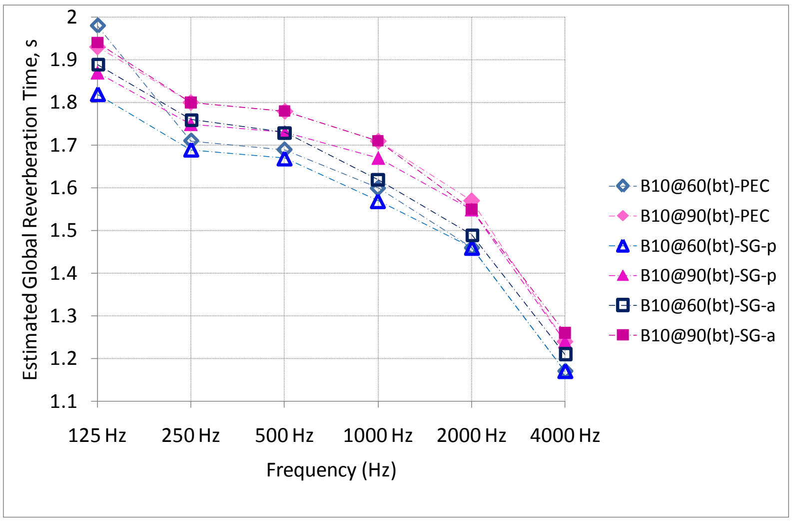
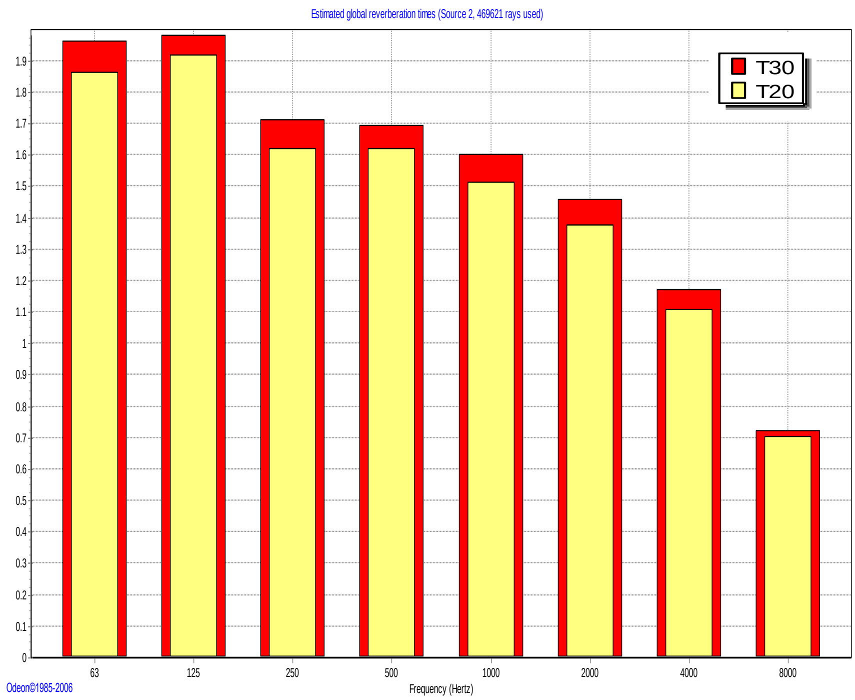


Figure 5.6 Comparison of treatment proposals B10@60(bt) and B10@90(bt) in terms of estimated GRT values for the PEC, SG-p and SG-a scenarios.

In addition, according to the simulation results, in the proposal B10@90(bt), T20-T30 difference at low and mid frequencies is more than the difference in the proposal B10@60(bt) (Figure5.7). This showed that the reflections from the interior surfaces of the roof above the suspended ceiling become more effective and after a point, the volume between the ceiling of the hall and suspended ceiling acts as a coupled-room. As observed from the performance comparisons of the proposals B10@30(at)-B10@60(at) and B10@60(bt)-B10@90 in terms of reducing the estimated GRT values in the hall, rather than additional excessive amount of material, there is an optimum solution for treatment (See groups in circles in Figure 5.3b).



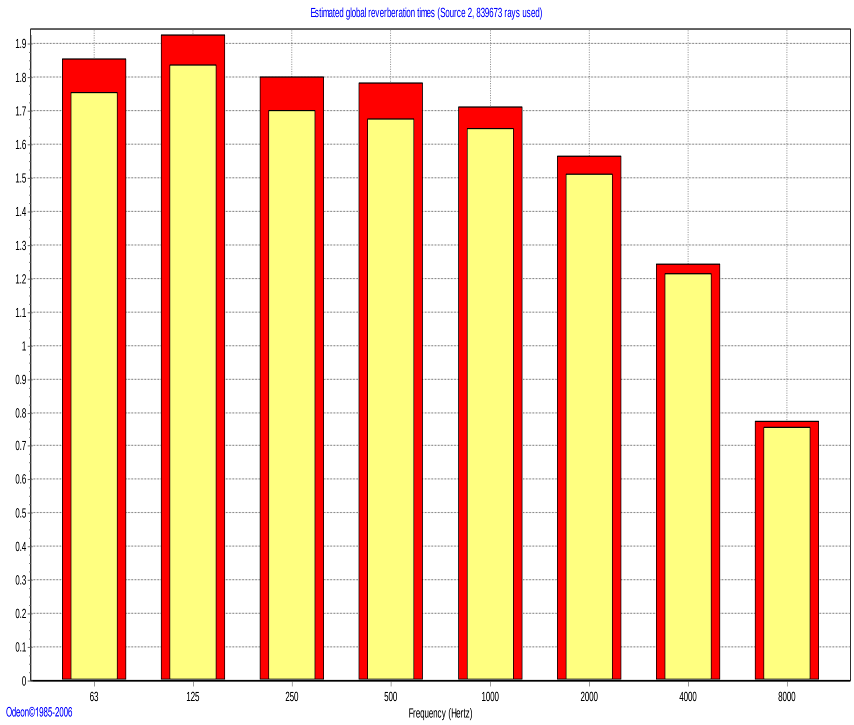


Figure 5.7 Estimated GRT values of proposals B10@60(bt) (above) and B10@90(bt) (below)

Among the types of baffle panelled suspended ceiling systems, the ceiling B10@60(at) is suggested for the acoustical improvement of the hall for its multi-purpose use due to the reasons of (i) its performance for reducing the GRT value of the hall, (ii) feasible use of materials and (iii) level of its application. Although treatment B10@60(bt) satisfies the first and second reasons mentioned above, the applications below the truss level reduce the overall volume of the hall with a decrease in the overall height about 60cm. That results in the height of the hall to be below the minimum height requirement given by Turkish Volleyball Federation (2014) and Turkish Basketball Federation (2014). A special care should be given while selecting those ceiling treatments since below-truss treatments may limit the height of the hall for some sportive activities and it is not suitable to be applied to the studied hall.

5.3 ACOUSTICAL IMPROVEMENTS WITH THE PROPOSED SUSPENDED CEILING SYSTEMS: PERMANENT INTERVENTIONS

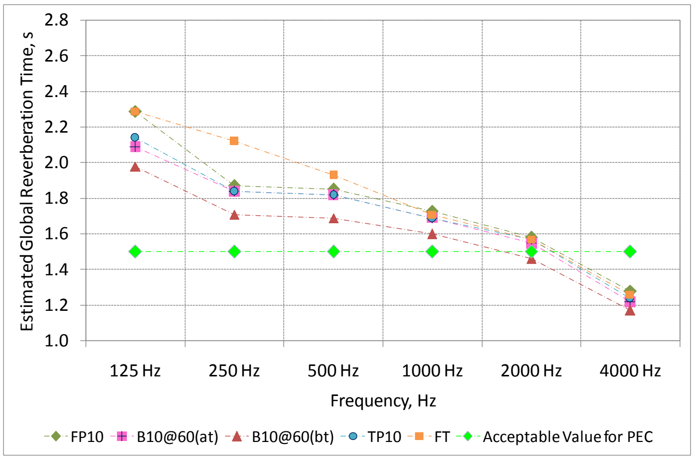
All suspended ceiling treatments proposed in the study, mainly the “flat panelled”, "baffle panelled”, “transverse panelled” and “fabric tension suspended ceiling systems” are the permanent interventions suggested for the main acoustical improvement of the sport hall. Those interventions were determined to decrease the GRT values in the hall noticeably. In other words, all these suspended ceiling systems that were suggested in the study provided considerable improvement in the acoustical features of the hall, especially for sportive activities including physical education class and sport games (Figure 4.1).

According to the simulation analyses, among four suspended ceiling proposals (flat panelled, baffle, transverse panelled and fabric tension), the application of baffle panelled suspended ceiling is determined to be the most effective treatment (Figure 5.8) due to the:

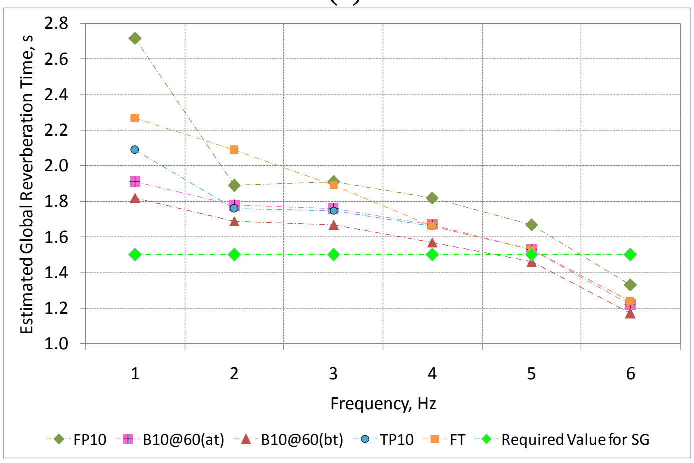
- lowest GRT values provided in the hall,
- gradual decrease of GRT provided with increase in frequency, and

- even distribution of sound in the hall determined by the grid response analyses.

Among the types of baffle panelled suspended systems, the ceilingsB10@30(at), B10@60(at) and B10@60(bt) decreased the GRT to the lowest levels, in the range of1.67s-1.73s, 1.71s-1.77s and 1.62s-1.67s, respectively, for sport activities (Table 4.4, Table 4.5).The transverse panelled suspended ceiling with 10cm-thick rock wool panels fixed between trusses (TP10) provided the similar performance with those baffle panelled ones with the GRT values in the range of 1.70s-1.76s. Following the baffle suspended ceiling treatments and the TP10 treatment, flat panelled suspended ceiling with 10 cm-thick rock wool panels (FP10) provided the next appropriate GRT values in the range of 1.79s-1.89s at mid-frequencies. The least decrease in GRT values was observed for the treatment of fabric tension suspended ceiling (FT) with the values in the range of 1.77s-1.82s at mid frequencies (Figure 5.8).



(a)



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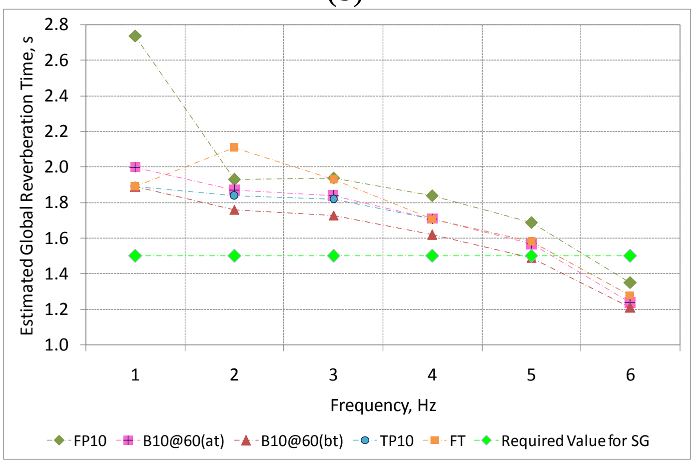


(c)

Figure 5.8 Estimated GRT values for the selected IMPROVED cases with ceiling treatments in comparison with the required GRT value for sportive activities: (a) PEC, (b) SG-p, (c) SG-a.

The simulation analyses have shown that both baffle and transverse suspended ceilings are still above the required GRT value of 1.02s at mid frequencies for the PEC scenario. This meant that there is the necessity for the use of additional treatments to the walls, such as use of sound absorptive curtains on wall surfaces in order to decrease the estimated GRT values to the acceptable ranges. The baffle and transverse panelled ceilings, on the other hand, are accepted to be enough to establish appropriate acoustical environment for the sport games due to their estimated GRT values close to the required values of 1.5s at mid frequencies. In short, in terms of GRT values, the baffle and transverse panelled suspended ceilings were determined to be the most effective proposal for sport games activities while additional interventions seemed to be needed for PEC and multi-purpose activities, such as sound absorptive curtains on wall surfaces.

According to grid response analyses, the suspended ceiling treatments B10@60 below and above truss level and TP10, providing the acceptable GRT values for sport game activities, were determined to improve the speech intelligibility within the hall due to the:

- decrease in the estimated EDT and T30 valuesat mid frequencies with the values in the range of 1.23s-1.48s and 1.47s-1.90s, respectively;
- estimated EDT values being lower than the GRT values;
- estimated T30 values similar with GRT values;
- increase in the STI values in the range of 0.57-0.62which fell into the STI ranges of “fair” and “good”(Figure 5.9, Table 4.15).

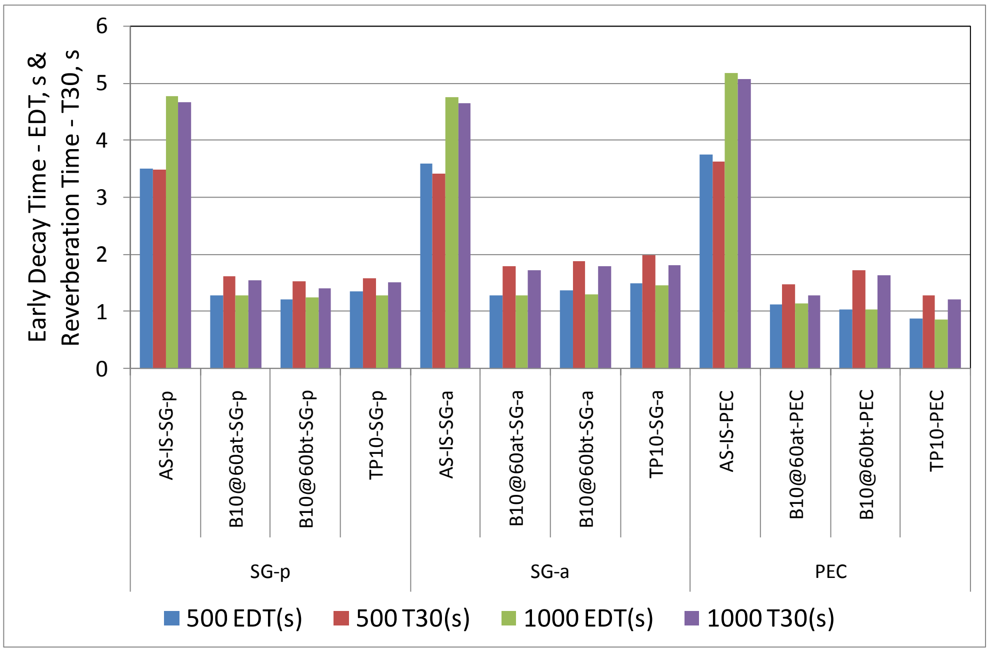


Figure 5.9 Estimated EDT and T30 X(50) cumulative distribution values of AS-IS and IMPROVED cases (ceiling treatments B10@60at, B10@60bt, TP10) for sportive activities – SG-p, SG-a, PEC scenarios.

In addition, the estimated SPL(A) differences were kept below 10dB (in the range of 6.4dB - 9.8dB (Table 4.15). It meant that adequate loudness was provided in the overall hall (see relevant figures in Appendix B and Appendix C).

Among the suspended ceiling treatments the even distribution of sound was achieved mostly by the B10@60(at) and B10@60(bt) suspended ceiling applications. The grid response maps of EDT and T30 obtained for the sport games activities presented the even distribution in the hall while some focusing of sound in the playfield and local increases in EDT and T30 values at some spot areas, such as at the corners of the play field and rear side of the tribune, were observed (Figure B.2, Figure B.3, Figure C.2, Figure C.3). The problem of sound focusing in the playfield needed to be solved with the use of sound absorptive perforated metal sheets that cover the parapets between the tribune and playfield. The other local defects observed at corners and edges seemed not to disturb the even-distribution of sound for the receiver positions (audience and/or the players). Those local defects can be eliminated simply with the use of sound absorptive or diffusive materials where defects are observed (Beranek, 2004). Considering all, the B10@60(at) and B10@60(bt) treatments were assessed to provide sufficient even distribution for PEC and sport games while some additional interventions were still needed.

The transverse panelled suspended ceiling with 10cm-thick panels (TP10), on the other hand, was not satisfactory to provide even distribution of sound in the hall for PEC and sport games activities (see relevant figures in Appendix A, Appendix B and Appendix C). Additional improvements such as using sound absorptive and/or diffusers at wall surfaces were necessary to achieve uniformity of sound in audience areas and eliminate the remarkable differences in EDT and T30 values at 500Hz and 1000Hz.

5.4 ACOUSTICAL IMPROVEMENTS WITH THE JOINT USE OF PROPOSED SUSPENDED CEILING SYSTEMS AND SOUND ABSORBING CURTAIN MODULES

All permanent treatments with additional use of satin curtain provided a decrease in the estimated GRT values in the hall for physical education class and multi-purpose activities.

The physical education class activity:

The configurations composed of both permanent suspended ceiling treatment and sound absorbing curtain modules attached in front of tribune’s rear-wall was observed to decrease GRT values more than the configurations using the curtain modules in front of the windows.The average estimated GRT values at mid-frequencies were in the range of 1.48s-1.58s with the joint use of curtain modules in front of the windows; 1.42s-1.50s with the joint use of curtain modules in front of the tribune’s rear wall and suspended ceiling proposals flat panelled suspended ceiling systems (FP5, FP10) (Table 4.16), baffle panelled suspended ceiling systems (B10@60(at), B10@30(at), B5@30(at), B10@60(bt)) (Table 4.17, Table 4.18), transverse panelled suspended ceiling systems (TP5, TP10) and fabric tension suspended ceiling system (FT) (Table 4.19). In short, when compared with the estimated GRT values provided by the permanent suspended ceiling treatments, a reduction of approximately 0.2s in GRT values was provided by the addition of curtain modules mounted in front of windows while a reduction of approximately 0.3s was achieved by mounting the curtain modules in front of the tribune's rear wall (Figure 5.10).

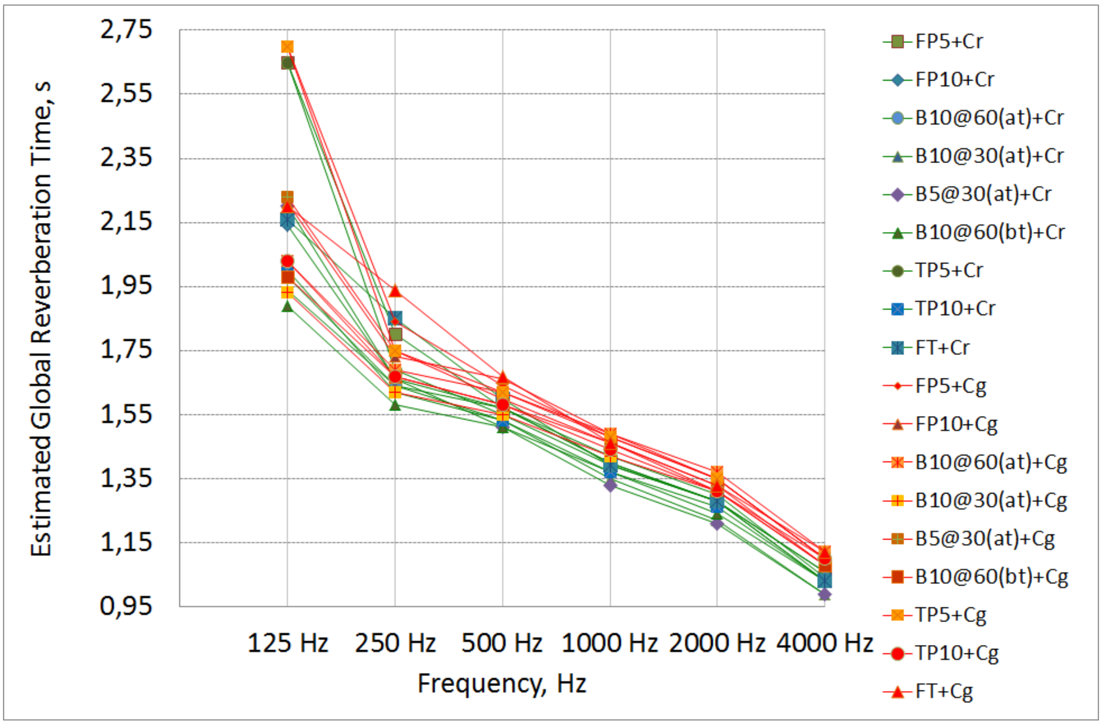


Figure 5.10 For the Scenario PEC, the estimated GRT values determined for the IMPROVED cases representing the performance of sound absorbing curtain modules positioned whether in front of windows or in front of tribune's rear wall, together with permanent ceiling treatments.

The average of GRT values at mid frequencies obtained for the treatments B10@60(at)+Cr, B10@60(bt)+Crand TP10+C_r were found to be below 1.5s, the required GRT value for sportive activities (Table 4.17, Table 4.18, Table 4.19 and Figure A.1). This means that those treatments are the configurations sufficient to decrease GRT values to required ranges. However, all treatments suggested are still above 1.02s, the required GRT value for lectures.

For the multi-purpose activities:

The additional treatments composed of 390-people filled seat, 263m^2 double layered satin curtains on walls, estimated GRT values decreased the average GRT values of selected ceiling treatments B10@60(bt), B10@60(at) and TP10 from approximately 2.0s to approximately 1.3s at low frequency range, approximately 1.7s to approximately 0.8s at mid-frequency range, approximately 1.5s to approximately 0.6s at high-frequency range for the speech and musical activities: MP-S and MP-P scenarios. The joint use of curtain modules in front of the windows, side walls and tribune's rear-wall with the baffle panelled suspended ceiling systems B10@60(at)+Ca, B10@60(bt)+Ca and TP10+Ca decreased the average GRT values at mid-frequencies to 0.82s, 0.80s, and 0.77s for speech activities(MP-S scenario); 0.89s, 0.88s, 0.80s for performance activities: (MP-P scenario) respectively.

After the addition of occupied seating and the curtain modules on the walls during multi-purpose activities, although GRT values decreased to the required values,the difference between T30 and T20 observed signalled the presence of acoustical coupling phenomenon after the joint use of ceiling and curtain (Figure D.1, Figure E.1).

In order to eliminate those late reflections, the sound breaks were provided with the use of double-layered satin curtains at the open entrances between the service area and the playfield. After the addition of curtain modules and with the joint use of all proposed curtain modules and ceiling treatments B10@60(at)+Ca+Co, B10@60(bt)+Ca+Co and TP10+Ca+Co, the average GRT values at mid-frequencies were found to be0.60s, 0.59s, and 0.51s for MP-S scenario; 0.68s, 0.66s, and 0.52s for MP-P scenario (Table 4.20, Table 4.21, Table 4.22), respectively (Figure 5.11). These configurations provided preferable acoustical environment for the multi-purpose activities by eliminating the coupling effect and keeping the estimated GRT values in the acceptable ranges (Figure D.2, Figure E.2). Although the estimated GRT values are in the ideal ranges with or without the sound breaks, since acoustical coupling phenomenon is not preferred for the multi-purpose scenarios, it is necessary to close the entrances with the curtain modules during those activities.

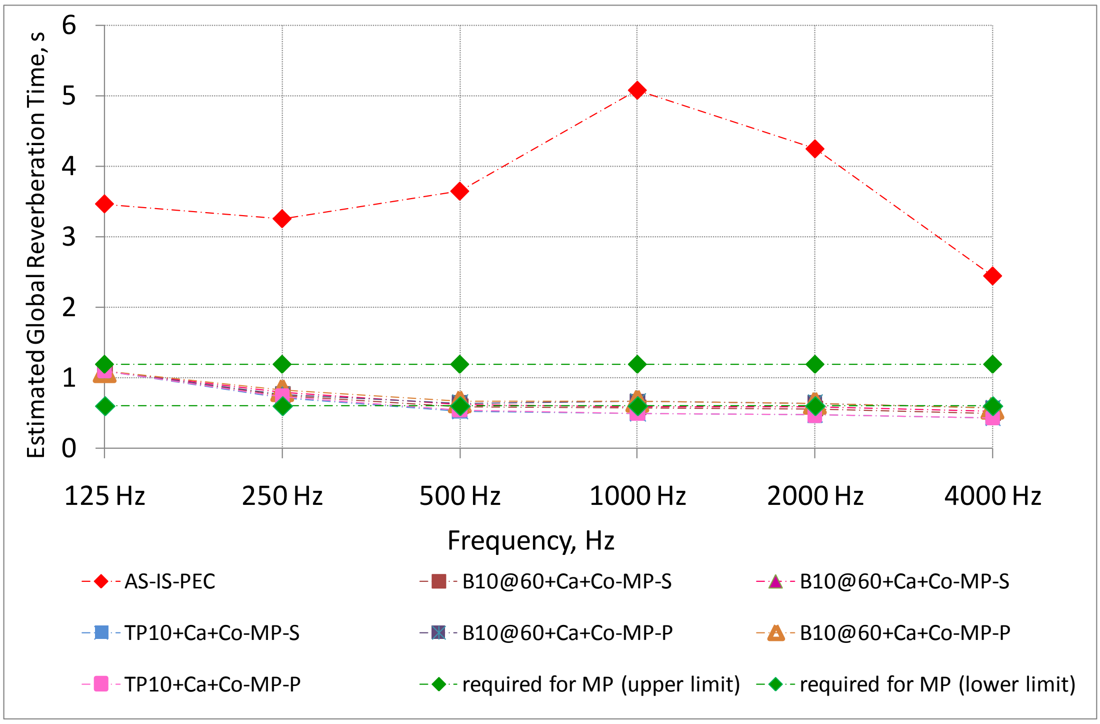


Figure 5.11 Estimated GRT values of the AS-IS case for PEC scenario and IMPROVED cases with ceiling and wall treatments for MP scenarios.

According to the grid responses analyses results for *physical education class activity*, joint use of curtain modules in front of the tribune's rear wall and the suspended ceiling treatments B10@60(at), B10@60(bt) and TP10were determined to improve the speech intelligibility within the hall due to the:

- decrease in the estimated EDT and T30values at mid-frequencies in the range of0.87s-1.13s and 1.25s-1.68s respectively;

- estimated EDT values being lower than the estimated GRT values;
- estimated T30 values similar with GRT values;
- increase in the STI valuesin the range of 0.59-0.63which fell into the STI ranges of “fair” and “good”(Figure 5.8, Table 4.23, Table 4.24, Table 4.25).

In addition, the estimated SPL(A) differences were kept below 10dB (in the range of 7.3dB-8.1dB). It meant that adequate loudness was providedin the overall hall (see relevant figures in Appendix A).

According to the grid responses analyses results for *multi-purpose use for speech and performance activities*, joint use of curtain modules in front of the wall surfaces and at the openings with the suspended ceiling treatments B10@60 above and below truss level and TP10, providing the acceptable estimated GRT values for sport game activities, were also determined to improve the speech intelligibility within the hall due to the:

- decrease in the estimated EDT and T30 valuesat mid frequencies with the values in the range of 0.32s-0.54s and 0.40s-0.66s, respectively;
- estimated EDT values being lower than the GRT values;
- estimated T30 values similar with GRT values;
- high average C80 values at mid frequencies in the range of 8.5dB-13.6dB (for performance activities - MP-P scenario);
- increase in the STI values in the range of0.74-0.77 (for speech activities –MP-S scenario)which fell into the STI range of “excellent” (Figure 5.12, Table 4.23, Table 4.24, Table 4.25).

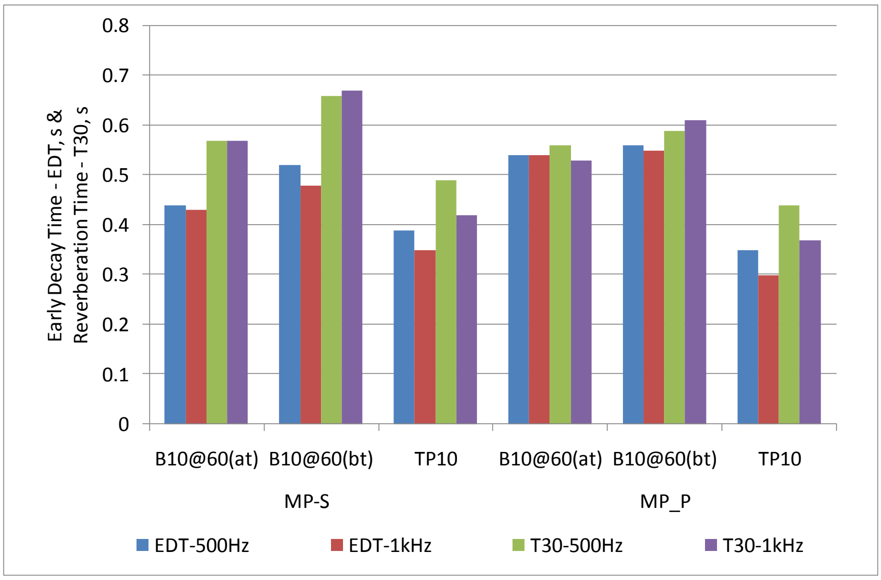
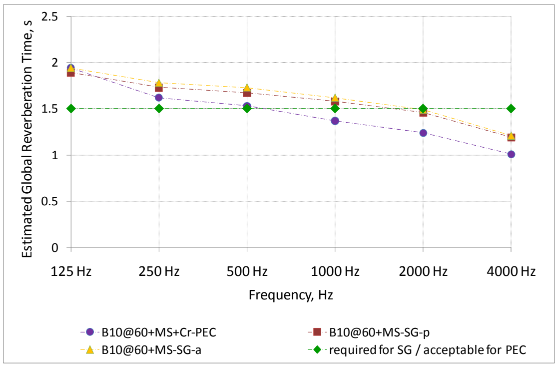


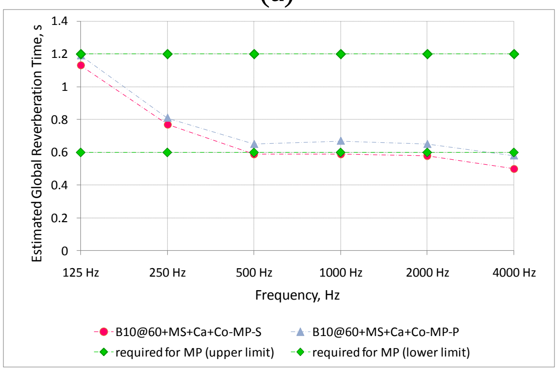
Figure 5.12 Estimated EDT and T30 X(50) cumulative distribution values of IMPROVED case with the ceiling treatments B10@60(at), B10@60(bt) and TP10 and all curtain modules on wall surfaces for MP scenarios.

In addition, the estimated SPL(A) differences were kept below 10dB (in the range of 6.1dB-10.5dB). It meant that adequate loudness was provided in the overall hall (Appendix D, Appendix E).

Similar to the analyses results for sport games activities, according to the estimated GRT values and grid response analyses maps, among the three suspended ceiling proposals, the baffle panelled ones provided sufficient acoustical improvement within the hall for the physical education class activity and multi-purpose activities. Due to height restrictions of the sports federations, baffle panelled suspended ceiling system with baffles located above truss level were selected as the appropriate ceiling treatment as permanent implementation. As temporary implementation, on the other hand, during PEC activities, curtain modules in front of the tribune's rear wall (configuration B10@60(at)+C_r); during MP activities, use of curtain modules in front of all proposed wall surfaces and at the openings between the service and sports areas (configuration B10@60(at)+C_a+C_o) provided the sufficient improvement within the hall. However, according to the grid response analyses results of the treatment configurations B10@60(at)+C_r for physical education class and B10@60(at) for sport games activities, focusing of the sound for the parameter T30was observed on the playfield(FigureA.3, Figure B.3, Figure C.3). This was thought to be caused by the reflections from the parapet between the playfield and the tribune which might have become more effective after additional sound absorption atthe walls and the ceiling. After the addition of sound absorbing perforated metal sheet as the second permanent material, the average estimated GRT values at mid frequencies were found to be 1.45s, 1.62s, 1.67s, 0.59s, 0.66s for PEC, SG-p, SG-a, MP-S, MP-P scenarios respectively which were in the required or acceptable ranges for each activity (Figure 5.13, Figure A.1, Figure B.1, Figure C.1,Figure D.2, Figure E.2).



(a)



(b)

Figure 5.13 Estimated GRT values of the permanent treatments B10@60(at)+MS with the joint use of determined temporary treatment for PEC, SG-p, SG-a scenarios with required/acceptable limit (a), for MP scenarios with required interval (b).

For the acoustical improvement, in the design or the treatment of the sport halls, not only additional sound absorption but also homogeneity of the sound absorption within the hall is important in order to prevent focusing of the sound caused by the ineffective sound reflecting surfaces that might become dominant. In the studied hall, application of sound absorbing perforated metal sheet is necessary since focusing of the sound was observed in front of the parapet surfaces after the treatments on the ceiling. After the application of sound absorbing perforated metal sheet, focusing of the sound was no longer observed.

According to the grid response analyses, the speech intelligibility within the hallfor all five scenarios was determined to be improved due to the:

- EDT values of 1.02s, 1.19s, 1.09s, 0.42s and 0.52s at mid frequenciesrespectively;
- estimated EDT values being lower than the GRT values;
- estimated T30 values of1.41s, 1.58s, 1.62s, 0.54s and 0.50s at mid frequenciesrespectively;
- estimated T30 values similar with GRT values;
- high average C80 value of 9.1dB at mid frequencies for MP-P activities;
- increase in the STI values of 0.61, 0.60, 0.59, 0.75respectively;

In addition, according the estimated SPL(A) differences of 7.3dB, 6.6dB, 8.9dB, 10.3dB and 6.2dB respectively, adequate loudness was provided in the overall hall for all the activities (Figure 5.14).

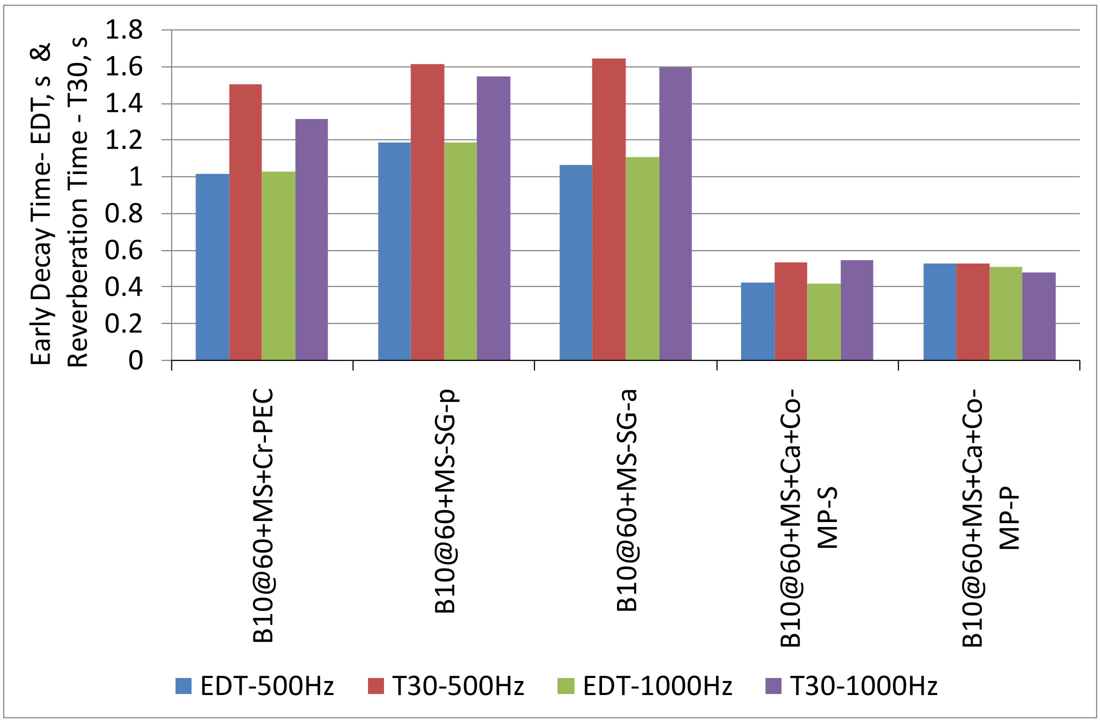


Figure 5.14 Estimated EDT and T30 X(50) cumulative distribution values of IMPROVED case with the treatments B10@60(at)+MS with the joint use of determined curtain modules for all scenarios.

Focusing of the sound was eliminated and the sound was evenly distributed within the hall for all the parameters sound absorbing perforated metal sheet on the parapet and the ceiling treatment B10@60(at) for SG-p and SG-a scenarios, B10@60(at)+Cr for PEC scenario, B10@60(at)+Ca+Co for MP-S and MP-P scenarios (see relevant figures in Appendix A, Appendix B, Appendix C, Appendix D, Appendix E). Furthermore, the construction cost of the proposal is found to bring less than 8% increase to the total construction cost which shows that it is possible to provide sufficient acoustical improvement with an economical solution (Figure G.1).

The acoustical coupling phenomenon from the service area during multi-purpose activities and focusing of sound for the parameter T30 during physical education class and sportive activities are observed after additional absorption on the walls and ceiling. Both these consequences show that it is important to be careful about the reflections from the untreated surfaces that might become influential which were not before the treatments. These situations reveal the fact that that not only the amount or the location of the materials used but also evenly distribution of those materials within the hall isimportant.

For providing variable acoustical environment, since they are easily mountable and operable, treatment by means of sound absorbing curtains with roller blind mechanism is a simple and economical solution in terms of its material and application cost. The disadvantage of these curtain modules is they are not diffusive. However, this is not obligatory in the content of this study since the curtains are used during the multi-purpose activities where the audience covering the playfield provides the necessary scattering as observed from the grid response analyses results (Appendix D, Appendix E).

5.5 GUIDING REMARKS FOR ACOUSTICAL IMPROVEMENT OF TYPICAL SPORT HALLS

The knowledge achieved by the study are summarized here in the form of guiding remarks for the renovation processes of typical sport halls, especially for the designers, engineers and practitioners. Those remarks should be taken into consideration to provide appropriate acoustical environment in sport halls for its use as physical education classes, sport games activities, speech and musical multi-purpose activities. They are also useful for the preliminary stages of design to obtain inherently well-designed acoustical conditions in typical sport halls.

The guiding remarks are summarised below:

- The GRT values at mid frequencies required for the lectures should be below 1.02s; for the sportive activities should be below 1.5sin case sound reinforcement systems are whether used or not; for multi-purpose activities should be between 0.6s 1.2s in case sound reinforcement systems are used. According to the results of this study, the acoustical situation in the untreated hall is improper for those activities and need to be improved.

- In order to enable different requirements for different activities, variable acoustical environment is needed to be provided within these halls.
- Because of their large surface areas, the ceiling, walls and floor are the key components for the control of sound field in the hall. Therefore, treatments with the sound absorptive and/or diffusive materials on those surfaces, such as application of a suspended ceiling on the playfield, are dominant interventions while precise adjustments can be done by local treatments.
- For the sports hall, the ceiling is the most appropriate component for making interventions and for the implementation of sound absorptive materials.
- For the major acoustical improvement of the sport hall, mainly four types of suspended ceiling systems are suggested. These are the flat panelled, baffle panelled, transverse panelled and fabric tension suspended ceiling systems.
- Among these suspended ceiling systems, baffle suspended ceiling proposals, especially the one composed of 10cm-thick rock wool panels which are positioned at 60cm intervals and aligned with the bottom level of trusses (B10@60(at)), provided the most efficient solution. That treatment provided GRT values in acceptable ranges and more even sound distribution in the hallin comparison to the flat, transverseand fabric tension suspended ceiling systems.
- If the budget is limited, instead of baffle panelled suspended systems, the fabric tension suspended ceilings, such as the ceiling composed of double layered sound absorptive fabric stretched crosswise between the trusses, is an alternative for the acoustical improvement in the sports hall. However, that proposal seems to be insufficient for the control of sound especially in low frequencies (125Hz and 250Hz).
- The permanent interventions recommended for the acoustical improvement of sports hall are:
  - the use of baffle panelled suspended ceiling with 10-cm-thick rock wool panels with 60cm intervals where the baffles are suspended 60cm above truss level (B10@60(at));
  - the use of sound absorbing perforated metal sheet covering the parapets which are located between the playfield and the tribune (B10@60(at)+MS).

- For sport games activities, those permanent interventions mentioned above are enough.
- For the physical education classes, in addition to the permanent interventions mentioned above, it is advised to use sound absorbing curtain modules with roller blind mechanism in front of tribune’s rear wall (Cr). The sound absorption performance of curtain modules are satisfactory when double-layered satin fabric is used and a cavity of 15 cm is kept between the wall surface and the curtain. Here, a special care should be given to keep that cavity to achieve the particular sound absorption required from the curtain application.
- For the multi purposes use of the sport hall, in addition to the permanent interventions, it is recommended to use double-layered satin fabric sound absorbing curtain modules with roller blind mechanism in front of tribune’s rear wall, side walls, front walls and at the openings between the service and sports areas. Here, the use of curtains at the openings between the service area and sports hall are essential to eliminate undesirable sound reflections.Again, a special care should be given to keep the cavity of 15 cm between the wall surface and the curtain.
- Apart from the acoustical concerns, the suspended ceiling and curtain modules proposed in the study should be considered as the architectural tools and have role to motivate the occupants. Therefore, the relationships especially between the baffle panels and curtain modules can be built for improving the indoor aesthetic quality and establishing more pleasant sport hall interiors.

CHAPTER 6

CONCLUSION

In this study, acoustical analyses of a typical sport hall project (Code: MEB 2004-63) were made with the help of the computer simulations regarding the AS-IS uses of the hall, namely physical education classes and sport activities, such as basketball and volleyball games. In addition to those activities, requirements for the acoustical environment during the multi-purpose use of the hall were explained. Treatments for the acoustical improvement and providing variable acoustical environment were suggested.

Acoustical problems within the typical sport hall project were defined with respect to the simulation results. According to those results, the acoustical performance of the AS-IS case is not suitable for the activities taking place in these halls. The estimated GRT values were found to be highly above the requirements at low, mid and high frequencieswhich signalled the insufficiency of the acoustical environment in these halls since long reverberation time degrades speech intelligibility and causes high ambient noise levels resulting in inconvenient environment for verbal communication.

Moreover, the results obtained from grid response analyses also signalled the existence of noisy and unintelligible environment in the halls. These problems lead to tiring communication ambience and cause improper environments for the activities/functions. Those results also showed that in addition to the lectures and sport activities, the acoustical environment in these halls is not suitable during their multi-purpose use for several speech and musical activities.

For the acoustical treatment of the hall, some types of sound-absorbing suspended ceiling systems were proposed. All proposed ceiling treatments provided acoustical improvement within the hall in terms of decreasing the estimated GRT values. Among all the ceiling treatment proposals (flat, baffle, transverse, fabric tension), baffle suspended ceiling proposals provided the most efficient solution in terms of acoustical improvement of the hall and material economy. The least efficient improvement was provided by fabric tension ceiling proposal.

For the optimization of the ceiling treatment and the selection of the most feasible proposal, suspended ceiling systems were compared in terms of material use and the layout of the sound absorbing units: When same amount of sound absorbing units are used, use of thicker material (10cm rock wool panels) was more effective than thinner material (5cm rock wool panel) in decreasing the estimated GRT values especially in low frequency ranges. The increase in amount of sound absorbing units resulting in frequently-spaced panels is effective to decrease GRT values due to the increase in sound absorbing surface area, but until a certain interval. The layout of sound absorbing units requires an optimized interval.

Ceiling treatments B10@60(at), B10@60(bt) and TP10 provided remarkable increase in the intelligibility of speech and adequate loudness in the overall hall was obtained. Baffle panelled suspended ceilings provided evenly distributed sound field in the overall hall, except some spot areas where local increases of the EDT and T30values at the corners, wall-floor intersections and focusing of the sound on the playfield were observed.The sound focusing observed on the playfield in front of the parapet surfaces was eliminated after covering the parapet surfaces with sound absorbing perforated metal sheet. The configuration composed baffle panelled suspended ceiling and parapet cladding with perforated metal sheet was recommended as permanent treatment for the acoustical improvement of a sport hall, especially for sport games activities.

Additional sound absorption treatment was needed to provide sufficient improvement for the physical education class and/or multi-purpose activities. The attachment of sound-absorbing curtain modules with roller-blind mechanism mounted in front of the wall surfaces with a 15cm cavity was suggested.For PEC activity, additional treatment of using sound absorptive curtains in front of the tribune’s rear wall provided acceptable GRT values. For the multi-purpose activities, additional seating and sound absorbing curtains in front of wall surfaces provided ideal GRT values. Excessive sound absorption let late reflections from the service area become effective. Sound absorbing curtains were mounted at the openings between the service and sports areas. That treatment eliminated later reflection.

After these treatments, variable acoustical environment with acceptable/required values for the parameters checked (GRT, EDT, T30, STI, C80 and ΔSPL(A)) were provided during the physical education classes, sport games and multi-purpose activities with evenly distribution of the sound in the overall hall. This implies that during those activities, a comfortable verbal communication environment free from echoes, with good/excellent speech intelligibility, with adequate loudness and without high ambient noise levels in the overall hall is achieved.

Total material and application cost of the selected proposals is found to be below8% of the total construction cost. So, it is possible to provide a sufficient solution to the obvious problem with a nominal cost increase.

To sum up, large volume character of the halls and use of rigid surfaces cause acoustical problems such as long reverberation, echoes and high ambient noise levels.This situation, which can be experienced in real life, is supported with the simulation results and it is revealed with this study conducted by the help of computer-based acoustical simulation that the acoustical situation in the hall is improper for the activities taking place. The simulation results provide scientific evidence/information to the already perceived condition causing the problems mentioned above, which has not been verified before. In the light of the results of this study it is found that additional sound absorption to these halls is needed. Even distribution of the sound absorption is important in order to provide evenly distributed sound field in the overall hall and prevent focusing of the sound caused by ineffective surfaces that might become effective after treatments. In addition, corners and wall-floor intersections are the surfaces that require attention.While deciding on the treatments, size requirements of sport federations for sport activities, spatial needs and requirements for multi-purpose activities and their convenience in terms of fire regulations must be taken into consideration. Due to different requirements for different activities taking place in these halls, variable acoustical conditions must be provided for each activity. It is noticed that the clear height of the typical sport halls with the value of 6.80m is below than the required clear height of 7.00m for basketball and volleyball games as defined by the relevant federations. Any intervention to the ceiling in the form of a suspended ceiling, therefore, is restricted due to the improper AS-IS height of the sport hall. The typical sports hall of schools should be designed according to the height requirements given by the federations. The sports hall designed with a certain height more than the required levels is recommended to tolerate any intervention to the ceiling which may be introduced during the renovations.

The results of this study are essential in terms of acoustical improvement of the sport halls for their current and multi-purpose uses. The definitions given in the content of this study also include acoustical design criteria in order to provide proper acoustical environment which enable to offer several system details regarding the sound absorption characteristics of the materials used on the surfaces of these halls and their organization within the hall. Such criteria were described as guiding remarks to the attention of the architects, engineers and acoustical designers. In addition to the computer simulation analyses, in-situ measurements are essential for the development of the proposals and for providing better acoustical environment within the sport halls.Furthermore, this study points out the hints for the acoustical design of the typical projects that has to be considered for better acoustical performance in sport halls, in future.

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APPENDIX A

SIMULATION DATA FOR THE SCENARIO PEC

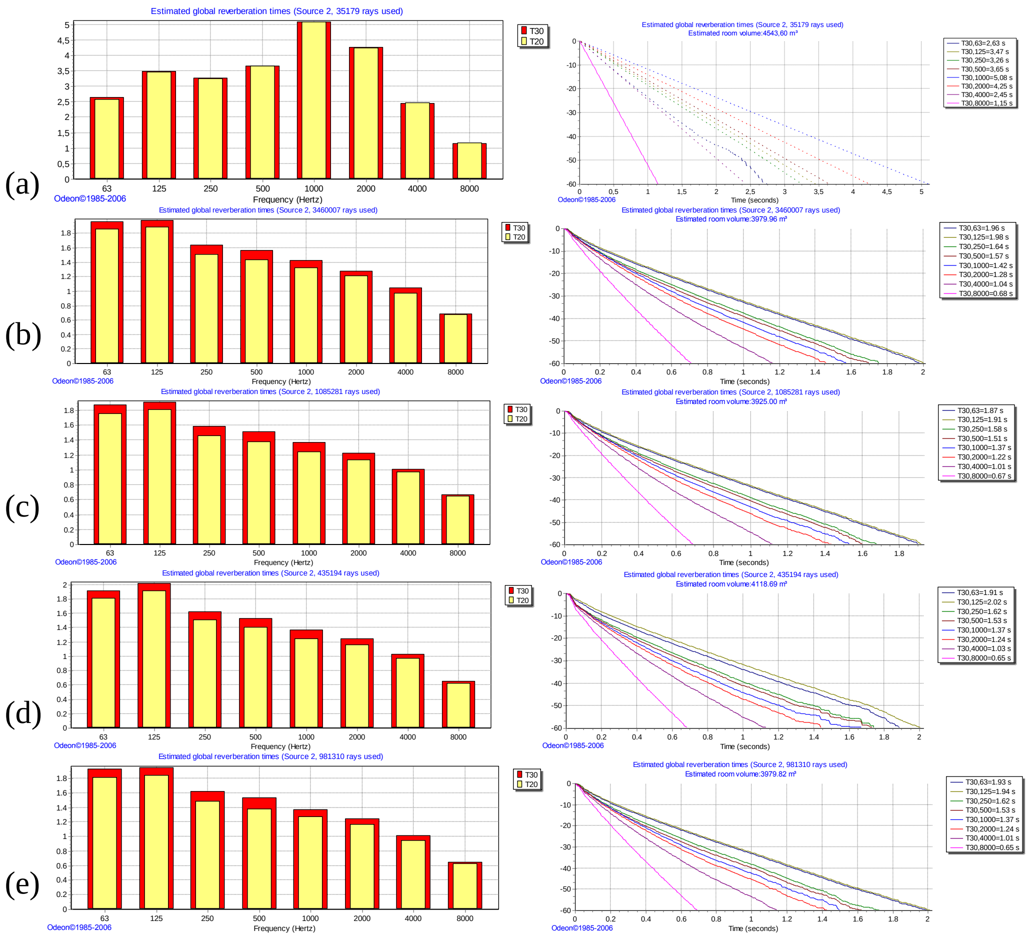
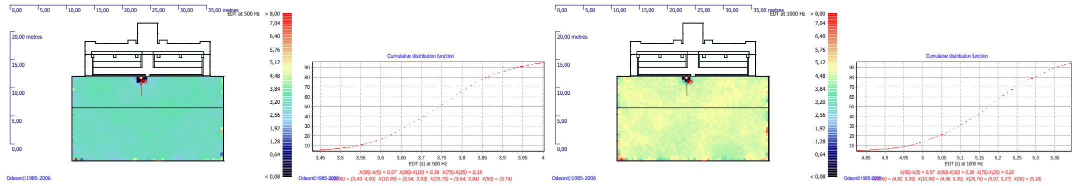


Figure A.1 Estimated GRT (T20 and T30) values (at the left) and T30 noise reduction curves (at the right) obtained for the Scenario PEC:
(a) AS-IS case, (b)Treatment B10@60(at)+Cr, (c)Treatment B10@60(bt)+Cr, (d)Treatment TP10+Cr, (e)Treatment B10@60(at)+MS+Cr.



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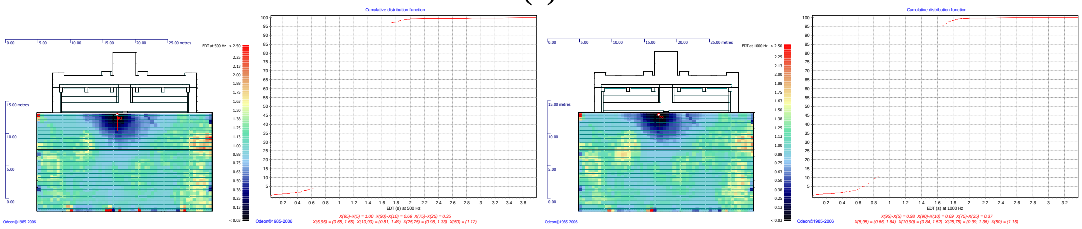

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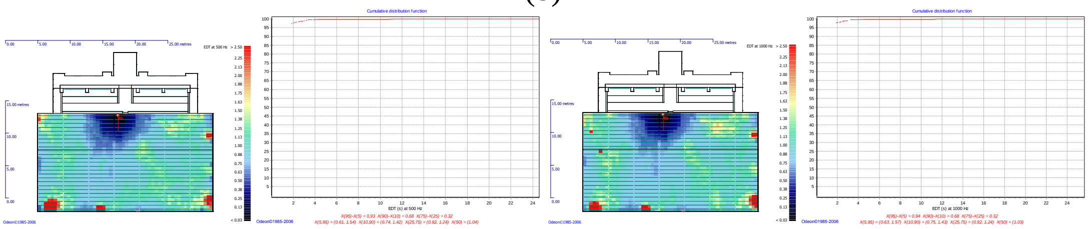
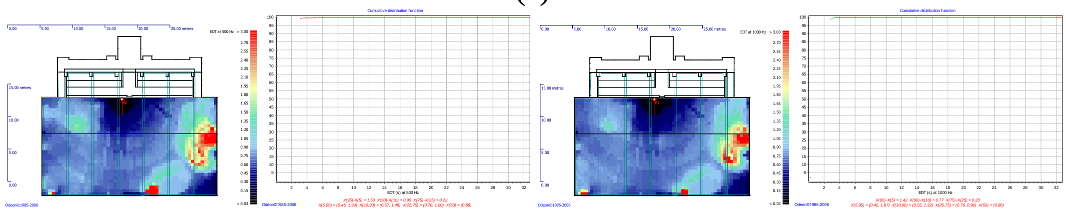
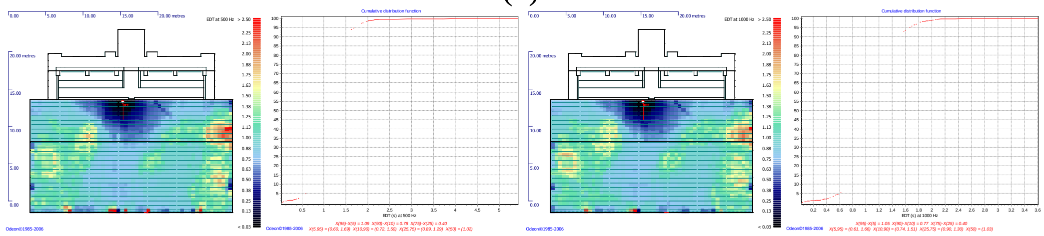


(c)



(d)



(e)

Figure A.2 The maps showing the distribution of estimated EDT data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphics for the Scenario PEC:

(a) AS-IS case, (b)Treatment B10@60(at)+Cr, (c)Treatment B10@60(bt) +Cr, (d)Treatment TP10+Cr, (e)Treatment B10@60(at)+MS+Cr.

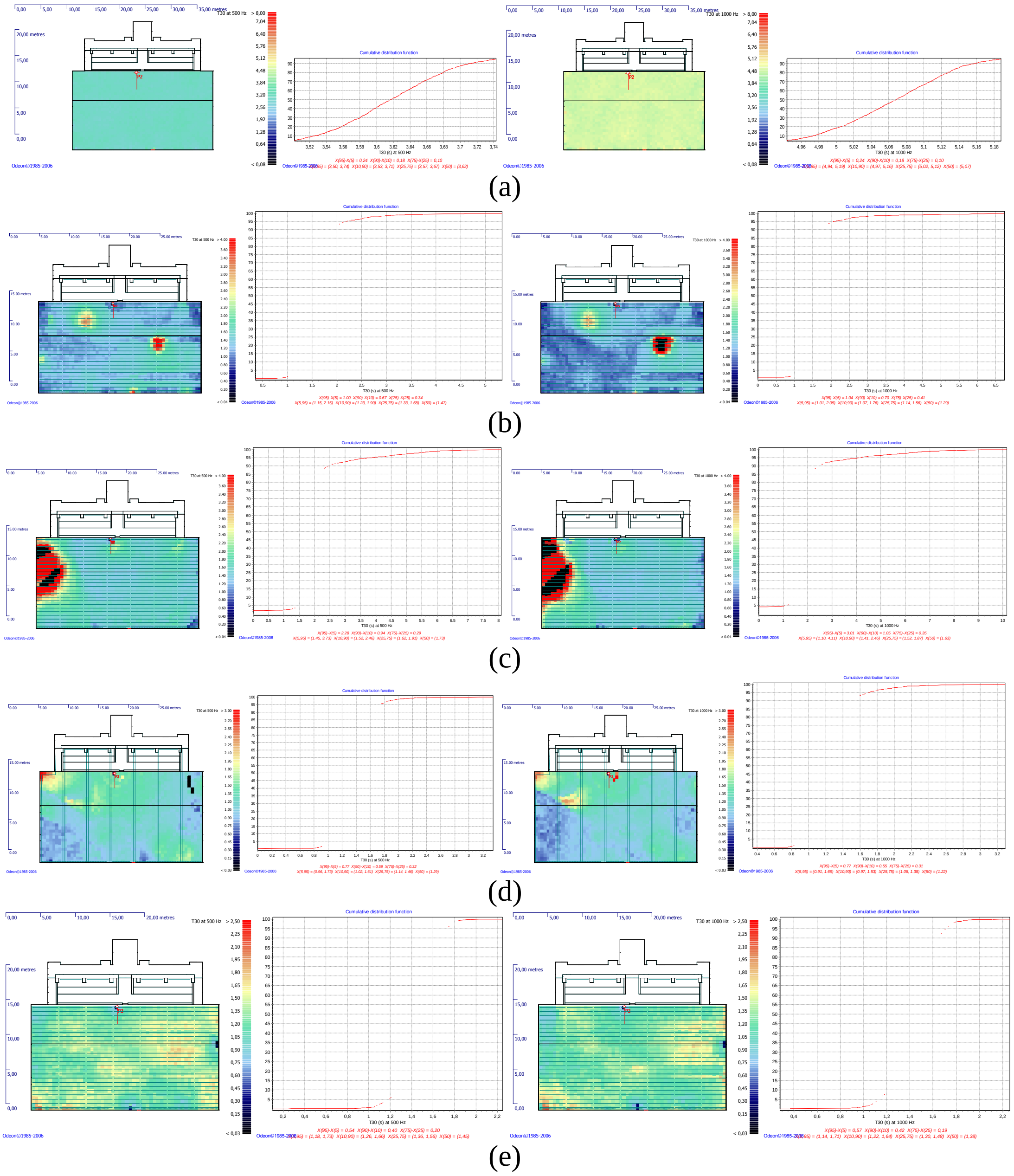


Figure A.3 The maps showing the estimated T30 data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphics for the Scenario PEC, :(a)AS-IS case, (b) Treatment B10@60(at)+Cr, (c) Treatment B10@60(bt) +Cr, (d) Treatment TP10+Cr, (e) Treatment B10@60(at)+MS+Cr.

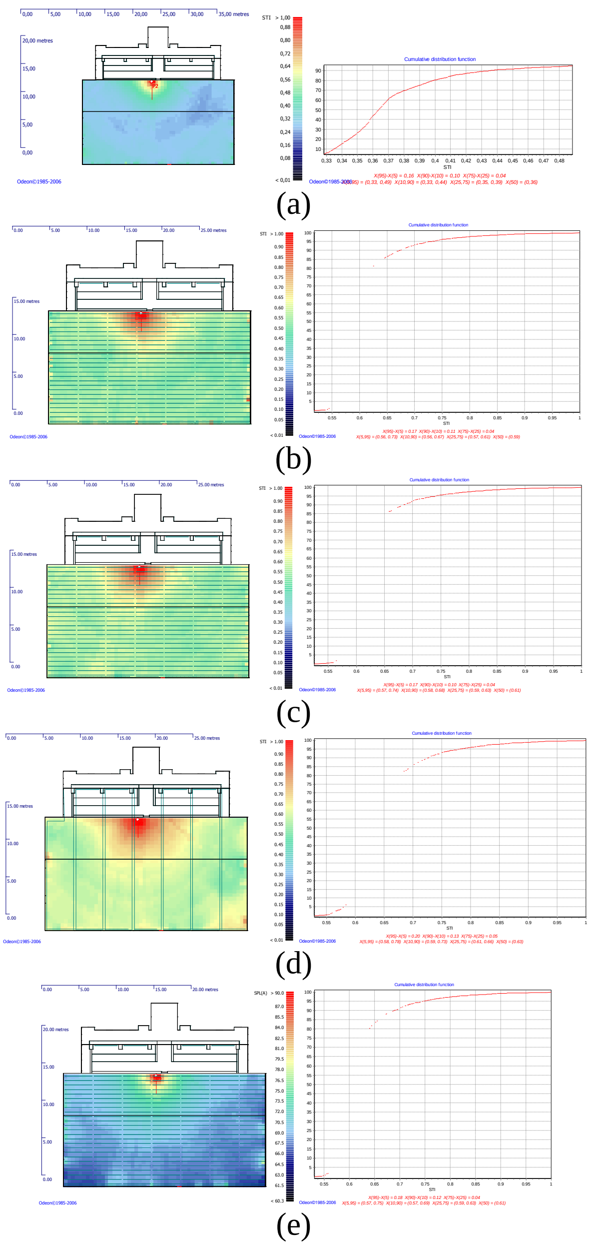
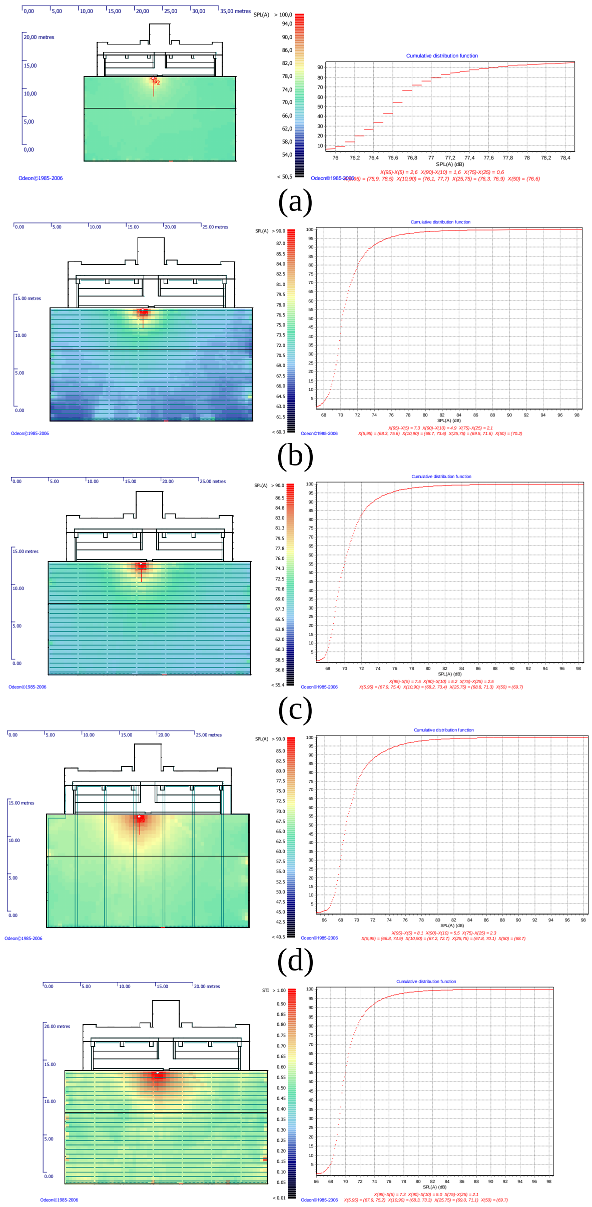


Figure A.4 The maps showing the distribution of STI data together with their cumulative distribution function graphics for the Scenario PEC, : (a)AS-IS case, (b) Treatment B10@60(at)+Cr, (c) Treatment B10@60(bt) +Cr, (d) Treatment TP10+Cr, (e) Treatment B10@60(at)+MS+Cr.



(a)

(b)

(c)

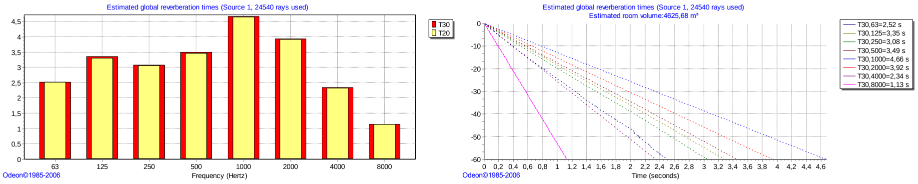
(d)

(e)

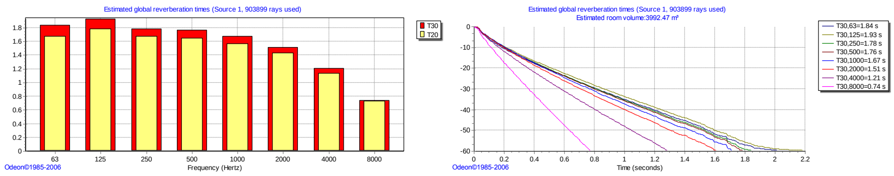
Figure A.5 The maps showing the distribution of estimated SPL(A) data together with their cumulative distribution function graphics for the Scenario PEC: (a)AS-IS case, (b) Treatment B10@60(at)+Cr, (c) Treatment B10@60(bt) +Cr, (d) Treatment TP10+Cr, (e) Treatment B10@60(at)+MS+Cr.

APPENDIX B

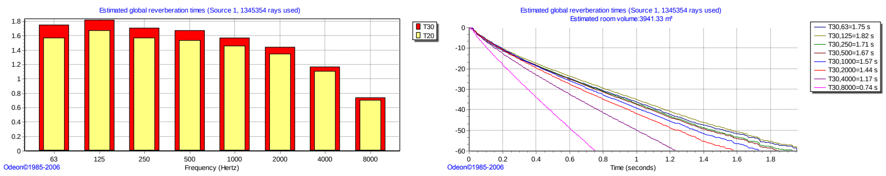
SIMULATION DATA FOR THE SCENARIO SG-p



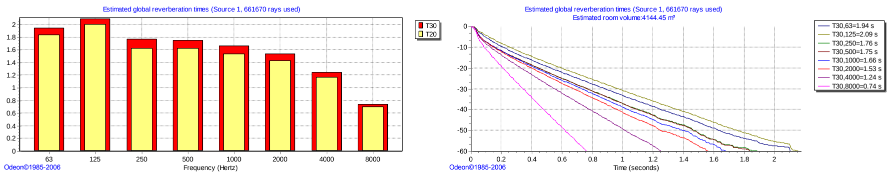
(a)



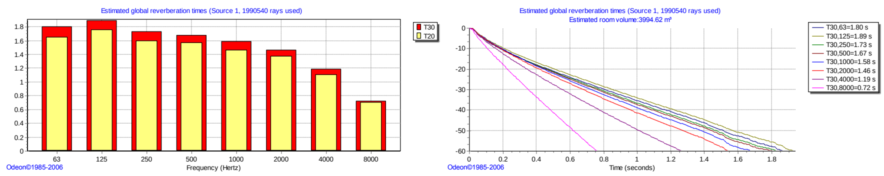
(b)



(c)

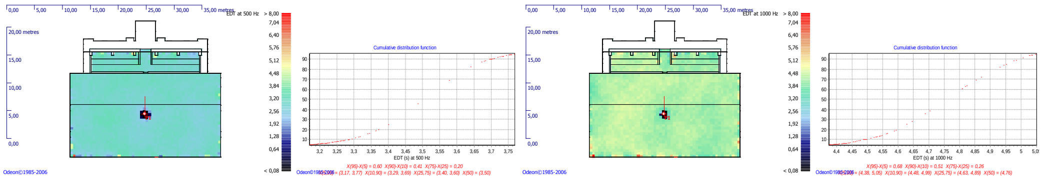


(d)

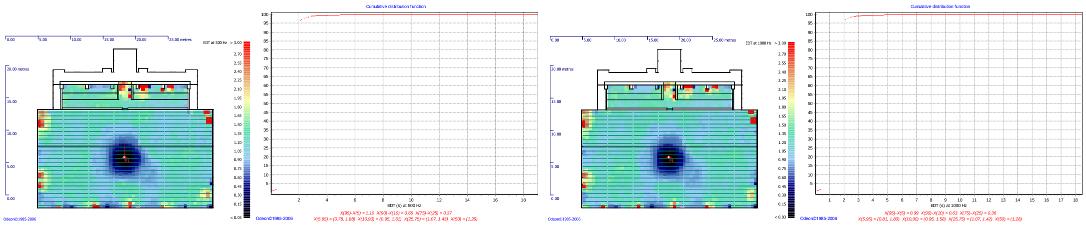


(e)

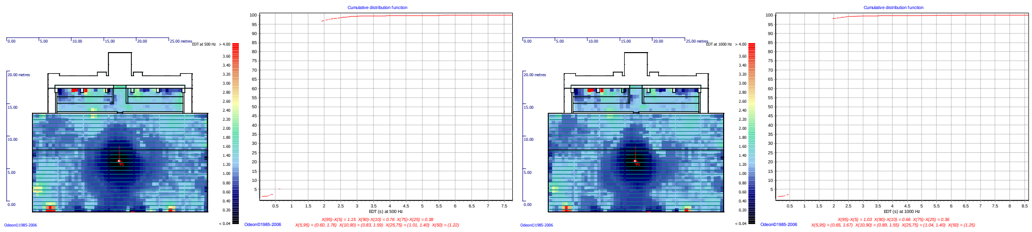
Figure B.1 Estimated GRT (T20 and T30) values (at the left) and T30 noise reduction curves (at the right) obtained for the SG-p scenario:
(a) AS-IS case, (b) Treatment B10@60(at), (c)Treatment B10@60(bt), (d) Treatment TP10, (e) Treatment B10@60(at)+MS



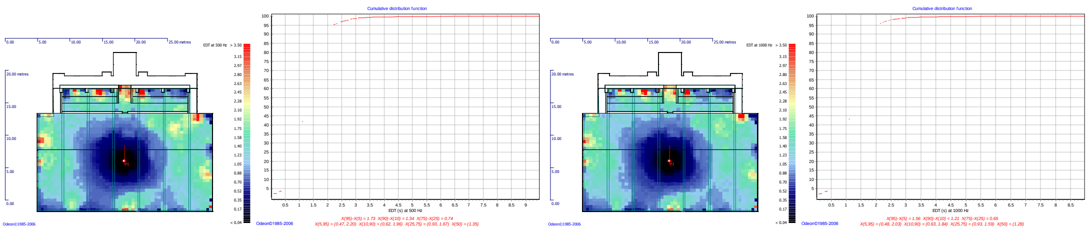
(a)



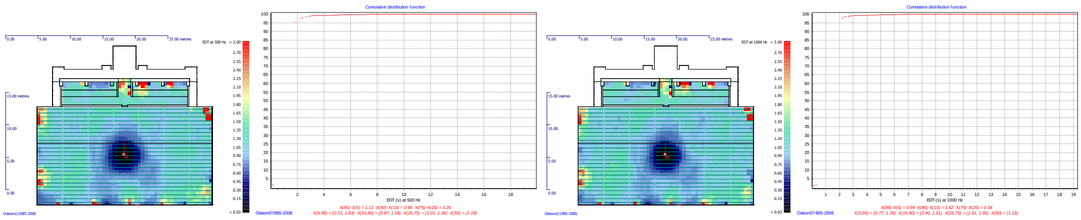
(b)



(c)



(d)



(e)

Figure B.2 The maps showing the distribution of estimated EDT data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphicsfor the Scenario SG-p:
(a)AS-IS case, (b) Treatment B10@60(at), (c) Treatment B10@60(bt),
(d) Treatment TP10, (e) Treatment B10@60(at)+MS

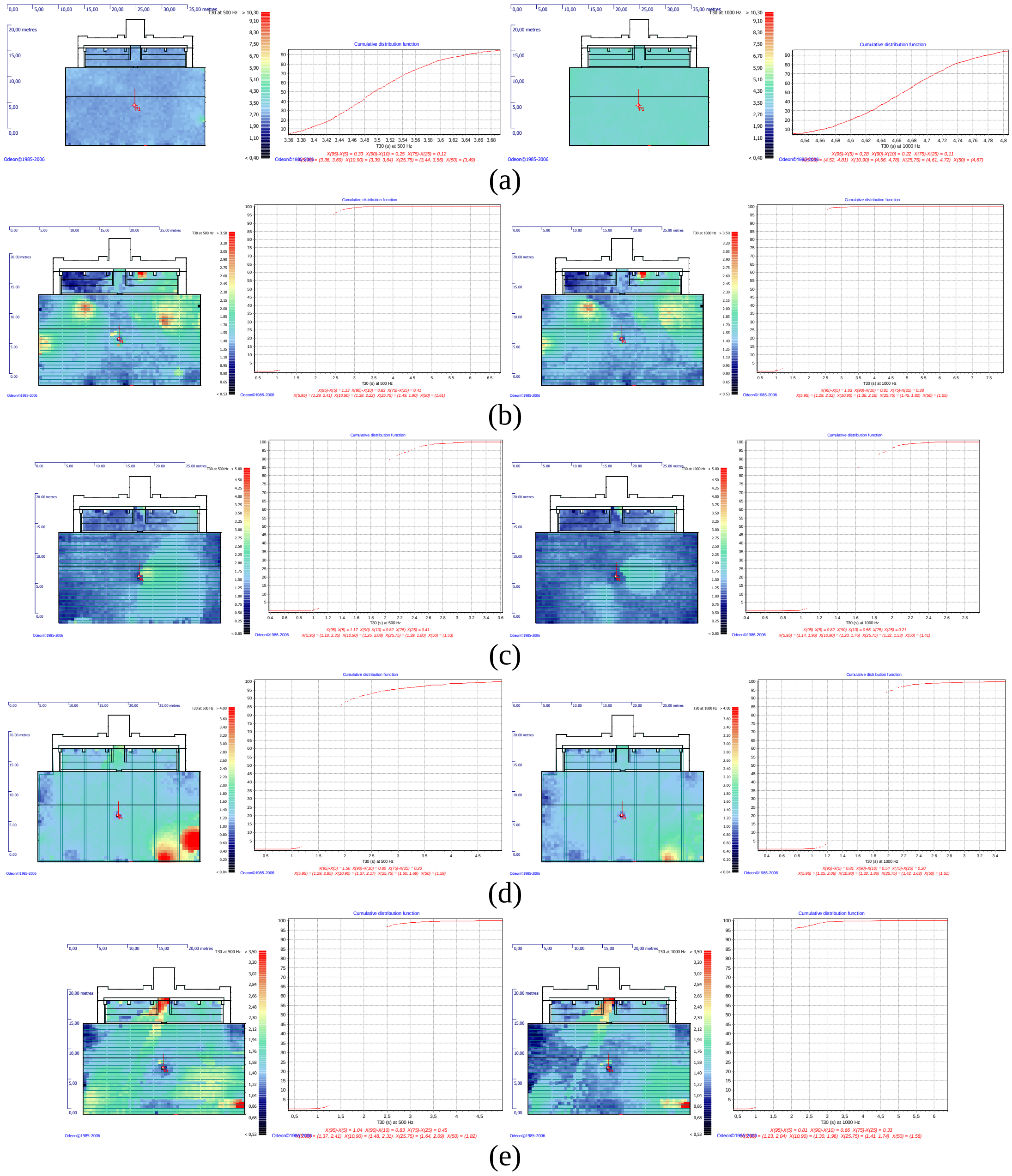
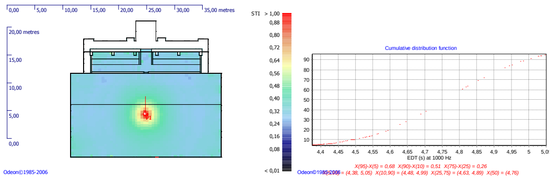


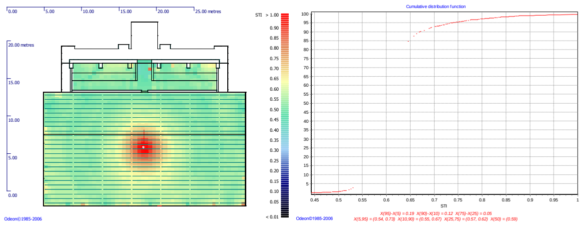
Figure B.3 The maps showing the distribution of estimated T30 data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphicsfor the Scenario SG-p:

(a)AS-IS case, (b) Treatment B10@60(at), (c) Treatment B10@60(bt),

(d) Treatment TP10, (e) Treatment B10@60(at)+MS



(a)



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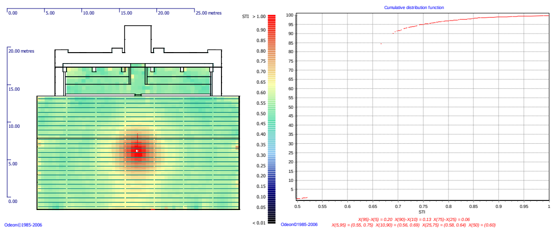

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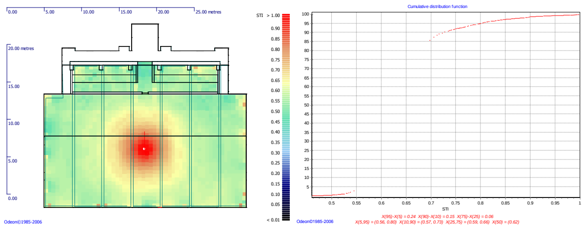
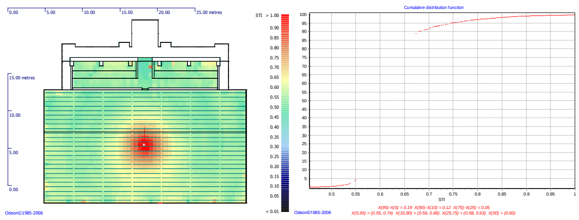
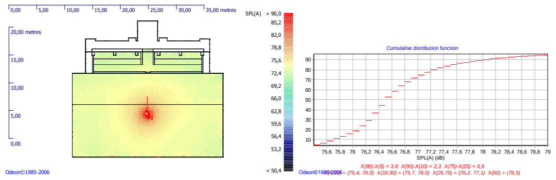


(d)

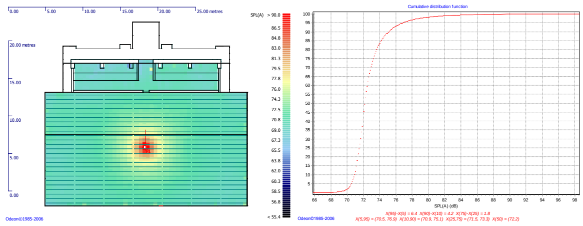


(e)

Figure B.4 The maps showing the distribution of STI data for the Scenario SG-p, together with their cumulative distribution function graphics: (a)AS-IS case, (b) Treatment B10@60(at), (c) Treatment B10@60(bt), (d) Treatment TP10, (e) Treatment B10@60(at)+MS



(a)



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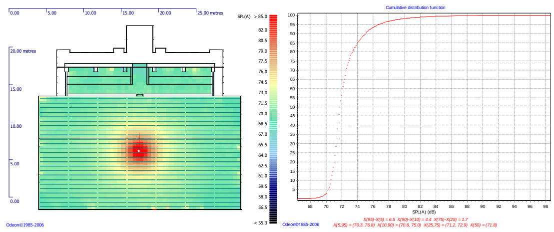

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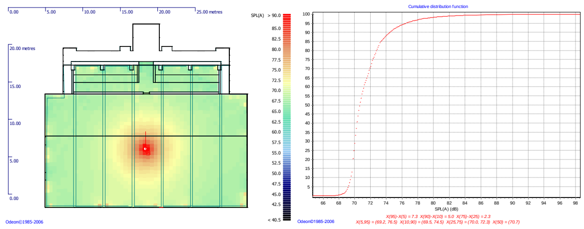

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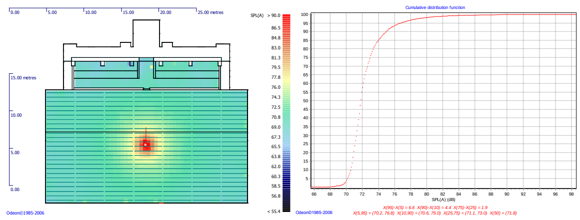


(e)

Figure B.5 The maps showing the distribution of estimated SPL(A) data together with their cumulative distribution function graphics for the Scenario SG-p: (a)AS-IS case, (b)Treatment B10@60(at), (c)TreatmentB10@60(bt), (d)Treatment TP10, (e)TreatmentB10@60(at)+MS

APPENDIX C

SIMULATION DATA FOR THE SCENARIO SG-a

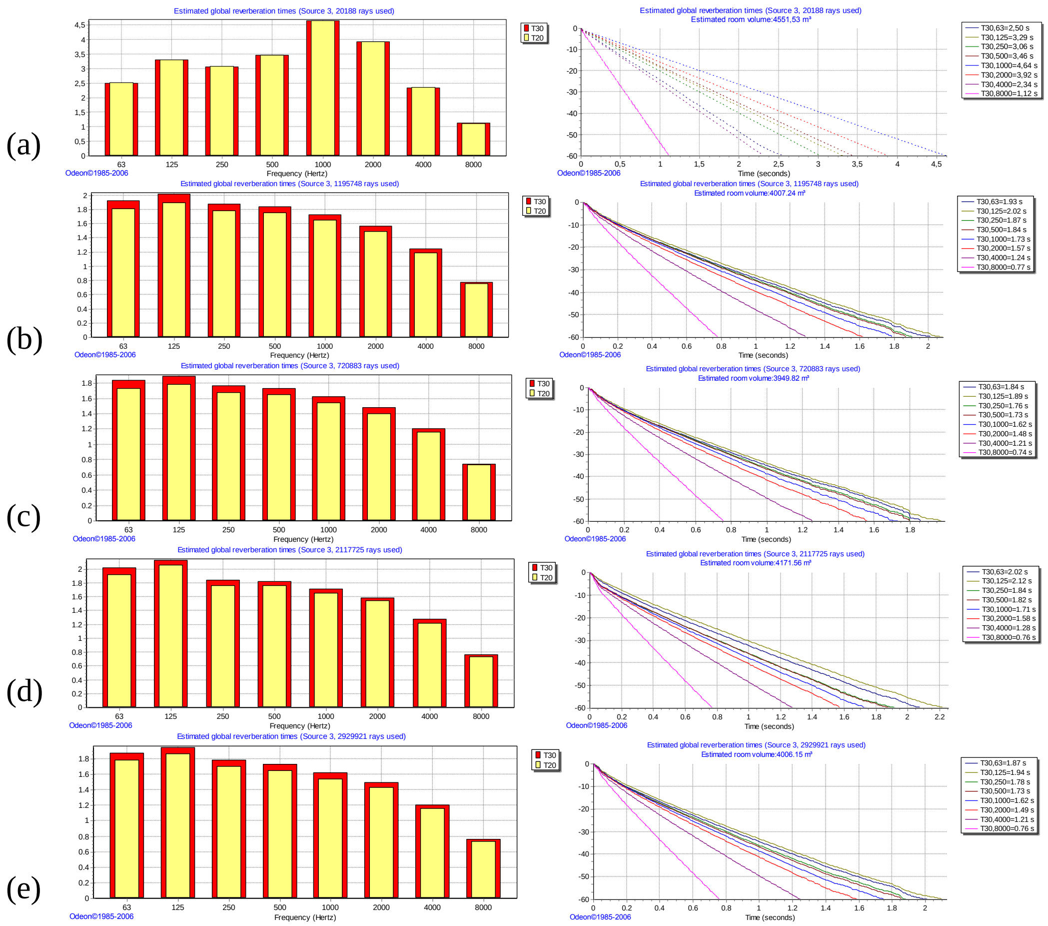
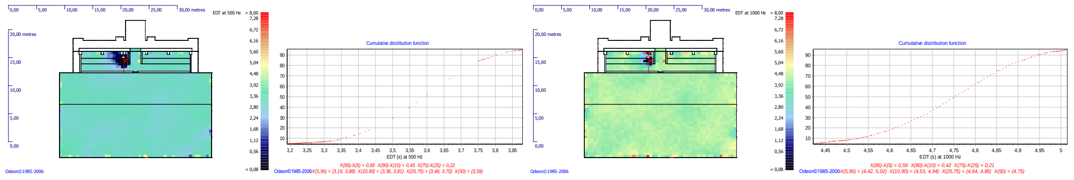
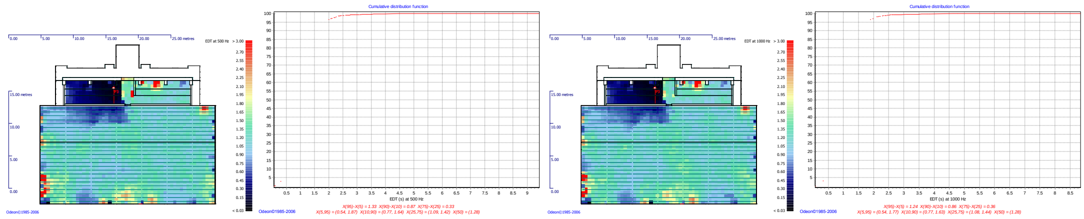


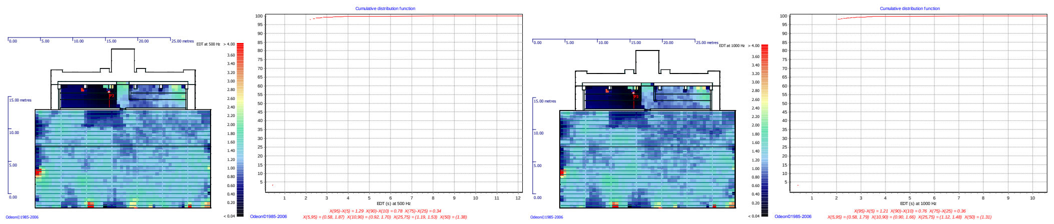
Figure C.1 The estimated GRT (T20 and T30) values (at the left) and T30 noise reduction curves (at the right) obtained for the Scenario SG-a: (a)AS-IS case, (b) Treatment B10@60(at), (c) Treatment B10@60(bt), (d) Treatment TP10, (e) Treatment B10@60(at)+MS.



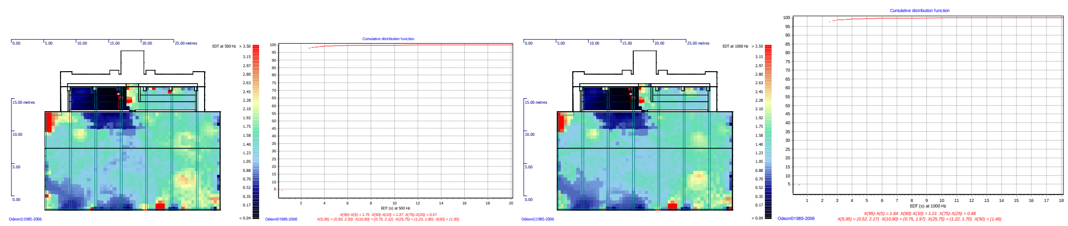
(a)



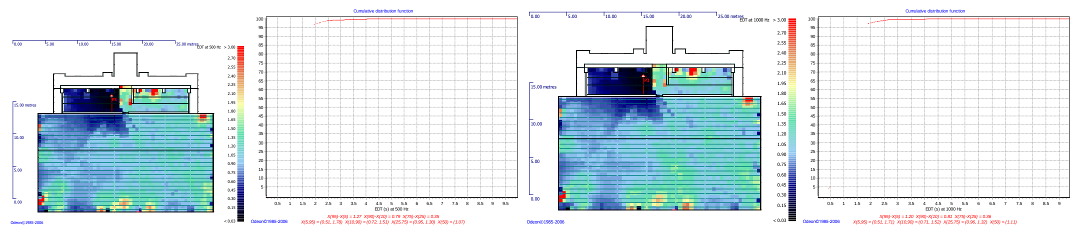
(b)



(c)



(d)

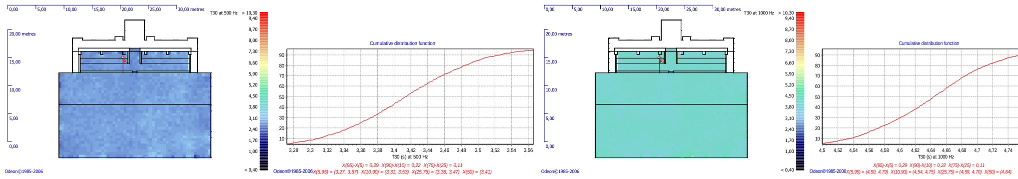


(e)

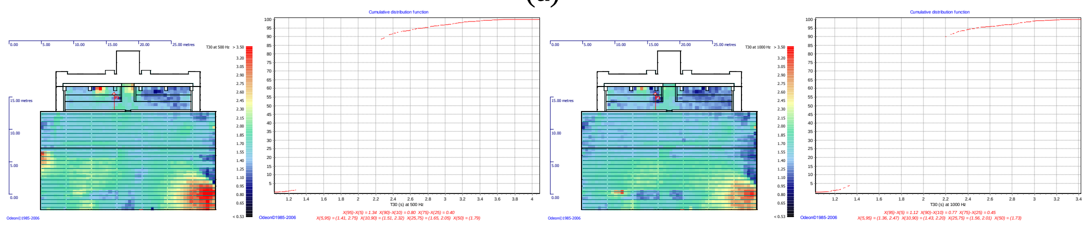
Figure C.2 The maps showing the distribution of estimated EDT data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphic for the Scenario SG-a, :.

(a)AS-IS case, (b) Treatment B10@60(at), (c) Treatment B10@60(bt),

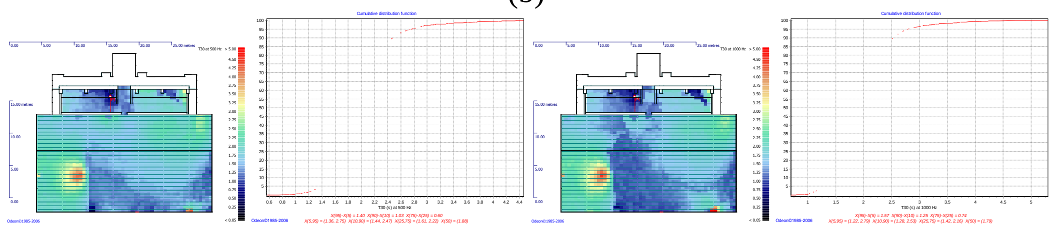
(d) Treatment TP10, (e) Treatment B10@60(at)+MS.



(a)



(b)



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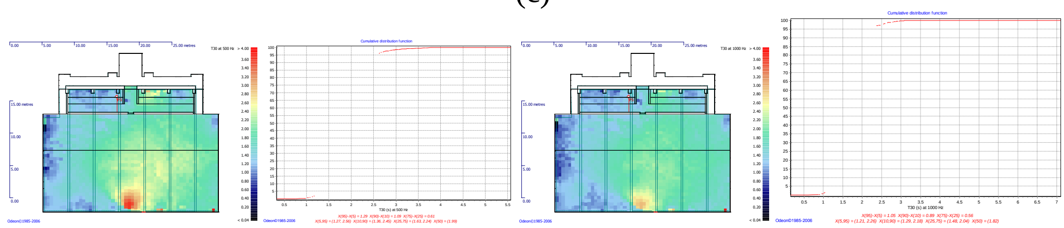

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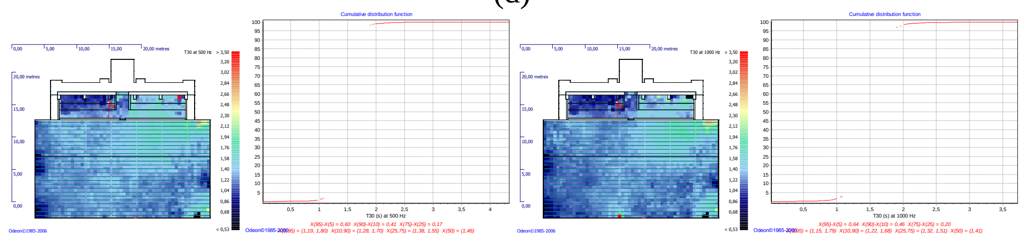
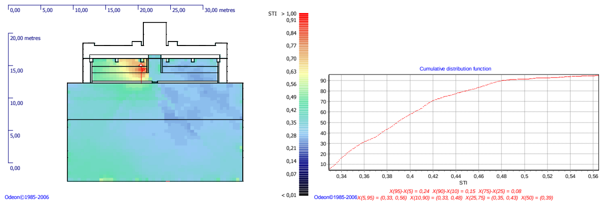


(e)

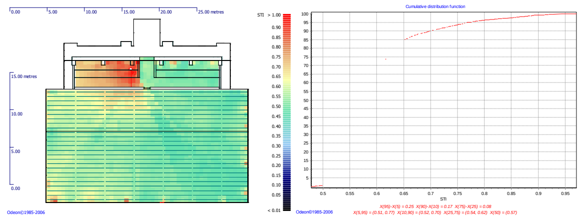
Figure C.3 The maps showing the distribution of estimated T30 data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphicsfor the Scenario SG-a:

(a)AS-IS case, (b) Treatment B10@60(at), (c) Treatment B10@60(bt),

(d) Treatment TP10, (e) Treatment B10@60(at)+MS.



(a)



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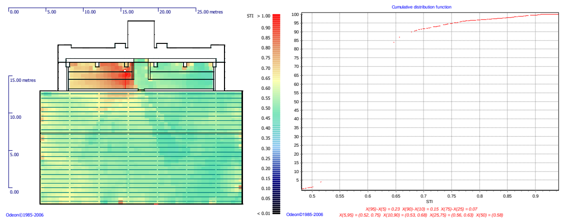
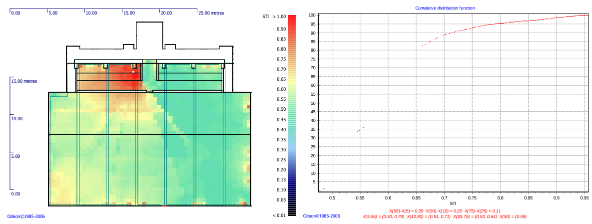


(c)



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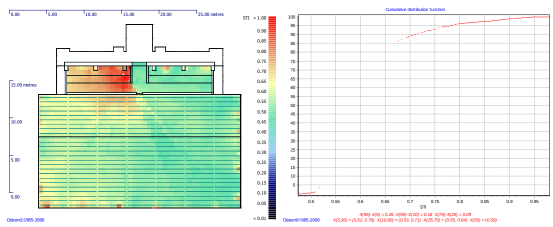
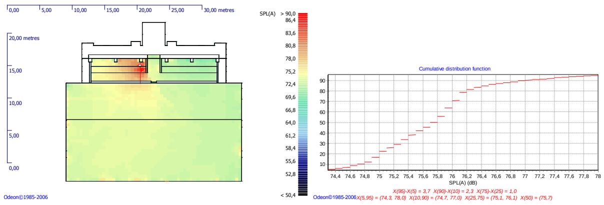
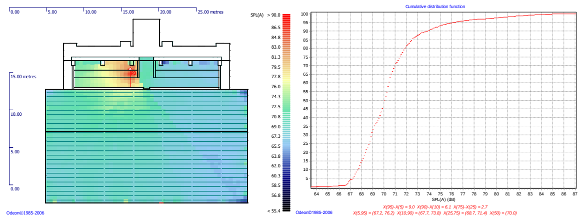


(e)

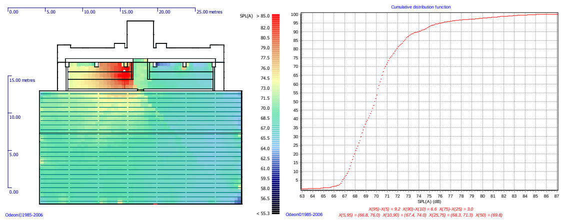
Figure C.4 The maps showing the distribution of estimated STI data together with their cumulative distribution function graphics for the Scenario SG-a: (a)AS-IS case, (b) Treatment B10@60(at), (c) Teatment B10@60(bt), (d) Treatment TP10, (e) Treatment B10@60(at)+MS.



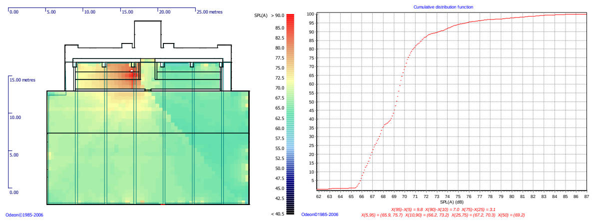
(a)



(b)



(c)



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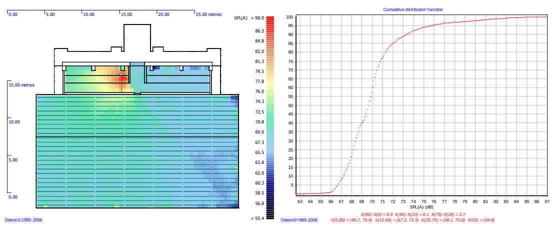
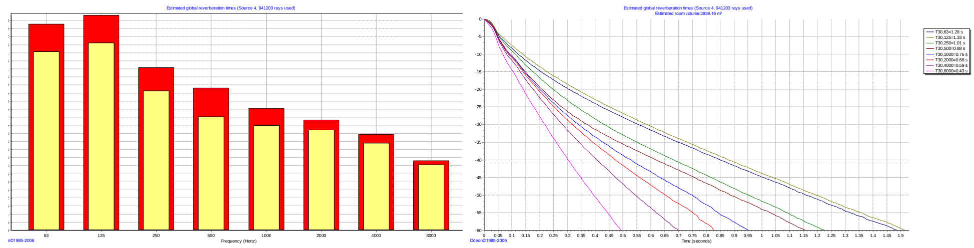


(e)

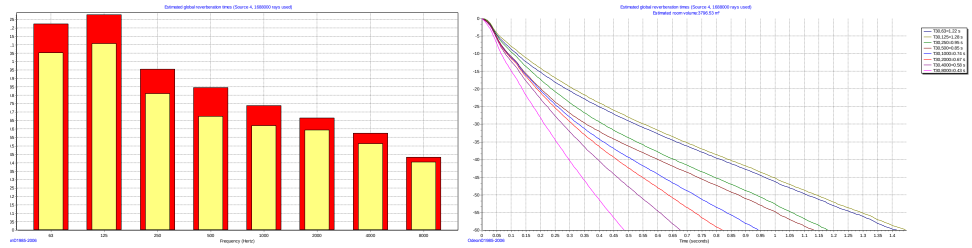
Figure C.5 The maps showing the distribution of estimated SPL(A) data together with their cumulative distribution function graphics for the Scenario SG-a: (a)AS-IS case, (b)Treatment B10@60(at), (c)TreatmentB10@60(bt), (d)Treatment TP10, (e)TreatmentB10@60(at)+MS.

APPENDIX D

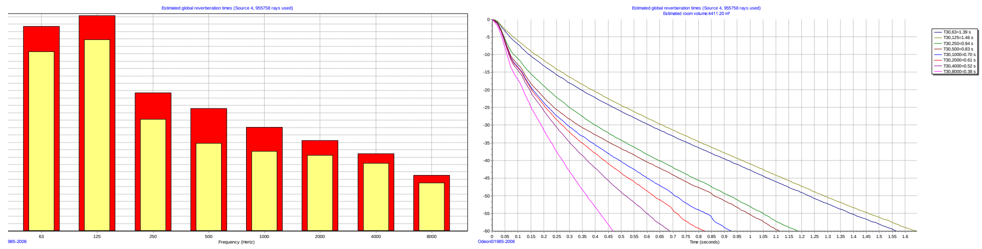
SIMULATION DATA FOR THE SCENARIO MP-S



(a)

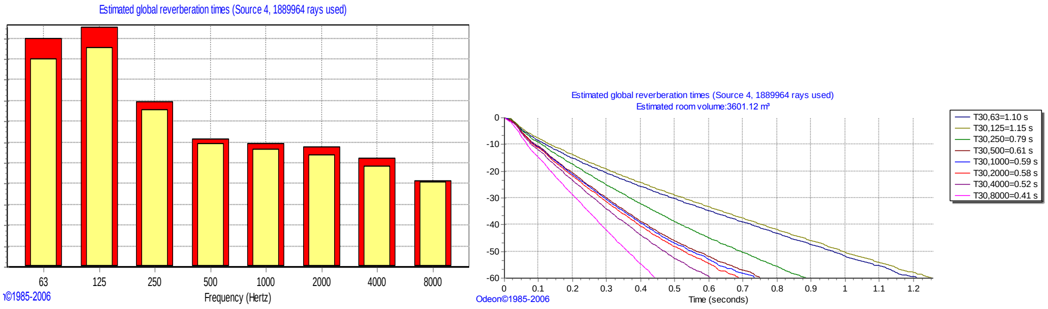


(b)

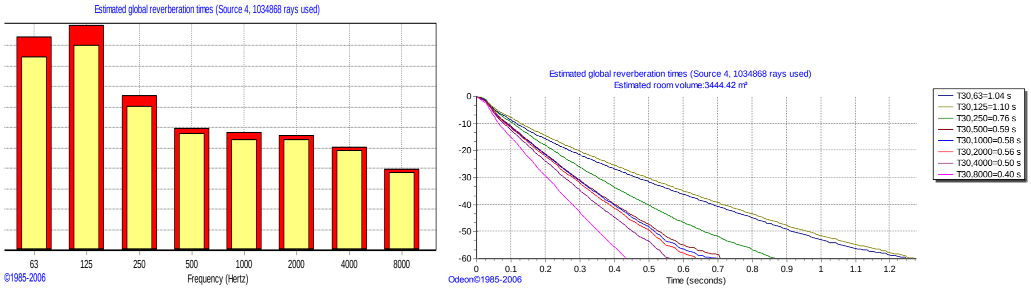


(c)

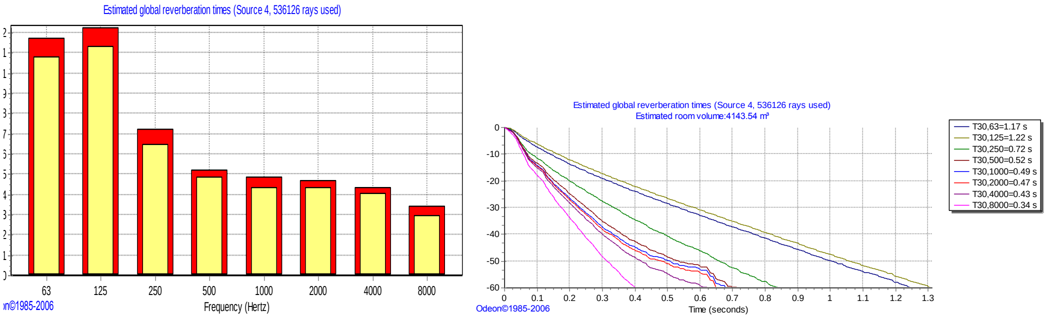
Figure D.1 Estimated GRT (T20 and T30) values (at the left) and T30 noise reduction curves (at the right) obtained for the MP-S scenario: (a)Treatment B10@60(at)+Ca, (b)Treatment B10@60(bt)+Ca, (c)Treatment TP10+Ca, (d)Treatment B10@60(at)+MS+Ca.



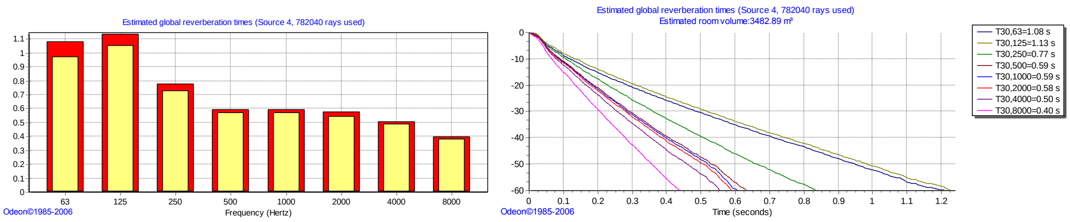
(a)



(b)

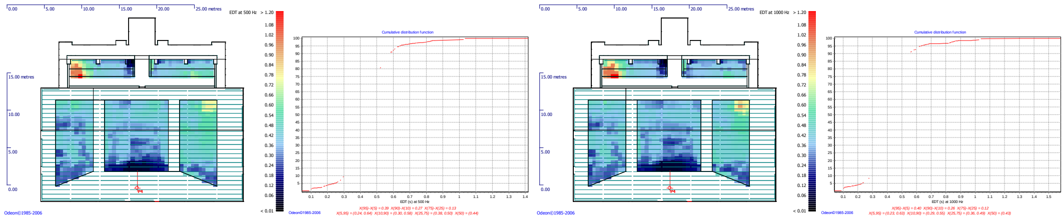


(c)

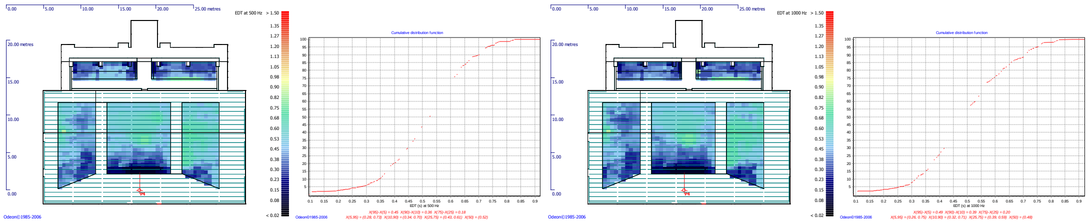


(d)

Figure D.2 Estimated GRT (T20 and T30) values (at the left) and T30 noise reduction curves (at the right) obtained for the MP-S scenario: (a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co, (c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.



(a)



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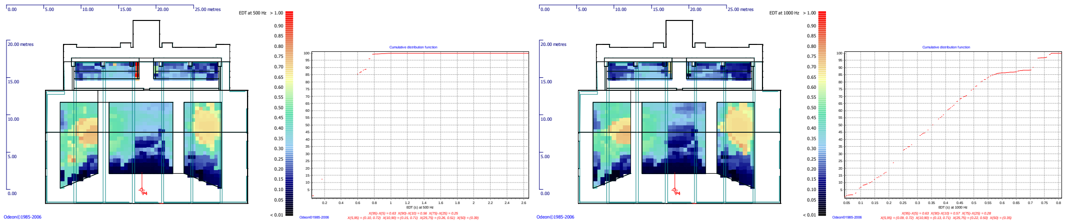
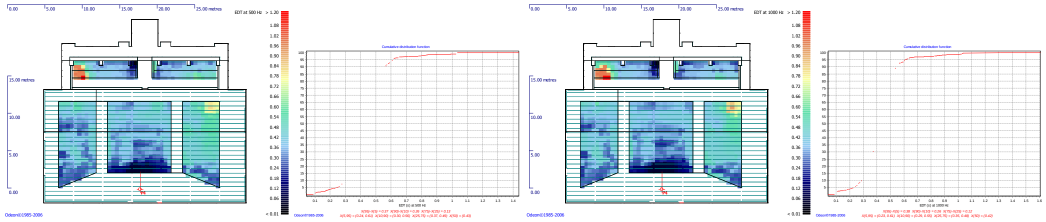
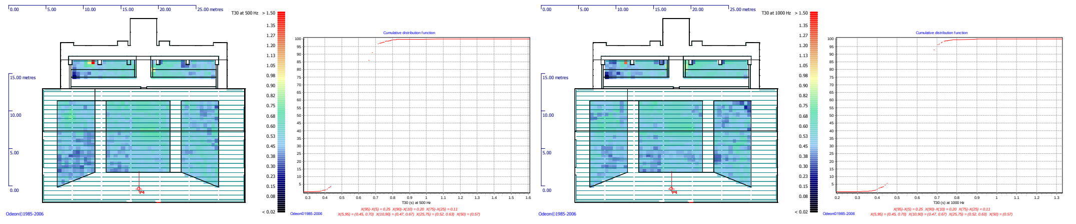


(c)

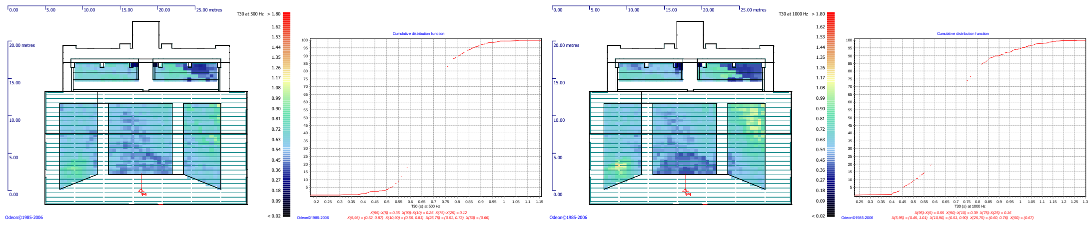


(d)

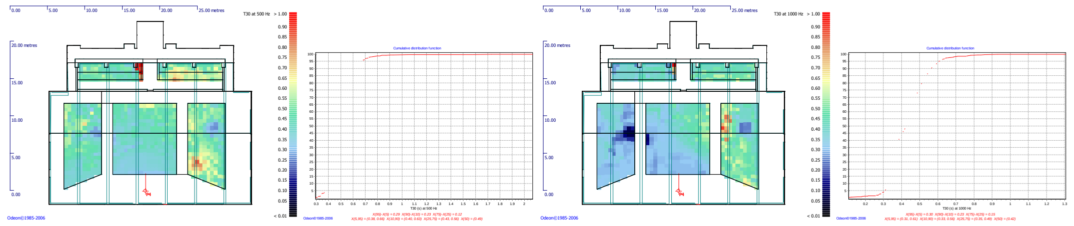
Figure D.3 The maps showing the distribution of estimated EDT data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphics for the ScenarioMP-S:
(a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co,
(c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.



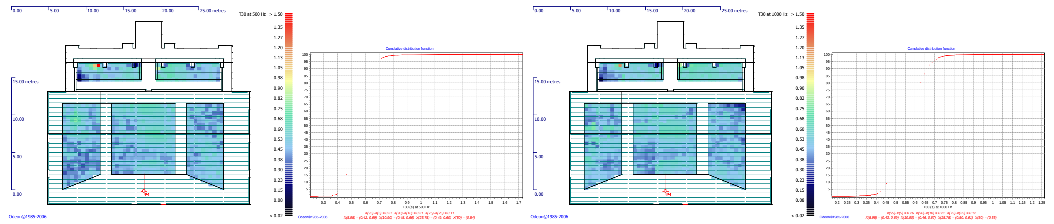
(a)



(b)



(c)



(d)

Figure D.4 The maps showing the distribution of estimated T30 data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphics for the Scenario MP-S:
(a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co,
(c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.

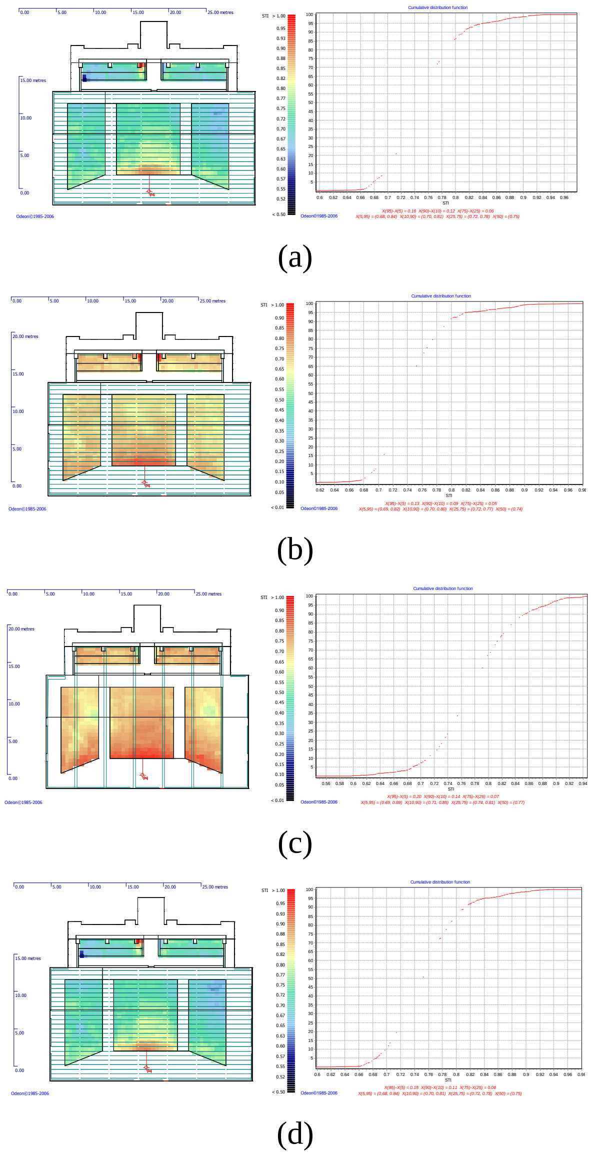
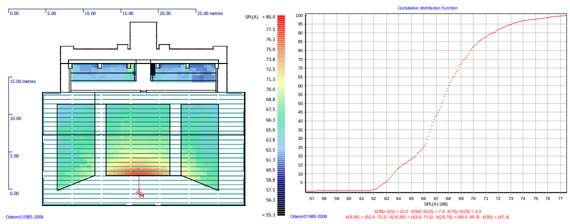
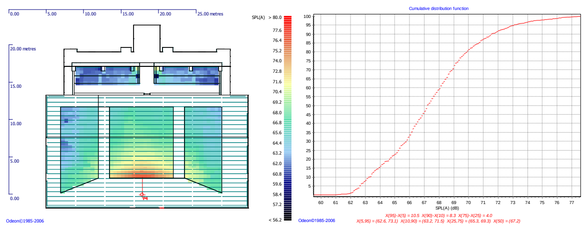


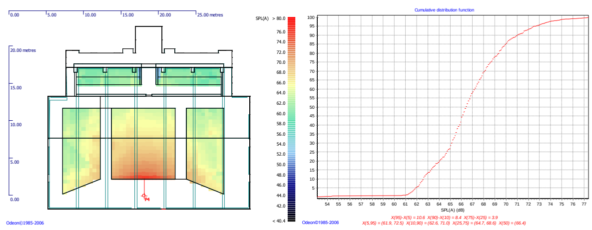
Figure D.5 The maps showing the distribution of estimated STI data together with their cumulative distribution function graphics for the ScenarioMP-S: (a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co, (c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.



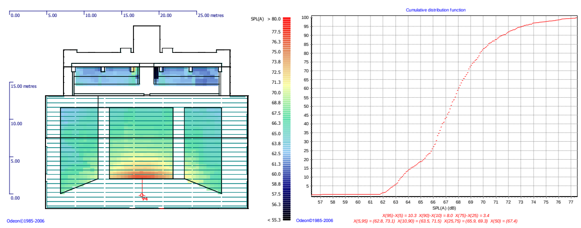
(a)



(b)



(c)

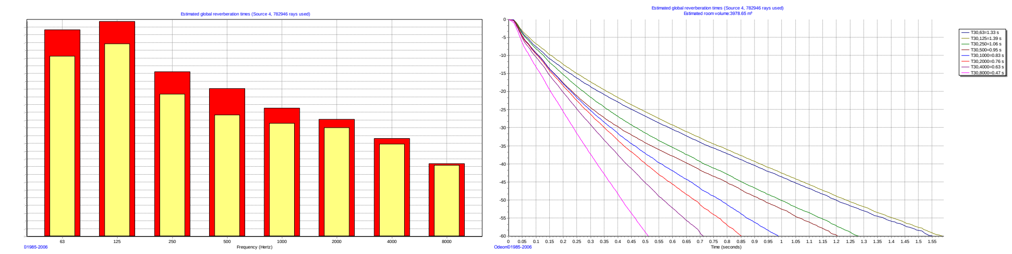


(d)

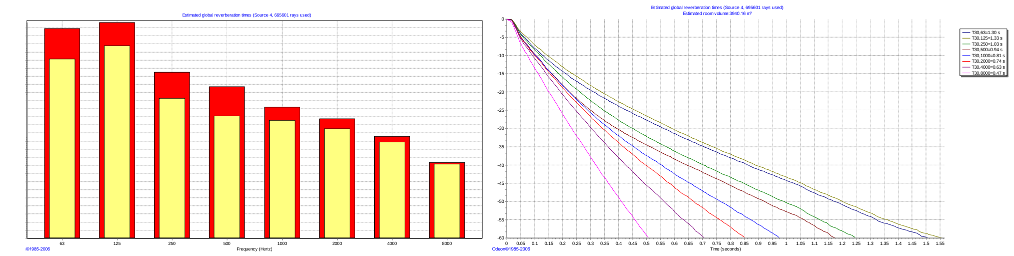
Figure D.6 The maps showing the distribution of estimated SPL(A) data together with their cumulative distribution function graphics for the Scenario MP-S: (a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co, (c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.

APPENDIX E

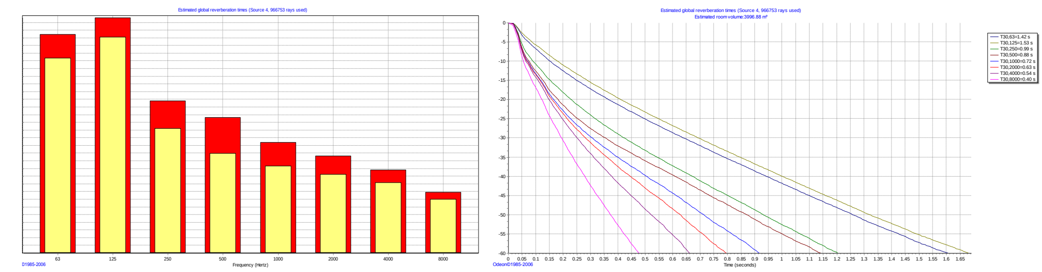
SIMULATION DATA FOR THE SCENARIO MP-P



(a)

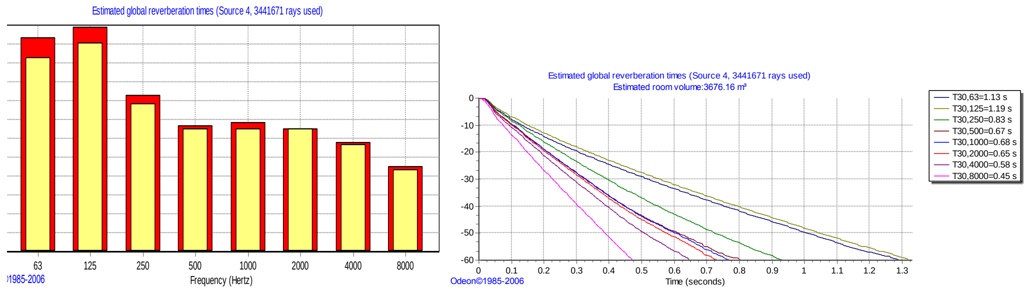


(b)

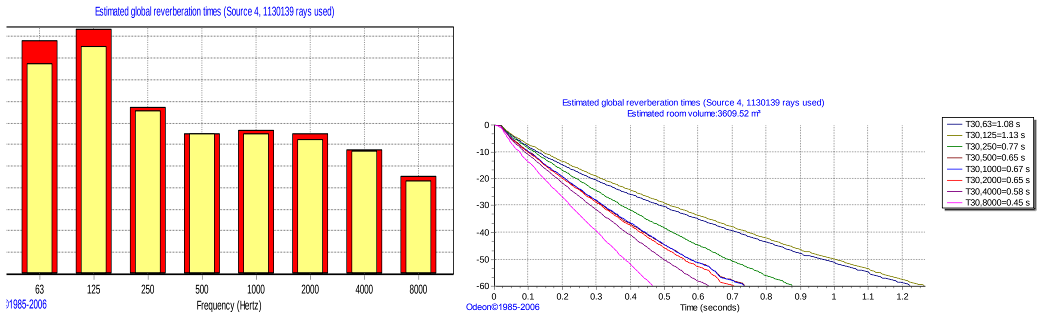


(c)

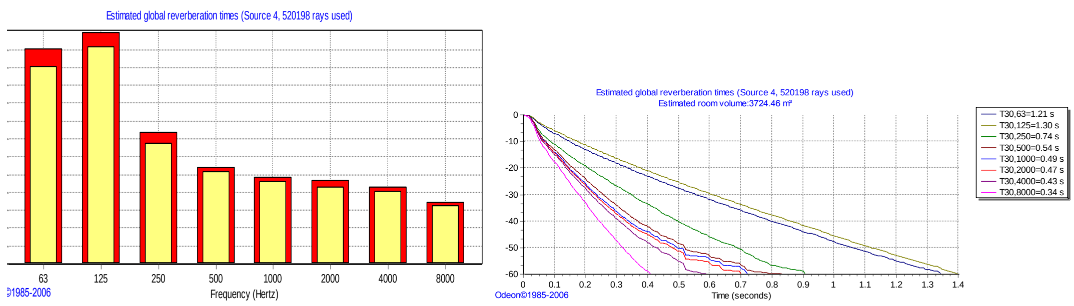
Figure E.1 Estimated GRT (T20 and T30) values (at the left) and T30 noise reduction curves (at the right) obtained for the MP-P scenario:
(a)Treatment B10@60(at)+Ca, (b)Treatment B10@60(bt)+Ca, (c)Treatment TP10+Ca, (d)Treatment B10@60(at)+MS+Ca.



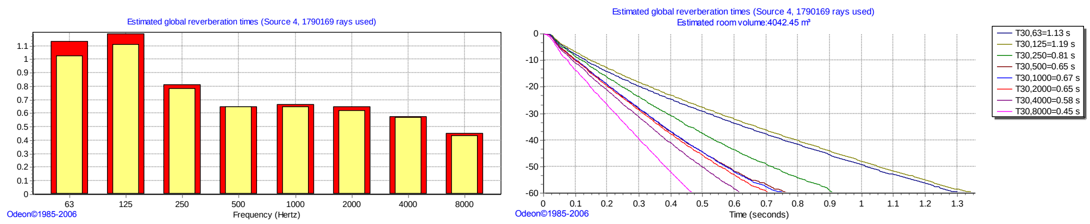
(a)



(b)

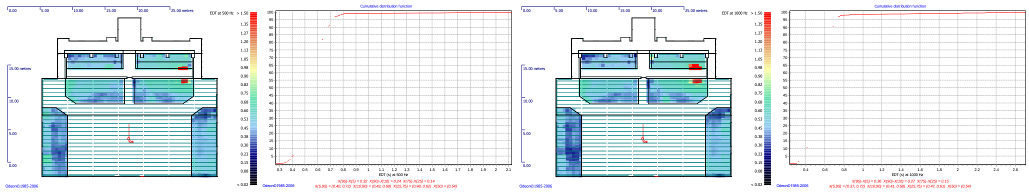


(c)

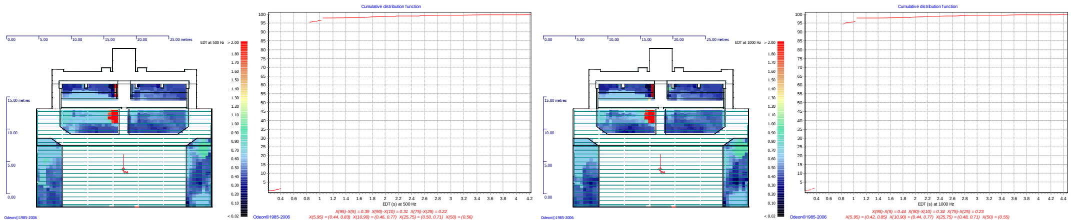


(d)

Figure E.2 Estimated GRT (T20 and T30) values (at the left) and T30 noise reduction curves (at the right) obtained for the MP-P scenario: (a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co, (c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.



(a)



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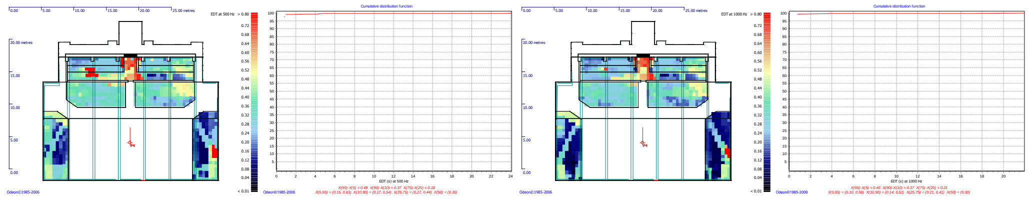

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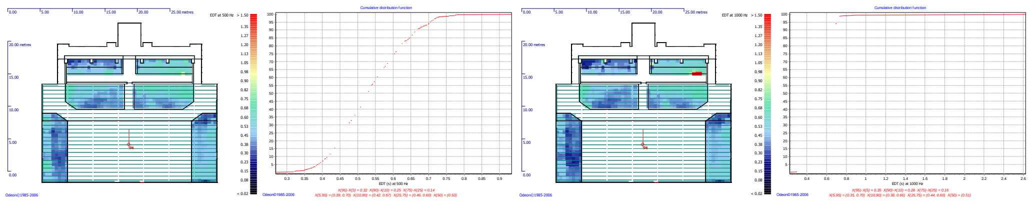
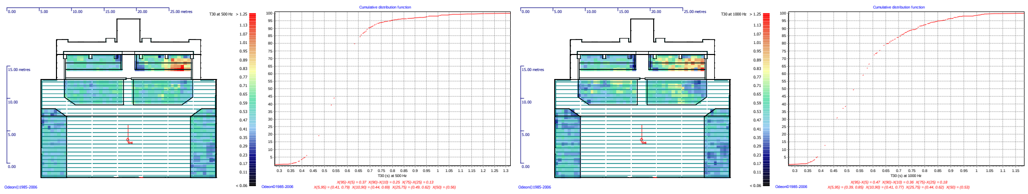
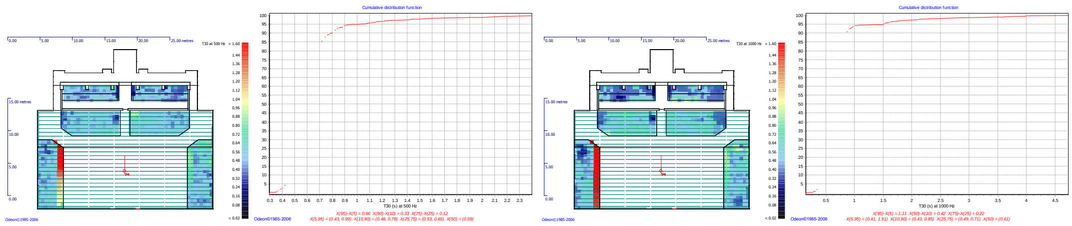


(d)

Figure E.3 The maps showing the distribution of estimated EDT data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphics for the Scenario MP-P:
(a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co,
(c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.



(a)



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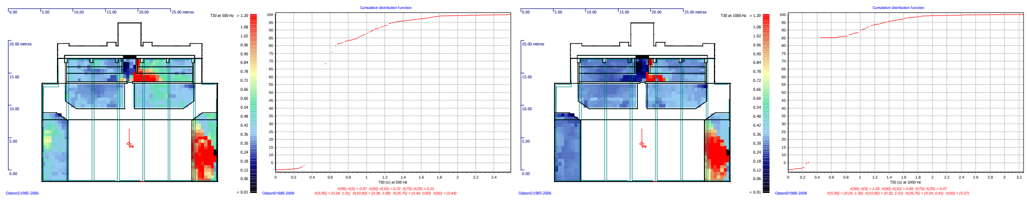

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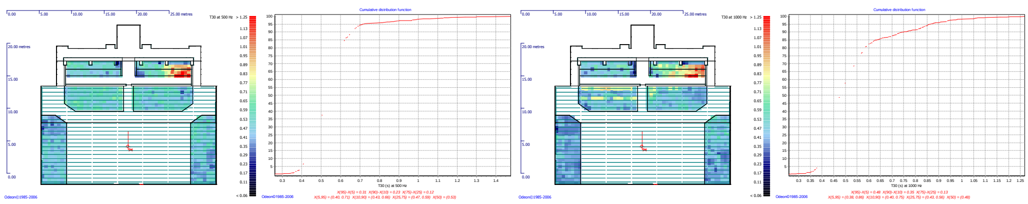
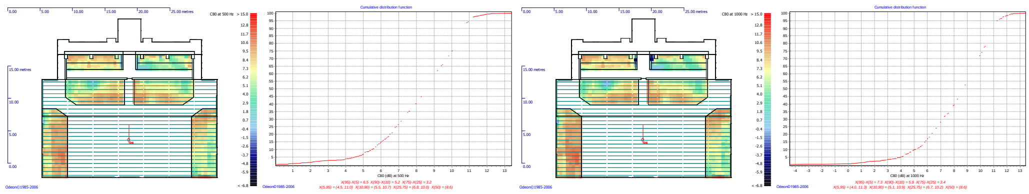
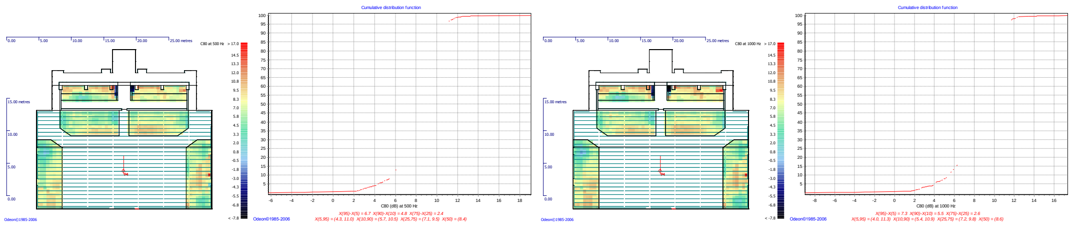


(d)

Figure E.4 The maps showing the distribution of estimated T30 data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphics for the ScenarioMP-P:
(a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co,
(c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.



(a)



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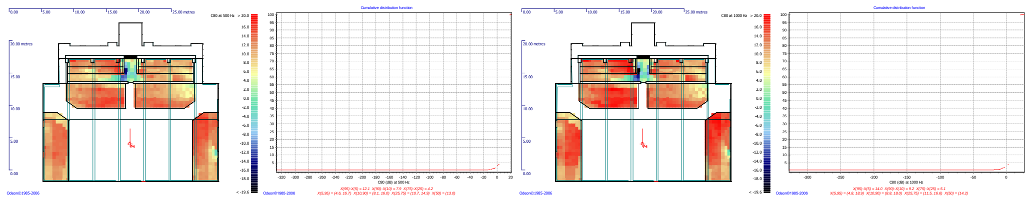
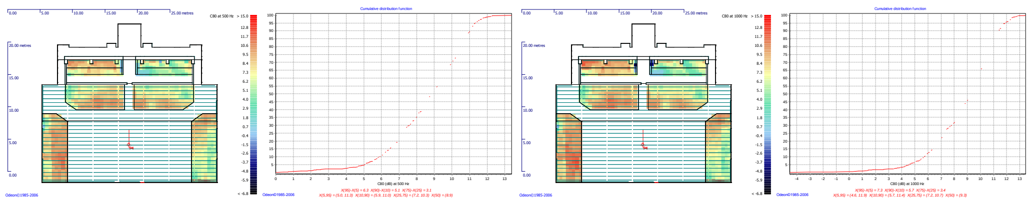


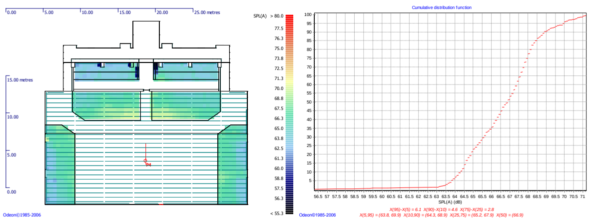
(c)



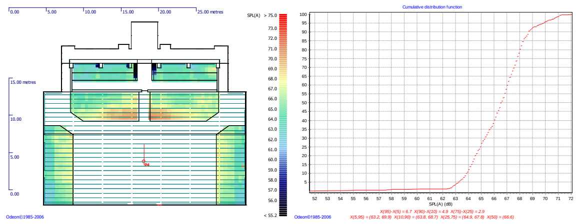
(d)

Figure E.5 The maps showing the distribution of estimated C80 data at 500Hz (at the left) and 1000Hz (at the right) together with their cumulative distribution function graphics for the Scenario MP-P:

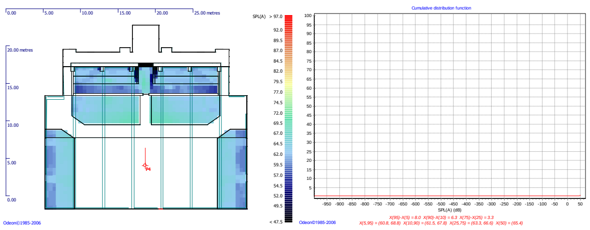
(a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co, (c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.



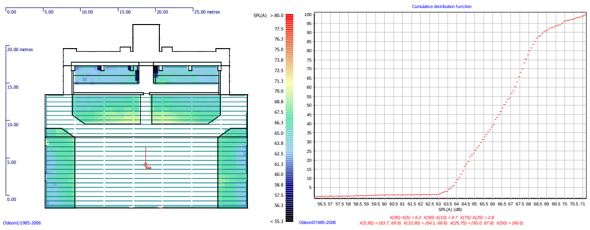
(a)



(b)



(c)



(d)

Figure E.6 The maps showing the distribution of estimated SPL(A) data together with their cumulative distribution function graphics for the Scenario MP-P: (a)Treatment B10@60(at)+Ca+Co, (b)Treatment B10@60(bt)+Ca+Co, (c)Treatment TP10+Ca+Co, (d)Treatment B10@60(at)+MS+Ca+Co.

APPENDIX F

MATERIAL QUANTITIES

Table F. 1. The treatments proposed for the ceiling and the amount of materials used for each proposal

Theceiling treatment	Material type	Total area (m^2)	Board thickness (m)	Total volume (m^3)
FP5	Rockwool board	405.0	0.05	20.25
FP10	Rockwool board	405.0	0.10	40.50
B10@60	Rockwool board	378.0	0.10	37.80
B10@30	Rockwool board	740.9	0.10	74.09
B5@30	Rockwool board	740.9	0.05	37.04
B5@60	Rockwool board	378.0	0.05	18.9
B10@60	Rockwool board	378.0	0.10	37.8
B10@90	Rockwool board	257.0	0.10	25.7
TP5	Rockwool board	455.2	0.05	22.76
TP10	Rockwool board	455.2	0.10	45.52
FT	Curtain fabric	455.2	-	

Table F. 2 The treatments proposed for the walls and the amount of materials used for each proposal

Material type	The placement of the material used	Total area(m^2)
Curtain (double-layered satin fabric with roller blind mechanism)	Tribune's rear wall-Cr	70
	Windows-Cg	117
	Side walls-Cs	122
	Openings (entrances)-Co	16
	All-Ca	247
Perforated Metal Sheet	Parapet between the playfield and tribune	40

APPENDIX G

TRIAL FOR THE ESTIMATED COST ANALYSES FOR THE CALCULATION OF B10@60(at)+MS+Ca+Co TREATMENT

Work item (Material and/or Labour Cost)	Unit Price (TL/m^2)		Area(m^2)	Total Price (TL)	
	Low	High		Low	High
Mineral Wool (fibreglass or rockwool:density=48 kg/m^3, 100 mm-thick)	9.8	10.9	378	3704.4	4120.2
Acoustically Transparent Fabric	10.0	20.0	882	8820.0	17640.0
Labour Cost ofSuspended CeilingConstruction	-				10000.0
Curtains, AV20 double layer satin installed 15 cm away from wallsurface (Unit weight = 550 g/m^2)	30.0	66.5	330	9900.0	21945.0
Labour Cost of Curtain Modules Construction	-				3000.0
Metals, Perforated metal (13% open, with over 50mm(2")-thick fiberglass)	40.0	53.0	40	1600.0	2120.0
Mineral Wool (fibreglass or rock wool, density=48 kg/m^3, 50 mm-thick)	4.9	5.5	40	196.0	218.0
Labour cost of Metal Cladding Construction	-				400.0
Estimated Cost of the Proposed Treatment B10@60(at)+MS+Ca+Co	85.0		699	37620.4	59443.2
Estimated Cost for the typical Sport Hall construction (excluding the estimated cost of proposed treatment)		1150	699		803850.0
Ratio of the estimated cost of proposed acoustical treatment to the estimated cost of the sport hall construction (Rate of increase in price) (%)				4.7%	7.4%
Ratio of the estimated cost of the proposed acoustical treatment to the estimated overall construction cost (including the estimated cost of proposed acoustical treatments) (%)				4.5%	6.9%

Figure G.1The description of work items for the construction of the acoustical treatment B10@60(at)+MS+Ca+Co and their unit prices: the estimated cost of the proposed treatment and rate of increase in the estimated cost of the overall construction. (Calculations are done by taking the unit prices from the market in 2014).