EXPERIMENTAL AND COMPUTATIONAL EVALUATION OF ACOUSTICAL PERFORMANCE OF MULTIPURPOSE MUSIC CLASSROOMS

A THESIS
SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE
AND THE GRADUATE SCHOOL OF ENGINEERING AND
SCIENCE OF ABDULLAH GUL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By

Ahmet ASLAN

August 2020

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SCIENTIFIC ETHICS COMPLIANCE

I hereby declare that all information in this document has been obtained in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

Ahmet ASLAN

REGULATORY COMPLIANCE

M.Sc. thesis titled Experimental and Computational Evaluation of Acoustic Performance of Multipurpose Music Classrooms has been prepared in accordance with the Thesis Writing Guidelines of the Abdullah Gül University, Graduate School of Engineering & Science.

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ACCEPTANCE AND APPROVAL

M.Sc. thesis titled "Experimental and Computational Evaluation of Acoustical Performance of Multipurpose Music Classrooms" and prepared by Ahmet Aslan has been accepted by the jury in the Architecture Graduate Program at Abdullah Gül University, Graduate School of Engineering & Science.

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……….. /……….. / ………..

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ABSTRACT

EXPERIMENTAL AND COMPUTATIONAL EVALUATION OF ACOUSTICAL PERFORMANCE OF MULTIPURPOSE MUSIC CLASSROOMS

Ahmet Aslan
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August 2020

The efficiency of education in schools is directly related to the quality of communication in classrooms. One of the crucial factors that determines the educational quality in schools is the acoustical performance of the classrooms. Considering the significance of communication in educational spaces, music education is one of the most auditory-related field of education due to its dependence on the ability to hear. The acoustic properties and performance of spaces designated to serve as music classrooms should be specific to the functions of music education. Using the music classroom as a multifunctional space for the teaching of music theory and practicing musical instruments is an application that is frequently practiced in schools. However, the requirements for lectures and practice differ in terms of room acoustics. Therefore, providing function-specific acoustic performance characteristics in multipurpose music classrooms is important for the quality of education.

This study investigates the acoustical performance of three multipurpose music classrooms of different schools by experimental and computational methods. The schools are located on the campus of an educational institute in Kayseri. Prior to the experimental and computational studies, the dimensions and spatial organization of classrooms and the properties of building elements and materials are defined in detail. At the experimental stage of the study, measurements are performed to evaluate the background noise levels of the classrooms by comparing the results with NC (noise criterion) curves. Impulse response measurements are conducted in the rooms in order to derive certain acoustic parameters related to the acoustical performance of multipurpose music classrooms. In the computational studies, three-dimensional models of the classrooms are generated and these models are simulated through Odeon room acoustics software. The compatibility of the acoustical simulations is inspected by comparing the simulation results with the measurement results of room acoustic parameters and the simulation models are calibrated. The data obtained from the studies are analyzed and the acoustical performance of the classrooms are evaluated by comparing the results with reference parameter values for educational institutions defined in the regulations and literature. In order to assess the acoustical problems in multipurpose music classrooms, an identification procedure is developed. The root causes of the acoustical problems are locally diagnosed in the classrooms. According to the findings acquired from the identification studies, solution proposals are discussed to improve the acoustical performances of the classrooms.

Keywords: Room Acoustics, Multipurpose Music Classrooms, Acoustical Parameters, Acoustical Simulation

ÖZET

ÇOK AMAÇLI MÜZİK SINIFLARININ AKUSTİK PERFORMANSLARININ DENEYSEL VE HESAPLAMALI YÖNTEMLERLE DEĞERLENDİRİLMESİ

Ahmet Aslan
Mimarlık Bölümü Yüksek Lisans
Tez Danışmanı: Dr. Öğr. Üyesi Buket METİN
II. Tez Danışmanı: Dr. Öğr. Üyesi Akın OKTAV
Ağustos 2020

Okullardaki eğitimin verimli bir şekilde yapılması sınıflardaki iletişimin kalitesi ile doğrudan ilgilidir. Sınıfların akustik performansları, okullardaki eğitimin kalitesinin tespit edilmesinde kritik rol oynayan faktörlerden biridir. Eğitim mekanlarında iletişimin önemi göz önüne alındığında, müzik eğitimi, temelde duyma işlevine bağlı oluşundan dolayı eğitim yöntemleri arasında işitsel özellikleriyle öne çıkmaktadır. Müzik eğitim sınıfı olarak hizmet vermek üzere belirlenmiş mekanların akustik özellikleri ve performansları, müzik eğitiminin işlevlerine özgü olmalıdır. Müzik sınıflarının, ders anlatımı ve müzik enstrüman provaları için çok amaçlı bir mekân olarak kullanılması okullarda sıklıkla uygulanan bir kullanım şeklidir. Diğer yandan, öğretim faaliyetleri ve müzik pratiklerinin hacim akustiği açısından gerektirdiği koşullar birbirinden farklıdır. Bu nedenle, çok amaçlı müzik sınıflarında işleve uygun akustik koşulların sağlanması, müzik eğitiminin verimli bir şekilde sürdürülebilmesi için gerekli şartlardan birisidir.

Bu çalışma, farklı okullarda yer alan üç adet çok amaçlı müzik sınıfının akustik performansını hesaplamalı yöntemlerle analiz etmektedir. Sınıfların bulunduğu okullar Kayseri'deki bir eğitim kurumunun kampüsünde yer almaktadır. Deneysel ve hesaplamalı çalışmaların öncesinde, sınıfların boyutları ve mekânsal kurguları, yapı elemanlarının ve materyallerin özellikleri ve nitelikleri detaylı bir şekilde ortaya konmuştur. Çalışmanın deneysel aşamasında, sınıflarda arka plan gürültüsü ölçümleri gerçekleştirilmiştir. Ölçüm sonuçları NC (gürültü kriteri) eğrileri ile karşılaştırılarak sınıfların arka plan gürültü seviyeleri değerlendirilmiştir. Çok amaçlı müzik sınıflarının akustik performansları ile ilgili belirli akustik parametreleri elde etmek için odalarda dürtü cevabı ölçümleri yapılmıştır. Hesaplamalı çalışmalarda, mekanların üç boyutlu modelleri bilgisayar ortamında oluşturulmuş ve bu modeller Odeon hacim akustiği yazılımı ile simüle edilmiştir. Gerçekleştirilen akustik simülasyonların uygunluğu, hacim akustiği parametrelerinin ölçümlerinden elde edilen sonuçlar ile simülasyon sonuçları kıyaslanarak denetlenmiştir ve simülasyon modelleri kalibre edilmiştir. Çalışmalardan elde edilen sonuçlar eğitim kurumları için tanımlanmış olan yönetmeliklerde ve literatürde açıklanan uygun parametre değerleri ile karşılaştırılarak çok amaçlı müzik sınıflarının akustik performansları değerlendirilmiştir. Çok amaçlı müzik sınıflardaki akustik problemlerin değerlendirilmesi için bir teşhis prosedürü geliştirilmiştir. Akustik problemlerin kaynakları sınıflarda bölgesel olarak tespit edilmiştir. Değerlendirme çalışmalarından elde edilen veriler ışığında, sınıfların akustik performanslarının iyileştirilmesi için çözüm önerileri tartışılmıştır.

Anahtar kelimeler: Hacim Akustiği, Çok Amaçlı Müzik Sınıfları, Akustik Parametreler, Akustik Simülasyon

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This thesis is dedicated
to my dear wife Hilal

Chapter 1

Introduction

The education systems of every nation are established and developed uniquely, related to the cultural, social, economic and political characteristics of the given society (Duman, 1991). The Turkish education system focuses on elevating individuals through the knowledge and skill sets they need to achieve competence across various fields (Ministry of National Education, 2018). In the Turkish Qualifications Framework (TQF), the Vocational Qualifications Authority defines eight main competencies that students need in their personal, social, academic and business environments. The competencies are declared as follows:

- Communication in First Language
- Communication in Foreign Languages
- Mathematical Competence and Basic Competencies in Science/Technology
- Digital Competence
- Learning to Learn
- Social and Citizenship Competencies
- Taking Initiative and Entrepreneurship
- Cultural Awareness and Expression (Vocational Qualifications Authority, 2015, p. 23-25)

The "Cultural Awareness and Expression" quality defined in the TQF includes music, drama, literature, and the visual arts (Ministry of National Education, 2018). The provision of the competencies depends on providing appropriate skill sets, physical conditions and implementation of the instructions. However, the education program of these disciplines varies in accordance with their characteristic requirements. Music education is among the fields of education that require specific attention due to its characteristics of playing instruments, singing and learning musical theory.

The current education system in Turkey is regulated in three phases: four years of elementary school, four years of middle school and four years of high school (Güven, 2012). The “Learning area approach” is considered the basis of the Music Lesson Teaching Program of the Turkish education system. The Ministry of National Education highlights the four important learning areas for each grade. These areas are stated as follows:

- Listening and Singing
- Musical Perception and Theoretical Information
- Musical Creativity
- Music Culture (Ministry of National Education, 2018, p. 10)

Educational buildings are the physical spaces where educational activities take place at every stage that support the essential elements of education. The classrooms, however, vary according to the requirements of education models and function. Communication in classrooms is extremely important, and thus, a good acoustical environment contributes and increase the efficiency of education. In this regard some classrooms require specific design features in order to provide an efficient acoustical environment. Music education classrooms in schools are one of those spaces that require specific acoustical conditions due to the characteristic functions of music education. Therefore, providing appropriate acoustic conditions in music classrooms is one of the important factors determining the quality of music education.

1.1. Problem and Research Question

Music classrooms in schools are the spaces that the basics of music education is established for students. Using the music classroom as a multipurpose space for lectures and music rehearsals is a common application in many schools in Turkey. This application prevents the use of classes separately for lessons and music practice by decreasing the number of required classrooms for music education. However, the requirements for performing music and teaching activities differ in terms of architectural acoustics. Multipurpose music classrooms should meet different acoustic requirements when active teaching and musical practice are performed in the same classroom. On the other hand, existing research doesn't state a consistent correlation between the standards and current music classrooms. Thus, the design criteria for multipurpose music classrooms in schools should be determined in terms of architectural acoustics.

1.2. Literature Review

The studies discussed in this section are chosen according to the volume, usage features and acoustic performance requirements of the rooms they examine. The studies are categorized and sorted in an order that is based on the combination of the acoustic performance parameters examined, the functions and the volumes of the rooms they investigate.

In the study carried out by Knudsen and Harris (1951), a generic classroom with a capacity of 40 students was analyzed in terms of room acoustics. The classroom in the study measures 27 feet (8.22 m) by 32 feet (9.75 m) with a height of 12 feet (3.65 m). The control of the reverberation time was the main consideration of the study along with the sound transmission between adjacent rooms. The appropriate reverberation time for the room was determined according to its volume. It was also stated in the study that the appropriate reverberation time for a small recitation room is 0.75 seconds at frequencies ranging in 512 Hz – 2048 Hz and 1 second at 128 Hz. The amount of absorption required for the room is calculated as 510 sabins at 128 Hz and 680 sabins at the 512-2048 Hz frequency range. The room supposedly accommodates an average of 32 students. The absorption for each person, including the individuals desks, was calculated as 2.6 sabins at 128 Hz, 4.2 sabins at 512 Hz and 4.6 sabins at 2048 Hz. For each of the eight unoccupied wooden desks in the classroom, the absorption is estimated as 0.4 sabins at all three frequencies. The amount of absorption required for the remainder of the classroom to be provided by the walls and ceiling was determined as 355 sabins at 128 Hz, 469 sabins at 512 Hz and 456 sabins at 2048 Hz. Therefore, in order to obtain the appropriate reverberation time, the surfaces have been improved by applying absorbent materials that accept deviations of 0.1 seconds from the specified appropriate reverberation time. As a result of the updated surfaces, the appropriate reverberation time was provided for the room.

The study of Zannin, Fiedler and Bunn (2013) investigated the acoustical quality of classrooms in a public national university. The main focus of the study was the reverberation time (RT) of the classrooms. The RT parameter of the classrooms was measured in different octave bands with the interrupted noise method which is stated in ISO 3382-1 standard. The study investigated the change in RT parameter after the renovation of the schools due to the administrative decisions. During the interrupted noise evaluations, an omni directional sound source, a sound power amplifier and a sound level analyzer were used. The evaluation includes four classrooms built in the 1960s at Parana Regional University in Brazil. The first two classrooms were designed as auditoriums and have volumes of 294 m3. The third classroom has a volume of 330 m3, while the fourth has a volume of 367 m3. The ceiling material in the classrooms was originally an acoustic material, but it was replaced with a PVC material in 2007. The PVC ceiling applied in the classrooms has reflective qualities and very low sound absorption characteristics. The results of the measurements indicated that the RT values are increased considerably when the ceiling material is changed. The RT values obtained from the study are compared with the appropriate RT values presented in national and international standards and regulations. According to the comparison, it was determined that the acoustic quality of the classrooms related to the reverberation time was inadequate and the administrative decision that changed the architectural characteristics affected the acoustical quality negatively.

Ronsse and Wang (2013) conducted a study about the relationship between the acoustical conditions of elementary school classrooms and the achievements of students who studied in those classrooms. Measurements of acoustical conditions were conducted in public schools located in Nebraska. The data obtained from the measurements were correlated with achievement scores of third and fifth grade students. Background noise levels (BNL) and reverberation times of 34 third-grade and 33 fifth-grade classrooms were obtained through the measurements, along with binaural room impulse response measurements conducted in a subgroup of the classrooms. According to the results of the study, it was found that some of the subject areas of students such as language and reading may be negatively impacted by higher unoccupied background noise levels of the classrooms. Equivalent A-weighted sound levels (LAeq) were gathered with a sound level meter mounted on a tripod at a height of 1.1 meter above the floor level. Also, measurements at different locations of the rooms were taken in order to detect possible differences in background noise levels at the center location. The reverberation time values (T20 - T30) were obtained from the unoccupied classrooms with an impulse response method similar to the method described in ISO 3382 standard. Instead of an omni-directional sound source, balloon pops were used as the sound source in the impulse response measurements. The impulse response was recorded with a sound level meter located in the center of the room. However, T20 values were calculated in octave bands ranging between 125 Hz and 8000 Hz with a utility software due to the inadequate energy level of balloon pop impulses at low frequencies when calculating T30 values. In addition to the background noise and reverberation time measurements, Binaural room impulse response measurements were conducted in 20 selected classrooms according to their wide range of reverberation time and background noise levels. Sixteen different measurement configurations were used in each classroom, with one source position and four receiver positions. A directional loudspeaker was used as a source for the similarity of its directivity characteristics to a human speaker. A high frequency transducer, an acoustic analyzer computer software and a sound and vibration manikin were used in the Binaural room impulse response measurements. The results indicate a relationship between the acoustical conditions of unoccupied classrooms and the achievements of elementary school students. The background noise levels are negatively affected the achievements of fifth grade students in language and reading subjects. According to the findings, the background noise of the classrooms may range between 28 dBA and 45 dBA for achieving the reading performance targets designated by northern Nebraska. In addition, negative correlations were found between distortion of the frequency-smoothed magnitude (DFSM) and student achievements. DFSM is a metric that is related to the ability of source localization. The study indicates that DFSM may be a more reliable metric to study than RT for the relationship between student achievements and the acoustical conditions of classrooms.

Sala and Viljanen (1995) conducted a study in Finland to determine the appropriate acoustical conditions for the intelligibility of speech. They used the rapid speech transmission index (RASTI) method to measure this. They also attempted to control it by placing mineral wool in a quiet classroom with the dimensions of 7.6 by 10 meters and a height of 3.3 meters. A total 20 different configuration of absorption materials were tested in the experimental classroom. The reverberation times of the classrooms were measured according to ISO 3382 standard with a building acoustic analyzer, a rotating microphone boom and an omni-directional sound source. The measured reverberation times at five octave bands ranging from 250 Hz to 4000 Hz were analyzed. RASTI measurements were conducted with a speech transmission meter according to the IEC 286-16 standard. The measured RASTI values were compared with the subjective speech intelligibility scale proposed by Houtgast and Steneken (1984). At eight of the experiments, the RASTI values were 0.75 or higher, which are indicated as 'excellent' based on the ranges between 0.75 - 1.00 according to the RASTI scale. The acoustical treatment configurations in this group of eight experiments also had reverberation times either shorter than 0.6 seconds or longer than 0.9 seconds. These are the limit reverberation time values for classrooms between 250 Hz and 2000 Hz octave bands that are revealed by Finnish Ministry of the Environment. It was found that the RASTI value of 0.75 or higher could be reached if 30 percent of the total area is covered with absorption materials.

In a study managed by Eggenschwiler (2006), the room acoustics of twelve classrooms in a school building that has an organic architectural style were investigated. Due to the organic form of the school building, each classroom has a different floor plan. Room acoustical conditions of the twelve classrooms were investigated through measurements of background noise levels, reverberation time (RT) and speech transmission index (STI). Within the experimental studies, an omni-directional loudspeaker was used during the measurements of RT and STI levels. According to the results of the measurements, appropriate levels of RT and STI levels were obtained. However, in some classrooms, the reverberation times were found to be slightly below the acceptable lower limit stated in DIN 18041. As a secondary method, questionnaire surveys were carried out among teachers in order to find possible correlations of the measurement results and the satisfaction levels of teachers. The teachers declared that they were satisfied with the acoustical conditions both for the intelligibility of the speech and for musical purposes. Also, the questionnaire results regarding the background noise levels indicate that the teachers found background noise levels high.

In the study conducted by Tang (2008), Hong Kong primary and middle school classrooms that have standardized architectural layouts were evaluated. The standardization of the architectural layouts of the classrooms are determined by local authorities. The study focused on laboratories and general teaching classrooms that have sizes similar due to the adaptation of the designs determined by the local authority between 1995 and 2000. The sizes of the 24 classrooms surveyed are typical and they have dimensions of 7m by 9m with a height of 3m and a volume of 189 m^3. The seven laboratories investigated in the study have dimensions of 9m x 12m and a height of 3m which corresponds to 324 m^3 volume for the laboratory spaces. It was also explained that the surfaces of the walls and the ceilings are generally reflective and non-diffusive. However, the basic furniture have scattering aspects to some extent due to their surface materials such as, wood and steel. The floors are covered with a plastic material which has a limited capacity of sound absorption and the notice boards provide absorption to some extent. The calculation and measurements of the acoustical parameters were conducted with Dirac software along with measurement equipment consisting of a sound level analyzer positioned at ear height of students and balloon pops as the sound source that is located at a height of 1.4m above the floor level (about the mouth location of the teacher) and 1m from the vertical centerline of the green board. The measurements were made for six to eight receiver positions and each Dirac measurement was between 2-5 seconds. The background noise levels were taken into account while conducting the impulse response measurements. The room acoustic parameters included in the study are: reverberation time (RT), definition (D), speech transmission index (STI), early-to-late energy ratio, and center time (Ts). The parameters were investigated in six octave bands ranging from 250 Hz to 8000 Hz. The correlations of the investigated parameters in different octave bands and relationships of the parameters were studied. It was also found that the relationships between different types of acoustic parameters (D, C80, RT) were not dependent on frequency bands in this case.

In the study conducted by Escobar and Morillas (2015), 17 auditorium and multipurpose conference rooms at a university in Spain were evaluated to measure the intelligibility of speech objective parameters such as, RT, STI and BNL. Speech tests were carried out to study the subjective responses of the listeners in terms of speech intelligibility. The 17 classrooms included in the study were divided in two groups. The first group included eight rooms that were being used only as regular classrooms where teaching activities are conducted. The secondary group included the rest of the classrooms that were being used for only or additionally for other functions such as conferences and institutional purposes. In the first group, the seats are made of wood, so it was stated that the presence of audience in the classrooms may alter the absorption level of the room. The second group of the rooms have medium-to-high upholstered seats, where the presence of people was not highly effective on the level of the absorption. In each room, several receiver points were chosen among the positions of the audience in order to conduct tests according to ISO 3382 recommendations. The sound source was placed in at least two positions in each room. The equipment used in the measurements of the rooms consisted of an omni-directional loudspeaker with a speaker amplifier, an acoustical analyzer and a computer software with acoustical analyzing capabilities. The room acoustic parameters were analyzed in six octave bands ranging from 125 dB to 4000 Hz. According to evaluations of the measurement results, the reverberation times in the rooms were higher than the recommended levels. The measured background noise levels were significantly higher than the recommended level stated in ANSI guidelines for school classrooms, which is 35 dBA. However, the impact of background noise levels on the STI parameter was not effective as the impact of RT. The evaluations demonstrated that the STI is a significant prediction parameter for the intelligibility of speech and there is a consistent relationship between RT and STI parameters for both octave bands and average values.

Gürel (2007) selected a primary school in Istanbul to investigate the acoustical performance of primary schools. She examined the selected elementary school in Istanbul on the scale of building and structural elements. She conducted surveys with students and teachers and on-site measurements of acoustic parameters. Room acoustic measurements were performed in four classrooms of the two blocks of the school. During the measurements, one omni-directional sound source, one power amplifier, one sound and frequency analyzer, one microphone, one light tripod, and DIRAC room acoustics software were used to conduct impulse response tests. Early decay time (EDT), RT, D50, Signal to Noise Ratio (SNR), and RASTI parameters were examined at the 500-2000 Hz octave bands. The sound source was placed 1.50m above the ground and the receiver points was placed 1.20m above the floor level. One source and five receiver points were determined during the measurements. According to the results it was found that the RT values were above the acceptable range of 0.6-0.8 seconds, and EDT values were above the acceptable range of 0.5-0.7 seconds. Inappropriate EDT parameter revealed that the classrooms do not have a uniform sound field and that the geometry of the space was not chosen appropriately. The results of D50 and SNR were appropriate, while the RASTI value was below the acceptable level. At the end of the study, the survey and measurement results were compared, and it was determined that the examined classrooms do not meet the acoustic performance criteria. The study noted that the C80 parameter being at low levels depending on the EDT value was a factor that reduces the efficiency of the music lessons performed in this school.

Özçevik (2005) compared the space variables, acoustical comfort and architectural requirements of Faculty of Architecture Studios at Anadolu University with open-plan offices, traditional classrooms and open-plan classrooms, and determined the appropriate values of the room acoustic parameters for architectural design studios. The aim of this study was to include useful data for similar studies for architectural design studios. In order to reveal the current status of acoustical comfort conditions in the designated places, a survey was conducted as part of the qualitative assessment. Noise control and room acoustic measurements (impulse response test) were conducted as quantitative assessments. BNL, RT, D50 and STI parameters were evaluated. According to the results, the optimum values of the related parameters were determined in terms of classroom acoustics.

In the study conducted by Karaman and Üçkaya (2015), the current acoustical performance of an architectural design studio and a classroom located in Dokuz Eylül University, Faculty of Architecture were investigated using experimental and computational methods as an objective evaluation. The subjective evaluation used in the study was carried out with survey questions answered by the students. The objective evaluations of room acoustics were conducted with on-site measurements and computer simulations. According to the results of the survey, an acoustically problematic studio and a classroom were selected as the pilot study areas and impulse response tests are applied in order to measure RT, EDT, D50, STI and RASTI parameters at 125 Hz and 4000 Hz octave band spectrum. Furthermore, performance simulation tests were conducted using Odeon 9 computer-based software on the digital models of the studio and classroom. At the end of the study, the results of on-site measurements and simulations were evaluated. According to the results, it was found: the RT was well above the acceptable value range; EDT, which is required to be parallel with RT, differed in certain receiver points; the STI and RASTI values were below the acceptable limit value of 0.45; and D50 was below the acceptable amount of 50 percent at almost all frequencies and receiver points. The results indicate that the sound is not spread properly, has masking effects and the speech intelligibility in the spaces is not provided sufficiently. For this reason, the study proposed materials to be used, which are removable, low cost and suitable for intensive use of spaces without changing the geometric size and shape of the volumes. The proposed solutions were developed on the computer environment with 3D modeling techniques and simulated using Odeon software to be verified.

A study conducted by P Zhu, Mo, Kang, and Zhu (2015), systematically compared on-site measurement and acoustic simulation in terms of STI, relationship curves and speech intelligibility scores. The study was conducted considering room impulse response and four general room conditions such as: a laboratory, an office, a multimedia lecture hall, and a semi an-echoic chamber. The results indicate that when there is a good agreement between the real rooms and the simulated virtual models, meaning that the STI parameter can be predicted accurately by acoustical simulation. Furthermore, the RT and SNR may apply less significant impact on the simulated STI.

Cunha et al. (2013) investigated the sound quality in three small music practice rooms located in a music school in Brazil. The music practice rooms are positioned side-by-side on the same axis. All three rooms have the same height of 3 meters and the volumes of the rooms are 45.5 m^3, 27.8 m^3 and 51 m^3, respectively. The rooms are used for teaching and practicing of musical instruments and the acoustical evaluation was carried out by conducting measurements of RT, BNL and standardized level difference. The RT was measured with impulse response method according to the ISO 3382-2 standard. The measurement equipment consisted of an omni-directional loudspeaker, a power amplifier, a sound level meter, and the Dirac software. Exponential sine sweeps were used during the measurements in order to excite the room. The background noise levels were measured with the same sound level meter used for the reverberation time measurements. The standardized level difference was calculated according to the ISO 140-4 standard by using the data obtained from the measurements of sound pressure levels of the rooms that are conducted with the omni-directional sound source generating white noise and the sound level meter. Two points of sound source and three to four receiver points were chosen for each room for the measurements of reverberation time. The reverberation times were analyzed in octave bands from 63 Hz to 8000 Hz. According to the results of the measurements, the first room has a RT higher than recommended values. The second room demonstrated satisfactory results for RT comparing with the recommended values. The third room demonstrated high variations of RT between octave bands. The RT is below the recommended values for the frequencies above 500 Hz and much higher at frequencies below 125 Hz. As a conclusion, the RT parameter is appropriate only for the first room, the background noise levels are less adequate at rooms closer to the street, and in terms of insulation, all three rooms demonstrated inadequate values considering the sound pressure levels of the musical instruments.

Özgencil (2015) studied six conservatory rehearsal rooms located in two conservatory buildings in order to evaluate their acoustical performance with qualitative and quantitative methods. Impulse response test measurements and acoustical simulations were conducted in the rooms and questionnaires were carried out in order to evaluate the user satisfaction of spaces. Improvement suggestions were developed with 3D modeling programs and the suggestion model was simulated with the Odeon room acoustics software. The users listened to improved simulation of the spaces through the auralization feature of the Odeon simulation software. During the measurements of reverberation time, an omni-directional sound source, a power amplifier, an omni-directional microphone, and an external sound card were used along with Odeon software as the analyzer of the room acoustic parameters. The positions of the sound source and the receiver points were determined at 1.5 meters above ground level. The reverberation times of the rooms were measured at eight octave bands ranging between 63 Hz to 8000 Hz. In order to compare the results with the recommended RT values explained in the regulations, the RT levels were mainly evaluated at mid frequencies such as 500-1000-2000 Hz. According to the evaluations of the existing acoustical performance of the rooms, acoustical solution suggestions were developed. After the developments were simulated with the Odeon software, a listening test was carried out with musicians. The conclusion of the study demonstrates that the rooms are not within the value ranges determined in the relevant standards as it was observed that the conservatory rehearsal rooms do not provide the desired acoustical performance from the musician's perspective.

In the study of Daloğlu (2019), the acoustic performance was evaluated of four art workshops in a municipal cultural center where music education, musical rehearsals and collective performances takes place. The acoustical performance of the workshops was analyzed and acoustical problems were identified. According to the findings, development suggestions were presented. Within the scope of the building acoustics, the noise levels arising from the service equipment, sound insulation from the airborne sound, impact sounds, and the sound absorption in the spaces were analyzed using three different methods such as impulse response measurements according to ISO 3382, mathematical calculation and computer aided simulation software. During the measurements of impulse responses an omni-directional loudspeaker, a power amplifier, an external sound card, and eight microphones are used with Audition CC for impulse response recordings and Dirac software for the analyzing the acoustical parameters. Also, AcoubatBIM and CypeSOUND simulation software were used to calculate the acoustical performance of the rooms. The conclusion of the study states that the rooms do not provide the appropriate level of acoustical performance designated for musical education and musical performances when comparing the test results with the regulations and recommended values stated in the literature.

In the literature review, studies that investigate the acoustical performance of educational spaces are analyzed. This analysis demonstrates that:

- The acoustical performances of classrooms were evaluated at certain room acoustic parameters. The core set of these parameters are RT and BNL.
- Besides the RT and BNL parameters, STI and RASTI parameters are determinative parameters for the evaluation of the speech intelligibility.
- The EDT, D50 and C80 parameters form an important parameter set in terms of evaluating the subjective perceptions of sounds. These parameters are used in the evaluations of the definition of speech and clarity of music in educational rooms with a relatively wide range of volumes.
- The evaluation of the parameters explained above is made in octave bands in a range of 63 Hz to 8000 Hz except for STI/RASTI. These parameters are evaluated in broad band range. At some cases the evaluation range is narrowed to six octave bands (125 – 4000 Hz).

- The investigation and evaluation of the acoustical performance of rooms were performed with objective methods that are experimental and computational. Subjective methods were used as supportive studies, including user surveys. In some studies, objective and subjective methods were combined and the results of both methods were compared.
- The acoustical performance of teaching classrooms, multipurpose halls and architectural studios are investigated frequently in the studies. The focus of these studies are mainly the intelligibility and definition of speech since these rooms are used for speech and teaching functions.
- Some studies investigate the acoustical performance of relatively small practice rooms at conservatories, music schools and music education facilities. These studies use experimental methods as the primary method of the study. Some also use computational methods. The focus of these studies is evaluating the music function in the evaluated rooms. They mainly investigate a parameter set of RT and BNL. However, it was found that EDT and C80 parameters are significantly important in terms of evaluating the music function.
- In order to investigate the acoustical performance of music classrooms with multipurpose usage, a combination of a parameter set consisting of RT/T30, EDT, D50, C80 and STI should be the focus of the investigation, since these parameters are correlated with both speech and music functions.
- It was found that studies based on the evaluation of acoustical performance of the multipurpose usage of music classrooms is rare.
- A combination of experimental and computational methods can provide opportunities of developing solution proposals for potential acoustical problems.
- Computer simulations increase the possibilities and potentials of the studies by creating virtual situations that are difficult to perform in real rooms.

1.3. Motivation and Objectives

The different functions and aspects of multipurpose music classrooms require different acoustical conditions. Teaching the theory of music, individual instrument rehearsals and choir rehearsals are three different function types can be seen in these spaces. The room acoustic parameters determined for the acoustical performance of spaces are stated in the ISO 3382-1 standard, with these parameters differing according to the function of each space. However, since each space has its own specific acoustical requirements, the acoustical parameters for the multipurpose music classrooms should be determined. Thus, this study seeks to analyze the acoustical conditions of existing multipurpose music classrooms, where teaching and music practicing functions are performed in the same place, with experimental and computational methods to determine the design principles for the multipurpose music classrooms in terms of architectural acoustics.

The music classrooms with multipurpose use are spaces designed for solving a problem in a practical way by combining multiple activities in a single space. This application develops opportunities for both lecturers and school administration to provide courses and use less space. These music classrooms should provide a volume that is acoustically efficient for both lecture and practicing music. Although there are quite a few studies on the acoustics of teaching classrooms, when music classrooms are examined, the recommended parameter values for classrooms with active teaching of theory are not suitable values for evaluation due to the fact that the music classrooms are also used to produce actual music. In this study, music classrooms of an elementary school building, a middle school building and a high school building are examined. The classrooms are being used for music courses with multiple practices such as teaching musical theory, instrumental practice and singing practice. These functions require different acoustical properties to make the classrooms acoustically efficient. The preliminary examinations of evaluating the noise factor and observations in the classrooms indicate that there are number of potential acoustical defects in the classrooms. It is expected to obtain results with high levels of reverberation and background noise and low levels of the signal-to-noise ratio. Therefore, low levels of speech intelligibility and musical clarity are anticipated through the results. According to the experimental and computational evaluations, the acoustical performances of the music classrooms are determined and an appropriate set of design principles are suggested for spaces that have similar components.

1.4. Scope and Context

In this study, three multipurpose music classrooms in three different schools of a private educational institution located in the center of Kayseri are investigated in terms of room acoustics with experimental and computational methods. The school buildings with the studied music classrooms are located in the campus of the educational institution and share the same schoolyard. The classrooms serve for different grades of students who study in elementary, middle and high school. The experimental studies are performed with a study where the room acoustic parameters are measured at seven selected receiver points in each classroom on different dates. Also, acoustical simulations are performed via computer software as a computational study to search for solutions to the acoustical performance problems of the rooms. According to the investigation results, potential problems regarding the acoustical performance of the music classrooms are determined, and the root causes of the acoustical problems are identified through computational methods. According to the identification of the root causes of acoustical problems, solution proposals are discussed to improve the acoustical performance of the classrooms. The scope and limitations of the study are as follows:

- Two types of functions are considered for the usage of multipurpose music classrooms: speech (teaching the theory of music) and music (teaching and practicing of playing musical instruments and individual singing).
- The defined functions are analyzed considering a single sound source and multi-receiver condition for both speech and music. Multiple sound sources are not defined and are beyond the scope of this study.
- Unoccupied condition of the multipurpose music classrooms is investigated in the experimental studies, since standards define that the experiments should be performed in unoccupied rooms.
- Because the room models are corrected with experimental data at the synthesis stage, the unoccupied condition of the rooms is considered in the computational studies. However, the occupied condition is also investigated as an additional study, following the calibration of room models (see Appendix).

- The acoustical performances of the classrooms are investigated and evaluated using the following acoustics parameters determined as: T30, EDT, D50, C80, and STI.
- Throughout the study, the term ‘acoustical problems’ is used to distinguish the room acoustic parameter values that do not meet the reference ones according to the defined functions.
- The root causes of acoustical problems are analyzed computationally using the experimentally corrected room models.
- Using the outcomes of the study, acoustical problems are identified locally in the spatial domain. Once the local contributions of the surfaces to acoustical problems are identified, it is possible to come up with various countermeasures. To give an idea, some of them are discussed.

1.5. Methods

Experimental and computational studies are performed in order to investigate the acoustical performance of the three multipurpose music classrooms. The experimental studies consist of the measurement of background noise levels and the measurement of the room acoustic parameters in the classrooms. The background noise level measurements are conducted at eight octave bands (63 Hz – 8000 Hz) in order to check the appropriateness of the classrooms according to NC curves and use the obtained data as a reference in the computational studies. The measurements of the room acoustic parameters are performed in in order to evaluate the performance of the classrooms in terms of room acoustics. Impulse response tests are conducted in the multipurpose music classrooms at six octave bands (125 Hz – 4000 Hz) for multiple receiver points. The parameter values obtained from the measurements are compared with the acoustical performance criteria provided in the standards and relevant studies.

At the computational stage of the study, three-dimensional models of the classrooms are produced with the Sketchup modelling software and these models are simulated with the Odeon room acoustics simulation software. The simulations are conducted with the same source and receiver types and positions that are used in the measurements of room acoustic parameters. The results of the measurements and simulations are compared and the three-dimensional models of the classrooms are calibrated. The simulation results are verified by providing compliance with the results of the measured parameters. According to the results of the investigation, solution proposals are developed for improving the acoustical performance of the classrooms on the calibrated models. The proposal models are tested with the simulations and their acoustical compatibility are inspected.

1.6. Sustainability

It is aimed to develop a procedure to identify the sources of acoustical problems using computational methods to discuss the countermeasures. In this respect, the framework of discussions on acoustical improvement is designed in terms of sustainability.

In the context of this study, sustainability refers to preserve the original architectural properties of the building. It is important in two ways: i) the building may be an ancient or a historical one; ii) preservation of the original design with cost-effective usage of materials can be considered.

The improvement of acoustical performance is planned by altering the materials of the surfaces. The importance of preserving the form and architectural properties of spaces is emphasized while developing suggestions to improve the acoustic performance of the classrooms. Since the multipurpose use of music classrooms is considered, some promising acoustical solutions are contemplated in terms of variable design principles of acoustics. In the future, if the usage of spaces is changed, the form and original materials of the space can be preserved by using demountable surfaces in the acoustical solutions. Acoustical solutions can be proposed by ensuring the balance between acoustical quality and cost of the application, as well. To design solution concepts, which use long-lasting materials and systems, are important in terms of efficiency of use. The matters above can be considered simultaneously when improvement proposals are planned for the acoustical performance of multipurpose music classrooms in terms of sustainability.

1.7. Societal and Scientific Impacts

The study will contribute to academic literature in terms of "Architectural Acoustics of Educational Buildings." Despite the fact that there are studies on the intelligibility of speech in the classrooms in literature, studies on the acoustics of music classrooms are limited. Although there are quite few studies and applications in this field in Turkey, critical acoustic parameters suggested for music classrooms can be obtained from the world literature. On the other hand, most of the international studies on music classrooms consider that these music classrooms mainly have music practice and exclude the acoustical requirements of the teaching function of these spaces. However, both functions of teaching and musical practice are performed together in these classrooms. According to these considerations, the original contributions of the current study are as follows:

- Considering the multipurpose use of music classrooms, the term of "Multipurpose Music Classroom" is introduced to the literature in this study.
- To the best of the author's knowledge, there is no such study encountered in the literature that investigates the multiple functions of music classrooms in schools within the combination of the parameters and method used in this study.
- An identification procedure is developed to assess the acoustical problems in multipurpose music classrooms.

Chapter 2

Design of the Study

In this chapter, the acoustical characteristics and fundamental functions of multipurpose music classrooms are discussed, basic information about the physics of sound is given and acoustical concepts related to the study are explained. Also, methods of the study are explained and physical definitions of spaces are given case by case.

2.1. Acoustical Characteristics of Multipurpose Music Classrooms

Room acoustics is one of the key design parameters in the design process of school classrooms due to importance of the communication in the auditory related education models. Inadequate acoustical conditions are affecting the quality of the learning environment, resulting in adverse physiological effects for teachers and students. Acoustical discomfort reduces the effectiveness of education and makes it difficult. High reverberation and background noise are among the inadequate acoustical factors in classrooms. These factors generate problems with intelligibility of speech and communication with the teacher (Wroblewska, 2010). On the other hand, the students of music education demand facilities to be used for both music practicing and quiet activities. Studying sheet music and the theory of music are some of the quiet activities of the students. Also, professional musicians need quiet zones for their break times (Laitinen, & Poulsen, 2008). Therefore, the acoustic comfort parameters in school classrooms that include both music practicing and teaching activities should be evaluated in order to increase the educational quality.

When sound passes through the room, the sound signal is altered by the acoustical conditions. The room filters the sound as it is propagated and transmitted through. The effects of these acoustical conditions can be measured and calculated mathematically. Although there are various acoustical measures that influence the intelligibility of speech, reverberation time is one of the most frequently considered measurements of room acoustics. When the reverberance in a room is increased, the speech gets distorted and the duration of speech components are extended. Therefore, it is possible to state that for most rooms, speech intelligibility is adversely affected by the increase in reverberation time. Minimizing the reverberation time in rooms is a frequently practiced approach of acoustical design to improve speech intelligibility (Galster, 2007).

The fundamental requirements for the volumes designed for speech are declared in six items as follows:

- The loudness level in the volume must be adequate.
- There should be a relatively uniform sound level across the volume.
- The reverberation attributes of the volume should be appropriate.
- The level of the signal-to-noise ratio should be high enough.
- In order to avoid interference with the listening environment, the levels of the background noise should be low enough.
- Acoustic defects such as flutter echoes, long delayed reflections, resonance, and focusing should not exist in the volume (Long, 2006).

The parameters determined in accordance with the research on the intelligibility of speech can be examined and evaluated under different categories. As a result of Hodgson's studies (1999), the variables related to the speech intelligibility in evaluating an existing volume in the classrooms have been identified as reference parameters to investigate. These are reverberation time (RT), early decay time (EDT), background noise levels (BNL), and speech transmission index (STI).

According to Bassuet (2011), the fundamental room acoustic parameters used for evaluating the acoustics of music performance spaces are: Clarity (C80), Loudness (G), Early Decay Time (EDT), Initial Time Delay (ITD), Lateral Energy Fraction (LEF), Inter Aural Cross Correlation (IACC), and Listener Envelopment (LEV). Appropriate conditions of practicing and learning musical instruments are essential for a musician's success in musical performances. Musicians use the practice rooms extensively for developing their performance skills. Therefore, the acoustical performance of rooms designated for learning and practicing music is crucial for the progress of musicians

(Cunha et al., 2013). When there are acoustical problems situated in a music classroom, teachers may experience complications in distinguishing the mistakes of students because of acoustical defects caused by the room (Osman, 2010). A satisfactory classroom requires an adequate size of volume, materials with absorbent characteristics and systematically placed sound diffusing elements, organized with the aim of providing clear auditory communication between students and teachers (Paek et al., 2003).

2.2. Acoustical Concepts

The acoustical concepts used in the study are mainly the objective parameters of room acoustics such as: reverberation time (T30), early decay time (EDT), clarity (C80), distinctness (D50), speech transmission index (STI), and background noise levels (BNL). These parameters are chosen in order to evaluate the acoustical performance of diverse usage types of multipurpose music classrooms. The theoretical information that explains the correlations of physics and the general parameters of acoustics are explained in Section “2.2.1. and the room acoustic parameters are given at Section 2.2.2. in detail.

2.2.1. Physics of Sound

Sound can be considered a wave form that mainly exists in an elastic medium that consists of air, water, earth and building materials. Sound is transmitted through the elastic medium in waves. These waves are referred to as ***sound waves***. Sound is a stimulus that is subjectively perceived by human ear. In this respect, sound is an auditory sensation that is investigated by psychoacoustical methods (Egan, 1988; Everest & Pohlmann, 2009).

The resemblance between the propagation of a sound wave and diffusion of ripples on the surface of a pond is observed due to their propagation patterns. These patterns are almost identical as both elements move away from their sources by an exchange of momentum at constant speed. The sound in the air is propagated by longitudinal waves whereas the ripples are propagated by transversal waves. This is a significant distinction between the two examples (Ginn, 1978).

The frequency of sound is explained with the vibration motion of sound waves. Vibration (back and forth motion) of air particles is created by compression and rarefaction waves. The frequency concept is termed as the number of cycles that the air particles vibrate in one second and it is expressed by 'f.' The unit of frequency is termed as Hertz. The frequency limits of auditory capacity of each living beings are different. A normal young adult is capable of hearing sounds ranging from 20 Hz to 20,000 Hz. Frequencies below 20 Hz are referred to as infrasonic frequencies. These frequencies are only perceived by humans as vibrations but not heard as a sound. Frequencies above 20,000 Hz, are called ultrasonic frequencies. These ultrasonic frequencies are also not heard by humans (Mehta et al., 1999).

The frequency of a sound wave is determined by the number of repetitions of its vibration cycles. The time it takes for a cycle to repeat itself is termed as period and it is expressed by 'T.' The number of cycles of the motion that take place in one second is called the frequency of the vibration and it is expressed by the following equation (Peters et al., 2011):

$$f = \frac{1}{T} \tag{2.2.1.1}$$

Octave bands are used to combine frequencies for measurement and analysis of sound. Since most of the sound sources consist of sound energy in a wide frequency range, the description of sound loudness at each frequency would be extremely detailed. Octave bands divide the frequency range into sections in order to simplify the definition of loudness across the sound spectrum (Egan, 1988; Ermann, 2015).

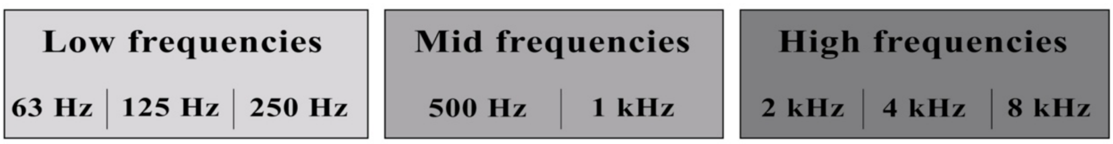


Figure 2.2.1.1 Octave center frequencies. Upper and lower level frequency limits.

In architectural acoustics, eight octave bands with certain center frequencies are important and these octaves are grouped as low, mid and high frequencies (see Figure 2.2.1.1). Octaves between 63 Hz and 250 Hz constitute low frequencies, the range between 500 Hz and 1000 kHz is referred to as mid-frequencies and the range between 2 kHz and 8 kHz are considered as high frequencies (Mehta et al., 1999). The frequency range of speech, music and acoustical laboratory tests across octave bands are provided in Figure 2.2.1.2.

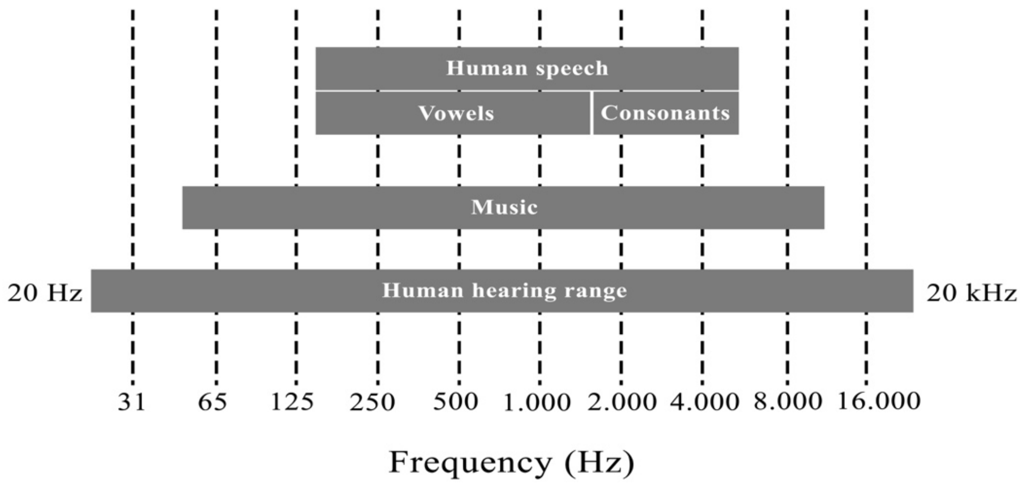


Figure 2.2.1.2 Frequency ranges of human hearing, music and human speech.

Speed of Sound (c) is the distance that sound waves take per unit time. The distance it reaches varies according to the environment characteristics of sound waves and propagation. The temperature for air dispersion at the ideal gas constant is (Rayleigh, 1945):

$$c = (gc\gamma RT)^{1/2} \qquad \textbf{(2.2.1.2)}$$

Where, c = Speed of Sound

gc = Unit conversion factor, Newton (1N= 1kg.m/s^2)

γ = Specific heat

R = Ideal gas constant, 287 J / kg

T = Absolute temperature, x

Room temperature is a function of pressure level and density. Accordingly, the equation for sound velocity is given as (m/s):

$$Cair = 331{,}2 + 0{,}6x\ (C°) \qquad \textbf{(2.2.1.3)}$$

In solids, speed depends on the elasticity coefficient and density of the substance. This size is related to the elasticity coefficient and density of the material which is indicated as (Rayleigh, 1945):

$$c = \sqrt{\frac{B}{\rho}} \qquad \textbf{(2.2.1.4)}$$

Where,	c	= Speed of Sound, m/s
	B	= Bulk Modulus of the medium (Pa)
	ρ	= density of the medium

Wavelength (λ) is described by Ginn (1978) as "the distance between two successive pressure maxima or between successive pressure minima in a plane wave" (p. 13). It is expressed by 'λ' and the relationship between wavelength and frequency is defined as:

$$\frac{c}{f} \qquad \textbf{(2.2.1.5)}$$

Where,	λ	= wavelength (m)
	c	= speed of sound (m/s)
	f	= frequency (Hz)

Amplitude of a sound wave is dependent on the magnitude of the pressure fluctuation and it corresponds to the maximum displacement of a vibrating particle. The displacement of the particle is defined as the distance between two positions of the vibrating particle: instantaneous position and mean position. The unit of the amplitude is meters (m) and the amplitude range of airborne sound is between 10^{-7}mm and a few mm (Ginn, 1978; Barron, 2010).

Sound Intensity (I) is referred to as the average value of the sound energy that passes through a unit area normal to the direction of diffusion. The expression of the intensity varies according to different types of sound fields. Sound intensity is termed as Watt/m^2 and its equation follows as (Ginn, 1978; American National Standards Institute [ANSI], 1994):

$$I = \frac{p_{rms}^2}{\rho c} \qquad \textbf{(2.2.1.6)}$$

Where, I = intensity (W/m^2)

p_{rms}^2 = mean square sound pressure (Pa)

ρ = density of air (kg/m^3)

c = speed of sound (m/sn)

Sound Pressure Level (SPL) is one of the most frequently used variables for designating the sound strength due to its adequate correlation with the human perception of loudness. The human auditory perception capacity is considered in a spectrum between 20 μPa (threshold of hearing) and 20 Pa (threshold of pain). The sound pressure level is expressed in decibels (dB) and each doubling of the sound energy corresponds to a 3 dB increase in SPL as it is defined in the equation (Long, 2006; Mommertz & Müller BBM, 2009):

$$L_p = 10log\frac{p^2}{p_{ref}^2} \qquad \textbf{(2.2.1.7)}$$

Where, p = root-mean-square sound pressure (Pa)

p_{ref} = reference pressure, 2 x 10^{-5} Pa

SPL is a variable that is measured with a microphone located in a sound field. In order to measure the SPL, portable equipment can be used that is referred to as sound level meter (Ginn, 1978). Figure 2.2.1.3 shows some typical sound pressure levels.

	Sound pressure ***p*** **[Pa]**	**Sound pressure level** L_{pA} **[dB]**	
■	20.0	120	Propeller aircraft take-off, threshold of pain
■	2.0	100	Pneumatic drill, discotheque
■	0.2	80	Shouting, busy road
■	0.02	60	Normal speech, loud dishwasher
■	0.002	40	Whispering, mechanical ventilation in offices
■	0.0002	20	Bedroom in quiet area, recording studio
□	0.00002	0	Threshold of hearing

Figure 2.2.1.3 Some typical sound pressure and sound pressure levels (Mommertz & Müller BBM, 2009).

Sound Power Level (SWL) is the amount of the propagated sound energy by a source. In this case, the space of the source is not regarded. If the absorption characteristics and volume of the room is known, it is possible to predict the SWL. It is defined by the following equation (Egan, 1988; Kuttruff, 2009):

$$SWL = 10log_{10}\left(\frac{W}{W_0}\right) \quad \textbf{(2.2.1.8)}$$

Where, SWL = Sound Power Level (dB)

W = Acoustic power of the source

W_0 = Reference acoustic power of 10^{-12}W

Decibel (dB) is a unit of a logarithmic scale used for measuring the sound pressure and sound intensity. It is acquired from a human auditory sensation which is capable of perceiving sound intensities in a wide spectrum. This sensation is also logarithmically proportional to the intensity of stimulation (Maekawa et al., 2011).

Room Acoustics are constituted according to the behavior of sound fields in a closed boundary. The sound waves that are transmitted away from the source and reach the boundaries of the room will behave in three different ways. Primarily, some of the sound energy that reach the boundary will be reflected back into the room. Some of the remaining sound energy will be absorbed from the contacted surface. The other part is transferred beyond the boundaries of the space (Ginn, 1978).

A free Field is a uniform environment which is free from the effects of reflections. When there are no obstacles or boundaries to reflect the sound, the sound propagates with complete straight waves. Free field conditions take place in open areas and in rooms that have surfaces with highly absorptive characteristics. It is also referred to as a direct field since some measurements consider the direct path between a source and a receiver. Sound in a free field is considered spherical (Rossing, 2007; Özgüven, 2008; Barron, 2010). The relationship between the power and pressure of a point source in a free field is explained by the equation follows (Long, 2006):

$$L_p = L_w + 10log\left[\frac{1}{4\pi r^2}\right] + K \quad \textbf{(2.2.1.9)}$$

Where, L_w = sound power level

L_p = sound pressure level

K = $10log(\rho_0\, c_0/400) + 20log(r_{ref})$

r = measurement distance

r_{ref} = 1 m for r

In a free field, the sound intensity at a distant point is inversely proportional to the square of the distance. This is referred to as inverse square law and this law is not effective at fields that are too close to the sound source. The region within 1/4 wave length of the sound source is referred to as ***near field.*** There is also the ***far field*** which is the region beyond the near field (Rossing, 2007; Özgüven, 2008)

Diffuse fields depend on the reverberation characteristics of the room. Unlike the free fields that exist in open areas and anechoic rooms, diffuse fields exist in rooms with defined boundaries. Since every surface reflects sound up to some extent, the diffuse field in a room is formed by complex sound rays that are reflected, absorbed and scattered. The diffuse field is also referred to as a ***reverberant field.*** The sound pressure level is directly related with reverberation time, a parameter depends on the absorption properties in the room. The reverberation time in a diffuse field is generally a single value throughout the room. In this case, the sound pressure levels are similar and not relevant with the location (Rossing, 2007; Kurra, 2009; Xiang, 2017).

The Directionality, Directivity, and Directivity Index concepts are explained with the properties of sound sources. Sound sources generally propagate higher amounts of energy in certain directions than in other directions. Therefore, sound waves from a sound source behave differently in different directions (e.g. the sound pressure generated by a sound source at any distance will be higher in the direction perpendicular to the face of the source than in the other directions). The directivity factor (D) at one point is defined as the ratio of sound intensity at that point to the intensity produced at the same point if the sound propagates properly. It can be defined by (Özgüven, 2008; Peters et al., 2011):

$$D = \frac{I}{I_{ref}} \qquad \textbf{(2.2.1.10)}$$

Where, D = Directivity factor

I = Intensity of sound at one point

I_{ref} = Theoretical intensity at the same point when sound is diffused with spherical waves

Also, by the directivity index, d, expressed in dB. It is defined by:

$$d = 10log_{10}D = 10log_{10}\left(\frac{I}{I_{ref}}\right) \quad \textbf{(2.2.1.11)}$$

Reflection of sound occurs due to the radial propagation of sound in a room in every possible direction. When sound waves make contact with the boundaries of a room, they proceed into different directions as though they are originated from the surface. This situation is referred to as the reflection of sound. If the surface size is two to four times larger than the wavelength, a specular reflection occurs. Specular reflections are typical reflection types that follow the same reflection rules as light. The angle of incidence is equal to the angle of reflection. If the surface size not larger than the wavelength the sound, the angle of reflection is not equal to the angle of incident. Therefore, sound is diffused by scattering (Egan, 1988; Everest & Pohlmann, 2009, Kuttruff, 2009). Reflection of sound is shown in Figure 2.2.1.4.

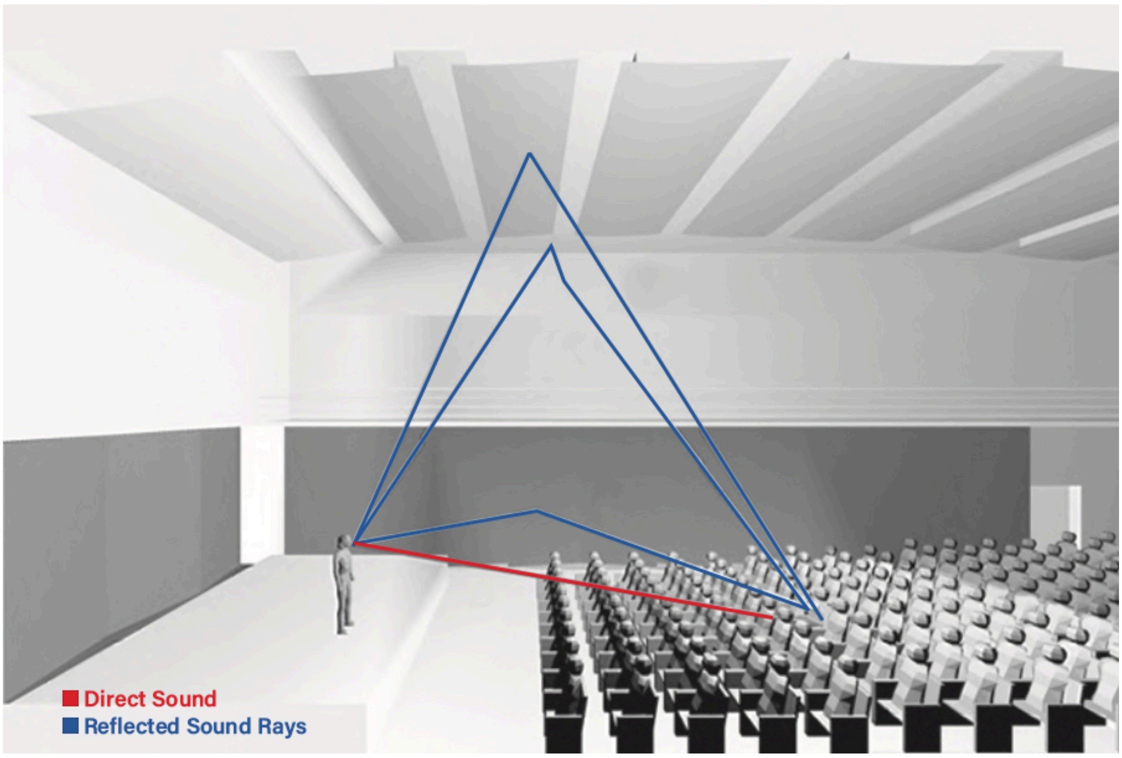


Figure 2.2.1.4 Sound rays in a room (Mommertz & Müller BBM, 2009)

Spherical waves are transformed to plane waves in a long distance due to the inverse square law. Therefore, sound that arrives to various surfaces can be considered as plane wavefronts. When plane waves reflect form a convex surface, the sound energy is scattered in multiple directions. If the contacted surface is in a concave form, the plane waves focus to a point. The focusing and scattering incidents in both situations depends on the size and form of the surfaces (Everest & Pohlmann, 2009).

The diffraction of Sound is the bending behavior of sound around the corners of an obstacle. When the reflected high-frequency sound creates shadow zones beyond the obstacle, the low-frequency sound waves are bent or diffracted. The diffraction phenomenon occurs when the low frequency sound waves are larger comparing with the size of the surface (Rossing, 2007; Barron, 2010).

Absorption of Sound is explained by the concept of absorption coefficients. The properties of the interior surfaces in a room determine the behavior of sound as it reaches the boundary. At this point, the sound energy divides into parts. Some of them are absorbed and transmitted through the boundary, while some of them are reflected back into the room. The absorption coefficient is the capability of a material in terms of sound absorption and is indicated with α. Sound absorption coefficients range from 0 to 1.0 in theory (e.g. Sound absorption coefficient of a material that absorbs 40 percent of the sound energy at a particular frequency is 0.40 for that frequency). The coefficient of a perfectly absorbing material is 1.0, while when no energy is absorbed, the absorbing coefficient is 0. The sound absorption is measured in sabins in honor of Wallace Clement Sabine, the founder of the concept (Egan, 1988; Everest & Pohlmann, 2009).

The growth and decay of sound in a room is a phenomenon that is explained by the concept of geometrical acoustics. Although growth and decay are considered as gradual processes, there is a high amount of intermediate steps that results in a smooth growth and decay pattern. Sound power is continuously applied during the course of growth. The sound source is turned off during the decay of sound. However, sound intensity gradually fades rather than a sudden disappearance. When the geometric acoustic theory is considered, the growth and decay of sound is evaluated with sound absorption coefficients since any material absorbs sound up to a certain level (Everest & Pohlmann, 2009; Maekawa et al., 2011)

2.2.2. Parameters of Room Acoustics Related to Multipurpose Music Classrooms

2.2.2.1. Reverberation Time (RT-T20-T30)

Reverberation time (RT) is a parameter that is explained as the time required for the sound energy to decrease 60 dB after the source is turned off in a room. Its unit of measurement is seconds. RT is directly related to the absorption capabilities of surfaces in the room. The strength of the sound rays decreases gradually due to the occurrence of sound absorption. Therefore, the reflected sounds weaken and die out over time (Beranek, 1996).

The reflections in a room occur after the propagation of direct sound. When the sound makes contact with a surface, it is partly absorbed and partly reflected back from the surface. The rate of the reflection depends on the absorption coefficient of that particular surface. While the reverberation time is proportional to the volume size, it is inversely proportional to the total area of the absorbing surfaces. The reverberation time is calculated and measured in low, mid and high frequency octave bands. These octave bands are in the interval of 63 Hz – 8 kHz (Beranek, 1996; Cavanaugh & Wilkes, 1999).

In room acoustics, the concept that leads to the discovery of reverberation time is first placed on a quantitative ground by Wallace Clement Sabine. Sabine was a professor of physics at Harvard University in the 1900s. The equation, expressed in his own name, is given below in a simplified form as 'Sabine Formula' (Mehta et al., 1999; Cavanaugh & Wilkes, 1999):

$$T = 0{,}16\ V/A \tag{2.2.2.1.1}$$

Where, T = Reverberation time in one second

V = Room Volume

A = Sum of sound absorption areas of all surfaces (including air)

In this equation,

$$A: S1.\alpha 1 + S.2\alpha 2 + \dots\dots\dots + Sn.\alpha n\ ,\ m^2 \tag{2.2.2.1.2}$$

Where, A = Total sound absorption in the space (sabine = m^2)

αn = Sound absorption coefficients of the materials (%)

Sn = Area of each surface (m^2) (Long, 2006).

The reverberation time varies in the frequency domain. A rise of a sound at low frequencies adversely affects the intelligibility of speech. However, most people favor the rise in low frequencies for music. Therefore, the situation in low frequencies can be controlled by the architect or the acoustician. The RT decrease in high frequencies since there is air absorption. The reverberation time is generally evaluated in the average value of mid-frequencies (500 – 1000 Hz) with a single figure (Barron, 2010).

Depending on the volume and function of the spaces, the optimum reverberation time varies. Reference values of RT are shorter for the speech function. Thus, the room should have special absorbing characteristics for speech. However, the desired reverberation time for music spaces is generally longer. The appropriate reverberation times according to volume and function of volumes are indicated in Figure 2.2.2.1.1.

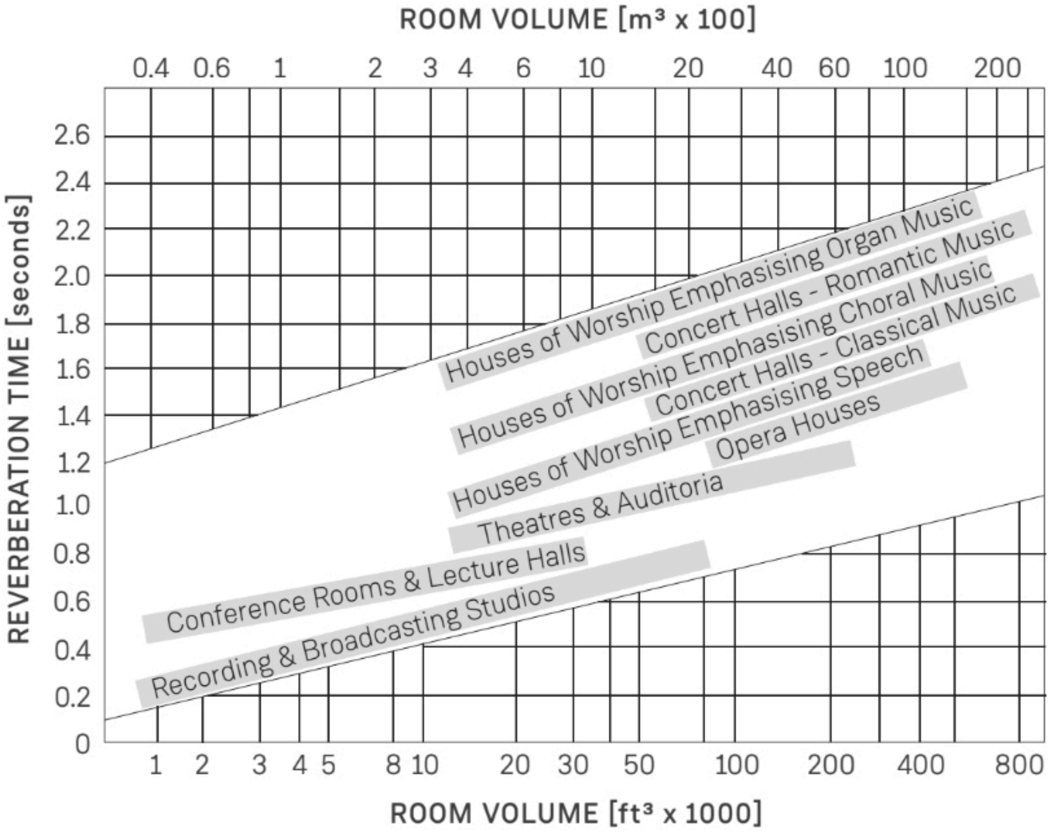


Figure 2.2.2.1.1 The graph of the reverberation time criteria that varies according to the volume and function of the spaces at 500 Hz (Adams, 2016).

According to the classroom acoustics standard published by the American National Standards Institute and Acoustical Society of America (2010), in a classroom with an enclosed volume less than 283 m^3, the maximum 500, 1000, 2000 Hz averaged RT values should be equal to or less than 0.6 seconds. For classrooms with a volume larger than 283 m^3 and smaller than 566 m^3, the RT should be equal to or less than 0.7 seconds. Table 2.2.2.1.1 indicates the recommended or required reverberation times according to regulations and standards of selected countries. The information presented in the table should be taken into account in the acoustical design of regular classrooms and multipurpose music classrooms in schools.

Country	**Room Type**	**Volume**	**Room Situation**	**RT Value / Calculation**
France	Classroom (Music, studying, practice)	$\leq$250 m^3	Furnished, unoccupied	0.4 $\leq$ T $\leq$ 0.8 s
	Classroom (Music, studying, practice)	250 m^3	Furnished, unoccupied	0.6 $\leq$ T $\leq$ 1.2 s
Austria	Communication (Classrooms and media rooms in schools)	30 – 1000 m^3	Occupied	= (0.32 $logV$ - 0.17) s
	Music practice rooms (Practice rooms in music schools)	30 – 1000 m^3	Occupied	= (0.45 $logV$ + 0.07) s
Spain	Classroom	< 350 m^3	With chairs	$\leq$ 0.05 s
UK	Classroom	–	Unoccupied	< 0.8 s
	Music Room	–	Unoccupied	< 1 s
USA	Core classroom	< 283 m^3	Furnished Unoccupied	< 0.6 s
	Core classroom	283 < V $\leq$ 566 m^3	Furnished Unoccupied	< 0.7 s
Finland	School Classroom	–	Built-in furniture, unoccupied	0.6 – 0.8 s
Israel	School Classroom	–	–	0.8 – 1 s
Switzerland	Teaching	30 – 5000 m^3	Occupied	= (0.32 $logV$ + 0.17) s
	Musical performance	30 – 5000 m^3	Occupied	= (0.45 $logV$ + 0.07) s

Table 2.2.2.1.1 Recommended reverberation times in a selection of countries (Deutsches Institut für Normung [DIN], 2004)

The appropriate reverberation times in facilities for medium frequencies are indicated in Figure 2.2.2.1.2. The data varies on the type of usage and the effective room volume. The target curves for music, speech and teaching apply to the room occupied (Deutsches Institut für Normung [DIN], 2004).

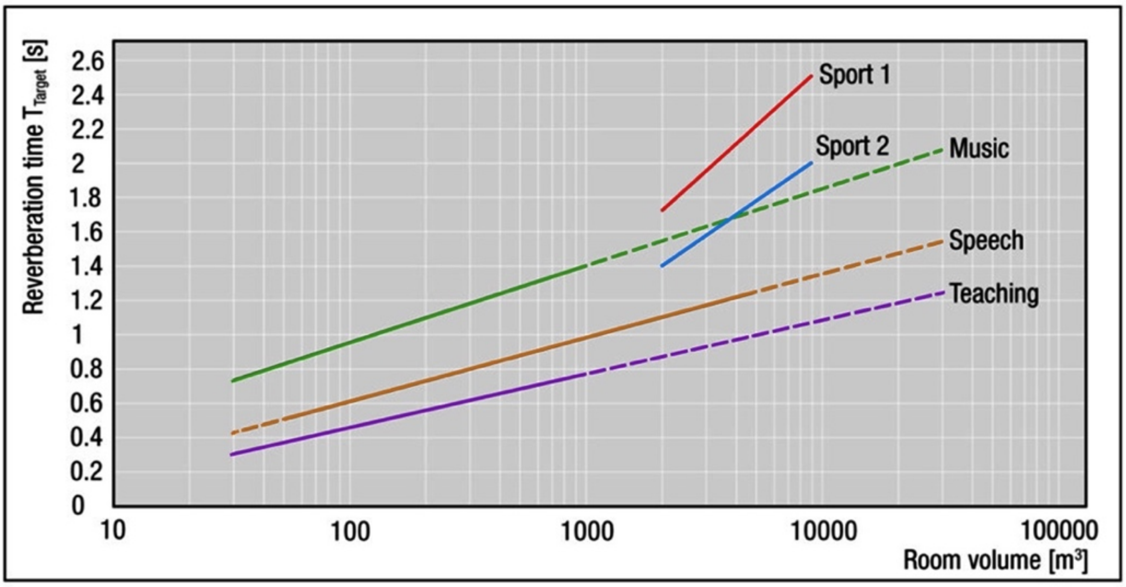


Figure 2.2.2.1.2 Target reverberation times for different functions of spaces in small to medium sized rooms (DIN, 2004).

For facilities that have multiple functions, the value related with the main type of function should be determined and the intermediate values related with the volume should be determined within the curves of reference criteria. Figures 2.2.2.1.3 and 2.2.2.1.4 indicate the reference range of reverberation times according to volume, for speech and music functions respectively. (DIN, 2004).

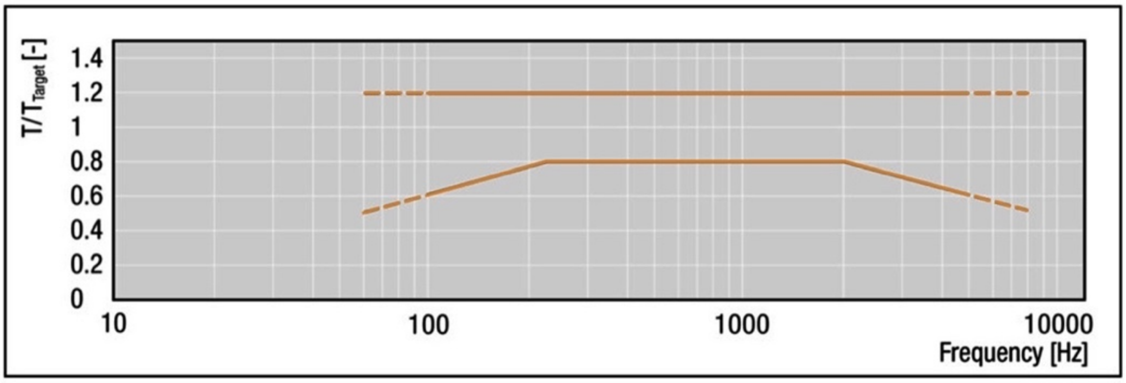


Figure 2.2.2.1.3 Target reverberation time range for speech (DIN, 2004)

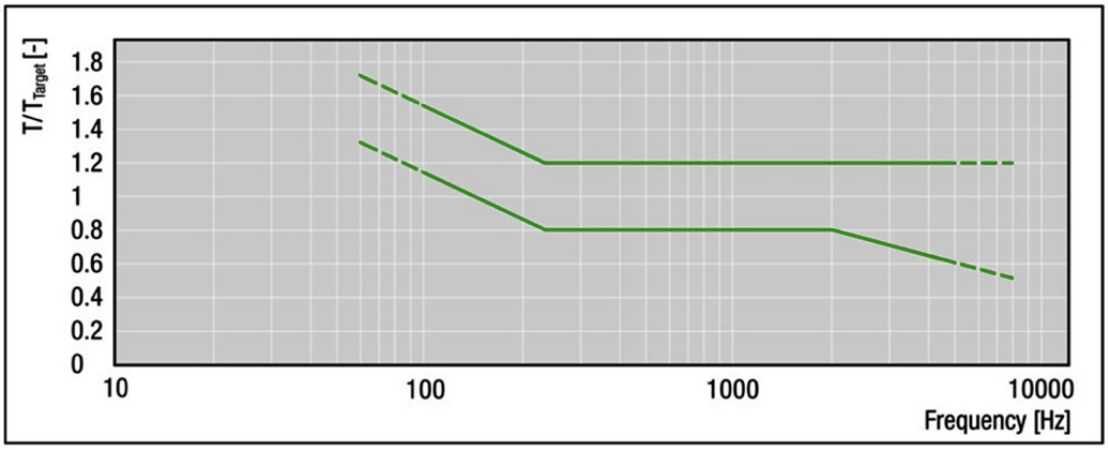


Figure 2.2.2.1.4 Target reverberation time range for music (DIN, 2004)

Reverberation time is highly effective for the music and speech functions in closed spaces. When the reverberance level in the room is above the appropriate limits, speech intelligibility starts to disappear due to the masking effect of louder and lasting sounds. On the other hand, reverberance contributes to the fullness of music function by generating a synthesis of different sounds that belongs to various instruments and vocals (Rossing, 2007). When the reverberation time is very low, the fullness of music is decreased and the room becomes too dry for music. This occurs when the sound level is inadequate at the rear parts of the room (Peters et al., 2011).

2.2.2.2. Early Decay Time (EDT)

In some cases, the sound level in the room is not able to exceed 60 dB above the high level of background noise. Therefore, reverberation time (T30) is obtained by multiplying the time taken to decrease the sound level from -35 dB to -5 dB by 2 after the sound source is turned off (see Figure 2.2.2.2.1). For a similar consideration, the Early Decay Time (EDT) is obtained as a result of multiplying the time taken by 6 to decrease the sound level in the room by 10 dB. The mathematical expression of the parameter is included as (Mehta et al., 1999),

$$T_{avg} = \frac{T_{500}}{2} + \frac{T_{1000}}{2} \quad \textbf{(2.2.2.2.1)}$$

$$EDT_{avg} = 1.1T_{avg} \quad \textbf{(2.2.2.2.2)}$$

The EDT value can be calculated by the following correlation:

$$EDT = t_{10}\ 6 \qquad \textbf{(2.2.2.2.3)}$$

Where, t_{10} = Time it takes for the first 10 dB of sound to decrease, (s)

The complete process of decay is only perceived by receivers during breaks in the music and speech due to masking. The later part of the reverberation, which is the weaker section, is masked by the subsequent musical note or syllable, during the course of speech and music. As a result of this, the EDT parameter is considered to be correlated better with the perceived reverberance for speech and music (Rossing, 2007).

The perception of reverberation is directly related to the first part of the decay where a few early reflections occur. The clarity and liveliness of sound is dependent on early reverberations. The clarity of sound increases when short EDT values are ensured. The clarity is decreased with the increase of late reverberations. Late reverberations provide the perception of liveliness and fullness of sound (Everest & Pohlmann, 2009). The reverberation time is relatively uniform throughout the room, whereas EDT depends on the positions of receivers (Peters et al., 2011).

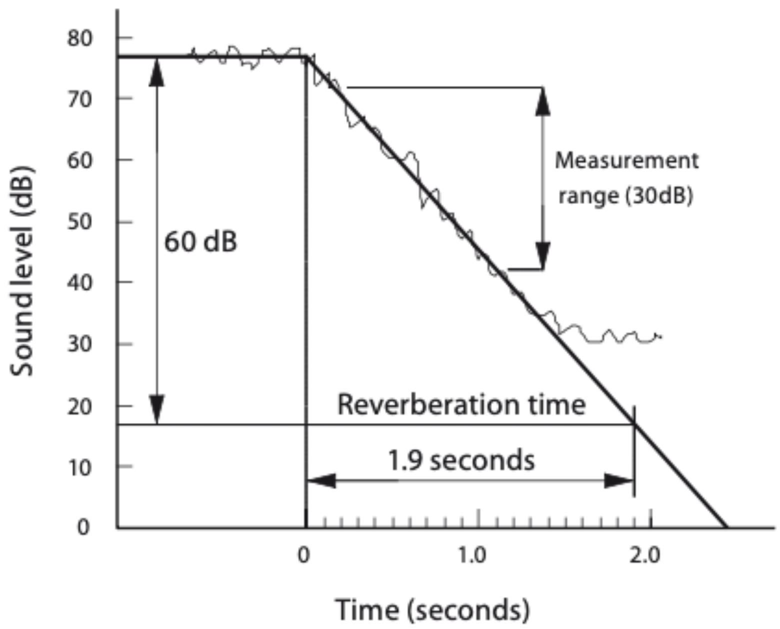


Figure 2.2.2.2.1 Measurement range of reverberation time (Barron, 2010)

2.2.2.3. Clarity (C80)

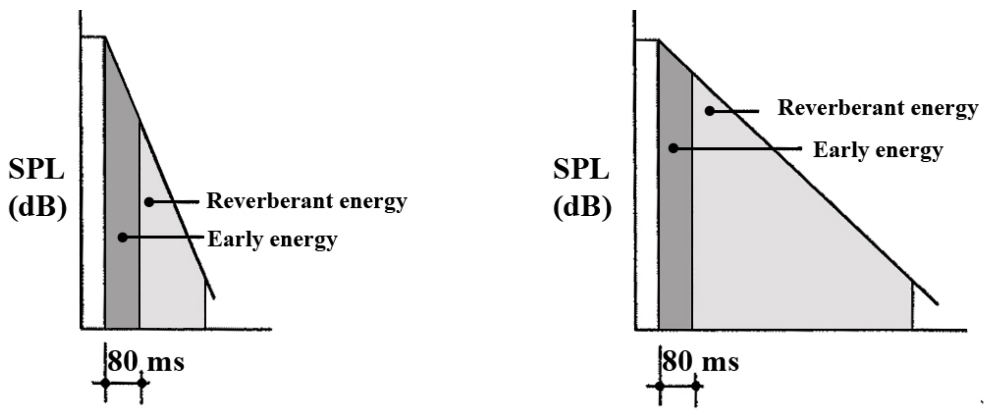
The clarity (C80) index describes the intelligibility and clarity of music and is expressed in dB. It is the logarithmic ratio of the sound energy reaching the receiver in the first 80 ms and the total sound energy arriving after that period. When the C80 gets higher, the clarity of music and intelligibility increases. It was first introduced by Thiele in 1953. It is produced based on the distinctness (D50) parameter which is used to determine the intelligibility of the speech. Clarity is expressed by the following equation (Barron, 2010; Ermann, 2015):

$$C80 = 10log\left(\frac{\int_{0}^{-0.08} p^2(t)dt}{\int_{0.08}^{-\infty} p^2(t)dt}\right) \quad \textbf{(2.2.2.3.1)}$$

Where, C80 = Clarity

$p_{(t)}$ = The instantaneous sound pressure level at 't' moment (Pa)

Investigations into the C80 parameter are generally carried out for traditional music. These parameters are highly variant, depending on the genre of music. The appropriate range for romantic music is between -3 dB and +4 dB, whereas the reference range for modern music can go up to an extent of +6 dB. C80 is an index that compliments reverberation. However, clarity and reverberation time are inversely proportional (Rossing, 2007; Xiang, 2017).



(a) Short RT - high clarity

Early energy (indicated by the darker area) is a large fraction of the total energy, giving greater clarity.

(b) Long RT - low clarity

Early energy (indicated by the darker area) is a small fraction of the total energy, giving greater clarity.

Figure 2.2.2.3.1 Relationship between RT and C80 (Mehta et al., 1999).

In the graph of Figure 2.2.2.3.1 (a), since the early sound energy occupies a large area in the total sound energy, a high clarity value is obtained. In the graph of Figure 2.2.2.3.1 (b), since the early sound energy occupies a small space in the total sound energy, it creates a low clarity value. Therefore, for Figure 2.2.2.3.1 (a), a short RT time gives a high C80 value, while for (b), a long RT time gives a low C80 value (Mehta et al., 1999).

2.2.2.4. Distinctness (Definition – D50)

D50 is a definition that is used for the intelligibility of speech in room acoustics. In 1953, Thiele introduced the concept of Distinctness (originally: Deutlichkeit in German). Distinctness (D50) is percent ratio of the arriving sound in the first 50 ms following the direct sound to the total arriving sound energy at a receiver position. It can be derived from impulse response of the room which is projected as a time-dependent linear system. The adverse effects of background noise are not considered in the calculation of Distinctness. It is expressed in the following equation that considers the logarithmic ratio between the sound energies of early and late reflections (Beranek, 1996; Özçevik, 2005; Long, 2006; Everest & Pohlmann 2009):

$$D50 = \frac{\int_0^{50} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \qquad \textbf{(2.2.2.4.1)}$$

Where, D50 = Distinctness

p^2 (t) = Sound pressure (Pa)

Figure 2.2.2.4.1 indicates the relation of D50 and speech intelligibility. According to the graph, the D50 ratio is recommended to be 50 percent or more to establish a good auditory environment, and it is considered appropriate to have a value between 0.3 and 0.7. The D50 value is inversely proportional to the reverberation time (RT) and is generally considered as a better indicator than the RT value in terms of speech intelligibility (Astolfi et al., 2001; Kuttruff, 2009).

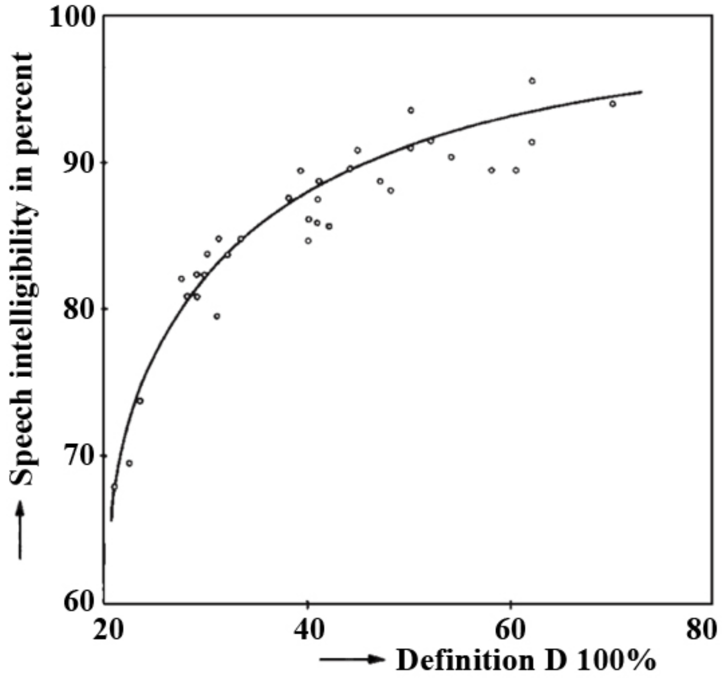


Figure 2.2.2.4.1 Relation Between Distinctness (D50) and Speech Intelligibility (Kuttruff, 2009)

2.2.2.5. Speech Transmission Index (STI)

The Speech Transmission Index (STI) is a metric obtained from the modulation transfer function (MTF) and is used for evaluating the intelligibility of speech. The results of speech recognition tests conducted in different laboratory setups are determined to be correlated with STI. In this concept, the sound field at a receiver's position can be constituted with components such as: direct field, reverberant field and background noise. Also, reverberation time, room volume, signal-to-noise ratio, and source-to-receiver distance are effective on the receiver's sound field (Houtgast et al., 1980).

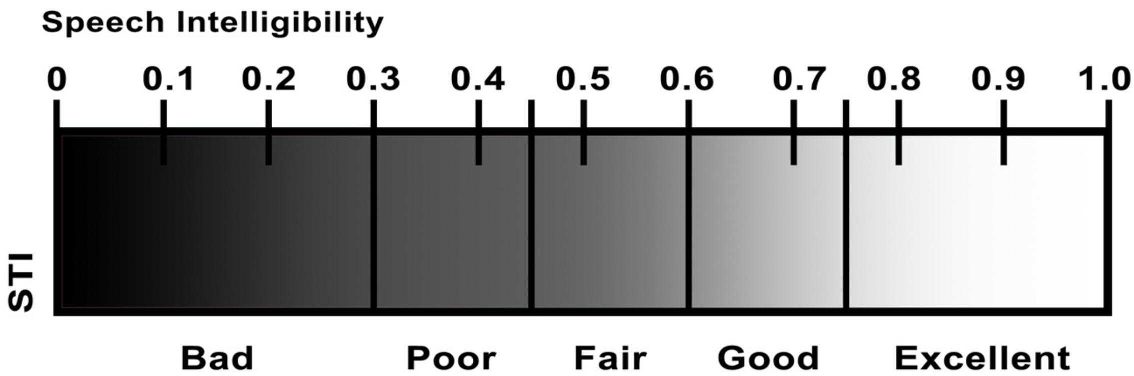


Figure 2.2.2.5.1 Results of various tests between STI and intelligibility values.

The relation of STI and speech intelligibility is established with the speech intelligibility test scores. Reverberation times, echo-delay times and the signal-to-noise ratio are effective in creating a classification scale for STI values. The STI value is referred to as ‘bad’ between 0.00 – 0.30, ‘poor’ between 0.30 – 0.45, ‘fair’ between 0.45 – 0.60, ‘good’ between 0.60 – 0.75, and ‘excellent’ between 0.75 – 1.00 intervals (Houtgast et al., 1980). Figure 2.2.2.5.1 shows the relation between speech intelligibility and STI.

2.2.3. Additional Parameters of Room Acoustics

The Signal to Noise Ratio (SNR) is an important factor that influences speech intelligibility. The difference between the sound levels of speech and noise is directly effective on speech recognition due to the masking of noise over speech. SNR is the ratio of speech and noise levels and its unit is decibels. In an enclosed volume, increasing the SNR can improve the intelligibility of speech because the sound level of a source can suppress the background noise level up to an extent (Mehta et al., 1999).

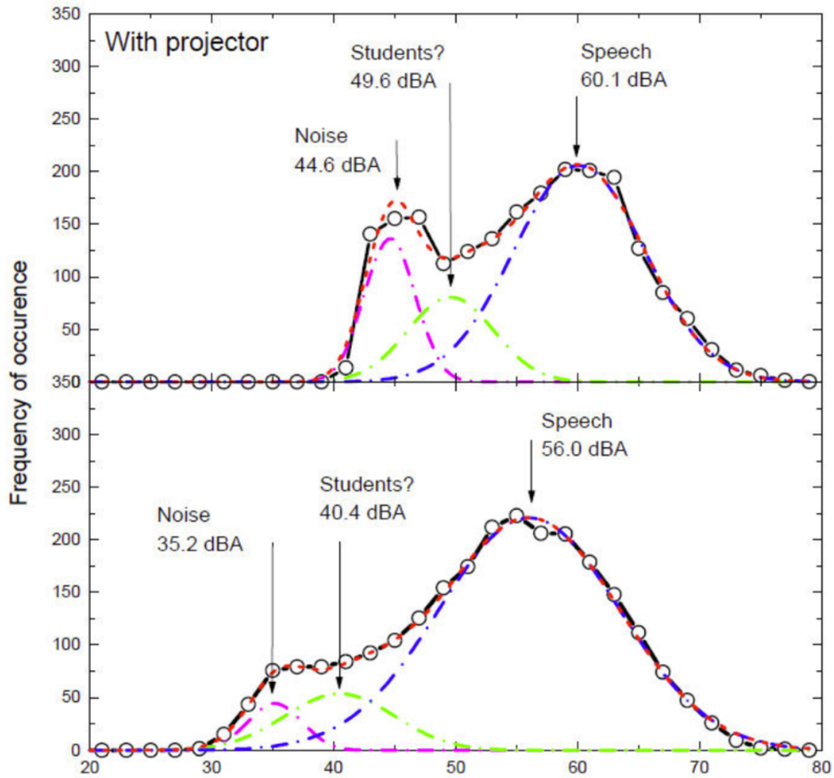


Figure 2.2.3.1 The effect of noise on teachers vocal effort (Bradley, 2002)

A signal level that reaches the receiver point is related with the vocal endeavor of the speaker source. In rooms, the characteristic propensity of speakers is to increase their voice levels to suppress the masking of background noise. This situation is referred to as the 'Lombard Effect.' Figure 2.2.3.1 shows this situation by showing the level distribution of a male teacher speaking in a classroom indicated by the upper panel when the overhead projector with a noise producing fan is turned on. The lower panel of the figure indicates the condition when the projector is turned off. It is observed that the teacher intrinsically raised his noise to suppress the masking noise of the projector (Bradley, 2002). This vocal endeavor of the teacher works as long as it continues. However, in order to achieve an appropriate condition for intelligibility of speech, the background noise should be taken under a value so that there will be an adequate signal-to-noise ratio. Despite the fact that there are various tests examining the speech intelligibility, when the SNR is 15 dB or higher, the best results are achieved (Bradley, 2002; Meriç, 2009).

Initial Time Delay Gap (ITDG) is an acoustical parameter introduced by Beranek (1996) to investigate early reflections in a sound field. A direct sound follows the shortest path to reach to a given receiver position. The reverberant sound arrives to the receiver position quickly after the direct sound. ITDG is defined as the time passes between the arrival time of the reverberant and direct sound. If this time is short, the sound is perceived as intimate. If the receiver is in a relatively small room where the reflectors are in a close range, the ITDG is small. Since the surfaces are close to each other in small spaces, a higher amount of reflection occurs than in large spaces. ITDG generally increases with the size of the room volume. In order to achieve successful ITDG results, the delay gap should be below 25 ms for music spaces. If the delay gap is greater than 40 ms, the receiver may not blend the direct and reverberant sounds well and this indicates a less intimate perception of the sound. ITDG is specifically important in the design consideration of concert halls as it is affected by the position of the receiver in large spaces (Beranek, 1996; Bayazıt, 1999; Everest & Pohlmann, 2009; Xiang, 2017). The Figures 2.2.3.2 – 2.2.3.3 explain sound arriving to a listener's ear. The sound arriving directly from the source reaches the listener first, then there is a gap. After this gap, reflections from the reflective surfaces arrive to the listener in a quick order. The gap indicates the initial time delay gap (ITDG).

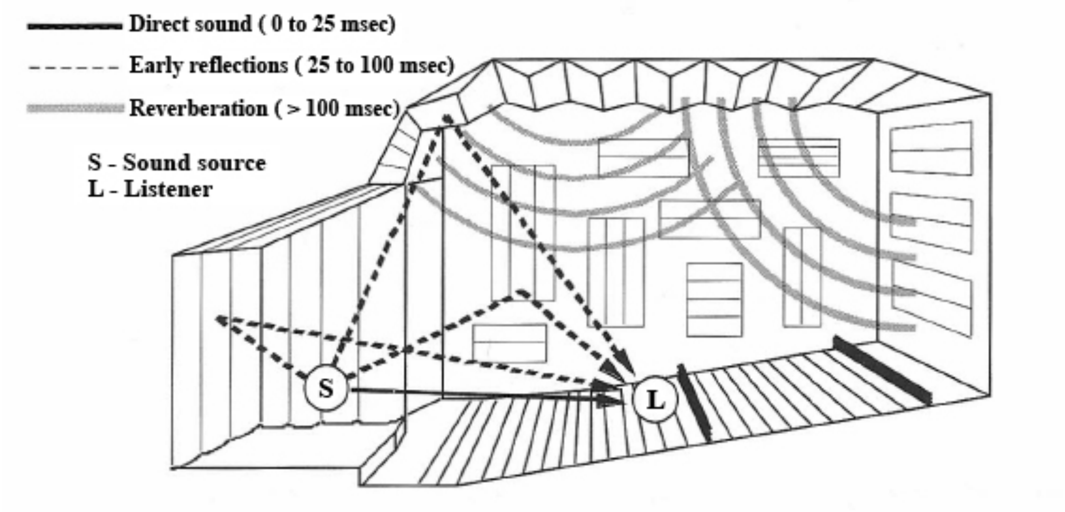


Figure 2.2.3.2 Direct, early reflections and reverberation of sound in an auditorium (Eargle, Foremann, 2002)

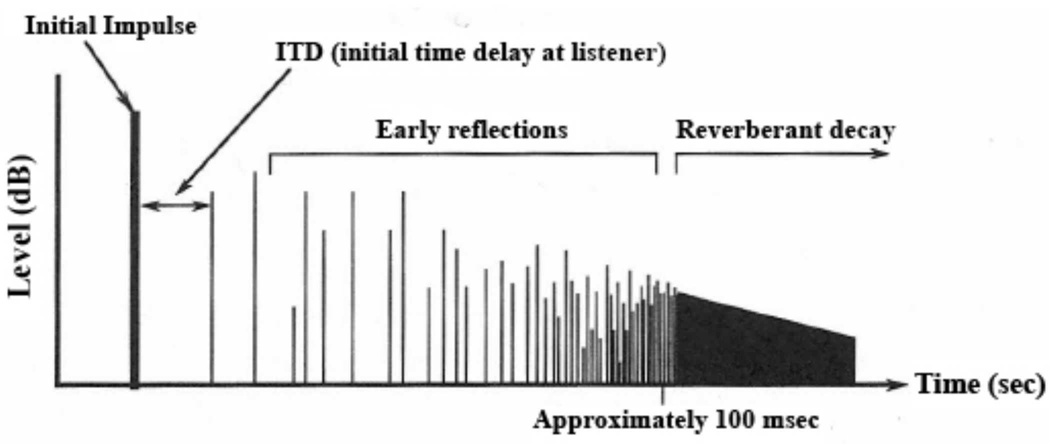


Figure 2.2.3.3 Time behavior of reflections in a room as measured at a listening position (Eargle, Foremann, 2002)

Lateral Energy Fraction is a concept that explains the effects of lateral reflections and is abbreviated as LEF. It is the energy of lateral components of impulse response arriving to a figure-eight microphone within the first 80 ms. The position of the axis is horizontal and perpendicular to the direction towards the sound source in order not to receive the direct energy from the sound source. LEF is the energy at low and mid frequencies that participates to perception of listener envelopment. However, the LEF parameter is not adequate solely to understand the listener perception of spaciousness (Rossing, 2007; Xiang, 2017).

For the measurement of LEF, the ratio between the early 80 ms part of the energy received by a figure-of-eight microphone and the sound energy received by an omni-directional microphone is considered. In this procedure, the figure-eight microphone and the omni-directional microphone are located in the same position directed towards the source. The LEF parameter is determined by the correlation below (Rossing, 2007; Barron, 2010):

$$LEF = \frac{\int_{0.005}^{0.08} P^2(T)cos^2\theta dt}{\int_0^{0.08} p^2(t)dt} \qquad \textbf{(2.2.3.1)}$$

Where, LEF = Lateral Energy Fraction

θ = Angle between the path of the incoming sound and the ear axis of the listener

Center time (T_S) is a parameter developed by Cremer in 1982. It is defined as the balance point of the square of impulse response time. Center time is greatly correlated with reverberation time and early decay time. It is a parameter to understand the dominant sound by showing the center of gravity between the early and late sounds. Besides the RT and EDT, T_s is directly associated to D50 and C80, and the balance of these parameters. The reverberation time and center time are directly proportional. As the center time parameter increases, the late sound energy increases. Therefore, when the center time takes high values, the clarity of music and intelligibility of speech are adversely affected. The center time parameter is determined by the following correlation (Rossing, 2007; International Organization for Standardization [ISO], 2009; Barron, 2010; Ermann, 2015):

$$T_s = \frac{\int_0^{\infty} tp^2(t)dt}{\int_0^{\infty} p^2(t)dt} \qquad \textbf{(2.2.3.2)}$$

Where, T_s = Center Time

P(t) = The instantaneous sound pressure level at ‘t’ moment (Pa)

2.2.4. Acoustic Defects

Rooms designed for listening purposes should not have acoustic defects. These acoustic defects can be listed as: audible echo, flutter echo, sound focusing, resonance, and excessive reverberance. The root causes of these defects are mainly the geometry of the room and the geometry of the source and receiver path. Acoustic defects should be avoided by proper countermeasures (Ermann, 2015).

Echo is a type of reflection that is perceived as a repetition of a sound that arrives to the receiver after the direct sound. Echo reaches to the receiver 50 ms later than the direct sound. The reflection of an echo is more distinctive than the accompanying reflections. Therefore, it is different than reverberation. When there is echo in the room, the intelligibility of speech and music decrease (Barron, 2010).

Flutter echo occurs as a periodically repeating sequence of reflections. If two parallel surfaces such as facing walls or ceiling-floor are produced with reflective materials, flutter echo is heard as multiple-tones that are repeated. Flutter echo creates adverse effects that distort speech and music (Mommertz & Müller BBM, 2009; Maekawa et al., 2011).

Sound focusing is the reflection of a sound from a concave surface that is larger than the wavelength. The sound pressure level at the focused point increases at an extreme rate. This situation creates an irregular distributed sound field in the room. The focusing leads to imperceptible spots at different locations. These spots are referred to as ***dead spots*** (Maekawa et al., 2011). This situation indicates that in a room with sound focusing, the sound field is not diffused properly, and the reverberation time formulas based on the diffuse field assumption become invalid.

Excessive Loudness is a defect which raises the sound level in a space up to an extent causing human hearing damage. It exists in relatively large spaces with a high amount of reflective surfaces. Since the reflected sound waves lose their energy and cover long average travel distances, the audience perceives this situation as excessive sound power. The receiver positions are considered in an ***acoustical shadow*** area if a surface in a room overshadows that particular area (Ermann, 2015).

Resonance emerges as an undesirable sound that depends on room dimensions. When one dimension of the room complies with half the wavelength or a multiple of the same dimension, the resonance take place. Phase cancellations and standing waves may be developed, when low frequency sound wavelengths have dimensions on the order of the dimensions of a room. Resonance is an extremely high or an extremely low sound pressure level that interferes with speech and music and perceived as a booming sound. It is significantly perceptible if there is a whole number ratio of length, height and width of the room. Therefore, in rectangular rooms dissimilar room dimensions are favorable. Resonance is generally identified in relatively small rooms. Music practice rooms, music recording studios and small music classrooms are among examples of where it can be found (Mommertz & Müller BBM, 2009; Ermann, 2015).

2.3. Method of Study

The methods used in the current study are categorized in two groups: experimental studies and computational studies. There are two experimental studies conducted in the study. These are the measurement of background noise levels and the measurement of room acoustic parameters. The computational studies consist of simulations of the room acoustic parameters and the testing of the acoustical design proposals. The purpose of conducting the background noise levels is to use the obtained data in the computer simulations for calculating the speech transmission index (STI) parameter which depends on background noise levels. Also, the noise levels of the classrooms during the education hours are analyzed by comparing the obtained data with NC curves, which is explained in detail in section 3.1.1. The measurements of the room acoustic parameters are very important in terms of investigating the acoustical performance of the multipurpose music classrooms for different educational functions. The measurement data obtained from the measurements of room acoustic parameters are used to calibrate the three-dimensional models that are simulated with the Odeon acoustical simulation software. This procedure is explained in section 3.3. According to the analyses of the results and the synthesis study, root causes of the acoustical problems are determined with an identification procedure, using the calibrated models (see Chapter 4).

The physical properties of the spaces that are measured and simulated are first described in detail in section 2.4. The dimensions of the spaces are measured with laser distance meter. The floor area and volume of the spaces are calculated according to the dimensions obtained. The dimensions and locations of structural elements, openings, divider elements, and educational elements are measured and their materials are defined. These data are used for measurements, three-dimensional modeling and simulation studies.

2.3.1. Experimental Studies

Measurement of Background Noise Level: The World Health Organization (WHO) Guideline on Social Noise states that 35 dBA (L_{Aeq}) should be taken during lecture as the acceptable background noise value and 55 dBA (L_{Aeq}) in gardens and playgrounds (World Health Organization, 1999). The background noise levels should also be measured and results should be evaluated according to "Regulation of Assessment and Management of Environmental Noise," which was published in the Official Newspaper No. 27601 dated June 04, 2010. It states: "The background noise is the total sound remaining in the given position and given state when sounds examined in an environment are suppressed." The same regulation also states: "For the classrooms in the schools, if there is no activity in the usage area, the indoor noise level is 35 dBA with the windows closed and 45 dBA with the windows open." (Official Newspaper, 2010). According to this information, the background noise levels of the multipurpose music classrooms during the lecture times are measured with a noise measurement system.

The background noise measurements are conducted in eight octave bands (63 Hz – 8000 Hz) according to the information stated in the ISO 1996-2 standard. The noise detection setup used in the current study consists of Oktaba Ekofizika 110 B vibration and spectrum analyzer, Oktaba Oktafon 110A - DIN sound level meter and a tripod. The measurements are taken at three non-parallel positions in each classroom at 1.50 meters height. Each measurement at a point is conducted for 10 minutes. The temperature and relative humidity of the rooms are measured for each noise level measurement with Cem Dt 172 Datalogger. The background noise levels are measured in three different periods during the education hours. The results of the measurements are analyzed and compared with NC (Noise Criterion) Curves in order to evaluate the compliance of the background noise levels of the classrooms.

Measurement of Room Acoustic Parameters: Experimental evaluation studies of acoustical parameters to be conducted in the multipurpose music classrooms are important in terms of revealing acoustic problems clearly. Experimental studies are used to measure the acoustic parameters and calibrate the digital models in order to develop solution suggestions. In the current study, experimental studies are performed by applying an impulse response test according to ISO 3382-1 standard. In order to determine the acoustic problems in the volume and to investigate the acoustical quality of the room, EDT, RT, C80, and D50 parameters are measured in the 125 - 4000 Hz octave band range by an impulse response test and the results are evaluated. The impulse response test method is an integrated function of the Odeon software and is the method used in the study for measuring the room acoustic parameters. The software generates sine sweeps to excite the room and the respond signal of the excitation is recorded at receiver points with microphones in real time. The recorded sweep response is deconvolved to calculate and provide the impulse response between the microphone and the source (Odeon, 2020).

During the room acoustic measurements, one laptop computer with Windows 10 Operating System, the Odeon 15 Auditorium software, a Focusrite Scarlet 2i2 external audio interface with two input channels, two Behringer ECM 8000 measurement microphones, two microphone tripods, one dodecahedron omni-directional loudspeaker, one power amplifier for the loudspeaker, and one loudspeaker tripod are used. The temperature and relative humidity values are measured for each impulse response measurement with Cem DT-172 datalogger. Measurements are carried out at a single source position at a height of 1.50 meters and at seven receiver positions at heights of 1.20 m for all the classrooms. The first measurement microphone is located at the first receiver position all the time in order to provide reference data while another microphone which is identical to the reference microphone serving as a mobile microphone. The mobile microphone measures the parameters at the other six receiver positions individually. The reference microphone provides reference data for the accuracy of the experimental study by measuring the room acoustic parameters at a stable location at each measurement of the mobile microphone. The measurement setup and the equipment used for the measurements are given at Figure 2.3.1.1.

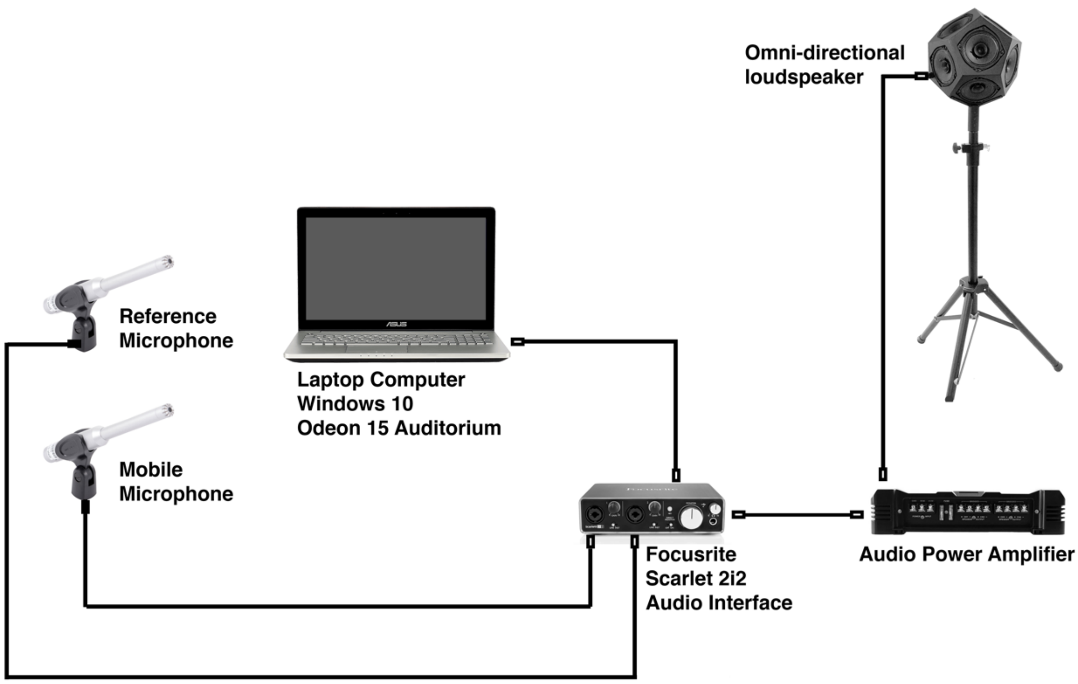


Figure 2.3.1.1 Equipment and setup used for measurement of room acoustic parameters

2.3.2. Computational Studies

Three-dimensional models of the classrooms are created with the Sketchup Pro 2019 software according to actual dimensions of the spaces. These models are simulated through the Odeon 15 Auditorium acoustic simulation software. The Odeon software analyzes the room acoustic parameters with a hybrid set of methods. These are: the image source, early-scattering, ray tracing, and ray-radiosity methods. The combination of these methods is used due to the limitations and restrictions of the individual use of the different methods. Figure 2.3.2.1 shows a sound ray that is originated from a source and travels through a receiver point in one of the simulation models used in the current study. The software calculates the room acoustic parameters of a room in eight octave bands (63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz) with the definitions of source and receiver positions on the three-dimensional model. With the definition of sound absorbing coefficients of the surface materials of the rooms on the three-dimensional models, room acoustic parameters such as EDT, T30, D50, C80, and STI are calculated. In this study, the computer simulation method is used alongside the on-site measurements as a quantitative study in order to determine the current acoustical performance of the multipurpose music classrooms.

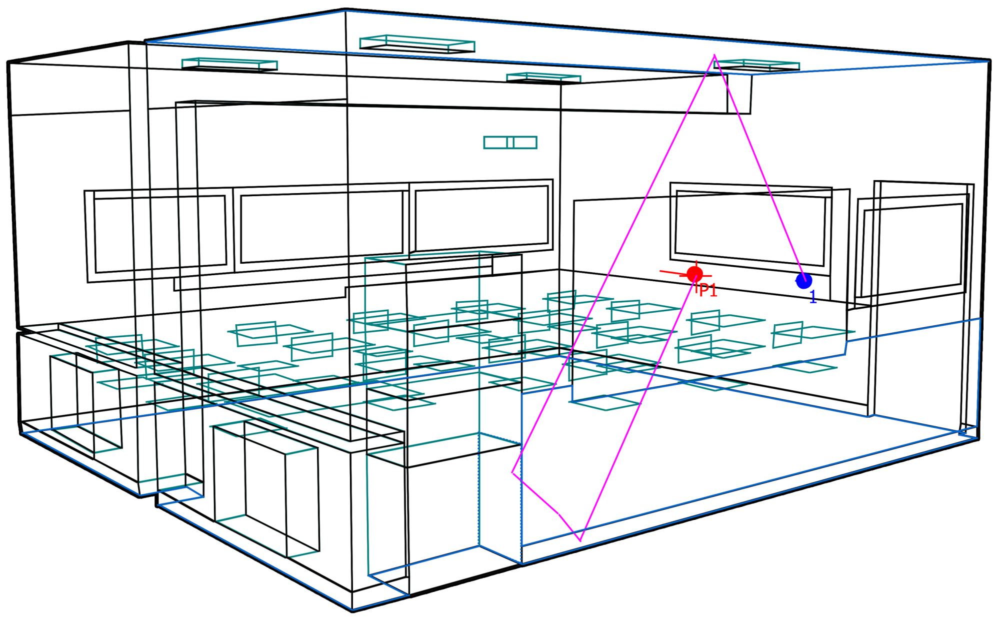


Figure 2.3.2.1 Transmission of a reflected sound ray from source to receiver in one of the simulation models

It is aimed to compare the measurement and simulation results of the classrooms on the basis of room acoustic parameters in order to calibrate the three-dimensional models. Furthermore, it is aimed to analyze the acoustical performance of the classrooms by evaluating the room acoustic parameters obtained from the studies. After the evaluation, it's aimed to diagnose the sources of the acoustical problems with grid analyses on the surfaces of classrooms using the calibrated models.

2.4. Physical Definitions of Spaces

The campus of the educational institution consists of six buildings. Three of them are school buildings, one is a dining and cafeteria building, one is a sports complex, and one is the administrative building of the foundation of the institution. The three multipurpose music classrooms selected in the study are in three different school buildings located in the campus. These buildings are the elementary school building, middle school building and high school building, respectively. The buildings are parts of the same educational facility and they share the same schoolyard. The music classrooms share some of their physical properties such as: finishing materials of some of the surfaces, number of desks and the dimensions of some of the furnishing elements. However, there are major differences such as the dimensions of classrooms, area of absorbing and scattering surfaces and situation-specific furnishing configurations.

2.4.1. Elementary School Music Classroom

The elementary school building was built in 2016 as an additional facility to the campus and it is located at its South-West wing. The building serves only elementary education. The ground floor of the elementary school building is reserved for the branch classrooms. The multipurpose music classroom is located on the ground floor along with other branch classrooms such as: IT classroom, chess and mind games classroom, creative drama classroom, robotic coding classroom, and classroom of visual arts. Figure 2.4.1.1 shows the location of the music classroom on the ground floor plan.

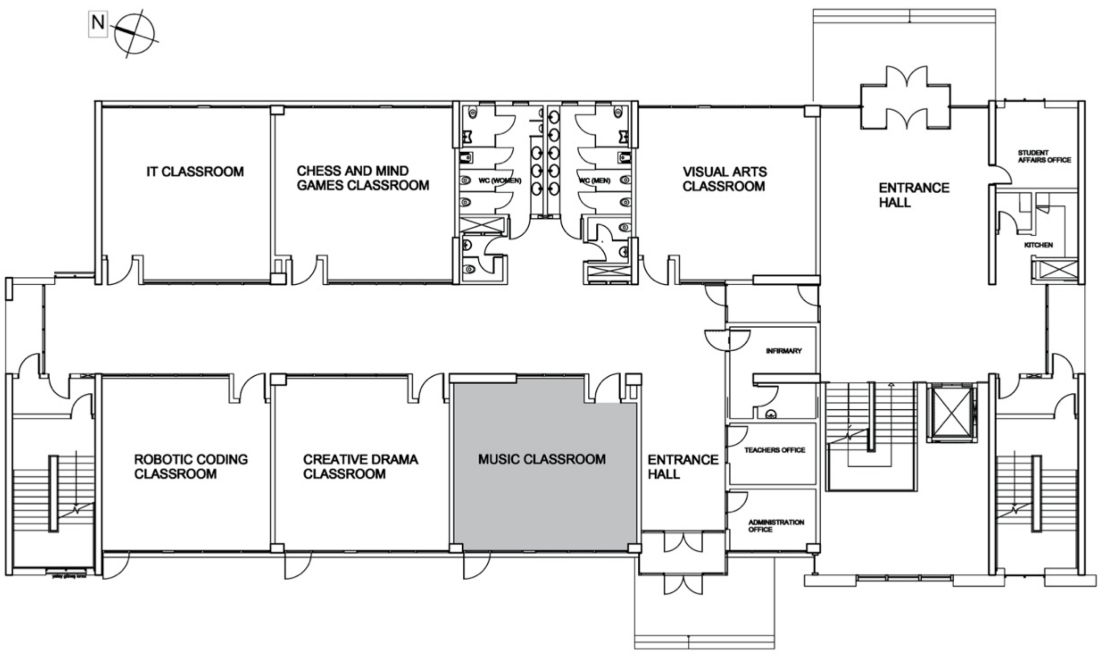


Figure 2.4.1.1. Ground floor plan of the elementary school

Figure 2.4.1.2. Music classroom of elementary school

The floor area of the elementary school music classroom is 59.70 m^2 and its volume is 171.60 m^3. The classroom has a length of 8.2 m, width of 7.5 m and height of 2.86 m. There is a wooden door measuring 120 cm x 220 cm with a glass window on its surface measuring 30 cm x 100 cm and an aluminum joinery garden door with glass measuring 120 cm x 275 cm. There are three aluminum joinery windows measuring 145 cm x 275 cm and one aluminum joinery window measuring 120 cm x 275 cm facing outside, as well as two aluminum joinery windows measuring 90 cm x 70 cm and two 120 cm x 70 cm window facing inside the building. There is a partial suspended ceiling measuring 790 cm in length, 105 cm in width and 8 cm in height, with an aluminum grill measuring 90 cm x 720 cm that is designed to hide the fan coil units. The furniture and educational elements consists of: 24 student desks made from werzalit measuring 65 cm x 50 cm with metal legs at 70 cm height, 24 werzalit chairs measuring 42 cm x 36 cm of seat area, 35 cm x 30 cm of seat back area with metal legs at 42 cm height, one educator desk with a table top made from wood measuring 110 cm x 60 cm at a height of 80 l cm, one white writing board measuring 300 cm x 125 cm at a height of 80 cm from the floor level, one wallboard measuring 100 cm x 50 cm at a height of 210 cm that is made from thin chipboard, two wooden bookshelf units measuring 70 cm x 50 cm at a height of 160 cm, two wooden bookshelf units measuring 70 cm x 50 cm at a height of 187 cm, one wooden bookshelf unit measuring 80 cm x 60 cm at a height of 154 cm, one wooden bookshelf unit measuring 70 cm x 50 cm at a height of 130 cm, six metal lighting fixtures measuring 120 cm x 15 cm that are mounted on ceiling, and one piano measuring 137 cm x 41 cm at a height of 80 cm that is made from wood. Table 2.4.1.1 indicates the physical and architectural properties of the classroom.

Unit / Element	**Size / Quantity**	**Material**
Floor	59.70 m^2	PVC coating over screed over concrete slab
Ceiling	47.56 m^2	Paint and plaster over gypsum over rockwool and insulation foam
Partial Suspended Ceiling	8.29 m^2	Paint and plaster over gypsum over rockwool and insulation foam
Grill (area of the surface applied)	6.48 m^2	Aluminum
Walls	52.49 m^2	Paint and plaster over gypsum over rockwool and insulation foam
Columns	12.86 m^2	Paint and plaster over concrete
Beams	4.56 m^2	Paint and plaster over concrete
Volume	171.60 m^3	-
Door	2.64 m^2	Pressed filler, 2 surfaces covered with 8 mm laminate and glass window
Garden Access Door	3.3 m^2	Aluminum joinery with double glass 6-8 mm thick with 16 mm gap in between
Windows (Glass Surface)	17.74 m^2	Double glass 6-8 mm thick with 16 mm gap
Student Desks	7.8 m^2	18 mm werzalit desk with metal legs
Student Chairs	6.14 m^2	18 mm werzalit chairs with metal legs
Educator Desk	2.1 m^2	18 mm chipboard, laminated on 2 sides with metal legs
Adjustable Office Chair	0.36 m^2	Polyurethane foam covered with fabric with polyurethane plastic legs
Writing Board	3.75 m^2	Aluminum framed laminate writing board
Wallboard	0.50 m^2	Thin chipboard
Bookshelves	21.60 m^2	18 mm chipboard, laminated on 2 sides
Lighting Fixtures	2.28 m^2	Aluminum fixture case with polycarbonate light diffuser cover
Projection Device	0.19 m^2	Plastic surface
Piano	3.41 m^2	Wood surface

Table 2.4.1.1. Physical and architectural properties of elementary school music classroom

2.4.2. Middle School Music Classroom

The Middle School Building was built and started education in 2019 as an additional facility to the campus. The building is located at the South-East side of the campus. The ground floor and first floor of the building partially serve as a kindergarten.

The multipurpose music classroom is the only classroom on the ground floor of middle school. The other rooms on the ground floor are the service units. There is also a storage room adjacent to the music classroom which could only be accessed from the music classroom by a double door. The storage room contains musical equipment and instruments of marching band and a drum set. At the back side of the classroom there is a chorus platform with stools which is a designated area for choral practices. The front side of the classroom serves for teaching theoretical classes, instrument practice and singing practice. Figure 2.4.2.1 shows the location of the music classroom on the ground floor plan.

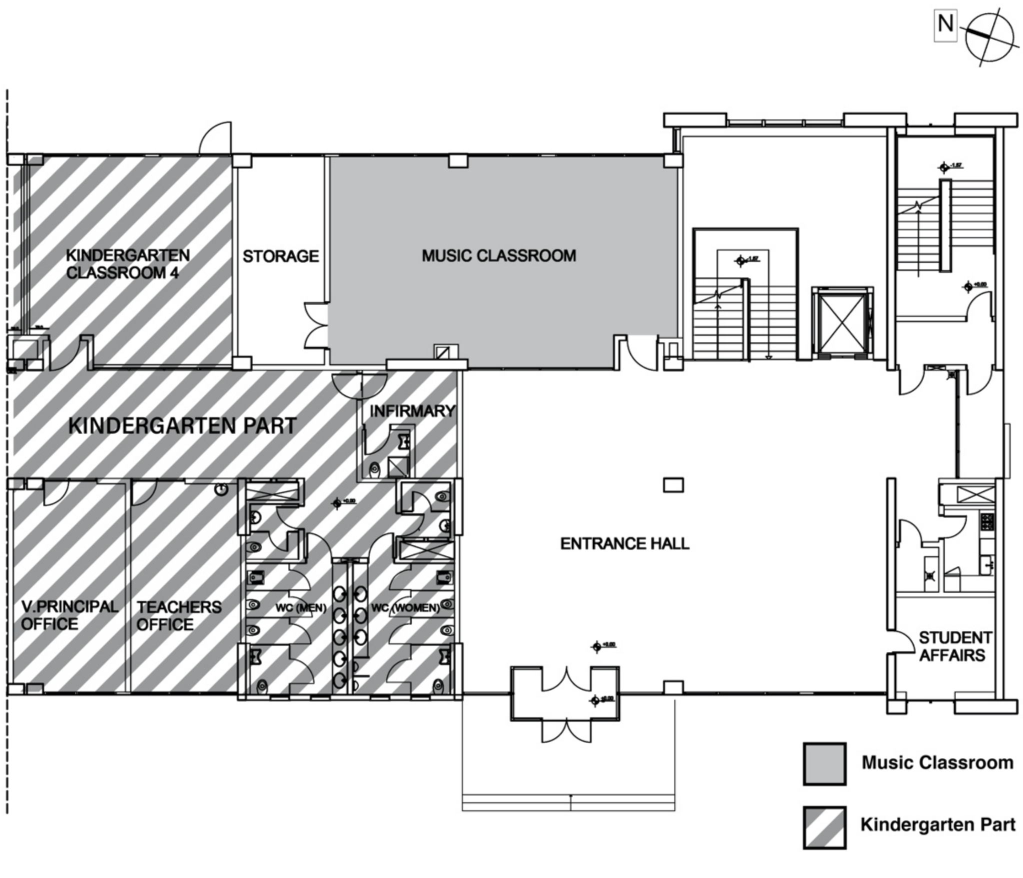


Figure 2.4.2.1. Ground floor plan of the middle school

Figure 2.4.2.2 Music classroom of middle school

The middle school music classroom has a floor area of 95.50 m^2 and a volume of 272.17 m^3. The length of the classroom is 12.85 m, its width is 7.5 m and its height is 2.85 m. There is a partial suspended ceiling measuring 12.85 m in length, 1.4 m in width and 8 cm in height with an aluminum grill measuring 0.9 m x 11.5 m that is designed to hide the fan coil units. There is a wooden door measuring 120 cm x 220 cm with a glass window on its surface measuring 30 cm x 110 cm, a wooden double door measuring 180 cm x 220 cm which connects the music classroom and the storage. There are four aluminum joinery windows measuring 120 cm x 275 cm, one aluminum joinery window measuring 160 cm x 275 cm, one aluminum joinery window measuring 145 cm x 275 cm, two aluminum joinery windows measuring 135 cm x 275 cm facing outside, four aluminum joinery windows measuring 135 cm x 50 cm, and one window measuring 120 cm x 75 cm facing inside the building. The furniture and educational elements are consists of: 24 student desks made from werzalit measuring 65 cm x 50 cm with metal legs at 70 cm height, 24 student chairs measuring 42 cm x 36 cm of seat area, 35 cm x 30 cm of seat back area with metal legs at 42 cm height, one educator desk with a wooden table top measuring 140 cm x 75 cm with metal legs at a height of 70 cm, one plastic adjustable office chair with a seat area measuring 45 cm x 50 cm at a height of 56 cm that is made from polyurethane foam and fabric, one white writing board measuring 200 cm x 125 cm at a height of 82 cm, two white boards measuring 100 cm x 125 cm at a height of 82 cm from the floor level, one wallboard made from thin chipboard and with wooden frame measuring 100 cm x 50 cm at a height of 210 cm, one wooden bookshelf unit measuring 70 cm x 35 cm at a height of 160 cm, two heat radiators measuring 90 cm x 125 cm fixed on the wall with a height of 20 cm from the floor, one 'L' shaped platform made from wood designated for choral practices, 24 cylindrical stools covered with fabric measuring 40 cm in diameter and 40 cm height, eight lighting fixtures mounted on the ceiling measuring 120 cm x 5 cm, one projection device measuring 32 cm x 30 cm that is suspended from ceiling, and one piano measuring 137 cm x 41 cm at a height of 80 cm that is made from wood. Table 2.4.2.1 shows the physical and architectural properties of the classroom.

Unit / Element	**Size / Quantity**	**Material**
Floor	95.50 m^2	PVC coating over screed over concrete slab
Ceiling	63.90 m^2	Paint and plaster over gypsum over rockwool and insulation foam
Partial Suspended Ceiling	15.10 m^2	Paint and plaster over gypsum over rockwool and insulation foam
Grill (area of the surface applied)	10.38 m^2	Aluminum
Walls	67.39 m^2	Paint and plaster over gypsum over rockwool and insulation foam
Columns	12.86 m^2	Paint and plaster over concrete
Beams	6.82 m^2	Paint and plaster over concrete
Volume	272.17 m^3	-
Doors	6.60 m^2	Pressed filler, 2 surfaces covered with 8 mm laminate and glass window
Heat Radiators	2.25 m^2	Aluminum
Windows (Glass Surface)	28.88 m^2	Double glass 6-8 mm thick with 16 mm gap
Student Desks	7.8 m^2	18 mm werzalit desk with metal legs
Student Chairs	6.14 m^2	18 mm werzalit chairs with metal legs
Educator Desk	1.43 m^2	18 mm chipboard, laminated on 2 sides with metal legs
Adjustable Office Chair	0.36 m^2	Polyurethane foam covered with fabric with polyurethane plastic legs
Writing Board	5 m^2	Aluminum framed laminate writing board
Wallboard	0.50 m^2	Thin chipboard
Bookshelves	2.97 m^2	18 mm chipboard, laminated on 2 sides

Lighting Fixtures	2.56 m^2	Aluminum fixture case with polycarbonate light diffuser cover
Projection Device	0.19 m^2	Plastic surface
Piano	3.41 m^2	Wood surface
Choir Platform	11.10 m^2	25 mm chipboard, laminated on 2 sides
Stools	14.88 m^2	Polyurethane foam covered with fabric

Table 2.4.2.1. Physical and architectural properties of middle school music classroom

2.4.3. High School Music Classroom

The building of the high school is the first educational building of the campus that was established in 1966. The building served as elementary, middle and high schools in years, and after the new education buildings started to be used, it was converted into a high school building that only served that purpose. Classrooms in the building have been functionalized for various purposes over the years and became permanent in 2019.

The multipurpose music classroom in the building is located on the first floor which is reserved for the branch classrooms of high school students. The floor was serving as a floor of middle school before the current building of middle school was opened. The music classroom of the high school was located on the basement floor prior to the commissioning of the new buildings. Therefore, the current location of the classroom is not a room designed to be a music classroom in the first place; it was later converted into a multipurpose music classroom. The plan of the multipurpose music classroom of the high school is provided in Figure 2.4.3.1.

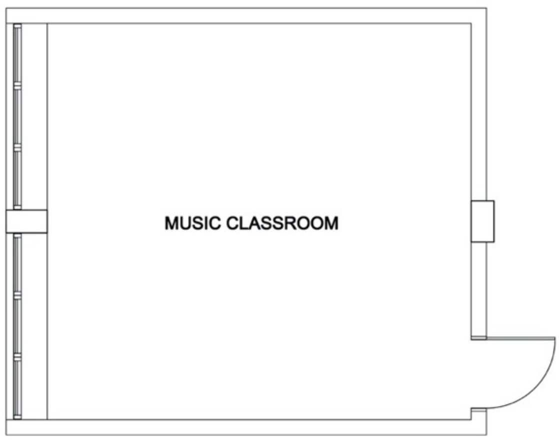


Figure 2.4.3.1. Plan of the high school music classroom.

Figure 2.4.3.2. Music classroom of high school

The multipurpose music classroom in the high school has a floor area of 30.50 m^2 and its volume is 93.9 m^3. The length of the classroom is 5.90 m, the width is 5.20 m and the height is 3.10 m. There is a wooden door measuring 90 cm x 210 cm and six PVC joinery windows measuring 80 cm x 175 cm. The furniture and educational elements in the classroom consists of: 18 werzalit student desks measuring 62 cm x 44 cm with metal legs at a height of 75 cm from the floor level, 18 werzalit student chairs measuring 40 cm x 40 cm of seat area and 40 cm x 17 cm of seat back with metal legs at a height of 43 cm from the floor level, one educator desk with a wooden table top measuring 120 cm x 60 cm with metal legs at a height of 72 cm, one plastic adjustable office chair with a seat area measuring 45 cm x 50 cm at a height of 56 cm that is made from polyurethane foam and fabric, one blackboard measuring 270 cm x 120 cm at a height of 90 cm, one wallboard with wooden frame measuring 150 cm x 80 cm at a height of 123 cm, one wallboard with wooden frame measuring 140 cm x 80 cm at a height of 123 cm, three wallboards measuring 200 cm x 80 cm at heights of 123 cm, one wooden bookshelf unit measuring 80 cm x 40 cm with a height of 180 cm, two heat radiators fixed on the wall measuring 90 cm x 60 cm x 21 cm with a height of 10 cm from the floor, and four lighting fixtures mounted on the ceiling measuring 64 cm x 34 cm, and one projection device measuring 32 cm x 30 cm that is suspended from the concrete beam. The physical and architectural properties of the high school multipurpose classroom are indicated in Table 2.4.3.1.

Unit / Element	**Size / Quantity**	**Material**
Floor	30.50 m^2	PVC coating over screed over concrete slab
Ceiling	29.90 m^2	Paint and plaster over concrete slab
Walls	54.19 m^2	Paint and plaster over brick wall
Columns	3.35 m^2	Paint and plaster over concrete
Beams	6.36 m^2	Paint and plaster over concrete
Volume	93.90 m^3	-
Door	1.90 m^2	Pressed filler, 2 surfaces covered with 8 mm laminate
Windows (Glass Surface)	8.62 m^2	Double glass 6-8 mm thick with 16 mm gap
Student Desks	4.9 m^2	18 mm werzalit desk with metal legs
Student Chairs	4.32 m^2	18 mm werzalit chairs with metal legs
Educator Desk	0.72 m^2	18 mm chipboard, laminated on 2 sides with metal legs
Adjustable Office Chair	0.36 m^2	Polyurethane foam covered with fabric with polyurethane plastic legs
Writing Board	3.24 m^2	Aluminum framed laminate writing board
Wallboard (Cloth Covered Surfaces)	5.18 m^2	Fabric covered foam over thin chipboard
Bookshelves	4.16 m^2	18 mm chipboard, laminated on 2 sides
Lighting Fixtures	1.04 m^2	Plastic fixture case
Projection Device	0.19 m^2	Plastic surface

Table 2.4.3.1. Physical and architectural properties of high school music classroom

Chapter 3

Determination of Acoustical Performance of Multipurpose Music Classrooms: The Case Study

3.1. Experimental Studies

The acoustical performances of the multipurpose music classrooms are investigated by obtaining the room acoustic parameter data such as EDT, RT, C80, STI, and D50 in six octave bands (125 Hz – 4000 Hz). In order to obtain the data, background noise levels and room acoustic parameters are measured in all three classrooms. The background noise levels are required to adjust the sound levels during the measurements of room acoustic parameters and to check that the noise levels of the room are compatible for education. After obtaining and evaluating the background noise levels, the room acoustic parameters are measured with an impulse response test. The compatibility of the acoustical performance of the music classrooms has been evaluated by comparing the parameter values obtained from the measurements and the appropriate parameter values defined in the regulations and literature for educational spaces. Also, the data obtained from the measurements are compared with the data obtained from the computer simulations in order to calibrate the digital models and verify the computational results.

3.1.1. Measurement of Background Noise

The fact that the background noise in the room is within the appropriate limits is crucial in terms of ensuring the intelligibility of the speech. Accordingly, background noise measurements for multipurpose music classrooms are carried out at three measurement points in each classroom, determined based on the size and spatial organization of the classrooms. The measurement points are located at a height of 1.5 m from the floor and at least 1.5 m away from the nearest walls. The measurements are performed based on the ISO 1996-2 standard with the noise measurement setup and properties described in Section 2.3.1. The positions of the measurement points with distances for multipurpose music classrooms of elementary school, middle school and high school are indicated on Figure 3.1.1.1, Figure 3.1.1.2 and Figure 3.1.1.3 respectively.

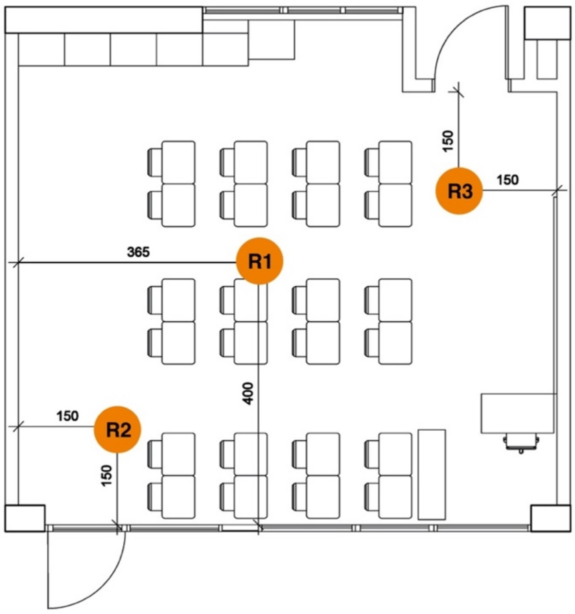


Figure 3.1.1.1 Receiver (R1-R3) points used for determining the background noise levels of elementary school music classroom

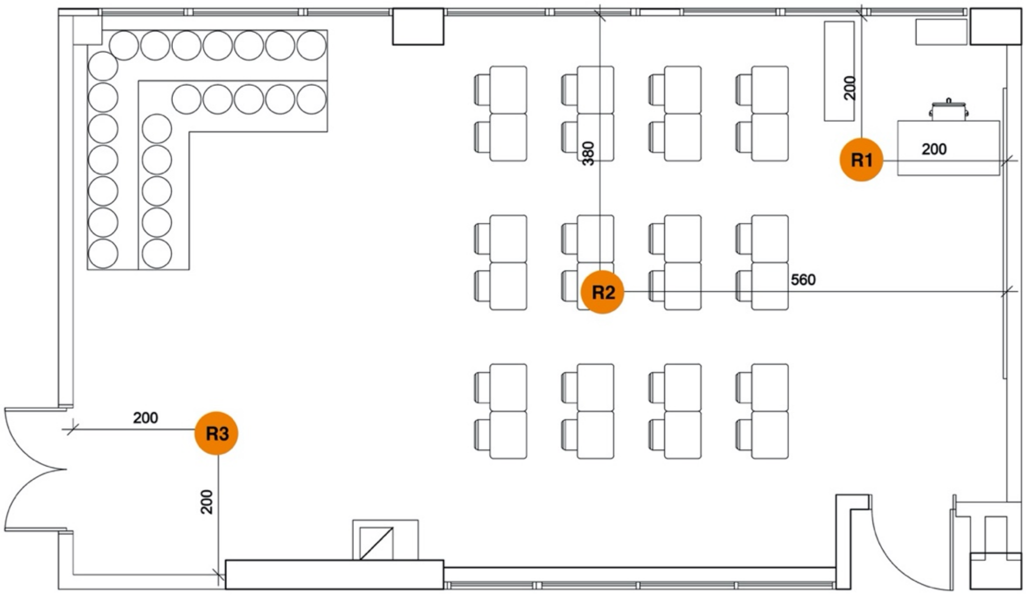


Figure 3.1.1.2 Receiver (R1-R3) points used for determining the background noise levels of middle school music classroom

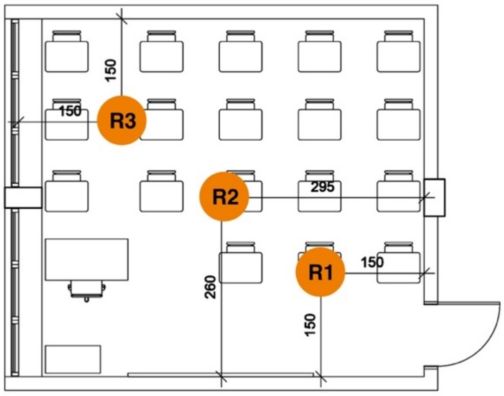


Figure 3.1.1.3 Receiver (R1-R3) points used for determining the background noise levels of high school music classroom

The measurements were carried out in unoccupied classrooms on March 31, 2020 between 9:00 AM – 05:00 PM because education in these schools is held during these hours (see Figure 3.1.1.4). There are three sets of background noise measurements performed in three different time frames such as: T1 (9:20 – 12:00), T2 (12:20 – 14:20) and T3 (15:00 – 17:00). In each time frame, the background noise levels were measured at all three points (R1, R2, R3) in each music classroom respectively. Also, the temperature and relative humidity (RH %) values were measured for each classroom. The background noise (Leq) values of the elementary school, middle school and high school music classrooms are given in Table 3.1.1.1, Table 3.1.1.2 and Table 3.1.1.3, respectively for each octave band with temperature and relative humidity values.

Figure 3.1.1.4. Background noise measurements in music classrooms

Time	Temp.	RH%	Point	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
T1	11 °C	56.4 %	R1	41.64	37.02	34.28	31.33	28.32	24.93	22.92	22.45
T1	11 °C	56.4 %	R2	40.69	34.03	34.39	31.08	27.78	23.84	22.23	22.43
T1	11 °C	56.4 %	R3	31.33	30.95	34.01	30.24	27.33	23.06	22.14	22.28
T2	17.3 °C	41 %	R1	45.20	35.94	36.08	30.77	28.50	24.39	22.13	22.32
T2	17.3 °C	41 %	R2	42.10	33.54	35.43	33.06	30.78	24.42	21.83	22.18
T2	17.3 °C	41 %	R3	38.98	34.17	35.11	33.27	30.12	25.85	22.62	22.50
T3	18.6 °C	41.3 %	R1	46.65	36.80	33.41	31.22	29.57	24.77	22.43	22.44
T3	18.6 °C	41.3 %	R2	44.44	36.73	33.68	31.73	29.80	24.58	22.43	22.53
T3	18.6 °C	41.3 %	R3	39.75	39.86	35.11	33.38	32.08	26.44	23.30	22.80

Table 3.1.1.1. Measured background noise levels of elementary school music classroom at R1, R2 and R3 receiver locations

Time	Temp.	RH %	Point	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
T1	16.5 °C	39.6 %	R1	52.36	42.10	38.51	36.13	25.48	22.77	21.84	24.11
T1	16.5 °C	39.6 %	R2	41.96	32.71	30.05	27.63	28.04	26.65	23.41	22.60
T1	16.5 °C	39.6 %	R3	31.79	31.09	30.63	28.49	25.40	24.32	22.68	22.59
T2	17.4 °C	41.7 %	R1	36.07	35.85	34.06	29.71	31.61	24.87	21.79	22.29
T2	17.4 °C	41.7 %	R2	39.21	33.94	35.32	29.91	26.70	24.43	22.34	22.45
T2	17.4 °C	41.7 %	R3	38.55	34.29	31.43	29.93	30.17	29.94	23.09	22.74
T3	18.7 °C	38.4 %	R1	37.22	37.94	35.20	29.79	26.62	23.34	21.82	22.29
T3	18.7 °C	38.4 %	R2	42.51	35.71	35.36	30.23	26.58	24.50	22.29	22.38
T3	18.7 °C	38.4 %	R3	32.84	32.64	31.23	29.23	27.84	24.07	22.00	22.37

Table 3.1.1.2. Measured background noise levels of middle school music classroom at R1, R2 and R3 receiver locations

Time	Temp.	RH %	Point	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
T1	17.3 °C	36.9 %	R1	39.00	37.73	29.23	27.18	22.54	20.25	20.34	21.89
T1	17.3 °C	36.9 %	R2	39.75	33.15	30.09	26.57	24.68	22.07	21.48	22.09
T1	17.3 °C	36.9 %	R3	36.56	34.36	28.31	25.80	23.87	21.80	21.37	22.19
T2	18 °C	39.5 %	R1	40.27	35.16	29.30	28.02	25.76	25.16	25.08	23.44
T2	18 °C	39.5 %	R2	41.86	35.13	31.41	28.09	25.93	24.05	21.94	22.16
T2	18 °C	39.5 %	R3	40.43	34.30	32.53	32.79	29.89	24.55	22.29	22.36
T3	18.5 °C	37.6 %	R1	39.87	31.67	26.73	25.28	23.97	20.78	20.93	22.08
T3	18.5 °C	37.6 %	R2	41.55	36.10	34.52	39.45	46.14	29.90	22.03	22.52
T3	18.5 °C	37.6 %	R3	42.49	33.99	29.17	26.63	25.46	22.89	21.60	22.24

Table 3.1.1.3. Measured background noise levels of high school music classroom at R1, R2 and R3 receiver locations

The measurements were taken with the windows closed and curtains not closed, since this configuration is the most frequently used situation during the classes to make maximum use of daylight despite the presence of artificial lighting. Also, the heating, ventilating and air conditioning (HVAC) system, artificial lighting, projection device, and sound equipment in the classrooms were not in use during the measurements since this equipment is only in use if required at certain periods of time during the education. The noise levels listed in the previous tables (3.1.1.1 - 3.1.1.3) indicate the noise levels at receiver points individually. In order to determine the background noise level of each classroom at each octave band, the logarithmic mean values of the measured noise levels of R1, R2, R3 receiver points are calculated for each classroom separately (see Table 3.1.1.4).

Music Classroom	Time	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Elementary S.	**T1**	39.65	34.68	34.23	30.91	27.83	24.01	22.44	22.39
Elementary S.	**T2**	42.81	34.67	35.56	32.50	29.90	24.94	22.21	22.34
Elementary S.	**T3**	44.44	38.06	34.13	32.21	30.64	25.35	22.74	22.59
Middle S.	**T1**	48.00	38.10	34.90	32.54	26.49	24.88	22.69	23.16
Middle S.	**T2**	38.14	34.78	33.89	29.85	29.94	27.19	22.44	22.50
Middle S.	**T3**	39.21	35.94	34.30	29.77	27.05	24.00	22.04	22.35
High S.	**T1**	38.64	35.53	29.27	26.55	23.78	21.44	21.09	22.06
High S.	**T2**	40.91	34.88	31.28	30.25	27.64	24.61	23.34	22.69
High S.	**T3**	41.43	34.29	31.39	35.06	41.43	26.34	21.54	22.28

Table 3.1.1.4. Background noise levels of music classrooms as the logarithmic mean values of receiver points in all time frames

The measurement set consisting of the highest level of noise for each classroom is considered as the background noise level of the related classroom since it will indicate the noisiest situation. In order to determine the time frame with the highest noise level, the measurement sets are compared with Noise Criterion curves (see Figure 3.1.1.5). However, the measured noise levels of both elementary school and middle school music classrooms in T1 time frame are not taken in consideration due to the inadequate temperature values as indicated in the Table 3.1.1.1 and Table 3.1.1.2.

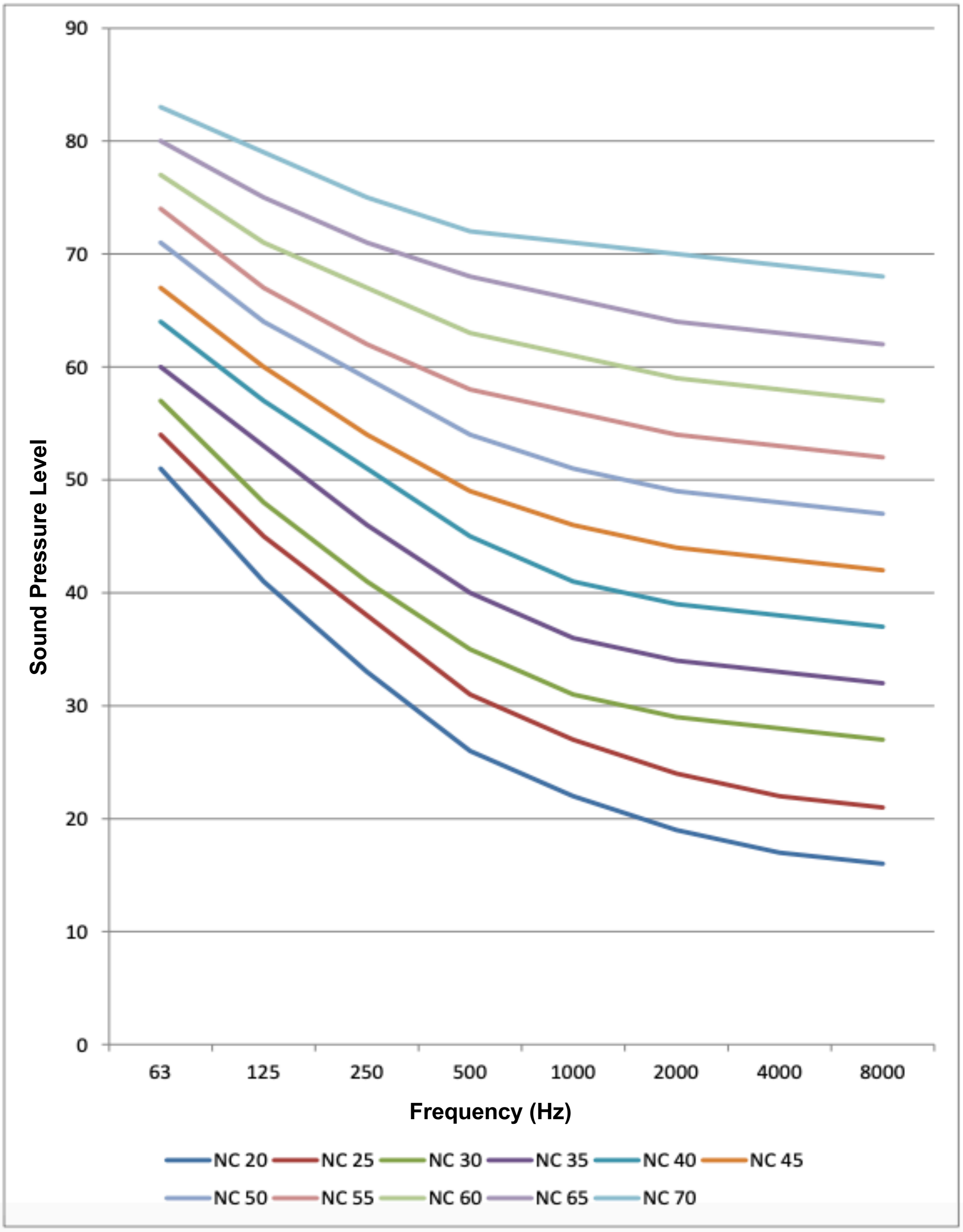


Figure 3.1.1.5. Noise Criterion Curves at octave bands (Cirrus Research plc., 2013).

The noise criterion curves, which are called "NC" for short, are used as a method for determining appropriate background noise in order to provide the necessary noise reduction. Each NC curve is defined by a different sound pressure level (dB) for eight octave band frequencies. The NC curve, where the sound pressure level is not exceeded in any octave band, is known as an appropriate environment in terms of noise (Egan, 1988). The appropriate NC levels according to the room and space types are listed at Table 3.1.1.5. According to this method, the background noise levels of the multipurpose music classrooms were evaluated through comparing the calculated results with NC curves.

Type of Room - Space Type	**Appropriate NC Level**	**Type of Room - Space Type**	**Appropriate NC Level**
	NC Curve		**NC Curve**
Residences		**Hospitals and Clinics**	
Apartment Houses	25-35	- Private rooms	25-30
Assembly Halls	25-30	- Operating rooms	25-30
Churches, Synagogues, Mosques	30-35	- Wards	30-35
Courtrooms	30-40	- Laboratories	35-40
Factories	40-65	- Corridors	30-35
Private Homes, rural and suburban	20-30	- Public areas	35-40
Private Homes, urban	25-30	**Schools**	
Hotels/Motels		- Lecture and classrooms	25-30
- Individual rooms or suites	25-35	- Open-plan classrooms	35-40
- Meeting or banquet rooms	25-35	Movie motion picture theaters	30-35
- Service and Support Areas	40-45	Libraries	35-40
- Halls, corridors, lobbies	35-40	Legitimate theaters	20-25
Offices		Private Residences	25-35
- Conference rooms	25-30	Restaurants	40-45
- Private	30-35	TV Broadcast studies	15-25
- Open-plan areas	35-40	Recording Studios	15-20
- Business machines/computers	40-45	Concert and recital halls	15-20
		Sport Coliseums	45-55
		Sound broadcasting	15-20

Table 3.1.1.5. NC rated noise limits indicated according to the Room - Space Type (Cirrus Research plc., 2013)

According to the comparison of each measurement set with NC curves, the time frames in each classroom that has the highest background level is determined and listed with their NC levels in Table 3.1.1.6. The elementary school music classroom has the highest level of background noise in the T3 time frame which corresponds to NC 30. It shows that the background noise level of the classroom is at a high level of the recommended range of ‘Lecture and classrooms’ that is provided in the Table 3.1.1.5. The background noise level of the middle school music classroom is detected at the measurement set that is obtained in the T2 time frame. The NC level of the middle school music classroom is NC 29 which is in the recommended range explained earlier. The high school music classroom has the highest level of background noise among the three, determined at the T3 time frame. The NC level of the classroom is NC 40 which is higher than the recommended range for classrooms.

Music Classroom	NC Level	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Elementary S.	30	44.44	38.06	34.13	32.21	30.64	25.35	22.74	22.59
Middle S.	29	38.14	34.78	33.89	29.85	29.94	27.19	22.44	22.5
High S.	40	41.43	34.29	31.39	35.06	41.43	26.34	21.54	22.28

Table 3.1.1.6 Background noise levels of the music classrooms with the corresponding NC levels

The background noise levels of the music classrooms were used during the impulse response tests to set the level of the output signal and to determine the decay ranges. Also, the background noise level values were entered in the ‘Room Setup’ menu of Odeon as a preset of the related room before performing the acoustical simulations. Defining the background noise levels at the related section of Odeon is required, especially for the determination of STI values due to the relation of background noise, signal-to-noise ratio and STI parameters that was explained in section 2.2.2.5.

3.1.2. Measurement of Room Acoustic Parameters

In order to determine the acoustical performance of the multipurpose classrooms, an investigation of the room acoustic parameters is required. As an experimental method, the room acoustic parameters of the classrooms are investigated by measuring the impulse response for multiple receiver positions in each classroom with the equipment and procedure described in section 2.3.2. The measurements are performed according to the ISO 3382-1 with an omni-directional sound source at a height of 1.5 m and two measurement microphones (one as a reference microphone and the other as a mobile microphone) that are positioned at seven receiver locations at a height of 1.2 m.

The appropriate settings for performing the impulse response measurements with the measurement equipment were determined with preliminary measurement trials. The trials were carried out in the middle school music classroom as a pilot study area. The trials indicated that adjusting the gain of the amplifier to the maximum level (100%) creates a distorted sound on the omni-directional loudspeaker. It was determined that the gain adjustment of the amplifier and audio interface is significantly important. There must be an agreement between the gain levels of the amplifier and the audio interface in order to generate a clear and adequate level of sound. The appropriate gain levels in the study were determined to be 20 percent for the amplifier and 50 percent for the audio interface. The gain levels of the microphone inputs are investigated in detail by conducting different trials. It was found that adjusting the microphone gain levels to 80 percent on the audio interface provides a good balance between the adequate input sound level and the suppression of noise floor in the rooms. The white noise and pink noise options were tested during the preliminary studies. Pink noise is determined as the signal type for the excitation of the rooms due to its capability of generating longer playback time for low frequencies (125, 250 Hz), resulting in more energy at this range.

The measurement window in the Odeon software is given in Figure 3.1.2.1. The sweep duration and silence duration before the measurement and impulse response length values were determined by trials of different combinations during the preliminary studies. The decay ranges and the impulse response graphics of the recorded signals were carefully examined in order to acquire the optimum configuration of measurement parameters. It was found that the sweep duration below the 6000 ms did not provide appropriate decay range values for the studied classrooms. The impulse response length was found to be appropriate above 4000 ms for the current study. The silence before parameter is found to be higher than 200 ms for gathering a healthy signal of an impulse response. It should be stated that these ranges of measurement parameters are determined as appropriate specifically for this study and it may vary for different rooms and conditions. The settings and parameters used in the measurements are given in Table 3.1.2.1.

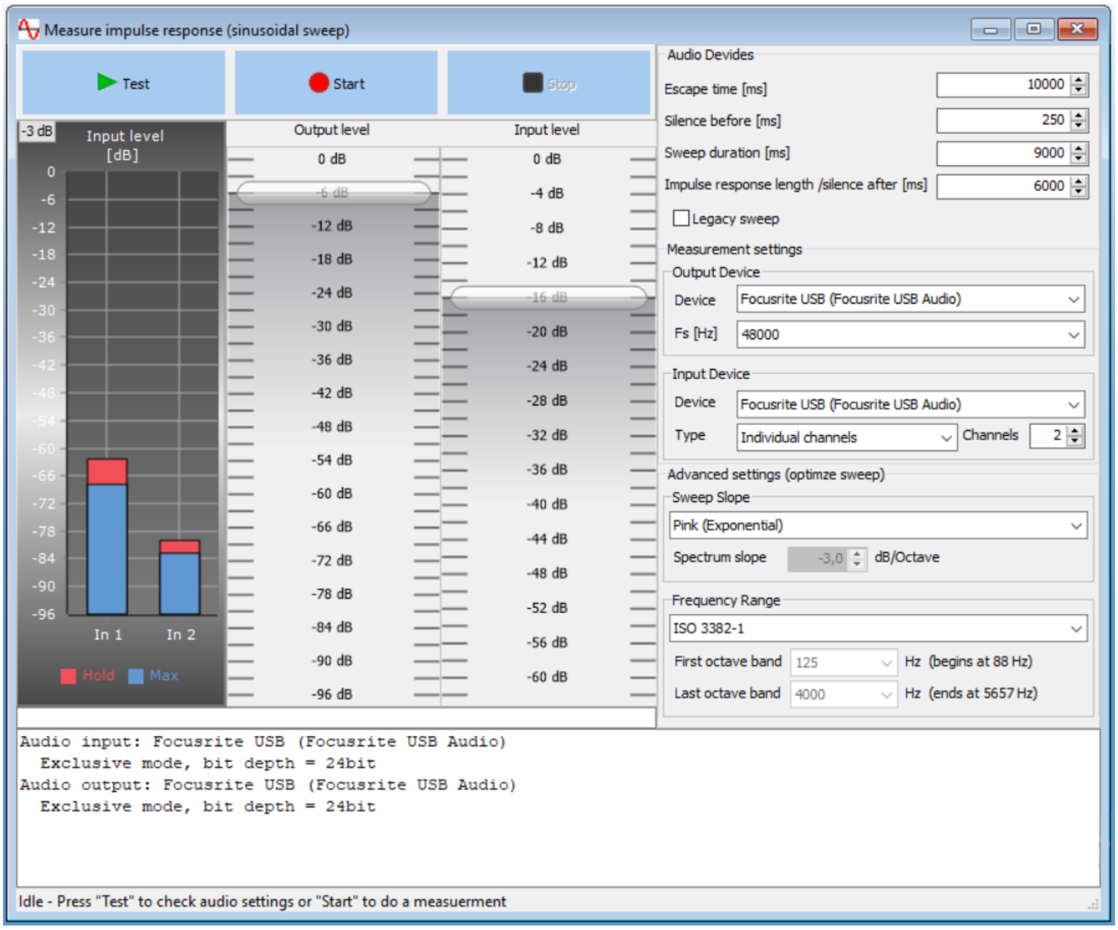


Figure 3.1.2.1 Odeon impulse response measurement interface

Measurement Setting / Parameter	Value
Gain level of amplifier	20%
Output gain level of audio interface	50%
Input gain level of audio interface	80%
Output level at Odeon	-6 dB
Input level at Odeon	-16 dB
Escape time (ms)	10,000
Silence before (ms)	250
Sweep duration	9,000
Impulse response length / silence after (ms)	6,000
Channel Type	Individual Channels
Number of channels	2
Sweep slope	Pink Noise (Exponential)
Spectrum slope	-3,0 dB/Octave (default value)
Frequency range	ISO 3382-1 (125 Hz – 4000 Hz)

Table 3.1.2.1 Settings and parameters of impulse response measurements.

There is one sound source position determined at the middle of the area that the teacher normally stands for teaching, singing and playing instruments in each room. The height of the sound source is 1.5 m above from the ground. The reference microphone is located at the R1 position for every measurement setup which is in the front row of the student desks and its location is not changed during the course of the measurements. The mobile microphone is located at R2-R7 receiver positions for each measurement respectively. Distribution of the receivers is arranged according to instructions provided in the ISO 3382-1 standard. The receiver positions are sampling the entire area where the students are normally located and each measurement point is a representative position that a student would be sitting during class. The microphones are located at a 1.2 m height at each measurement point (ISO, 2009). Figure 3.1.2.2 shows the measurement conditions and placement of the equipment in the classrooms during the measurements. Three measurements were taken at each specified receiver point, and in each of these measurements, the reference microphone took measurements at point R1. In this way, every measurement taken at the receiver points were checked for any deviations with the reference information provided by the reference microphone. The measurement results from each receiver point were compared and checked for any deviations between them. Some measurements with deviations in certain parameters were excluded from the scope of the evaluation and compatible data was used. In this section, the results of the measurements are presented, however, a comprehensive evaluation of the room acoustical parameter values is made in section 3.4.

Figure 3.1.2.2 Measurement studies of the room acoustic parameters in music classrooms

The measurements for the elementary school music classroom were conducted at a temperature of 22.5° C and 35 percent relative humidity. The measurements were performed when the classroom was unoccupied, with the curtains opened, windows closed, the HVAC system turned off, and with retaining the original positions of the furniture and spatial elements of the classroom. The sound source is located 1.5 m away from the whiteboard and 3.75 m and 2.85 m away from the side walls. The reference microphone is located at the R1 receiver position, 1.08 m away from the outside-facing windows and 2.84 m from the wall with the writing board. The other receiver locations are distributed to the area of the student desks, where R2 and R6 are at the mid-point of the edges, R3, R5 and R7 are at the corners of the edges and R4 is at a relatively mid-point of the area. The source and receiver positions are indicated in Figure 3.1.2.3.

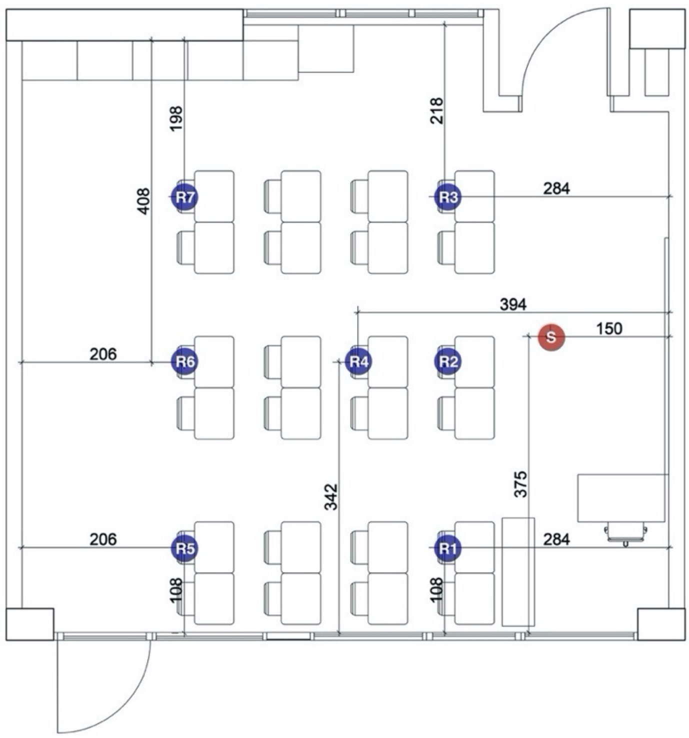


Figure 3.1.2.3 Source (S) and receiver (R1-R7) positions of the measurements of the room acoustic parameters in elementary school music classroom.

According to the analyses made with the Odeon software, the EDT, T30, D50, and C80 acoustical parameters were obtained and the results for each receiver point is given in Figures 3.1.2.4 – 3.1.2.7. The results of the measurements indicate that:

- When the measured EDT results are evaluated in the octave bands, it is determined that the results at different points are close to each other.
- T30 values measured at different points appear close to each other as parallel to the EDT results, considering the octave bands separately.
- D50 results are examined in different octaves, and it is observed that in most cases, the values are decreased slightly as receiver points moved away from the sound source.
- C80 parameter values in different receiver points are close to each other at low frequencies (125 Hz – 250 Hz), while there are fluctuations at the middle to high frequencies (1000 Hz – 4000 Hz).

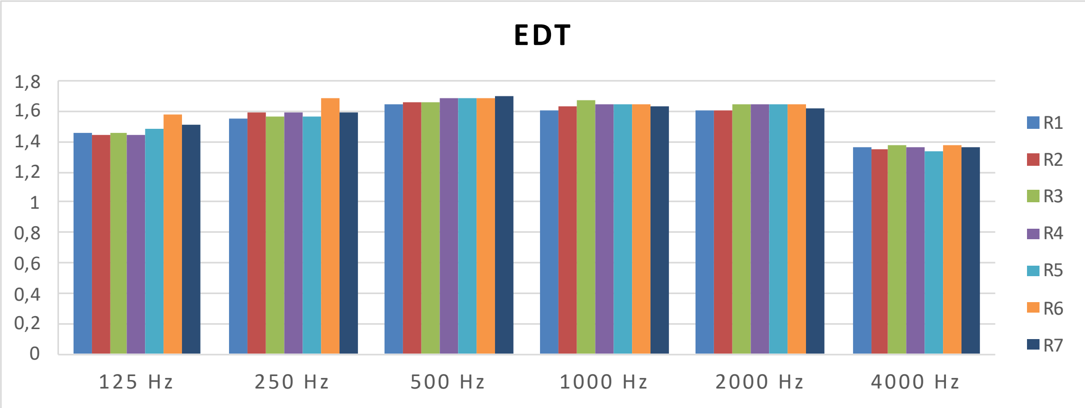


Figure 3.1.2.4 Results of the EDT measured in elementary school music classroom.

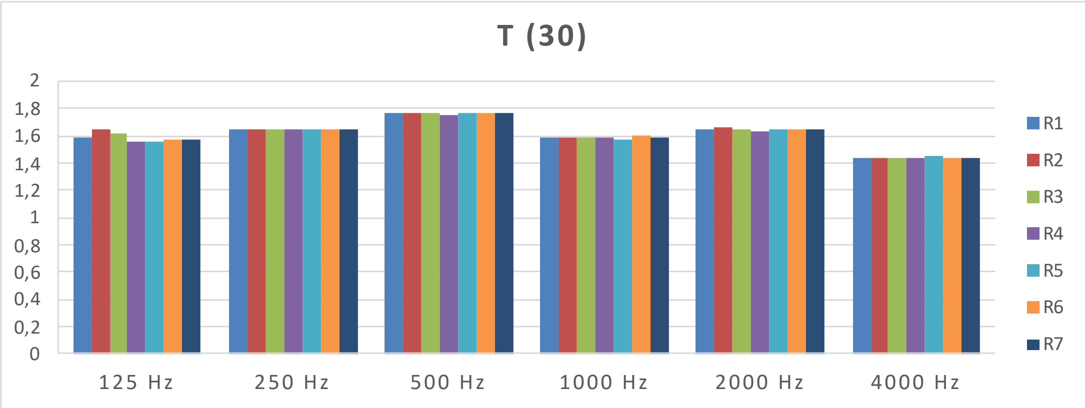


Figure 3.1.2.5 Results of the T30 measured in elementary school music classroom.

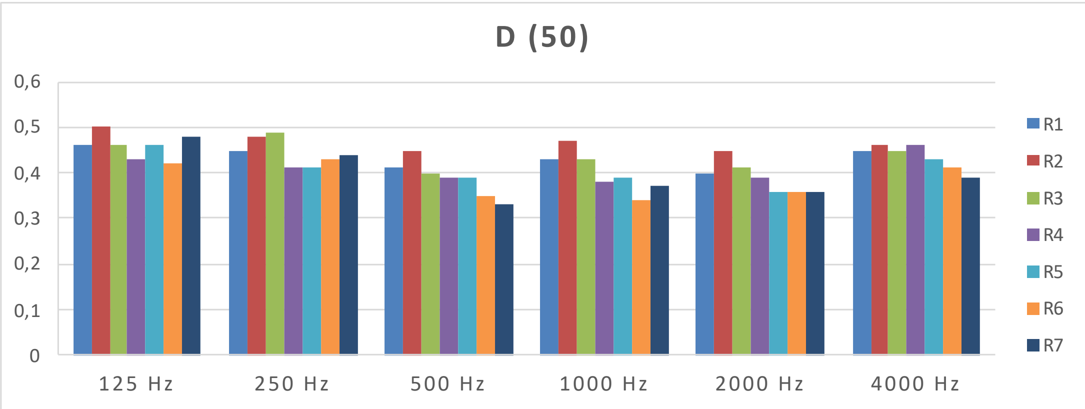


Figure 3.1.2.6 Results of the D50 measured in elementary school music classroom.

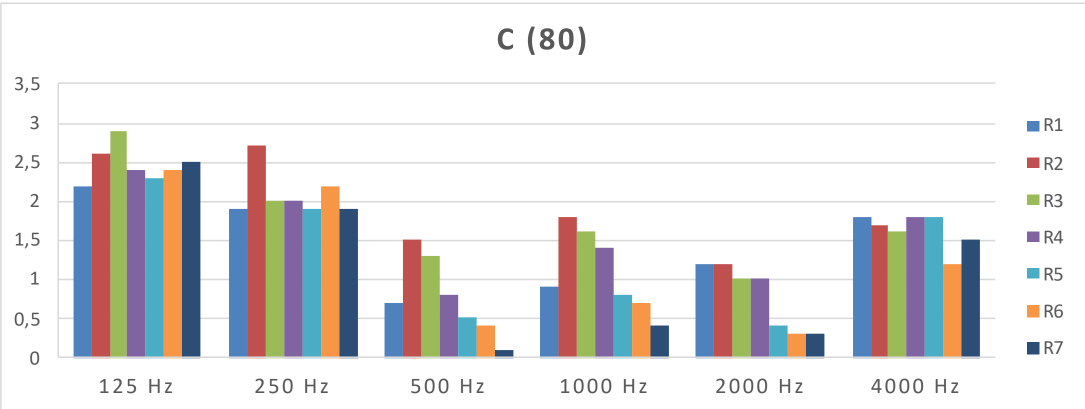


Figure 3.1.2.7 Results of the C80 measured in elementary school music classroom.

The measurements of the room acoustic parameters in the middle school music classroom were carried out with a temperature of 22.5° C and 44.5 percent relative humidity values. An unoccupied state of the classroom was used for the tests according to the ISO 3382-1 standard. During the measurements, the front door and back doors that leads to the storage room were closed, the curtains were open, the windows were closed, and the HVAC system was turned off. Also, the spatial organization of the classroom was kept in its original layout, where the furniture and educational elements are in their permanent positions. The position of the sound source is 1.5 m away from the writing board and 3.10 and 3.5 m away from the side walls. The receiver positions are distributed to the area where the audience normally sits, where the R1 point is the fixed position of the reference microphone and the other receiver points (R2 – R7) are determined in an arrangement to exemplify the audience area. The positions of the source and the receivers are given in Figure 3.1.2.8.

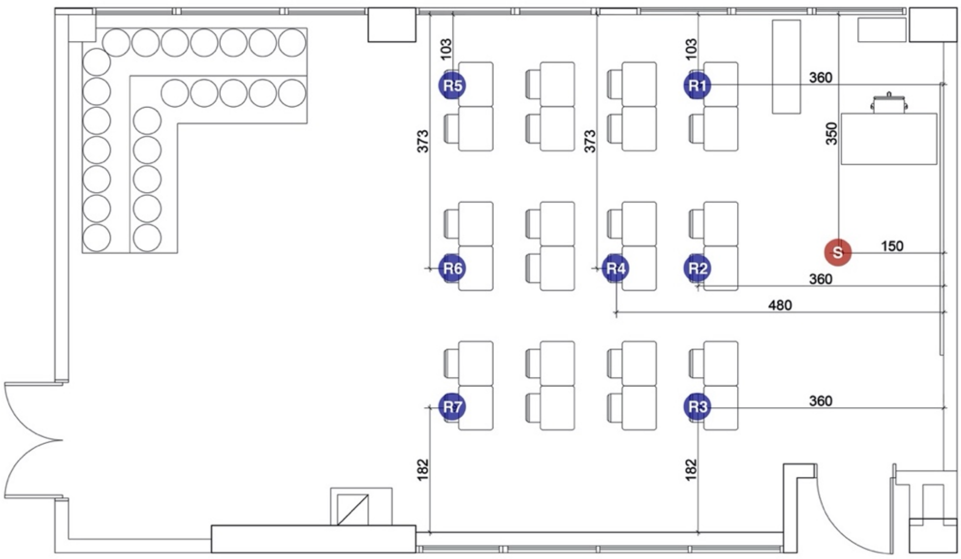


Figure 3.1.2.8 Source (S) and receiver (R1-R7) positions in middle school music classroom for the measurements.

The derived impulse responses were analyzed with the software in order to achieve the parameter values of room acoustics which are given in Figures 3.1.2.9 – 3.1.2.12. According to the results of the measurements:

- The EDT results obtained from receivers at different points contain a difference of 0.1 ms at 500 Hz, while other frequencies are within a uniform range.

- Results of the T30 from receivers at different points indicate a difference of 0.11 ms at the frequency of 125 Hz. However, differences in other frequencies can be considered neglected since they are within a range of 0.01 to 0.02 ms.
- In the analysis of the D50 parameter in different octave bands, it is determined that the values decrease as the receivers move away from the sound source.
- In the evaluation of C80 parameter, it is observed that the values decreased in the back rows of the classroom compared to the front rows.

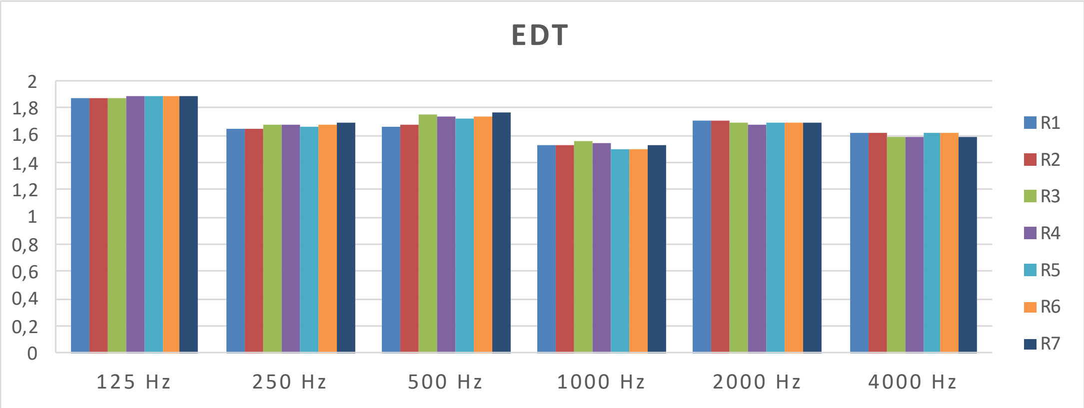


Figure 3.1.2.9 Results of the EDT measured in middle school music classroom.

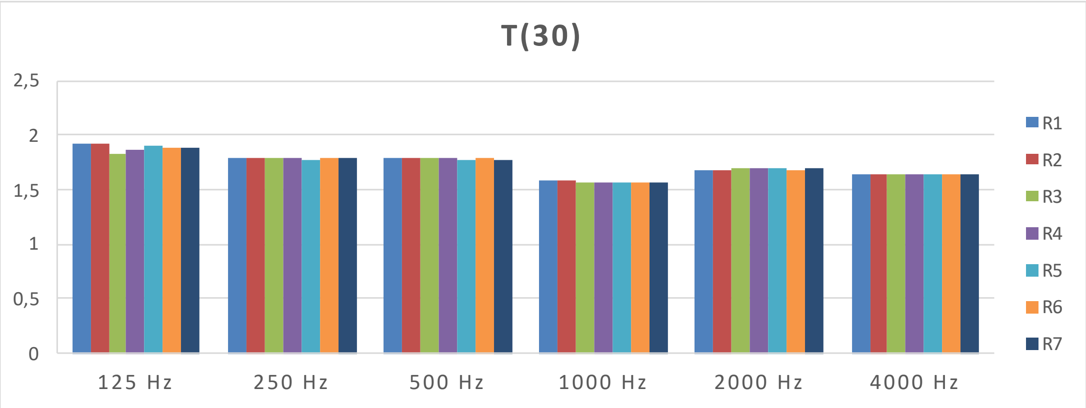


Figure 3.1.2.10 Results of the T30 measured in middle school music classroom.

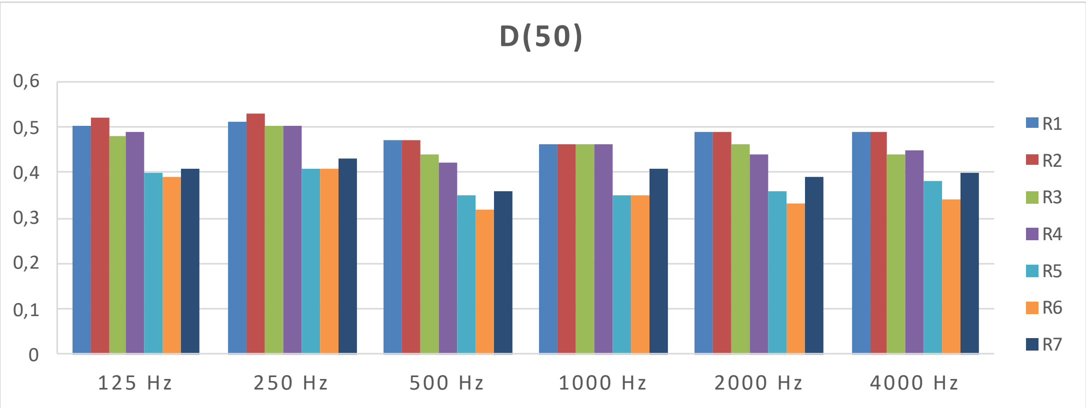


Figure 3.1.2.11 Results of the D50 measured in middle school music classroom.

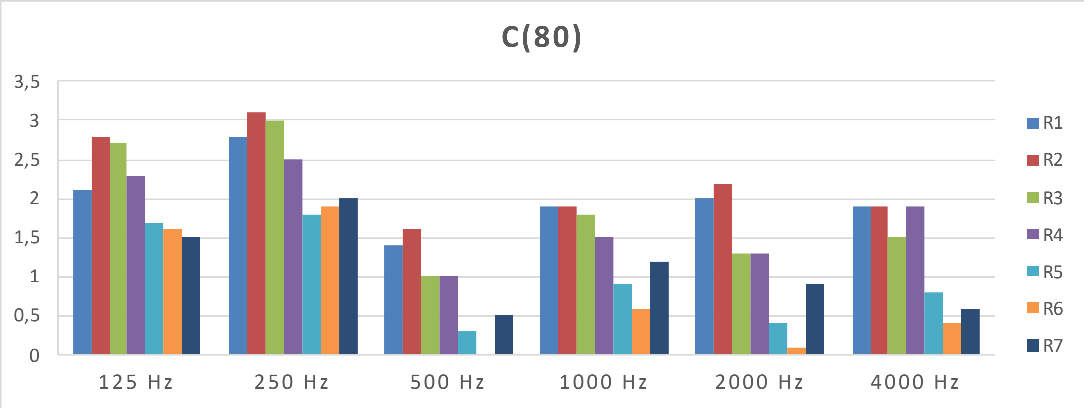


Figure 3.1.2.12 Results of the C80 measured in middle school music classroom.

In the high school classroom, which has a smaller area than the other two classrooms investigated, the measurements were carried out with temperature and relative humidity values of 24° C and 35 percent respectively. The classroom was unoccupied with the curtains open and windows and door are closed. As done in the other classrooms, the furnishing and educational elements were kept in their original locations. The position of the sound source is 1.3 m away from the blackboard and 3.2 m from both side walls. The receiver positions are arranged in order to sample the entire area of the students. The R1 point is the fixed position of the reference microphone and the other receiver points (R2 – R7) are the locations where the mobile microphone is placed. The positions of the source and the receivers are shown in Figure 3.1.2.13.

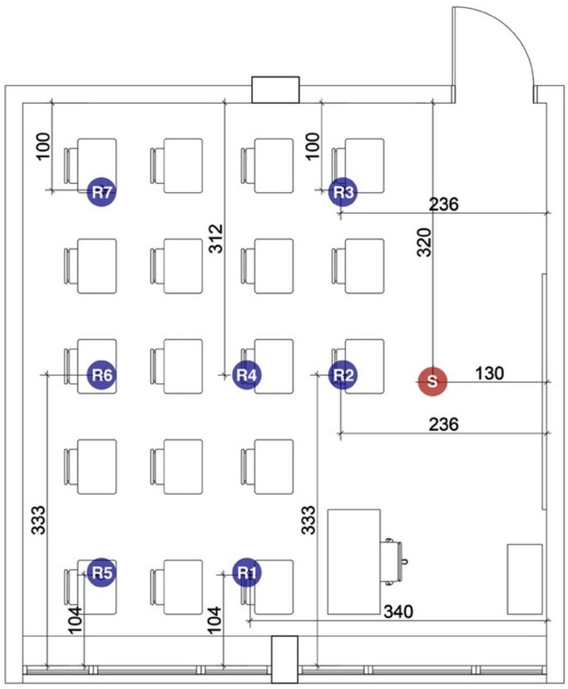


Figure 3.1.2.13 Source (S) and receiver (R1-R7) positions of measurements of the parameters of room acoustics in the high school music classroom.

The analyzed results of the measurements are given in Figures 3.1.2.14 – 3.1.2.17 that indicate the values of EDT, T30, D50, and C80. According to the analysis of the results:

- In the evaluation of the EDT parameter, notable variations in different receiver positions at some frequencies (500 Hz, 1000 Hz) are observed. The standard deviation values at these frequencies are in the range of 0.04 – 0.05 respectively.
- When the T30 parameter is analyzed, fluctuations at different positions are determined at the frequency of 500 Hz. The standard deviation value at this frequency are calculated as 0.04
- In the analysis of the D50 parameter, it is found that the values are considerable varying according to the receiver positions. However, it is estimated that the distance to the source is not the only reason for the occurrence of these differences.
- The analysis of the C80 parameter reveals that there are significant differences between the obtained values of different receivers at each octave band.

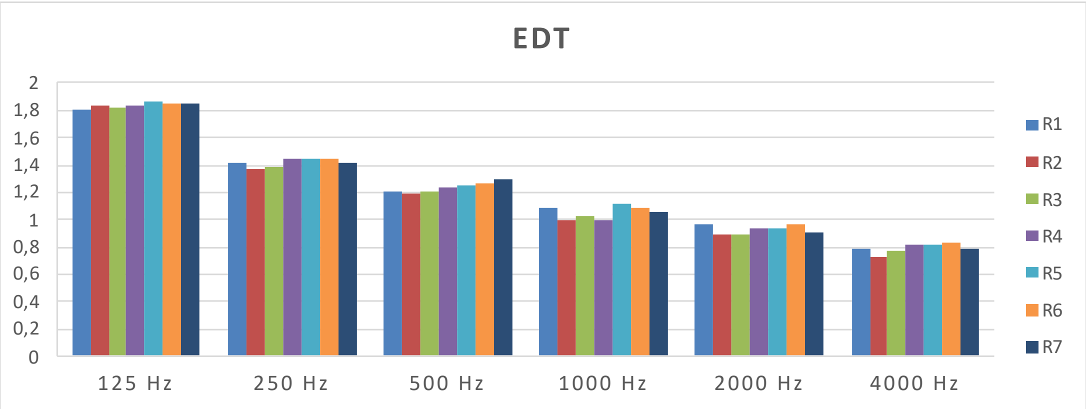


Figure 3.1.2.14 Results of the EDT measured in high school music classroom.

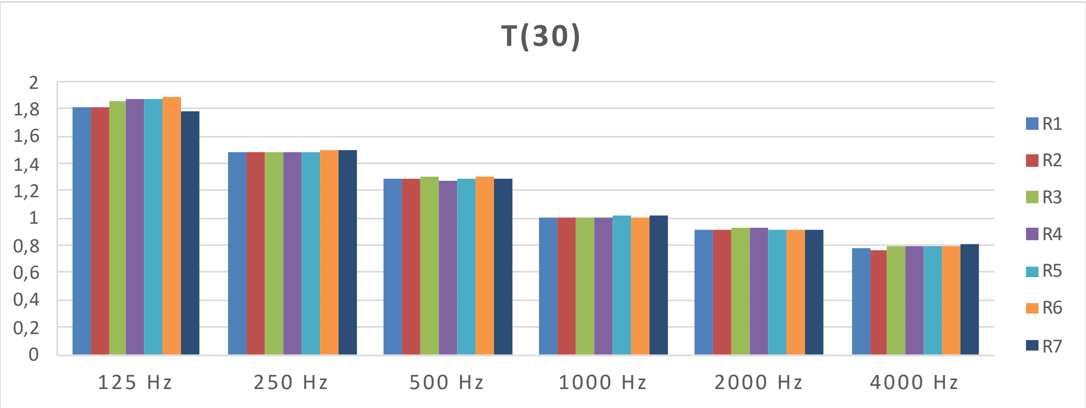


Figure 3.1.2.15 Results of the T30 measured in high school music classroom.

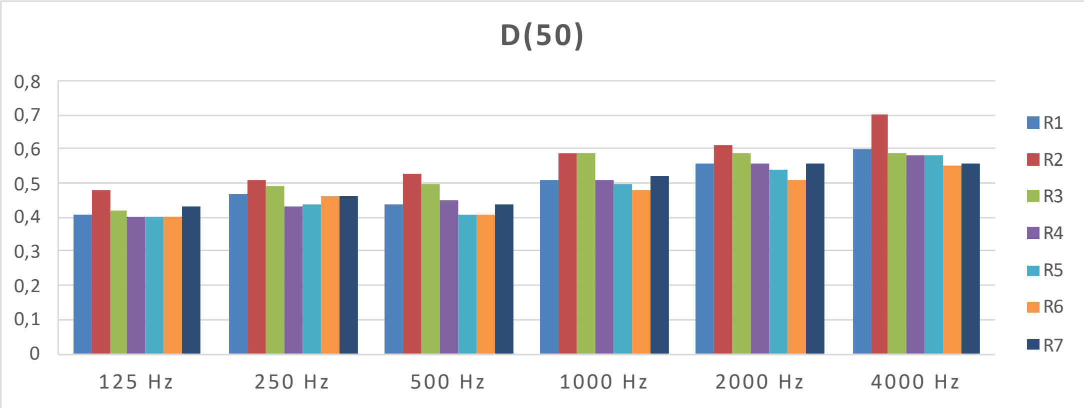


Figure 3.1.2.16 Results of the D50 measured in high school music classroom.

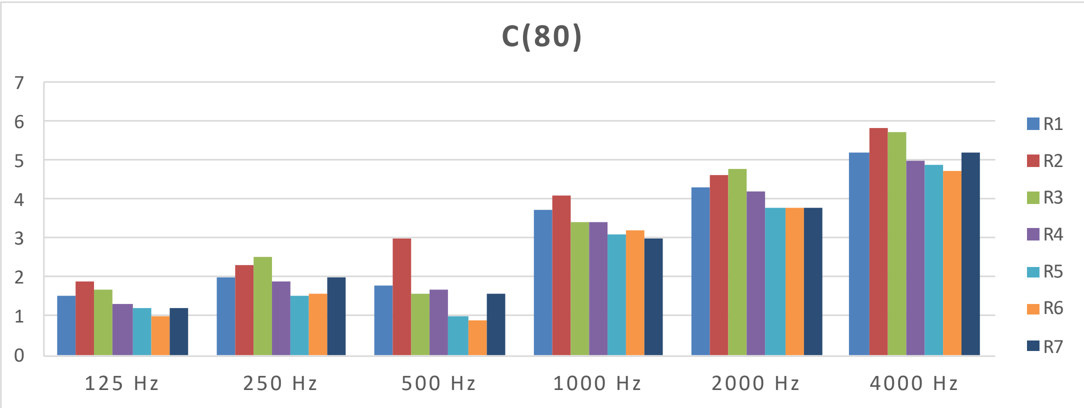


Figure 3.1.2.17 Results of the C80 measured in high school music classroom.

3.2. Computational Studies

Three-dimensional models of the multipurpose music classrooms were produced with Sketchup Pro 2019 version based on the existing dimensions of the building and furnishing elements of the classrooms to represent the real situation in the rooms. In the models, surfaces that would not have an effect on the room acoustics calculations due to the insignificant area sizes are not included. These surfaces with insignificant areas are included in the related surfaces of the elements with larger areas adjacent to them. Three-dimensional models of the primary, middle and high school multipurpose music classrooms are shown in Figure 3.2.1. While modeling three-dimensional designs of the rooms, elements consisting of the same materials are grouped in layers. Creating layer groups facilitates the selection of appropriate materials at the material assignment stage in the Odeon software.

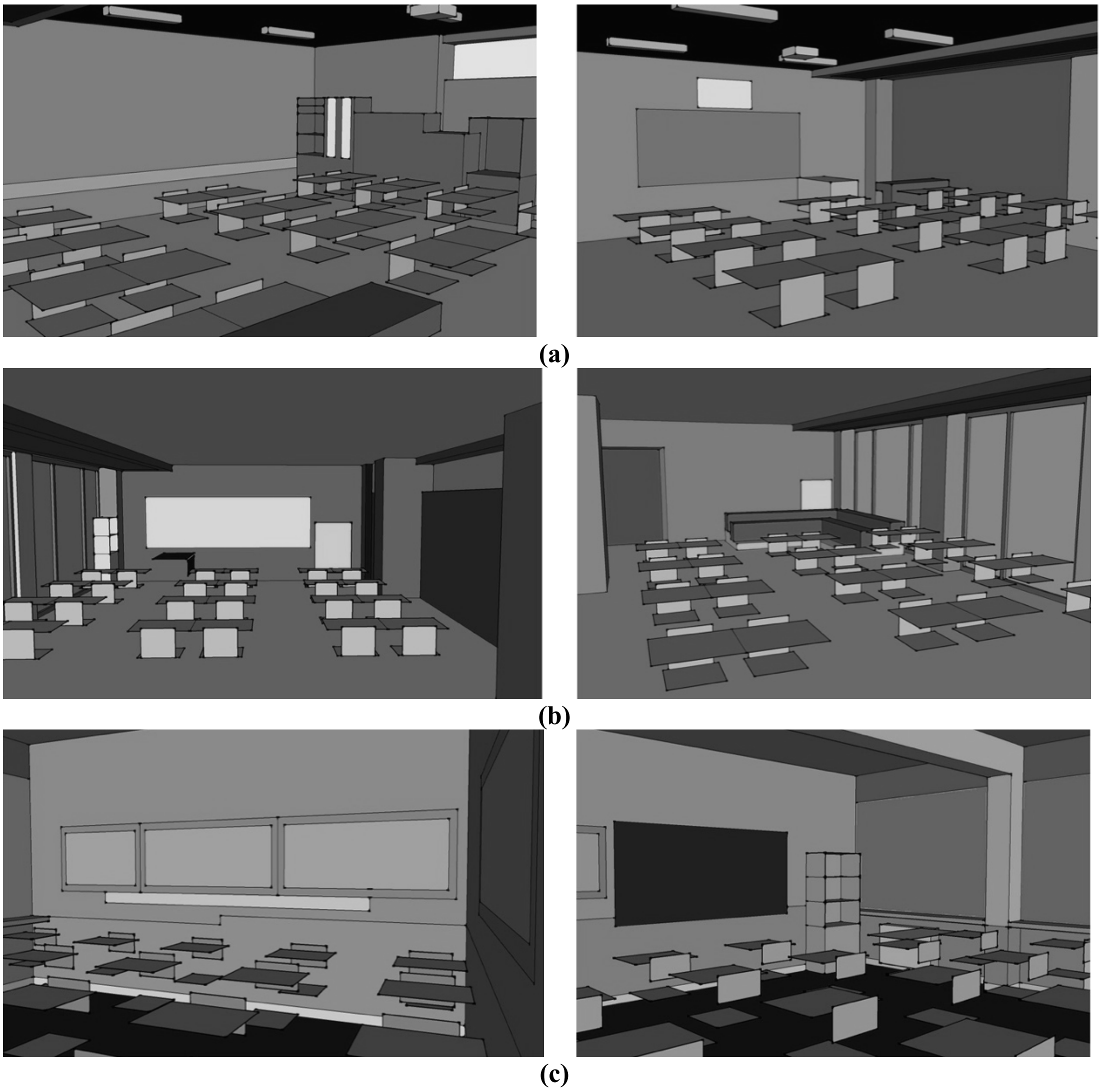


Figure 3.2.1 Images exported from three-dimensional models of elementary school (a), middle school (b) and high school (c) multipurpose music classrooms created in Sketchup software.

The models of the classrooms are exported from the Sketchup software with the appropriate extension (.par) and imported to Odeon with the same extensions. In order to control the leakage of rays in the imported models, materials with various sound absorption coefficients were assigned to the elements defined as the surfaces and closedness of the models were checked and verified by using the *3DView, 3DOpenGL display, 3DGeometry debugger,* and *3D investigate rays* functions of the software. The main calculation parameters used in the simulation study for the computational analysis are given in Table 3.2.1 and default values are used for the rest of the calculation parameters.

Calculation Parameter	Analysis Criteria
Impulse Response Length	2,000 ms
Number of late rays	1,000
Maximum reflection order	10,000
Impulse response resolution	3.0 ms
Minimum distance to walls	0.1 meters
Transition order	2
Number of early rays	1,000
Number of early scatter rays	100

Table 3.2.1 Calculation parameters used in the simulation studies.

In the simulation studies, receiver points were assigned to the same receiver positions used in the measurements of room acoustic parameters and a source point is assigned to the same source position used in the measurements as well. An omni-directional source *(omni)* was selected as the sound source, as its directivity order is seen in Figure 3.2.2, in accordance with the ISO 3382-1 standard and the omni-directional sound source used during the actual measurements. The sound source is positioned at 1.5 m above the floor level in each classroom. *Speech raised vocal effort* is the selected spectrum to apply to the sound power of the source from the EQ list provided in the related interface of the software. In determining the sound power spectrum at the octave bands, instructions given in references (American National Standards Institute/Acoustical Society of America, 1997; Rindel et al., 2012) are followed. The power of the sound source in octave bands is given at Table 3.2.2.

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000
Spectrum (dB)	48.00	59.00	69.50	74.90	71.90	63.80	57.30	48.40

Table 3.2.2 Sound power of the omni-directional sound source in the frequency spectrum

In each classroom, seven receiver points (R1-R7) are determined in accordance with the instructions given in the ISO 3382-1 standard and the measurements of room acoustic parameters conducted in the classrooms. The receiver points are positioned at a height of 1.2 m, which is the same height of the microphones used in the impulse response measurements. The source and receiver points in each music classroom are shown in Figures 3.2.3 – 3.2.5. In the simulation studies, the unoccupied conditions of the classrooms are analyzed with doors and windows closed, curtains open and the HVAC system turned off. These conditions are the same as the impulse response measurements performed in the classrooms. The occupied condition is also investigated through computational analyses as an individual study (see Appendix).

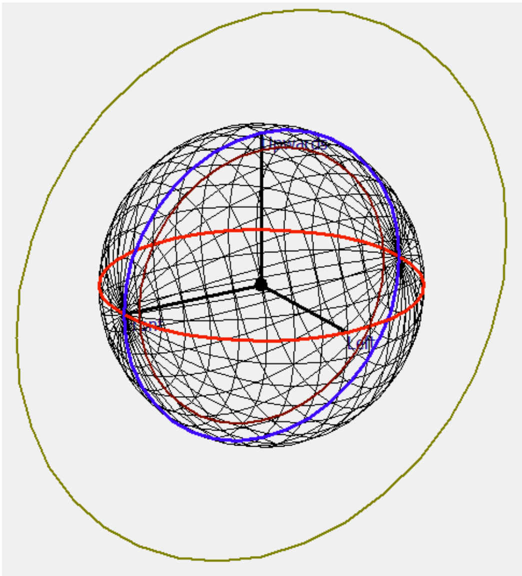


Figure 3.2.2 Directivity balloon of the omni-directional sound source selected for the computational investigation (Odeon, 2020).

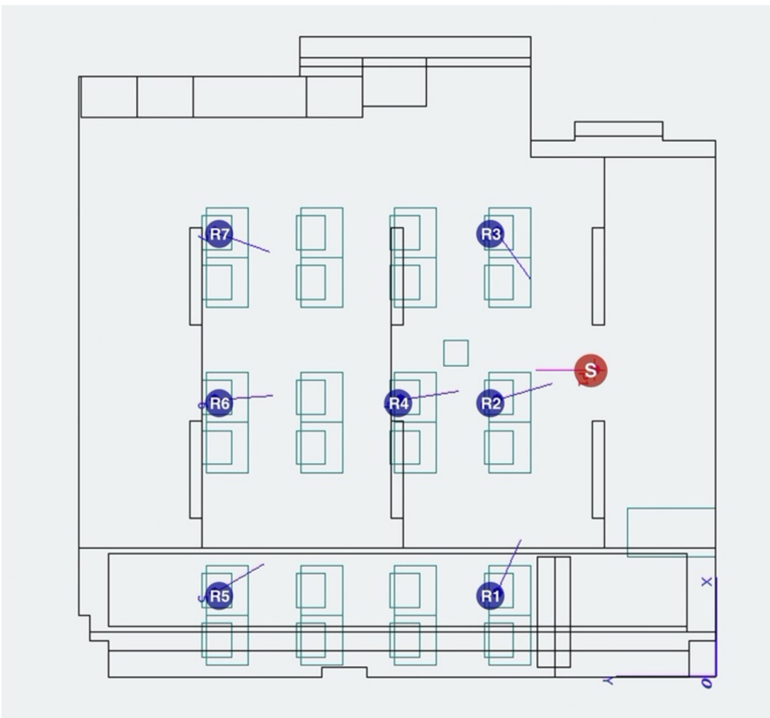


Figure 3.2.3 Source (S) and receiver (R1-R7) points determined for the computational studies in the elementary school music classroom.

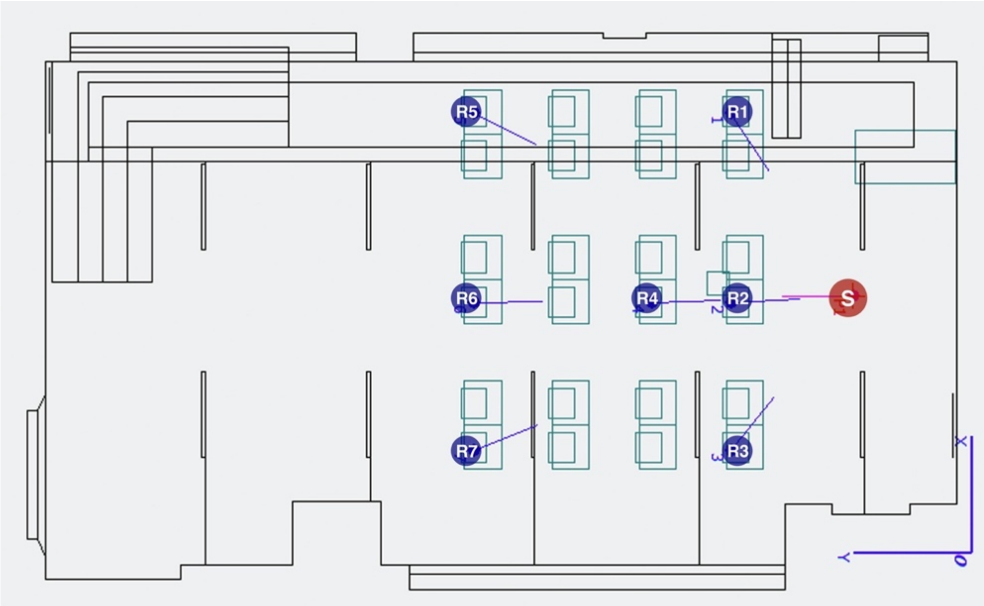


Figure 3.2.4 Source (S) and receiver (R1-R7) points determined for the computational studies in the middle school music classroom.

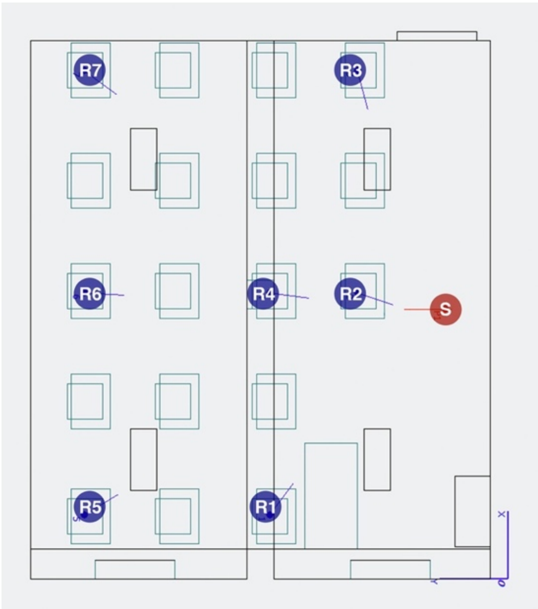


Figure 3.2.5 Source (S) and receiver (R1-R7) points determined for the computational studies in the high school music classroom.

Before deriving the results of the room acoustic parameters from the simulations, initial studies were conducted as trials for the surface materials and the sound power of the sources. The assigned materials of the surfaces were selected from the material library of Odeon and relevant studies and regulations (Seep et al., 2000; Department of Education and Science, 1975) in the literature. The results of the initial studies were compared with the results derived from the measured impulse responses. Incompatibilities were detected between the simulation results and measurement results according to the values of just noticeable differences (JND) which are provided in the ISO 3382-1 standard. In order to achieve compatible results with impulse response measurements, synthesis studies were carried out. According to these studies, the absorption coefficients of some of the materials were updated and different materials were assigned to some of the surfaces. This process is explained in detail in section 3.3. The list of the sound absorption coefficients of the updated materials used in the final stage of the simulations performed for the classrooms are provided in Tables 3.2.3 – 3.2.5. These materials are assigned to the related surfaces according to the inspections of the current situation in the classrooms and the characteristics of the materials used in surfaces of the rooms. Since the production and application details and the physical properties of the accompanied layers of a material assigned to a surface are not exactly known in the real situation, the materials assigned to the surfaces are selected from the materials that are estimated to be the closest to the real situation. The models of the classrooms with assigned materials are shown in Figure 3.2.6.

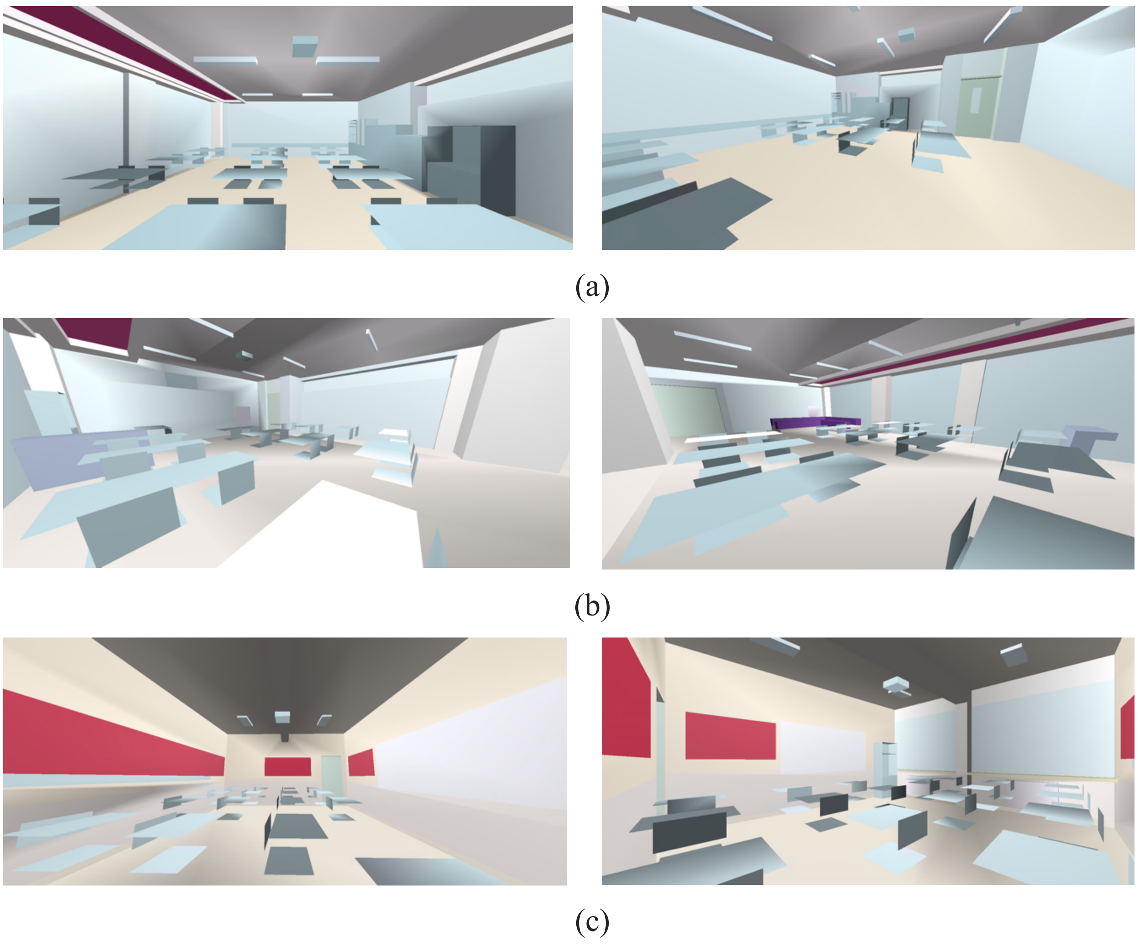


Figure 3.2.6 Views of elementary (a), middle (b) and high school (c) music classroom models after the materials are assigned to the surfaces

Elementary School Multipurpose Music Classroom								
Surface	Sound Absorption Coefficients							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Floor	0.02	0.02	0.02	0.04	0.05	0.05	0.1	0.1
Ceiling	0.01	0.01	0.01	0.01	0.04	0.02	0.01	0.01
Partial Suspended Ceiling	0.07	0.07	0.1	0.4	0.55	0.6	0.1	0.2
Columns	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Beams	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Walls	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03
Door	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1
Windows on Facade (Glass)	0.1	0.1	0.07	0.05	0.03	0.02	0.02	0.02
Interior Windows (Glass)	0.08	0.08	0.04	0.03	0.03	0.02	0.02	0.02
Student Desks / Chairs	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Educator Table	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Bookshelves	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
White Board	0.08	0.08	0.1	0.04	0.03	0.03	0.01	0.01
Wallboards	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Lighting Fixtures	0.08	0.08	0.1	0.04	0.03	0.03	0.01	0.01
Projection Device	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Piano	0.2	0.2	0.28	0.26	0.09	0.12	0.11	0.11

Table 3.2.3 Sound absorption coefficients of the materials assigned to the surfaces on the 3D model of elementary school music classroom.

Middle School Multipurpose Music Classroom								
Surface	**Sound Absorption Coefficients**							
	63 Hz	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**8000 Hz**
Floor	0.02	0.02	0.02	0.04	0.05	0.05	0.1	0.1
Ceiling	0.01	0.01	0.01	0.01	0.04	0.02	0.01	0.01
Partial Suspended Ceiling	0.07	0.07	0.1	0.4	0.55	0.6	0.1	0.2
Columns	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Beams	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Walls	0.08	0.08	0.11	0.05	0.03	0.02	0.03	0.03
Door	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1
Windows on Facade (Glass)	0.1	0.1	0.07	0.05	0.03	0.02	0.02	0.02
Interior Windows (Glass)	0.08	0.08	0.04	0.03	0.03	0.02	0.02	0.02
Student Desks / Chairs	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Educator Table	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Bookshelves	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
White Board	0.08	0.08	0.1	0.04	0.03	0.03	0.01	0.01
Wallboards	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Choir Platform	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07
Choir Stools	0.3	0.3	0.6	0.55	0.5	0.3	0.25	0.25
Heat Radiators	0.05	0.05	0.05	0.05	0.06	0.04	0.02	0.02
Lighting Fixtures	0.08	0.08	0.1	0.04	0.03	0.03	0.01	0.01
Projection Device	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Piano	0.2	0.2	0.28	0.26	0.09	0.12	0.11	0.11

Table 3.2.4 Sound absorption coefficients of the materials assigned to the surfaces on the 3D model of middle school music classroom.

High School Multipurpose Music Classroom								
Surface	**Sound Absorption Coefficients**							
	63 Hz	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**8000 Hz**
Floor	0.02	0.02	0.02	0.04	0.05	0.05	0.1	0.1
Ceiling	0.01	0.01	0.01	0.02	0.05	0.07	0.07	0.06
Columns	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Beams	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Walls	0.01	0.01	0.05	0.02	0.08	0.1	0.12	0.1
Wood Panels on the Walls	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07
Door	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1
Windows on Facade (Glass)	0.1	0.1	0.07	0.05	0.03	0.02	0.02	0.02
Windowsill	0.05	0.05	0.05	0.05	0.08	0.14	0.2	0.2
Student Desks / Chairs	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Educator Table	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
Bookshelves	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07
White Board	0.08	0.08	0.1	0.04	0.03	0.03	0.01	0.01
Wallboards (Cloth Covered)	0.1	0.1	0.4	0.6	0.7	0.7	0.5	0.5
Heat Radiators	0.02	0.04	0.05	0.05	0.06	0.04	0.02	0.02
Lighting Fixtures	0.08	0.08	0.1	0.04	0.03	0.03	0.01	0.01
Projection Device	0.18	0.18	0.12	0.1	0.09	0.08	0.07	0.07

Table 3.2.5 Sound absorption coefficients of the materials assigned to the surfaces on the 3D model of high school music classroom.

The result graphs of the simulations carried out for the models of elementary school (see Figures 3.2.7 – 3.2.10), middle school (see Figures 3.2.11 – 3.2.14) and high school (see Figures 3.2.15 – 3.2.18) music classrooms are given in the following figures respectively. The results provided in the graphs are limited to the room acoustic parameters obtained from the measurements such as EDT, T30, D50, and C80, since the calibration study of the room models is based on these parameters. The frequency range of the results between 63 Hz and 8000 Hz are included due to the fact that the default calculation range in Odeon is in this range. However, the current study is investigating the parameters between 125 and 4000 Hz. Therefore, the results in 63 Hz and 8000 Hz are not included in the evaluations and discussions made in sections 3.3 and 3.4.

Elementary School Multipurpose Classroom

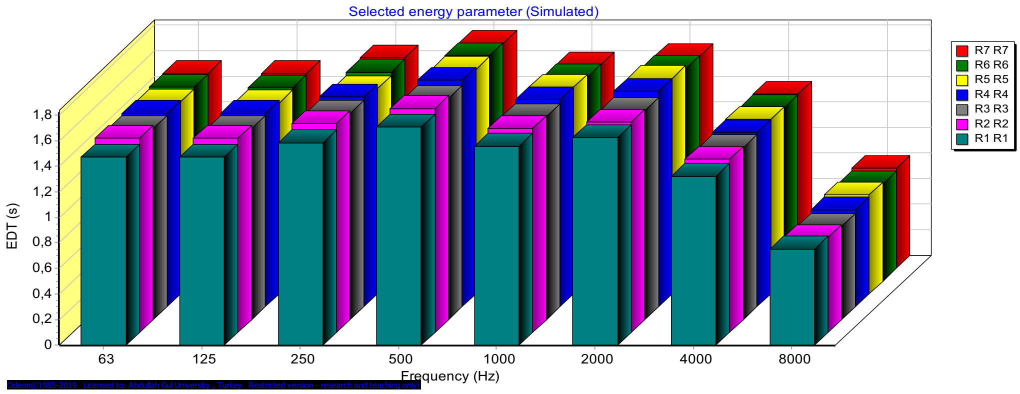


Figure 2.3.7 Elementary school music classroom EDT parameter simulations results

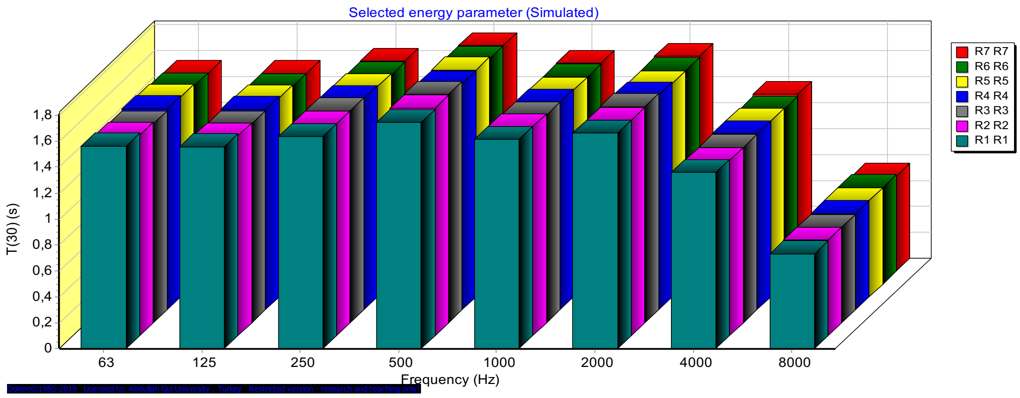


Figure 2.3.8 Elementary school music classroom T30 parameter simulations results

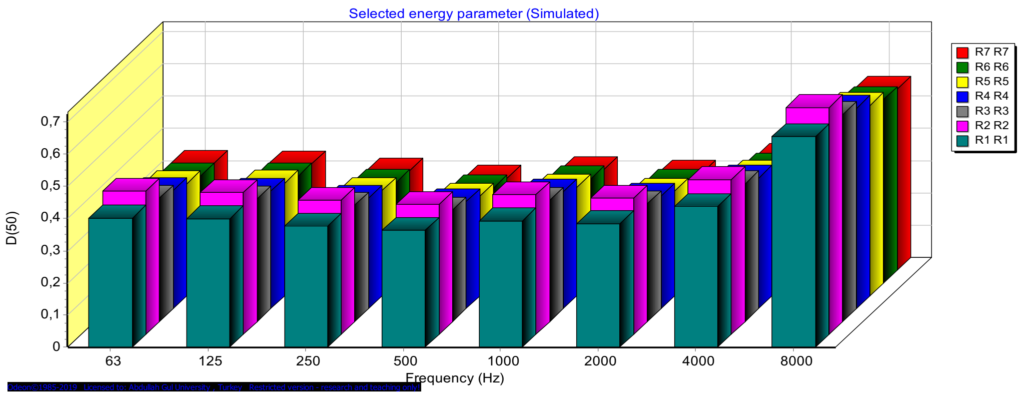


Figure 2.3.9 Elementary school music classroom D50 parameter simulations results

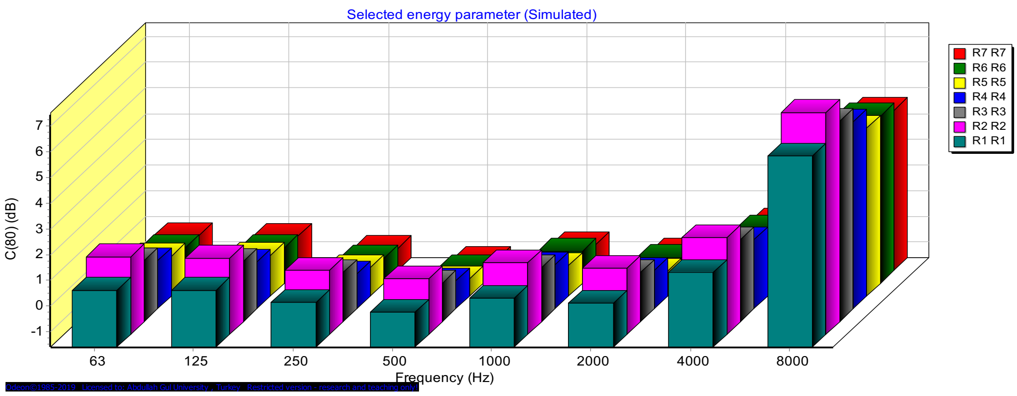


Figure 2.3.10 Elementary school music classroom C80 parameter simulations results

Middle School Multipurpose Classroom

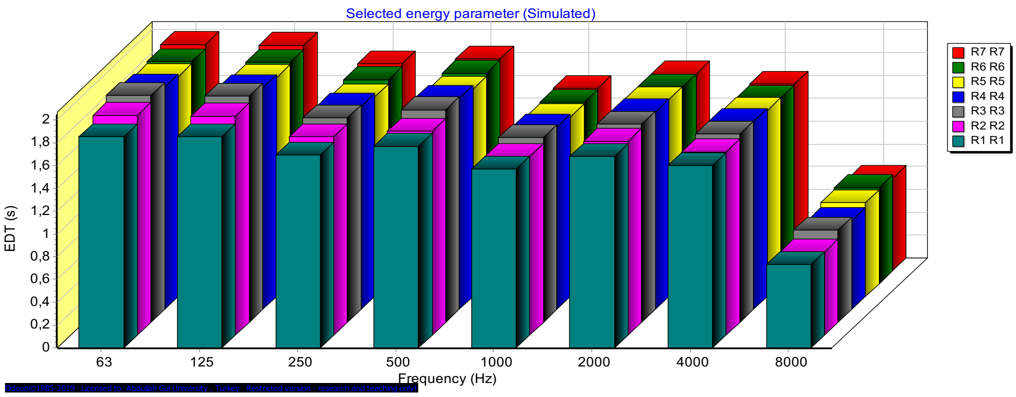


Figure 2.3.11 Middle school music classroom EDT parameter simulations results

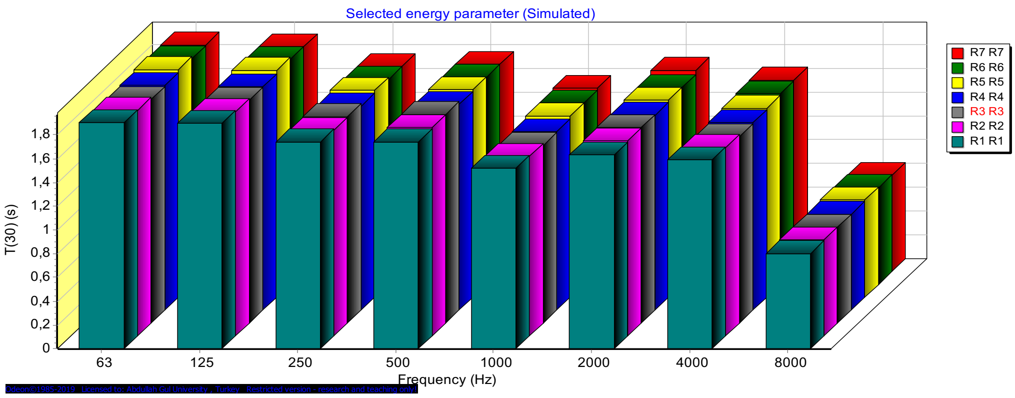


Figure 2.3.12 Middle school music classroom T30 parameter simulations results

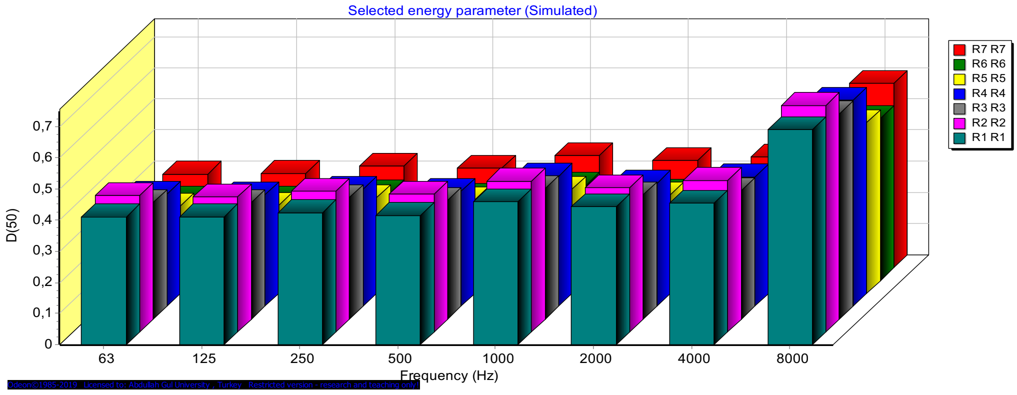


Figure 2.3.13 Middle school music classroom D50 parameter simulations results

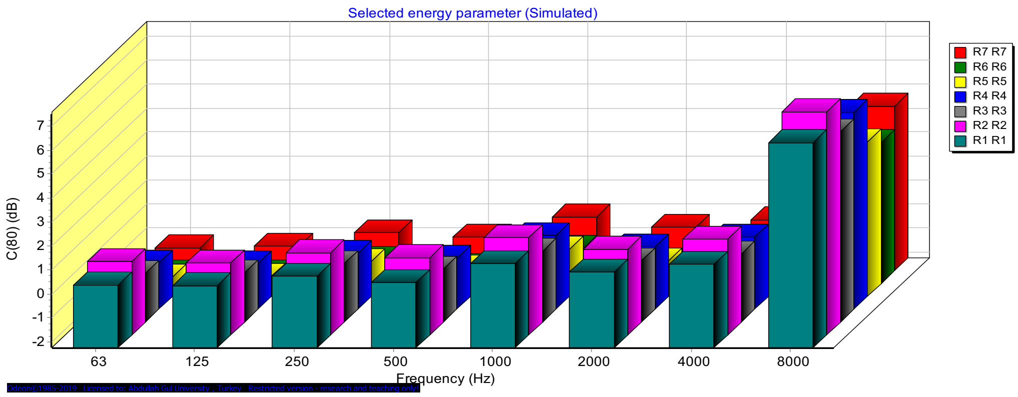


Figure 2.3.14 Middle school music classroom C80 parameter simulations results

High School Multipurpose Classroom

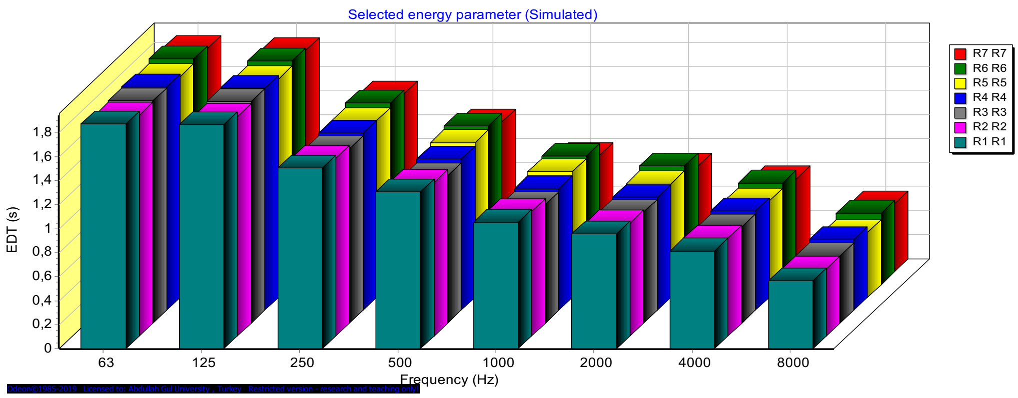


Figure 2.3.15 High school music classroom EDT parameter simulations results

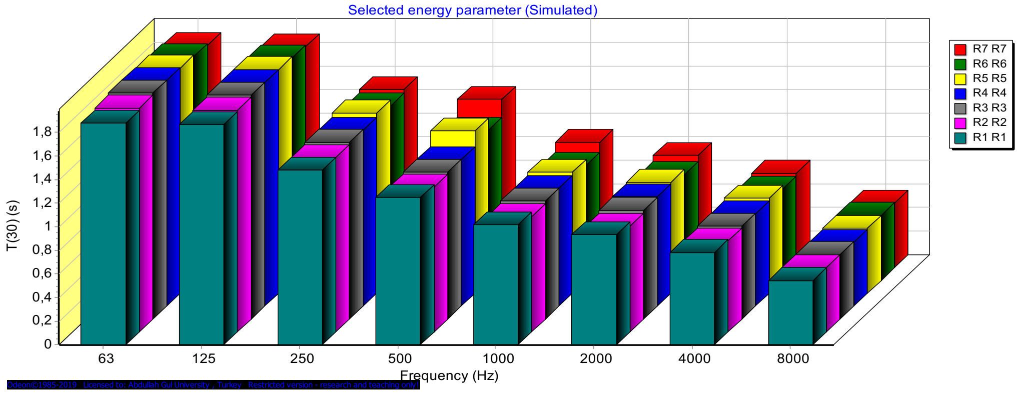


Figure 2.3.16 High school music classroom T30 parameter simulations results

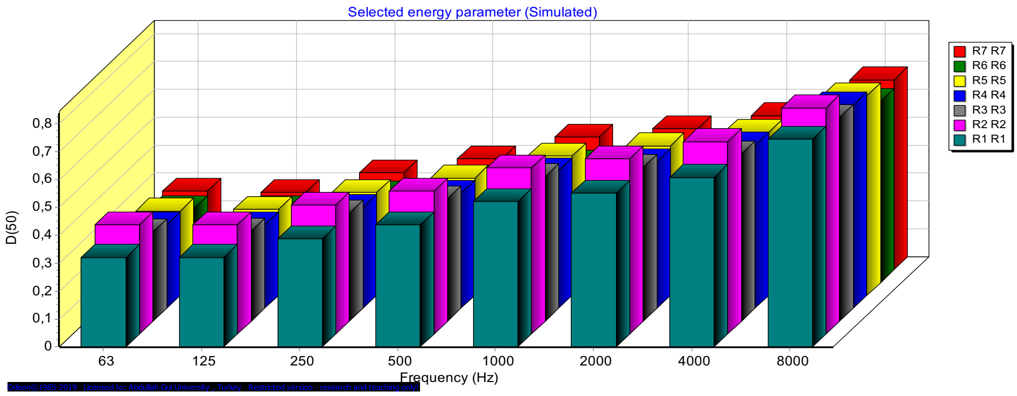


Figure 2.3.17 High school music classroom D50 parameter simulations results

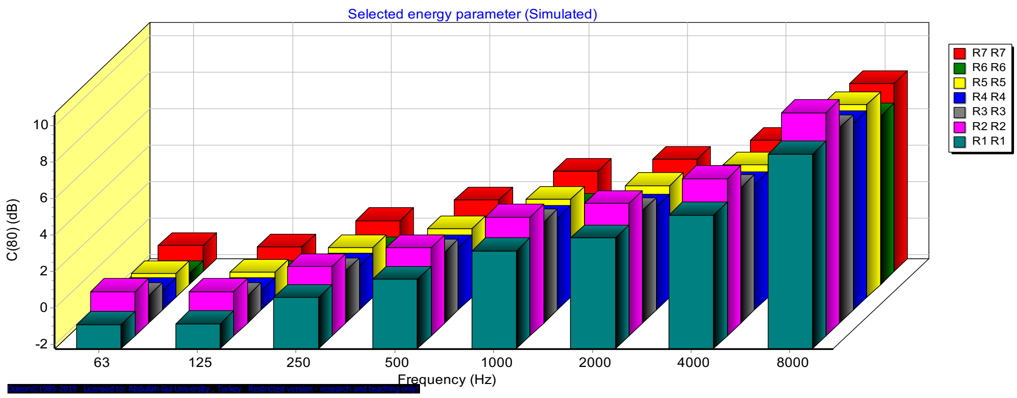


Figure 2.3.18 High school music classroom C80 parameter simulations results

3.3. Synthesis

The compatibility criteria of the results of the measurements and simulations is the subjective limen (just noticeable difference – JND) values provided in standards which are given in Table 3.3.1. If the errors between the measured and simulated room acoustical parameters are not higher than one subjective limen, the results are considered as precise. In some cases, being slightly above 1 JND would still be considered as satisfactory, if it is difficult or impossible to obtain results below 1 JND (Odeon, 2020).

Parameter	**Definition** **(ISO 3382-1, 2009) and (IEC 60268-16, 2003) for STI**	**Just noticeable difference (JND)**
EDT (s)	Early decay time	5% rel.
T30 (s)	Reverberation time	5% rel.
D50 (%)	Distinctness	5% abs.
C80 (dB)	Clarity	1 dB abs.
Ts (ms)	Centre time	10 ms abs.
G (dB)	Sound level at 10 m distance	1 dB abs
LF (%)	Early lateral energy ratio	5% abs.
STI	Speech transmission index	0.03 abs.

Table 3.3.1 Room acoustic parameters and their just noticeable difference (Bork, 2000; Bradley, 1986).

The results of the measurements and the initial simulations were compared in order to calibrate the three-dimensional models of the classrooms. The results of the initial studies of simulations demonstrated incompatibility with the results of the measurements. The graphs in Figures 3.3.1 – 3.3.3 indicates these incompatible results obtained from the elementary, middle and high school music classrooms in certain parameters (EDT, T30, D50, and C80). In most cases, the degree of the detail in the geometry of the room models is not the main reason for the uncertainties in the simulations due to the wavelength of audible sound. The acoustical data of the materials, such as absorption and scattering coefficients, are more effective in this matter. Also, the influence of the scattering coefficients on the uncertainty of the calculations may be less effective compared to the influence of the absorption (Christensen et al., 2013).

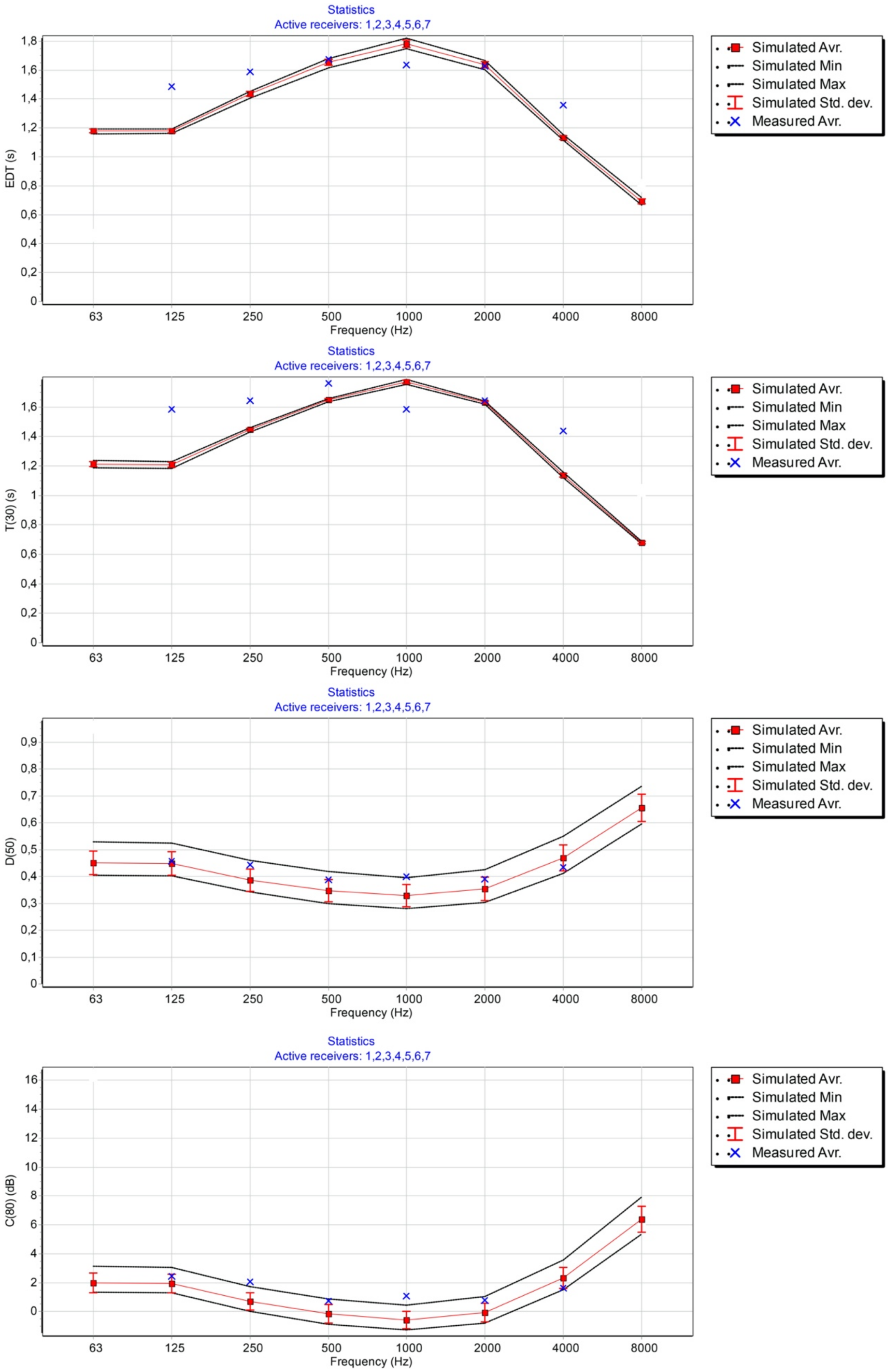


Figure 3.3.1 Elementary school music classroom comparison graphs of the measurements and simulations in EDT, T30, D50 and C80 parameters.

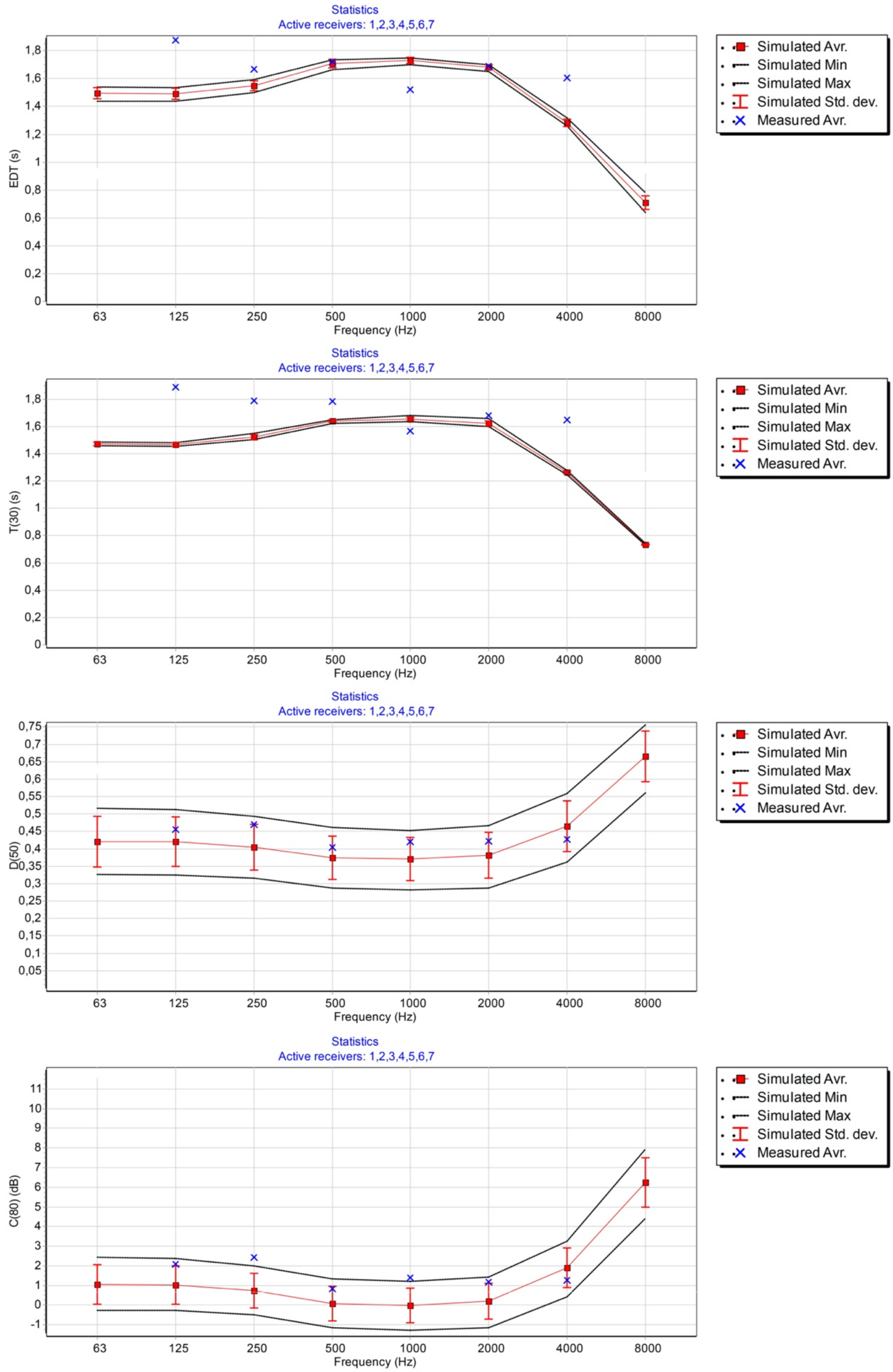


Figure 3.3.2 Middle school music classroom comparison graphs of the measurements and simulations in EDT, T30, D50 and C80 parameters.

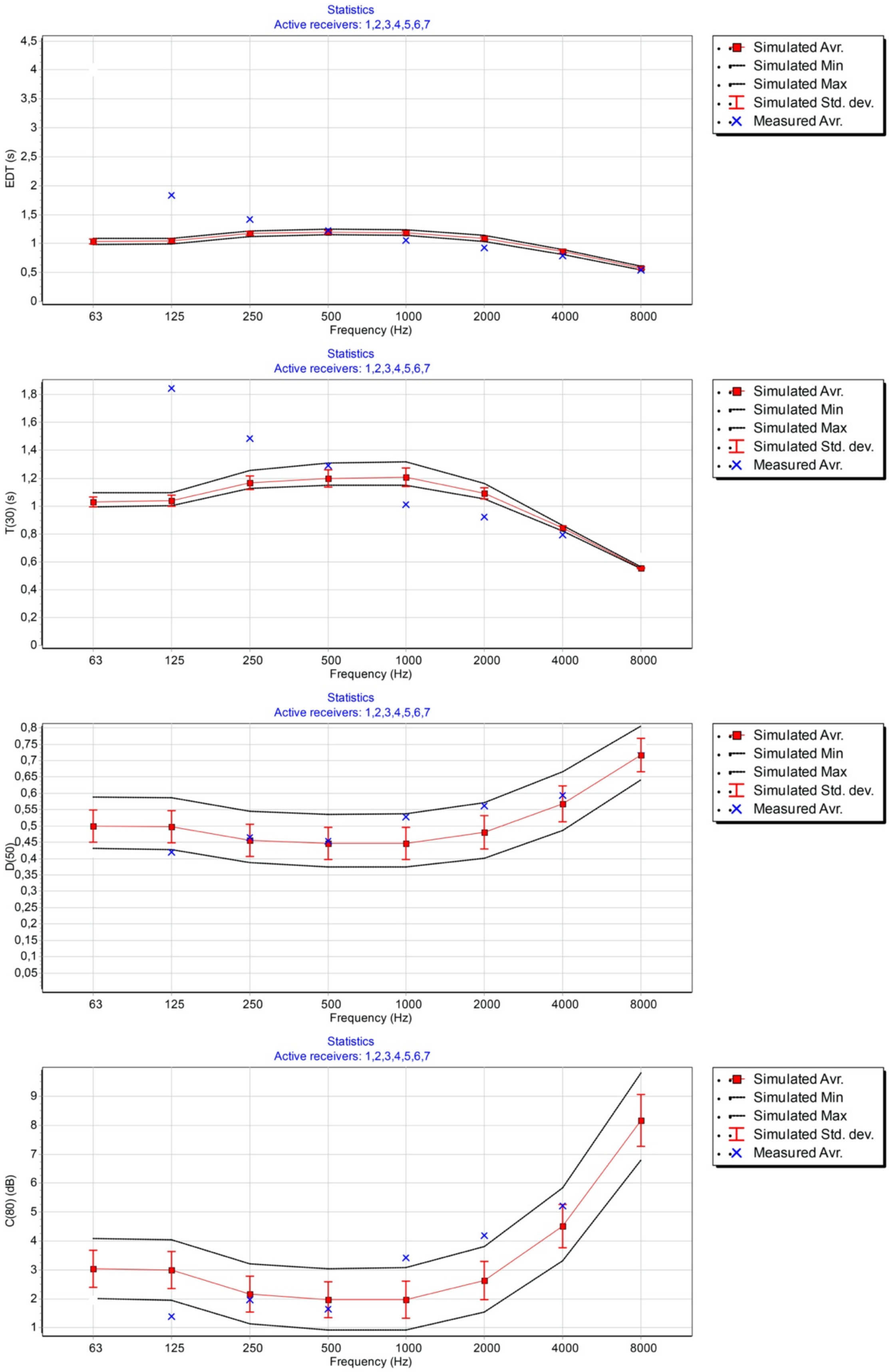


Figure 3.3.3 High school music classroom comparison graphs of the measurements and simulations in EDT, T30, D50 and C80 parameters.

According to the comparison statistics of elementary school music classroom:

- EDT parameter is not compatible at the 125, 250, 1000, and 4000 Hz frequencies.
- T30 parameter is not in the appropriate JND range at the 125, 250, 1000 and 4000 Hz frequencies.
- Although the values in parameter D50 demonstrate a coherent graph, they fall outside the acceptable range at some receiver points.
- C80 parameter displays a consistent graph, except for some receiver points at the 250 and 1000 Hz bands.

The results of the comparison study of middle school music classroom demonstrate that:

- EDT parameter is not compatible at certain frequencies (125, 250, 1000, and 4000 Hz).
- T30 parameter comparison results are above 1 JND at the 125, 250, 500, and 4000 Hz frequencies.
- D50 comparison results are compatible at most frequencies, however, there are incompatible results at some receiver points.
- For the C80 parameter, the results at some receiver points demonstrate incompatibility at octave bands of 125, 250 and 1000 Hz.

The comparison results of the high school music classroom indicate that:

- EDT parameter is not consistent at frequencies except 500 Hz.
- In the T30 parameter, consistency is not observed except for some receiver points in the 500 and 4000 Hz bands.
- While the comparison results of D50 parameter are inconsistent at the 125, 1000 and 2000 Hz bands, consistent results are observed at the other bands.
- While the comparison results for the C80 parameter at 250, 500 and 4000 Hertz are below 1 JND, most of the results at 125, 1000 and 2000 Hz frequencies are above 1 JND.

The comparison results demonstrated that JND values at certain frequencies should be reduced to the range of 0-1 in order to calibrate the models with the measurement results. The absorption coefficients of the materials assigned were inspected and coefficients that can be adapted were determined on the basis of frequencies in order to provide coherence. The absorption coefficients of the surface materials can vary according to the techniques applied during the construction and production stages. Also, the thickness of the materials used and the properties of the adjacent materials have a significant influence on the absorption coefficients. Therefore, variations of the assigned materials are produced with adjusted absorption coefficient values at some of the octave bands. In some situations, a different material that has a similar sound absorption coefficient is assigned instead of the previously selected materials and the updated situations of the models are tested. The updated absorption coefficients of the materials and final simulation results are provided in section 3.2. Each result is evaluated in terms of parameters and individual receiver points. Figure 3.3.4 and Figure 3.3.5 are examples of the optimization results for T30 at one receiver position. According to the comparison of the revised simulations and the measurements of the classrooms, the compatibility graphs of the acoustical parameters (EDT, T30, D50, and C80) for the three classrooms are provided in Figures 3.3.6 – 3.3.7.

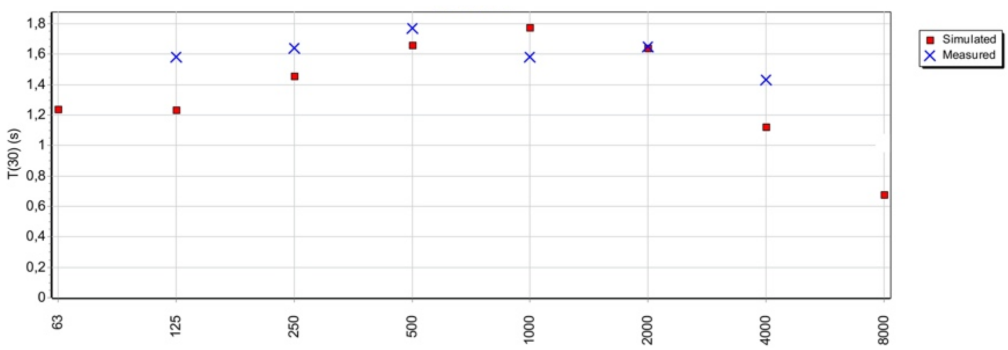


Figure 3.3.4 Elementary school music classroom T30 parameter compatibility results for R1 receiver before the optimization

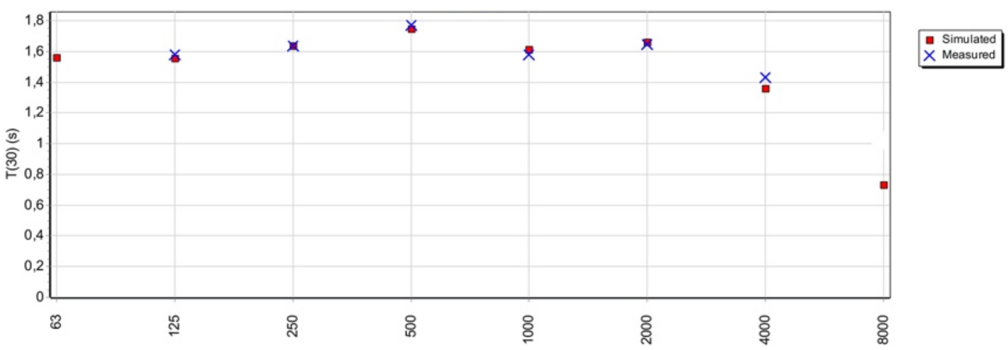


Figure 3.3.5 Elementary school music classroom T30 parameter compatibility results for R1 receiver after the optimization

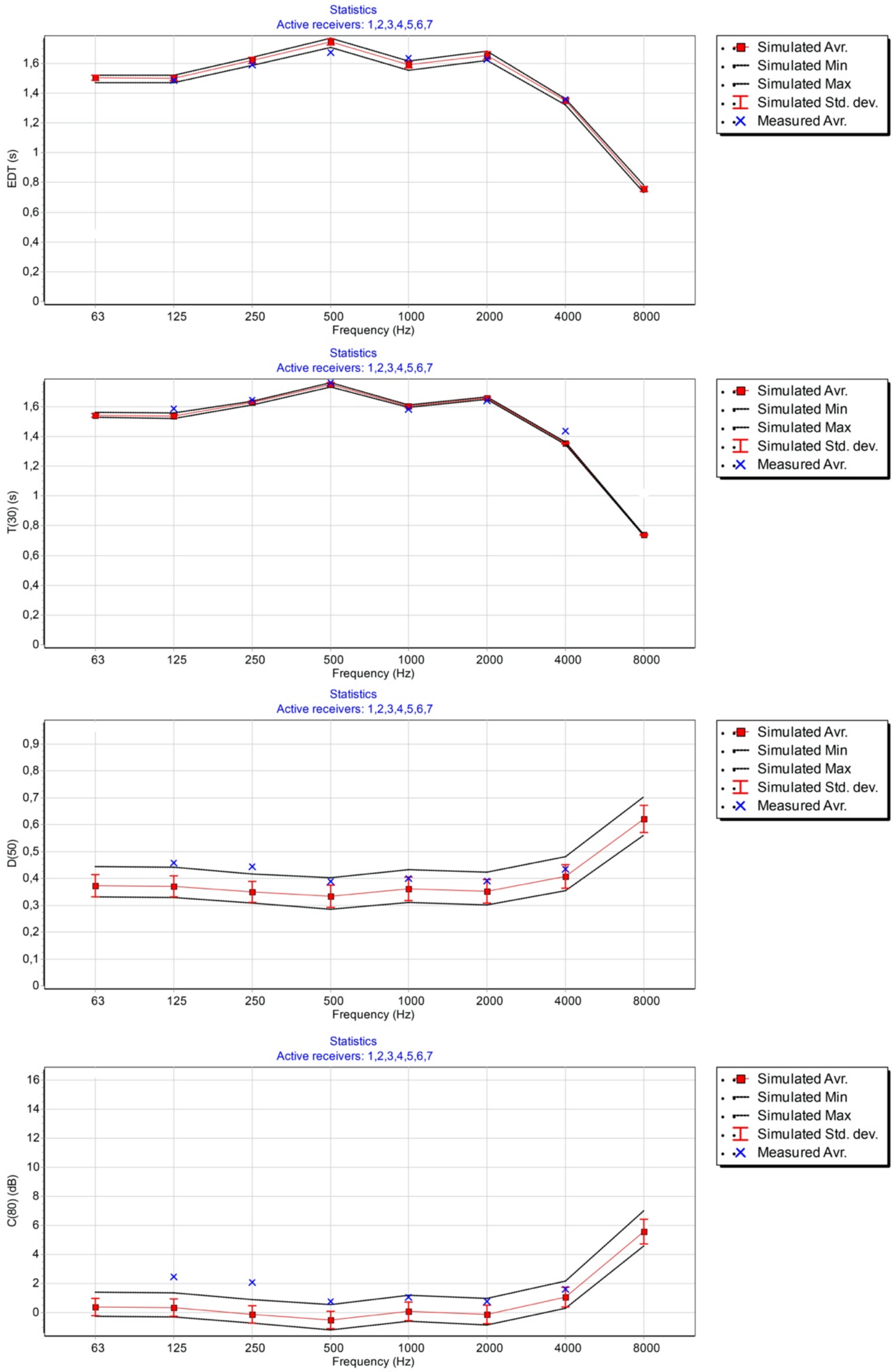


Figure 3.3.6 Elementary school music classroom comparison graphs of the measurements and upgraded simulations of room acoustic parameters (EDT, T30, D50, C80).

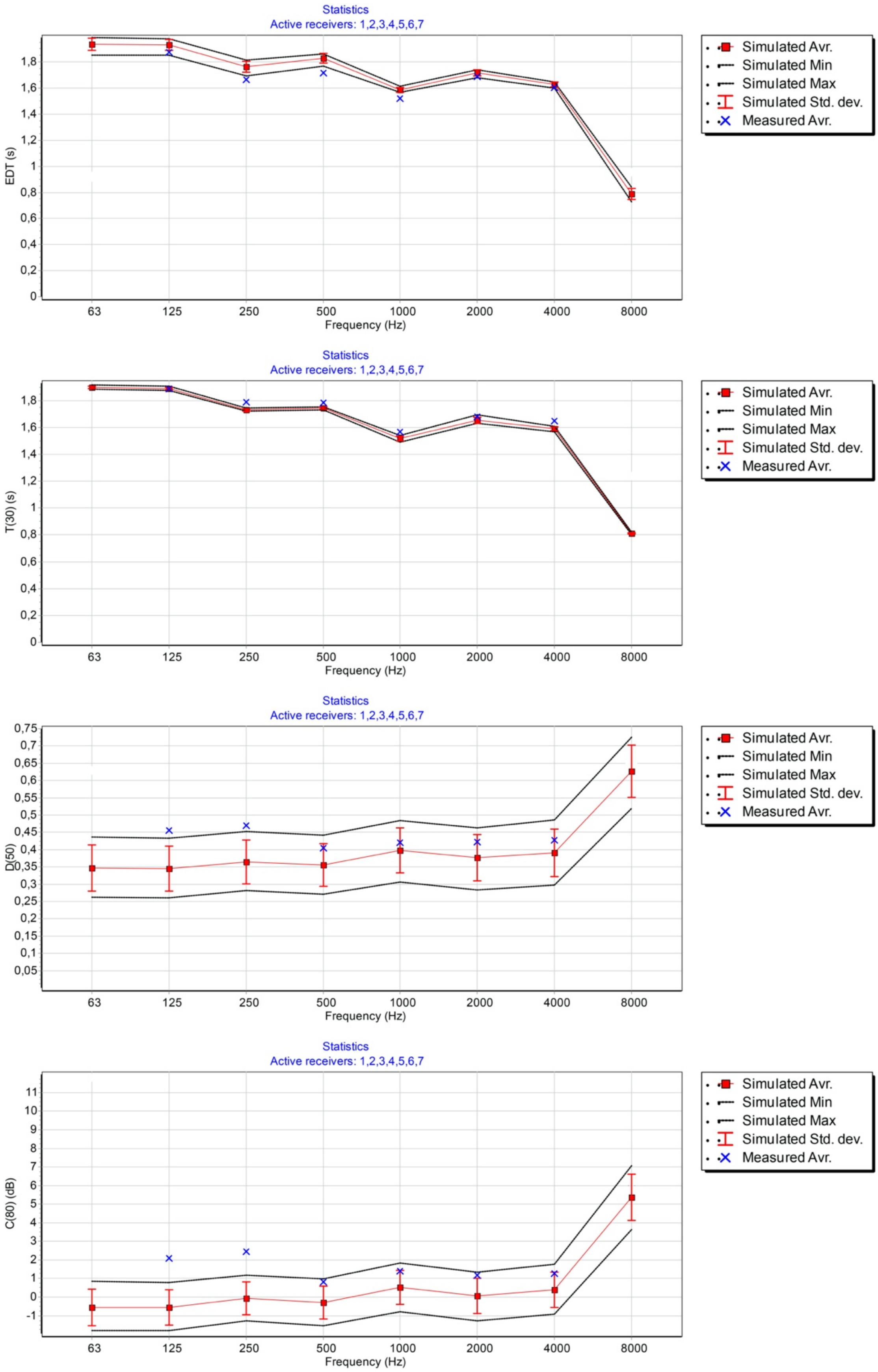


Figure 3.3.7 Middle school music classroom comparison graphs of the measurements and upgraded simulations of room acoustic parameters (EDT, T30, D50, C80).

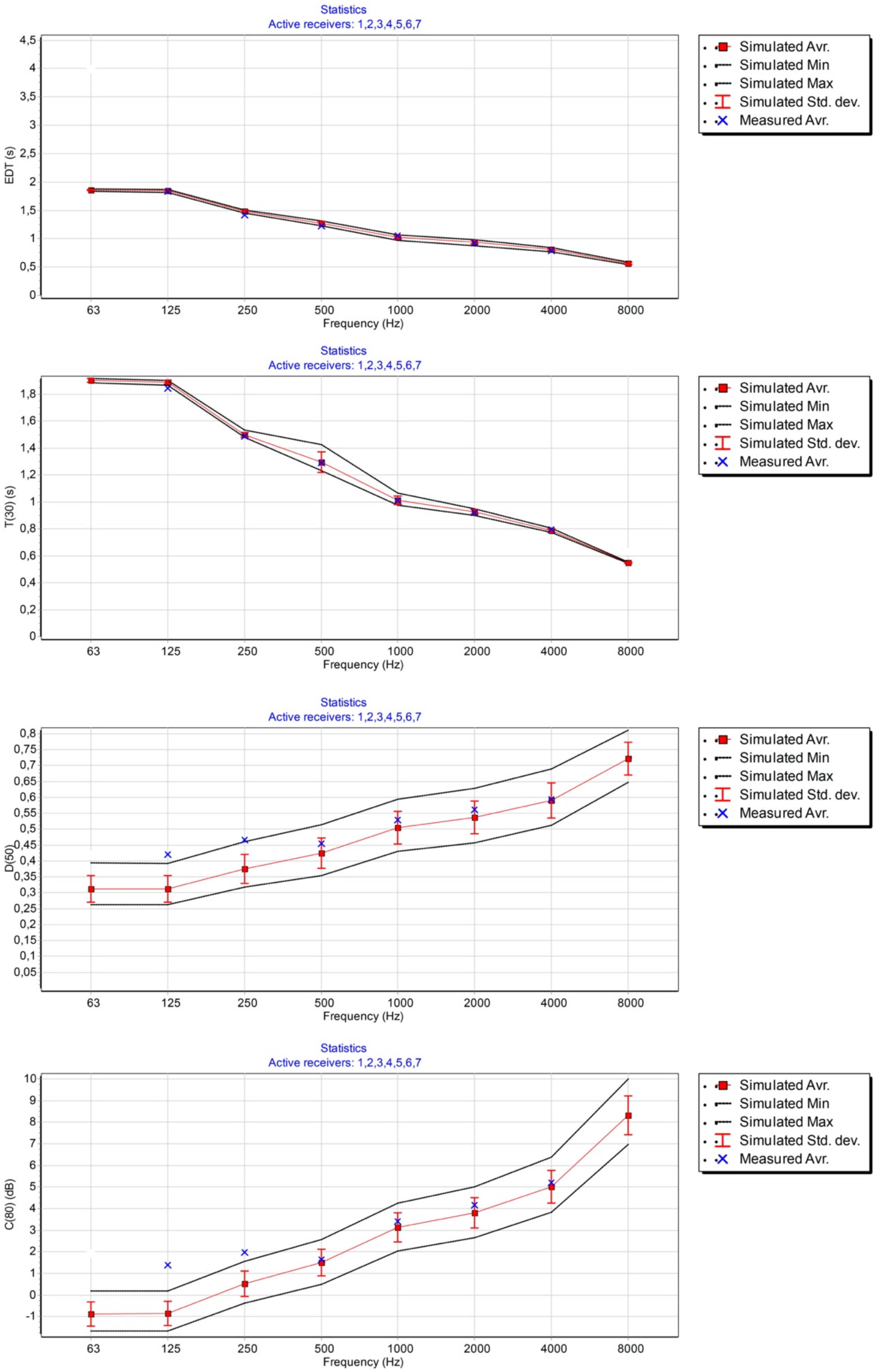


Figure 3.3.8 High school music classroom comparison graphs of the measurements and upgraded simulations of room acoustic parameters (EDT, T30, D50, C80).

The comparison graphs of the elementary school music classroom indicate that:

- The results of measurements and simulations are matching in the EDT parameter for all the octave bands.
- T30 results are parallel to the EDT results with slight differences and demonstrate a coherent graph.
- The D50 parameter is in the appropriate range at mid to high frequencies (500 – 4000 Hz). However, the comparison results at low frequencies (125 and 250 Hz) are slightly above 1 JND.
- C80 comparison results are below 1 JND except for low frequencies (125 and 250 Hz).

According to the comparison results of middle school music classroom:

- EDT parameter results are matching at all octave bands (125 – 4000 Hz).
- The results of the T30 parameter is parallel to EDT parameter and below 1 JND.
- D50 comparison results are in the appropriate range at octave bands of 500 – 4000 Hz. However, there are results slightly above the appropriate range at 125 and 250 Hz.
- C80 parameter simulation results are in line with measurement results at mid to high frequencies (500 – 4000 Hz). The results at low frequencies (125 – 250 Hz) are above 1 JND.

The comparison statistics of high school music classroom reveals that:

- EDT results of simulations are matching with the measurement results precisely.
- T30 simulation results are compatible with measurements and below the 1 JND criterion.
- Compatibility for D50 parameter is provided at octave band range of 500 – 4000 Hz. However, there are results slightly higher than the appropriate range of compatibility at bands of 125 and 250 Hz.
- C80 results are in the appropriate range except the results at low frequencies (125 – 250 Hz), which are above this range.

As stated in the previous sections, objective acoustic parameter values are achieved as a result of the acoustic measurements performed in the rooms according to the specified standards. Also, the three-dimensional models of the rooms are generated with the actual dimensions that are measured prior to the experimental and computational studies. The surface materials in the rooms are carefully examined and the layers accompanying are analyzed as detailed as possible. The sound absorption coefficients of the surfaces are selected from materials estimated to be as close to the real situation as possible. The updates to the material absorption coefficients are performed within the limits of the material characteristics. When the room acoustic parameter values achieved as a result of the acoustic analysis are examined, it is observed that the simulation results are significantly close to the measurement values. According to the frequency-based examination, it is observed that the subjective limen (just noticeable difference) values are exceeded at low frequencies (125 Hz – 250 Hz) in some of the parameters, such as D50 and C80. However, it is estimated that this situation occurred due to some important reasons:

- A high amount of different materials used in an irregular arrangement in the relatively small sized rooms.
- The production and application details and the sound absorption coefficients of these materials are not completely known.
- The rooms may not be simulated precisely at low frequencies due to the standing waves that are prominent at low frequencies especially in small sized rooms.

Considering the results of the comparison, it is observed that the values obtained at all frequencies and receiver points are among the appropriate limits, except for this situation which occurs at low frequencies for D50 and C80 parameters. Therefore, the accuracy and calibration of the simulation models are considered as verified and the studies performed after this stage are carried out on the basis of these models.

Since, the purpose of the study is to investigate the acoustic performances of the multipurpose music classrooms depending on the different functions, simulation studies addressing different situations are carried out using verified models. The first study is performed in order to investigate the speech intelligibility during the theoretical classes by calculating the speech transmission index (STI) parameter in all of the classrooms. In order to analyze the STI parameter, the omni sound source used in the previous simulations is replaced with *BB 93_RAISED_NATURAL* source type with a total sound power of 78 dB, due to the directivity of the source (see Figure 3.3.9) and the sound levels at different frequencies (see Table 3.3.2) are optimized for a human speaker with a raised vocal effort.

Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Spectrum (dB)	65.00	65.00	69.60	74.80	71.80	63.80	57.30	48.50

Table 3.3.2 Sound power of BB 93_RAISED_NATURAL sound source in the frequency spectrum

The simulation results of the STI at broad band range between 0.49 – 0.56 in the elementary school, 0.46 – 0.55 in the middle school and 0.56 – 0.64 in the high school music classrooms. The STI results at seven receiver points are given in Table 3.3.3.

Receiver Point	**Simulated Classroom**		
	Elementary School Music Classroom	**Middle School Music Classroom**	**High School Music Classroom**
R1	0.50	0.50	0.58
R2	0.56	0.55	0.64
R3	0.50	0.48	0.57
R4	0.51	0.51	0.57
R5	0.49	0.47	0.58
R6	0.50	0.46	0.56
R7	0.49	0.49	0.57
Average	0.51	0.50	0.58

Table 3.3.3 Broad band simulation results of STI parameter in the multipurpose music classrooms at 7 receiver points.

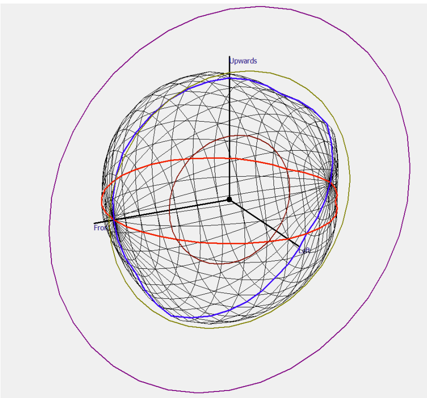


Figure 3.3.9 Directivity balloon of BB 93_RAISED_NATURAL sound source (Odeon, 2020).

3.4. Results & Discussion

The appropriate range of the room acoustic parameters are explained in Section 2.2.2. Table 3.4.1 demonstrates the reference values for the speech and music functions in terms of the room acoustic parameters. The reference values listed in the table are determined according to the volumes and functions of the rooms according to the calculations and explanations provided in relevant studies, standards and regulations. Tables 3.4.2 – 3.4.4 demonstrate the average values at the seven receiver points of the room acoustic parameters (EDT, T30, D50, C80, and STI) obtained in the elementary, middle and high school music classrooms, respectively. These values are compared with the reference criteria, and the acoustical performance of the multipurpose music classrooms are evaluated for their different functions. This section evaluates the acoustical performances of classrooms in unoccupied condition. The occupied condition is also investigated through computational analyses as an individual study (see Appendix).

Performance Criteria	**Reference Values for Speech (Teaching)**	**Reference Values for Music**
Early Decay Time (EDT) (500 – 1000 Hz avg.)	< 1.00 s	> 1.00 s
Reverberation Time (T30) (500 – 1000 Hz avg.)	0.45 – 0.80 s (for volumes between 90 – 300 m^3)	0.95 – 1.4 s (for volumes between 90 – 300 m^3)
Distinctness (D50) (500 – 1000 Hz avg.)	> 0,5	-
Clarity (C80) (500 – 1000 Hz avg.)	> +2 dB	-1 dB - +3 dB
Speech Transmission Index (STI)	0.00 – 0.30 Bad 0.30 – 0.45 Poor 0.45 – 0.60 Fair 0.60 – 0.75 Good 0.75 – 1.00 Excellent	-

Table 3.4.1 Appropriate values for acoustical performance of speech and music functions (Houtgast et al., 1980; DIN, 2004; Bistafa and Granado, 2005; Kuttruff, 2009; ISO, 2009; Odeon, 2020).

Elementary School Music Classroom						
EDT (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1.45	1.55	1.65	1.6	1.6	1.34
Maximum	1.58	1.68	1.7	1.67	1.65	1.37
Average	1.49	1.59	1.68	1.64	1.63	1.36
T30 (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1.55	1.64	1.75	1.57	1.63	1.43
Maximum	1.65	1.65	1.77	1.6	1.66	1.45
Average	1.59	1.65	1.76	1.58	1.64	1.44
D50						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	0.42	0.41	0.33	0.34	0.36	0.39
Maximum	0.5	0.49	0.45	0.47	0.45	0.46
Average	0.46	0.44	0.39	0.4	0.39	0.44
C80 (dB)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	2.2	1.9	0.1	0.4	0.3	1.2
Maximum	2.9	2.7	1.5	1.8	1.2	1.8
Average	2.5	2.1	0.8	1.1	0.8	1.6
STI						
Minimum	0.49					
Maximum	0.56					
Average	0.51					

Table 3.4.2 Room acoustic parameter values of elementary school music classroom.

According to the results of the studies carried out for the elementary school music classroom:

- The reverberation time in the classroom is relatively homogeneous, with average values of 1.62 at the low, 1.67 at the middle and 1.54 at the high frequencies. The average reverberation time (T30) at the mid-frequencies is above the reference range for both speech and music functions with 1.67 s. The graph of reverberation time is increasing from low to mid frequencies and decreasing from mid to the high frequencies. The graph curves at different receiver points are almost parallel to each other.
- The EDT parameter demonstrates a consistent graph with T30 in the six octave bands. This indicates that there is a diffuse sound field in the classroom. It is also noted that the average EDT at mid frequencies is 1.66 s, which is an appropriate value for music functions. However, it is higher than the reference limit for speech, which is 1.00 s.
- The values of the D50 parameter at the 125 – 4000 Hz octave band range are mostly in line with each other. However, the distinctness is slightly decreasing from the front rows to the rear rows of the classroom. The D50 parameter should be above 0.5 for the intelligibility of speech in the room. The results are below this limit at all receiver positions except for R2 at only 125 Hz octave band.
- The C80 parameter is important for the clarity of music in the rooms. The average value of clarity at mid frequencies is 0.95 dB, which is appropriate for music function. However, C80 is lower than the reference limit for speech function. It is also identified that the C80 values are higher at the front rows than the rear rows of the classroom at certain frequencies (500 - 1000 - 2000 Hz)
- The STI value of the room is 0.51 and it corresponds to *fair,* according to the scale provided by Houtgast et al. (1980). This indicates that the intelligibility of speech is provided to a certain level of acceptability on the basis of STI parameter.

Middle School Music Classroom						
EDT (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1.87	1.65	1.66	1.5	1.68	1.58
Maximum	1.89	1.69	1.76	1.55	1.7	1.62
Average	1.88	1.67	1.72	1.52	1.69	1.61
T30 (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1.82	1.78	1.78	1.56	1.67	1.64
Maximum	1.93	1.8	1.79	1.58	1.69	1.65
Average	1.89	1.79	1.79	1.57	1.68	1.65
D50						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	0.39	0.41	0.32	0.35	0.33	0.34
Maximum	0.52	0.53	0.47	0.46	0.49	0.49
Average	0.46	0.47	0.4	0.42	0.42	0.43
C80 (dB)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1.5	1.8	0	0.6	0.1	0.4
Maximum	2.8	3.1	1.6	1.9	2.2	1.9
Average	2.1	2.4	0.8	1.4	1.2	1.3
STI						
Minimum	0.46					
Maximum	0.55					
Average	0.50					

Table 3.4.3 Room acoustic parameter values of middle school music classroom.

The results of the room acoustic parameters at the middle school music classroom demonstrates that:

- The reverberation time at the seven receiver points are uniform at each octave band. The T30 graph curve is rising from 125 Hz to 500 Hz and decreasing to 4000 Hz. The average T30 value at mid frequencies is 1.68, which is above the appropriate upper reference limits of 0.8 s and 1.4 s that are determined for both speech and music respectively.
- It is expected that the EDT value difference should be equal to T30 or ± 0.2 sec different from T30 in rooms with a diffuse sound field. The EDT results in elementary school music classroom are parallel to the T30 results at all the octave bands and they are in the specified range of diffusivity. The average EDT value at mid frequencies is not in the reference ranges of speech. In terms of music functions, the EDT is within the acceptable limits. The early decay time is inversely proportional to the clarity (C80) parameter. Since the EDT results are higher for the speech functions, the C80 parameter is negatively affected by the result.
- The distinctness parameter (D50) is slightly decreasing from the front rows to the rear rows of the classroom with a standard deviation of 0.05. The average values of all frequencies are relatively close within a range of 0.41 – 0.46. The average value at the mid frequencies is 0.41, which is lower than the reference limit of 0.5 for the speech intelligibility in the room.
- The receiver averaged values of the clarity parameter are decreasing from low to mid frequencies and demonstrates a stable graph curve to the high frequencies. It is also noted that clarity is increasing from the rear rows to the front rows of the classroom. The frequency averaged value at the mid frequencies is 1.1 dB which is below the specified limit for the speech function. However, at some receiver points, the clarity result is in the appropriate levels for speech such as, R1, R2, R3 and R4 at 125, 250 and 200 Hz octave bands.
- The speech transmission index (STI) is 0.50 for the classroom and it is in the range of *fair* that is specified for the intelligibility of speech. According to this result, the speech intelligibility is at a moderate level based on the STI parameter.

High School Music Classroom						
EDT (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1.81	1.37	1.19	1	0.89	0.73
Maximum	1.87	1.45	1.3	1.12	0.96	0.83
Average	1.84	1.42	1.23	1.06	0.93	0.79
T30 (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1.78	1.48	1.28	1	0.92	0.77
Maximum	1.89	1.5	1.3	1.02	0.93	0.81
Average	1.85	1.49	1.29	1.01	0.92	0.79
D50						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	0.4	0.43	0.41	0.48	0.51	0.55
Maximum	0.48	0.51	0.53	0.59	0.61	0.7
Average	0.42	0.47	0.45	0.53	0.56	0.59
C80 (dB)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1	1.5	0.9	3	3.8	4.7
Maximum	1.9	2.5	3	4.1	4.8	5.8
Average	1.4	2	1.7	3.4	4.2	5.2
STI						
Minimum	0.56					
Maximum	0.64					
Average	0.58					

Table 3.4.4 Room acoustic parameter values of high school music classroom.

The high school music classroom room acoustic parameters are analyzed and the results indicate that:

- The reverberation time (T30) is constantly decreasing from 125 Hz to 4000 Hz at all the receiver points, averaging at 1.85 for 125 Hz and 0.79 for 4000 Hz. The average value of T30 at mid frequencies is 1.15 s, and it is in the appropriate range of music function. However, it is above specified the range of speech function at the mid frequencies.
- The EDT parameter is in line with the T30 parameter, which demonstrates that this classroom has a diffuse sound field. The EDT results of the classroom are in the reference range for music function with an average value of 1.14 at the mid frequencies. The fact that the T30 and EDT parameters are within the range determined to be acceptable for music also positively affected the levels of C80.
- The results of the distinctness parameter indicate an increasing graph curve from low to high frequencies. The mid-frequency average value of D50 is 0.49, which is slightly below the reference limit of 0.5. However, it should be considered as acceptable for the intelligibility of speech, since the difference is within the limits of JND (just noticeable differences).
- The values of the C80 parameter are increasing from 125 Hz to 4000 Hz, with average values of 1.4 dB and 5.2 dB respectively. The average value at the mid frequencies is 2.55 dB, which is appropriate for both speech and music functions in terms of the reference values.
- The level of STI is 0.58 at the high school music classroom, which is in the *fair* range. It is also very close to the range of *good,* which indicates that this classroom has a good speech intelligibility based on the results of D50 and STI.

Chapter 4

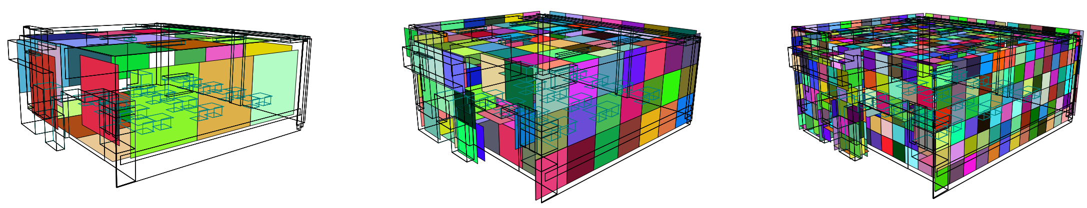
Identification of Acoustical Problems in Multipurpose Music Classrooms

The acoustical performance of the multipurpose music classrooms is determined with the results of the experimental and computational studies. According to the results, the obtained values of the T30, EDT, D50, C80 and STI parameters at certain octave bands are not in the reference limits considered in section 3.4. Therefore, potential sources of the acoustical problems are investigated in this chapter. Surfaces that have a negative impact on the acoustical performance of the classrooms are determined with computational analyses on the calibrated 3D models. Grids are defined on the surfaces of the classrooms, and the acoustical responses to the inputs in terms of the five room acoustic parameters are computed. The mentioned acoustic parameters and the reference values are tabulated in Table 3.4.1. The acoustical problems are defined according to the table mentioned. The values that are not in the given limits are defined as acoustical problems.

The grid analyses are carried on by reducing the grid sizes systematically. Thus, irrelevant surfaces that do not lead to an acoustical problem are eliminated from the analyses and the focus of the study is directed on the problematic surfaces. The values of room acoustic parameters at the grids are investigated and problematic sections of the surfaces are identified. The root causes of the acoustical problems defined are stated along with the relevant surfaces. The three case studies below investigate the acoustical problems of the elementary, middle and high school multipurpose music classrooms, respectively. In the case studies, the grid receivers are assigned on the surfaces of the classroom models with the omni-directional sound source positions previously used for the computational analyses in Section 3.2. The responses on the grids are analyzed in the mid-frequencies (500 Hz – 1000 Hz).

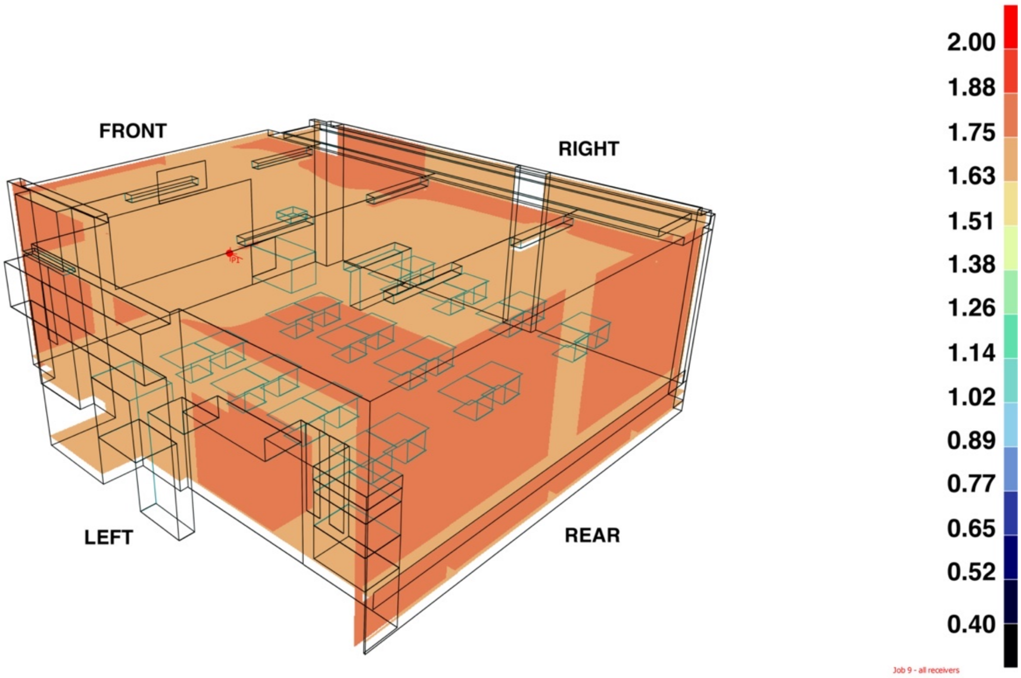
4.1. Case Study I: Elementary School Multipurpose Music Classroom

The surfaces of the building, structure and furnishing elements on the calibrated model of the classroom are analyzed with grid response analysis. Grids are assigned to all of the surfaces in the classroom model and the grid responses are calculated. The grid sizes are reduced and the analyses are repeated to detect relevant parts of the potential sources of the acoustical problems. The mid-frequencies (500 Hz – 1000 Hz) are considered in the grid analyses to compare the results with the reference criteria discussed in Section 3.4. The omni-directional sound source in section 3.2 is used at the same position, 1.5 m above the floor level. In the first grid simulation, the distance between the receiver grids are determined to be 2 m and the five room acoustic parameters (T30, EDT, D50, C80, and STI) are analyzed (see Figures 4.1.2 – 4.1.6). According to the results of the first phase, the distance between the grid receivers are decreased systematically from 2 m to 1 m and 1 m to 0.5 m, respectively. The grid sizes used in the case study are provided in Figure 4.1.1. Since the results of 1 m distance and 0.5 distance are converged, only phases with 2 m and 0.5 m receiver distances are provided in this case study.

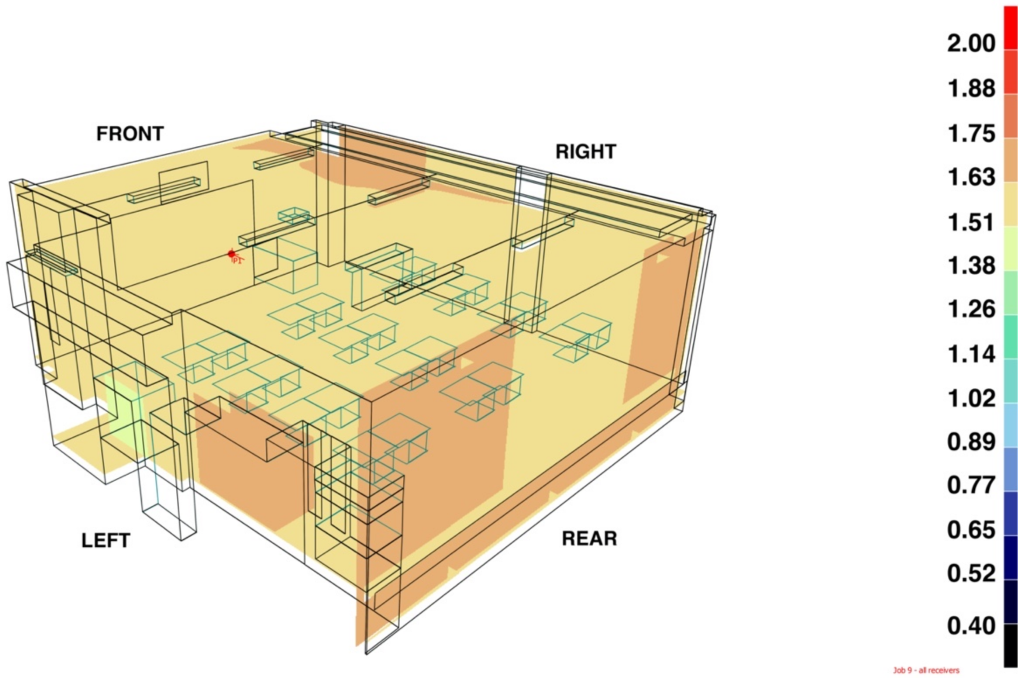


2 m receiver distance **1 m receiver distance** **0.5 m receiver distance**

Figure 4.1.1 Grid sizes according to the receiver distances determined for Case Study I.

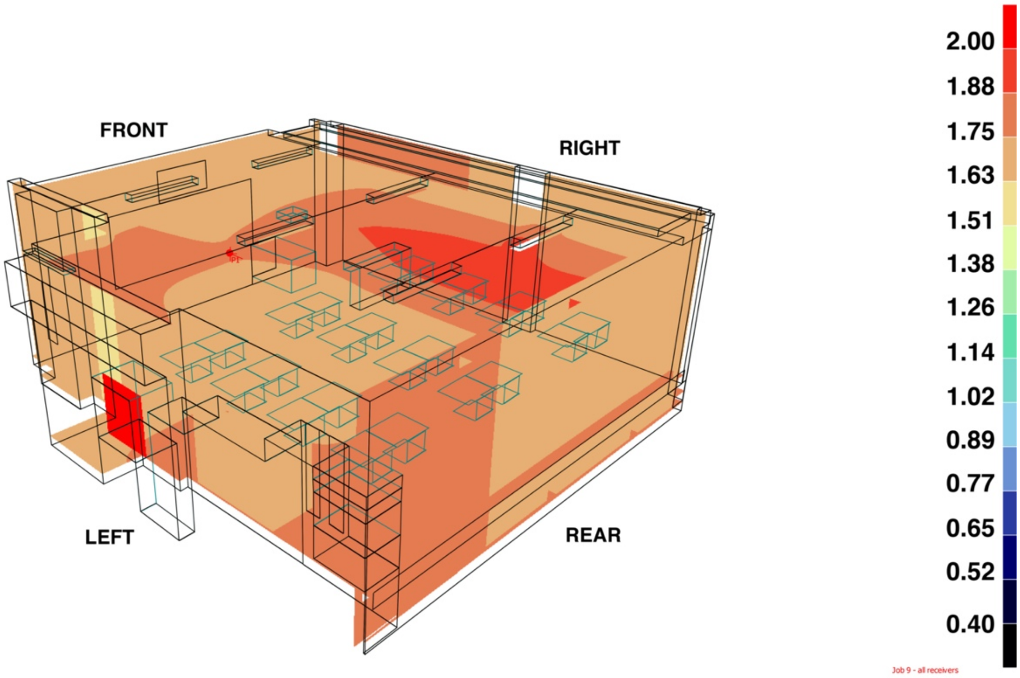


500 Hz

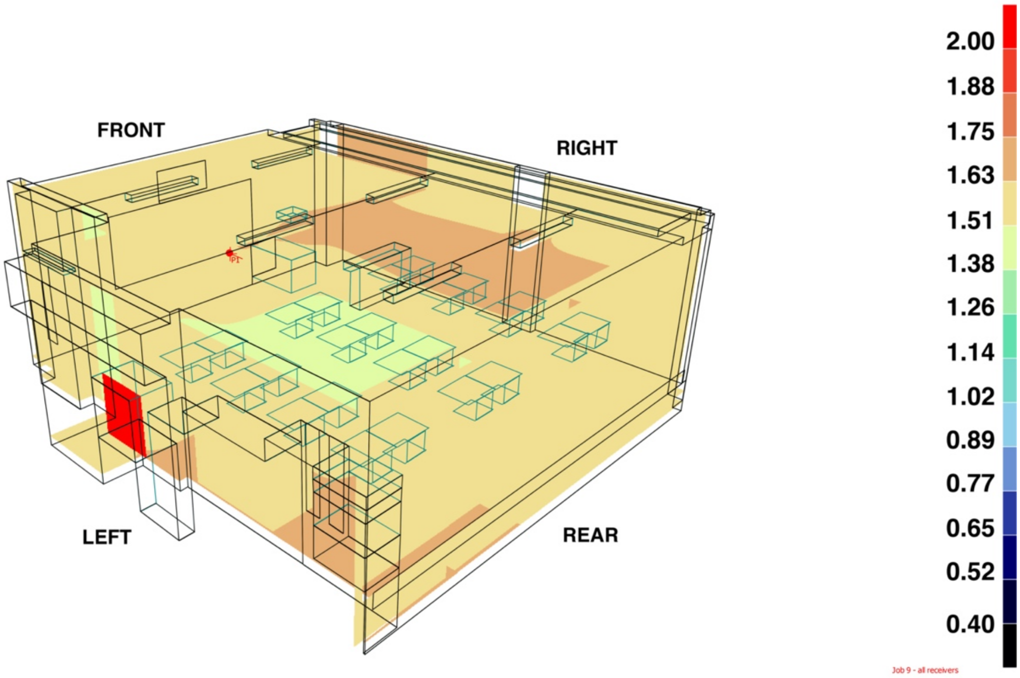


1000 Hz

Figure 4.1.2 Elementary school multipurpose music classroom grid responses of T30 parameter with 2 m receiver distance.

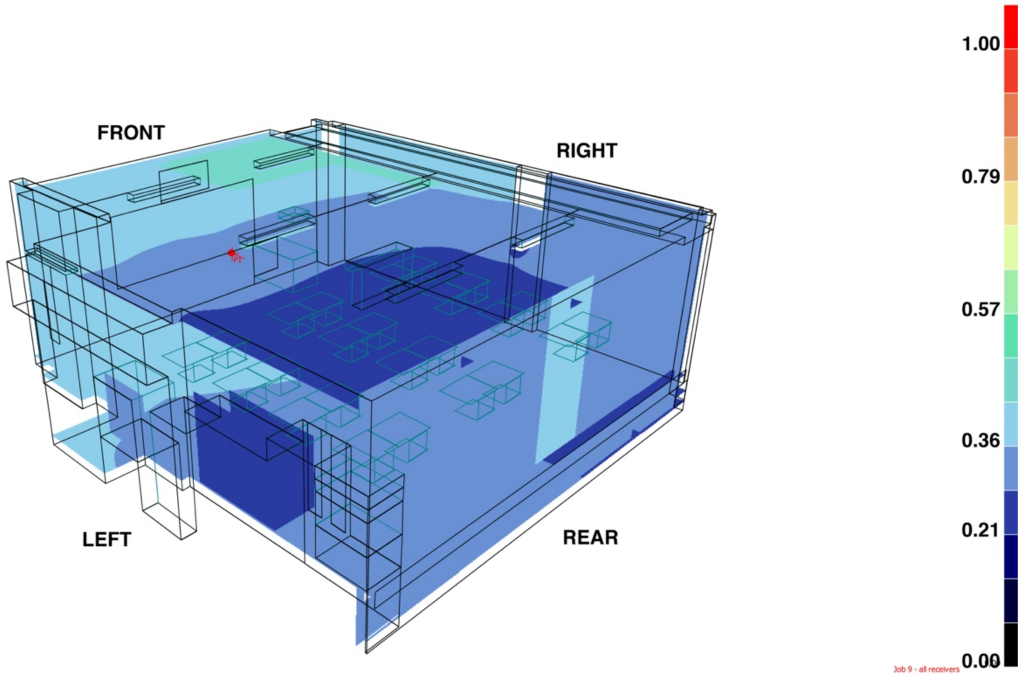


500 Hz

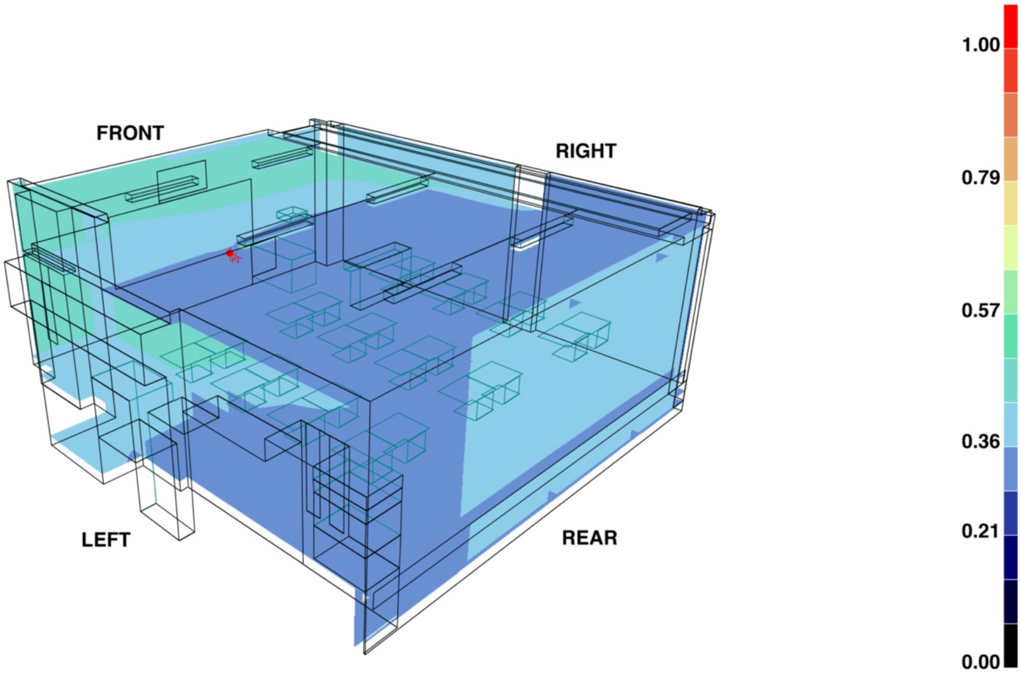


1000 Hz

Figure 4.1.3 Elementary school multipurpose music classroom grid responses of EDT parameter with 2 m receiver distance.

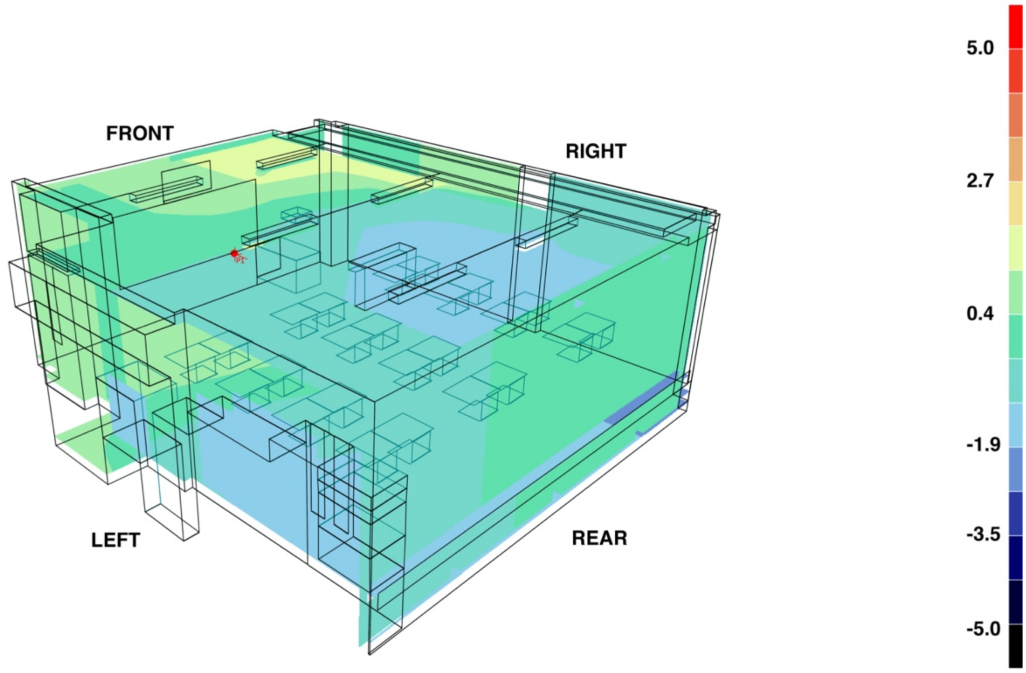


500 Hz

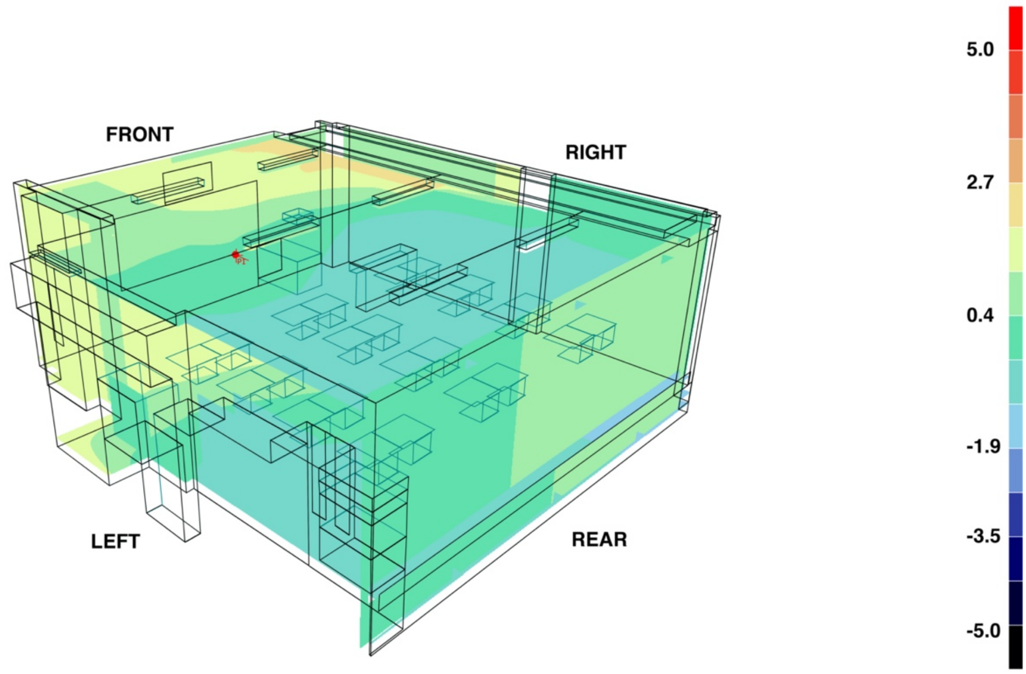


1000 Hz

Figure 4.1.4 Elementary school multipurpose music classroom grid responses of D50 parameter with 2 m receiver distance.



500 Hz



1000 Hz

Figure 4.1.5 Elementary school multipurpose music classroom grid responses of C80 parameter with 2 m receiver distance.

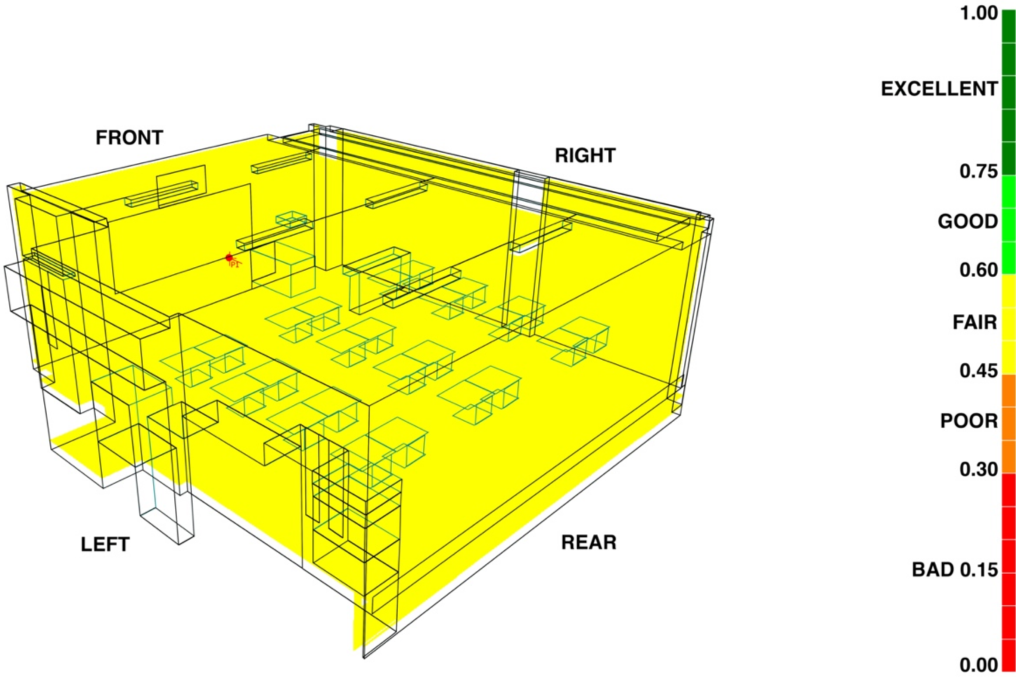
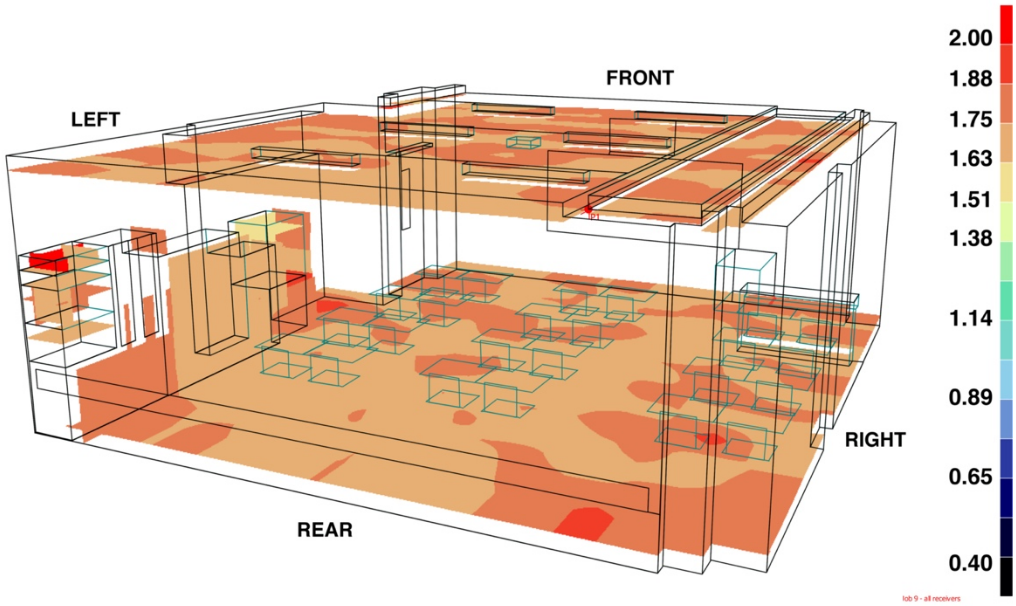
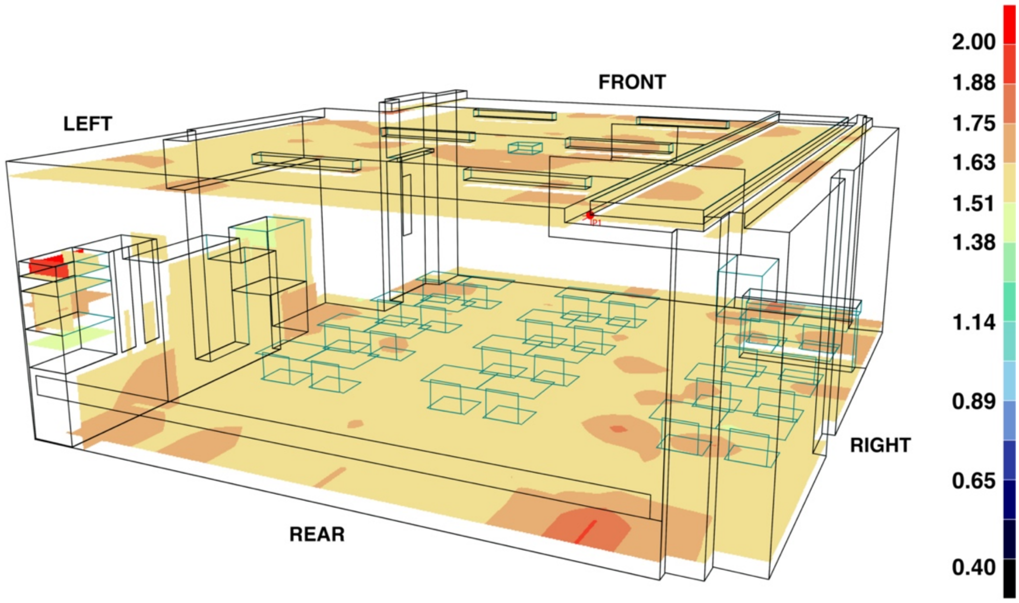


Figure 4.1.6 Elementary school multipurpose music classroom grid responses of STI parameter with 2 m receiver distance.

The grid analysis results at the 2 m receiver distance indicates that the rear part of the ceiling, various parts on the floor surfaces and the vertical surfaces of the bookshelves have the highest values of the T30 and EDT parameters with 1.75 s – 2.00 s. At this point, EDT is a more critical parameter than T30 since the decay of the sound at the first 10 dB is considered. In the T30 parameter, the situation of a uniform reverberation is detected. The D50 and C80 parameters address the same surfaces with lower values. D50 is around 20 percent and C80 is about -1.9 dB on the surfaces mentioned above. The STI results give a complete uniform distribution graph which corresponds to the *fair* level in the entire room. For the values of the T30, EDT and STI parameters, almost all of the surfaces are not in the reference ranges provided in Section 3.4. Also, in the D50 and C80 parameters, there are surfaces with values that do not meet the reference criteria at various parts. In the first phase of the grid analyses, the worst surfaces in terms of acoustical problems are identified and these surfaces are analyzed in the second phase. The rest of the surfaces are not included in the following study. Detailed analyses of the room acoustic parameters are conducted through grids that are defined with 0.5 m distance between the receivers. The results are given in Figures (4.1.7 – 4.1.11).

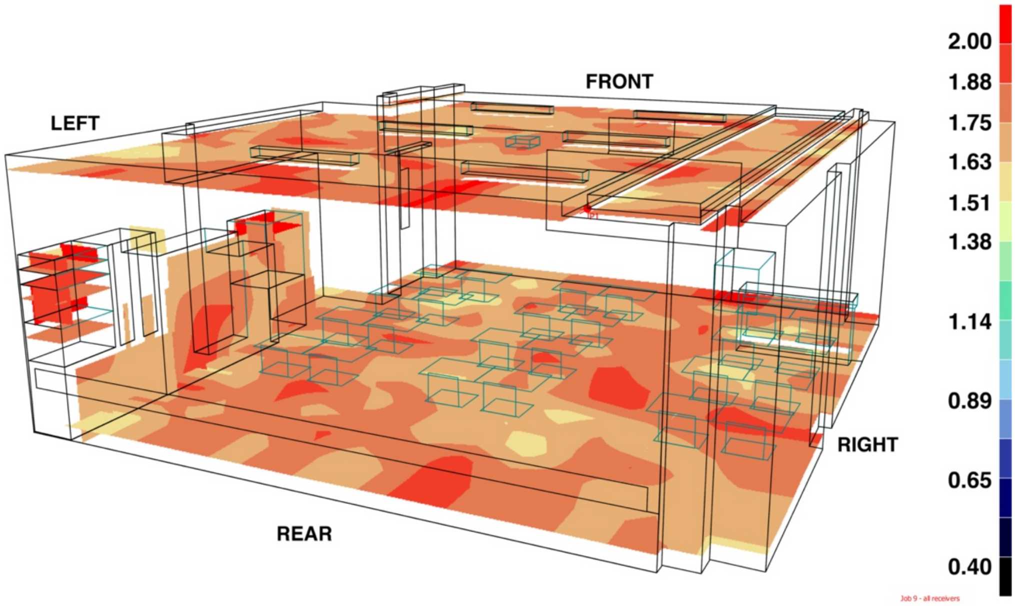


500 Hz

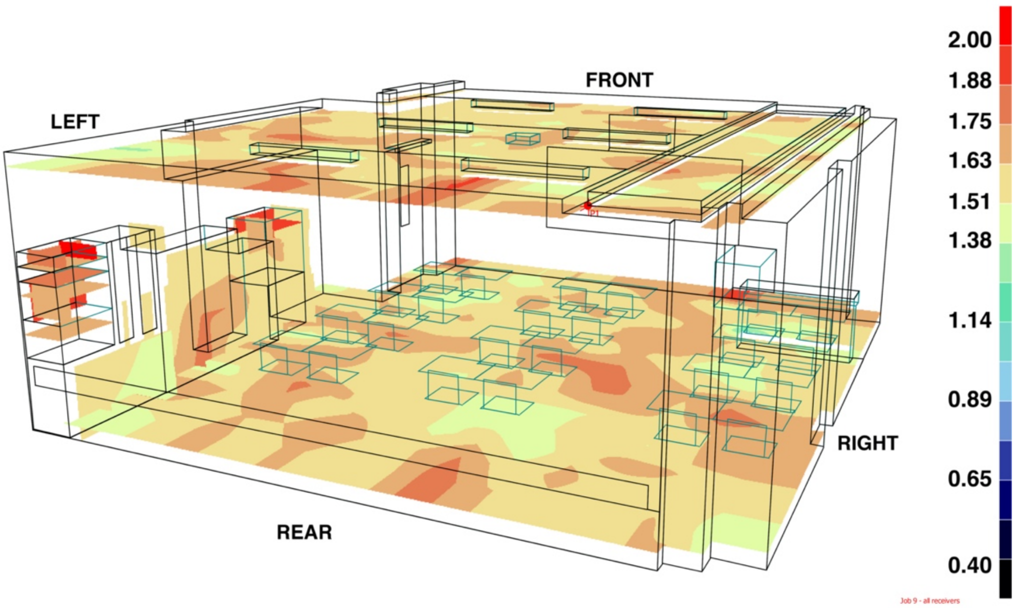


1000 Hz

Figure 4.1.7 Elementary school multipurpose music classroom grid responses of T30 parameter with 0.5 m receiver distance.

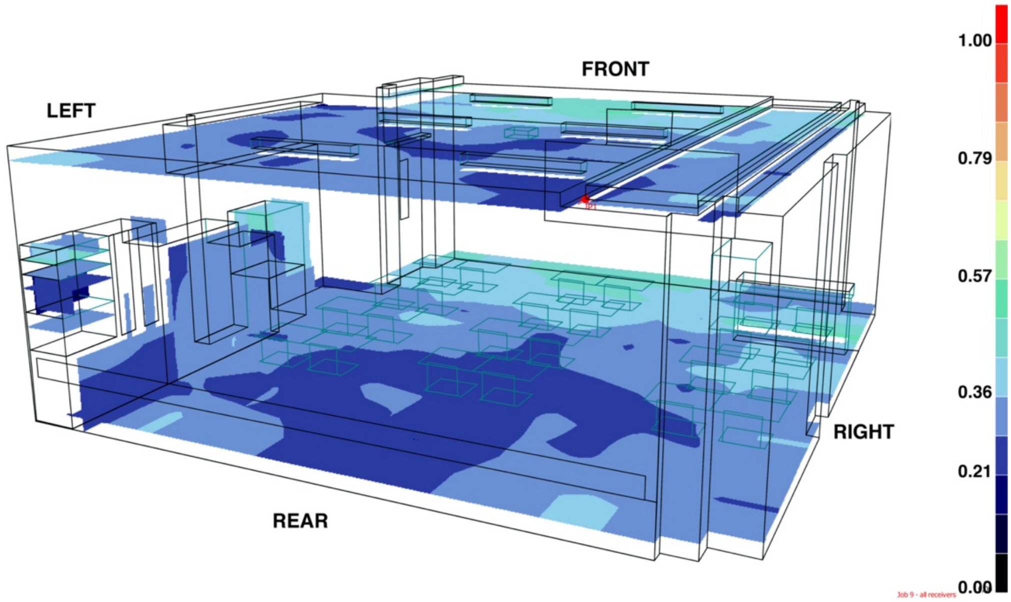


500 Hz

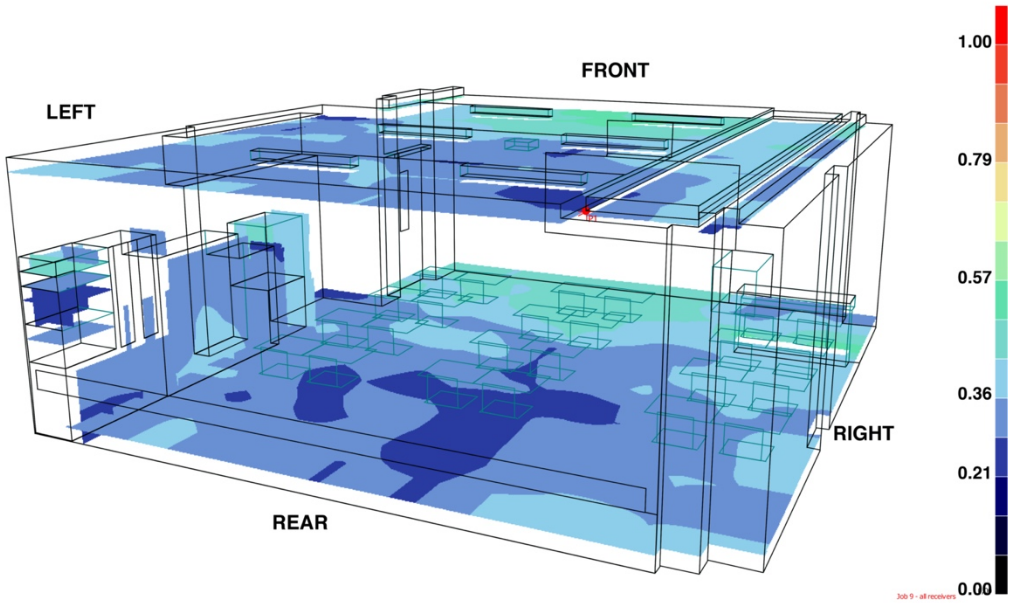


1000 Hz

Figure 4.1.8 Elementary school multipurpose music classroom grid responses of EDT parameter with 0.5 m receiver distance.

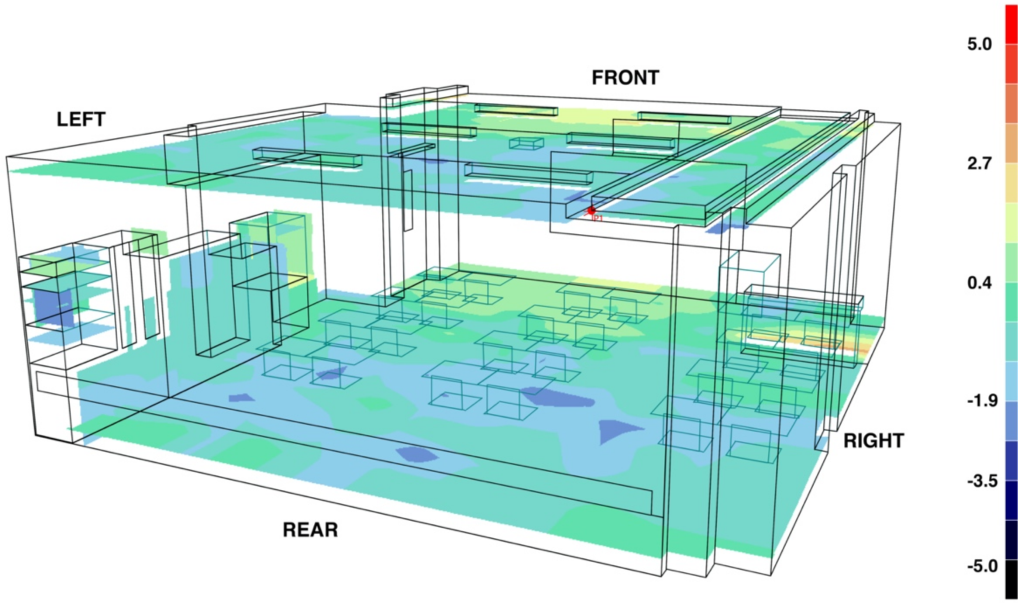


500 Hz

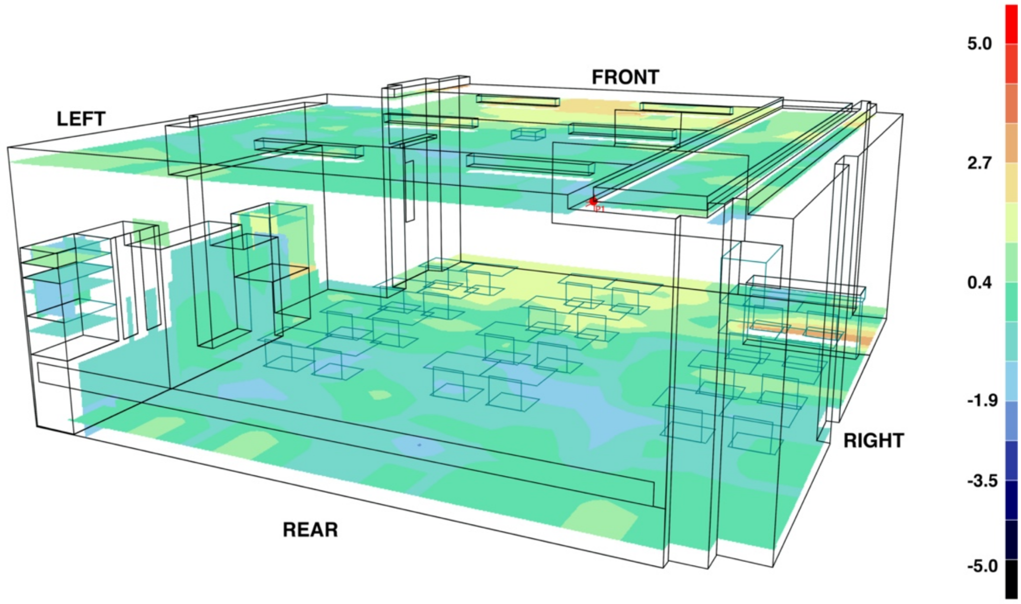


1000 Hz

Figure 4.1.9 Elementary school multipurpose music classroom grid responses of D50 parameter with 0.5 m receiver distance.



500 Hz



1000 Hz

Figure 4.1.10 Elementary school multipurpose music classroom grid responses of C80 parameter with 0.5 m receiver distance.

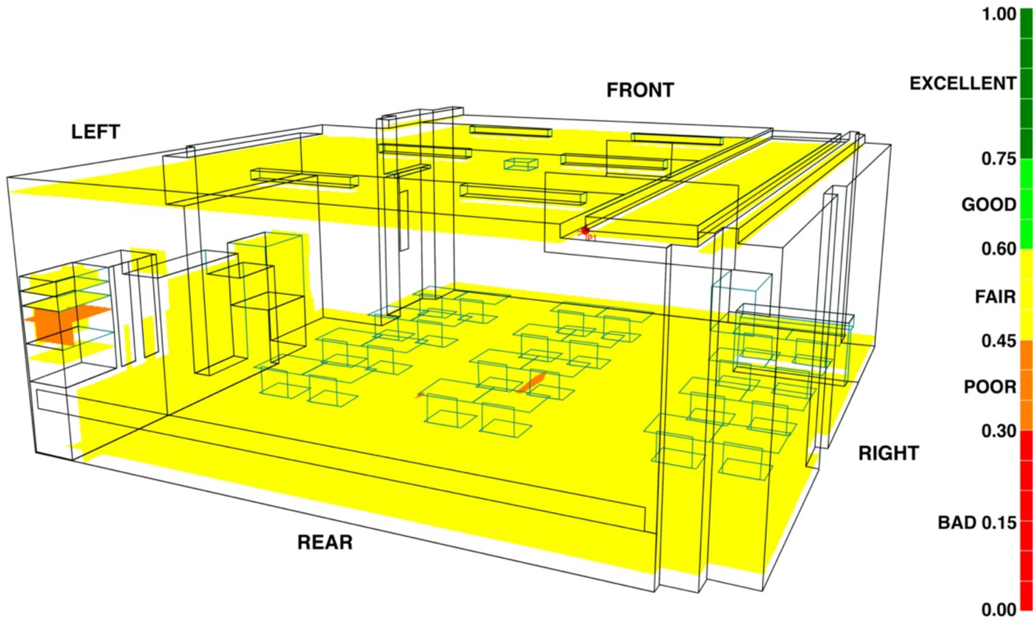


Figure 4.1.11 Elementary school multipurpose music classroom grid responses of STI parameter with 0.5 m receiver distance.

In the second phase, the analyses are focused on the aforementioned surfaces: the ceiling, floor and the surfaces of the bookshelves. The distance between the receivers is determined as 0.5 m in order to conduct a detailed analysis only on the selected surfaces. According to the results of the grid analyses in the classroom of elementary school:

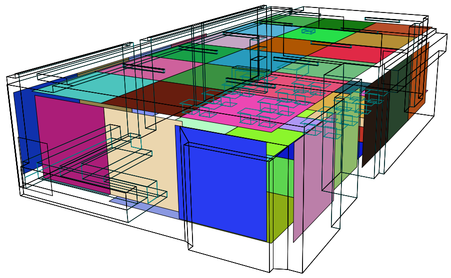
- The reverberation is consistent throughout the room with values between 1.60 – 1.70 s at mid frequencies. This indicates that the room has a diffuse sound field. The rear-right and middle-right parts of the floor (PVC material) and various parts on the surfaces of bookshelves (18 mm chipboard material) have the highest values in the interval of 1.85 – 2.15 s (allowable reference values are 0.45 – 0.80 s and 0.95 – 1.40 s for speech and music, respectively). The EDT parameter should be examined along with T30 to make a precise determination of the problematic sections of the surfaces.
- The EDT results are more decisive in terms of identifying the most problematic surfaces, since the first 10 dB decay range is considered. The graph demonstrates that the highest EDT values are distributed on the analyzed

surfaces at different sections. However, front-right, middle-right, middle-left parts, and entire rear part demonstrates the highest EDT values on the floor and ceiling surfaces with 1.90 to 2.10 s (appropriate values are EDT < 1.00 s for speech and EDT > 1.00 s for music). The interior surfaces of the shelves of bookcases have the highest EDT results between 1.95 – 2.20 s. This indicates that the sound waves are trapped inside these areas in the first 10 dB decay range. Also, certain parts on the cabinet doors of the bookcases (18 mm chipboard material) have an EDT value over 2 s, as seen in Figure 4.1.7. The parts mentioned above are the primary sources of acoustical problems in terms of EDT.

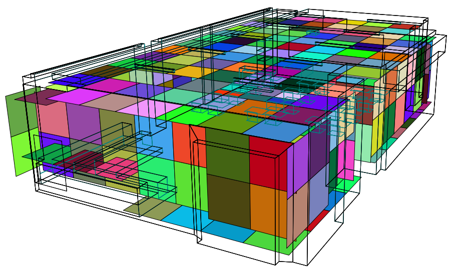
- In the front side of the classroom, the D50 parameter is around 50 percent and higher, which is the appropriate range for the definition of speech. It is identified that the D50 values decrease from front towards rear areas of the classroom. In the middle and rear parts of the floor (PVC material), the D50 is even below 20 percent. The interior surfaces of the bookshelves have the lowest D50 values, similar to the situation observed in the EDT parameter. There are points at the rear-right, middle and middle-left parts of the ceiling (plastered gypsum over rockwool), which demonstrate the lowest D50 results between 20 and 30 percent.
- The clarity of music decreases from the front side to the rear side of the classroom. The maximum C80 value is +3 dB which is appropriate for both speech and music. Surfaces that have the minimum C80 values are located on the floor around the rear rows and interior surfaces of the bookshelves with -2.5 dB and -2.3, respectively (appropriate values for C80 are between -1 dB and +3 dB for music and C80 > +2 dB for speech). Also, the rear right parts of the ceiling (plaster over gypsum over rockwool) have values between -2.0 dB and -1.8 dB. The aforementioned parts of the surfaces are the most problematic surfaces in the classroom in terms of the C80 parameter.
- STI is almost uniform through the classroom with an exception of a surface inside a bookshelf which was previously mentioned in the evaluation of the other parameters of room acoustics. The STI results of the classroom are between 0.45 – 0.55 which corresponds to *fair* level (0.60 – 0.75 is considered as *good*).

4.2. Case Study II: Middle School Multipurpose Music Classroom

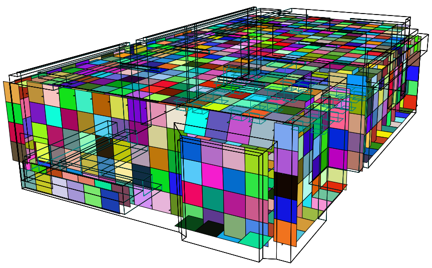
Surfaces of the middle school multipurpose music classroom are divided in to grid receivers. The input responses on these grids are analyzed in the mid-frequencies to identify the potential root causes of the acoustical problems. The reference values given in Table 3.4.1 are considered in evaluating the results. The acoustical properties and position of the sound source is identical to the omni source used in the computational analyses explained in section 3.2. The previously considered five room acoustic parameters are first analyzed with a grid receiver distance of 2 m and the results are provided in the following graphs (see Figures 4.2.2 – 4.2.6). The distance between the grid receivers are reduced systematically in the case study from 2 m to 1 m and 0.5 m systematically to analyze the surfaces in detail (see Figure 4.2.1).



2 m receiver distance

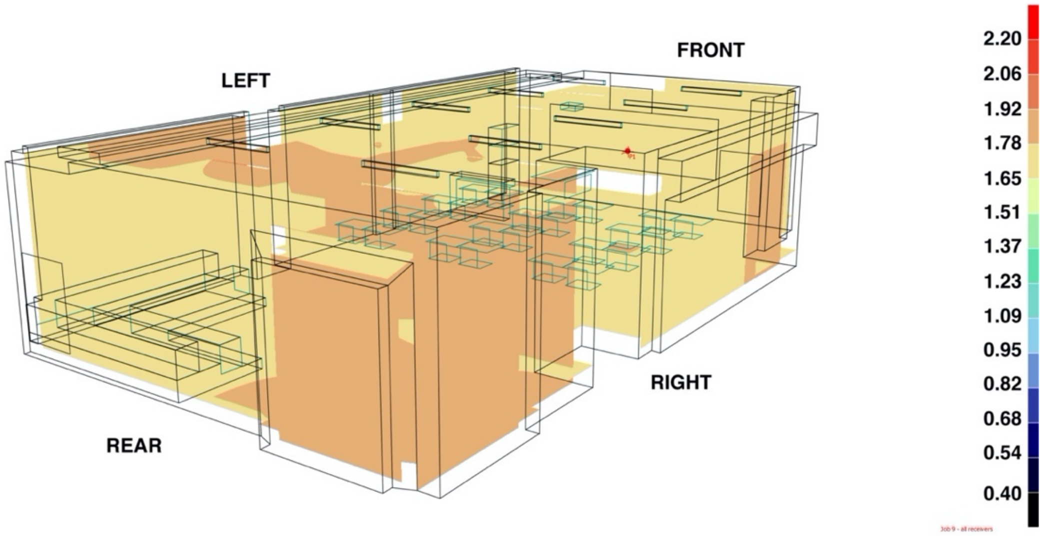


1 m receiver distance

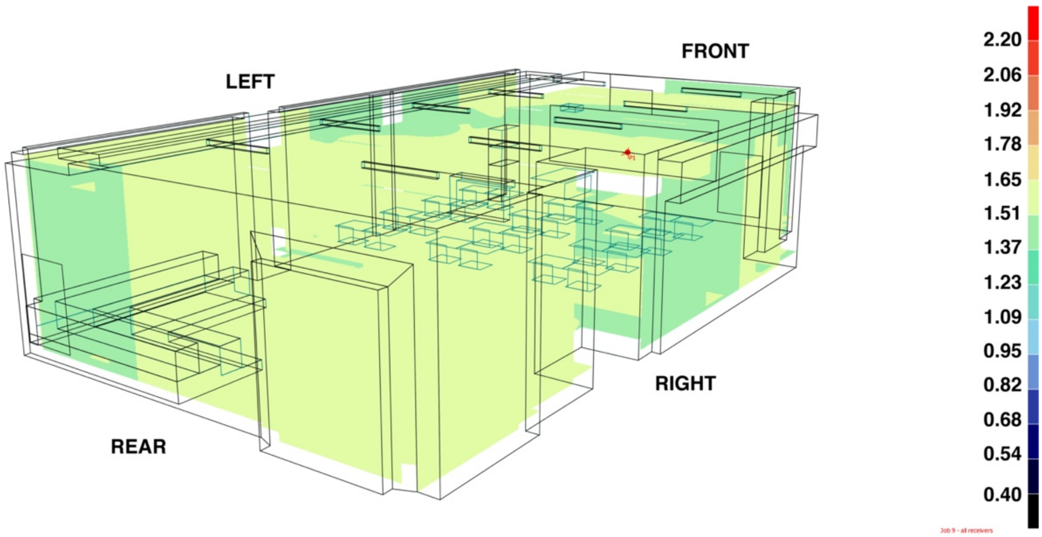


0.5 m receiver distance

Figure 4.2.1 Grid sizes according to the receiver distances determined for Case Study II.

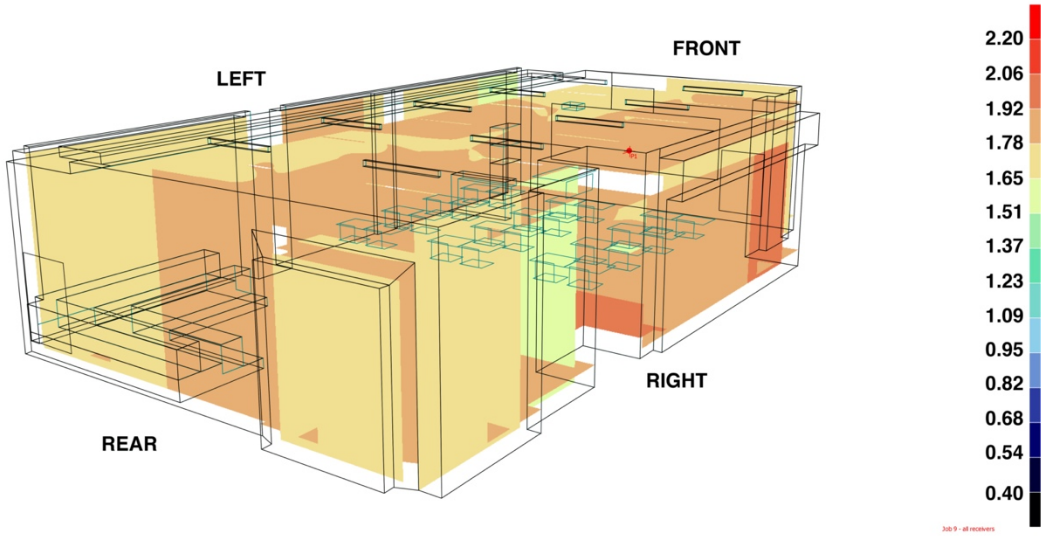


500 Hz

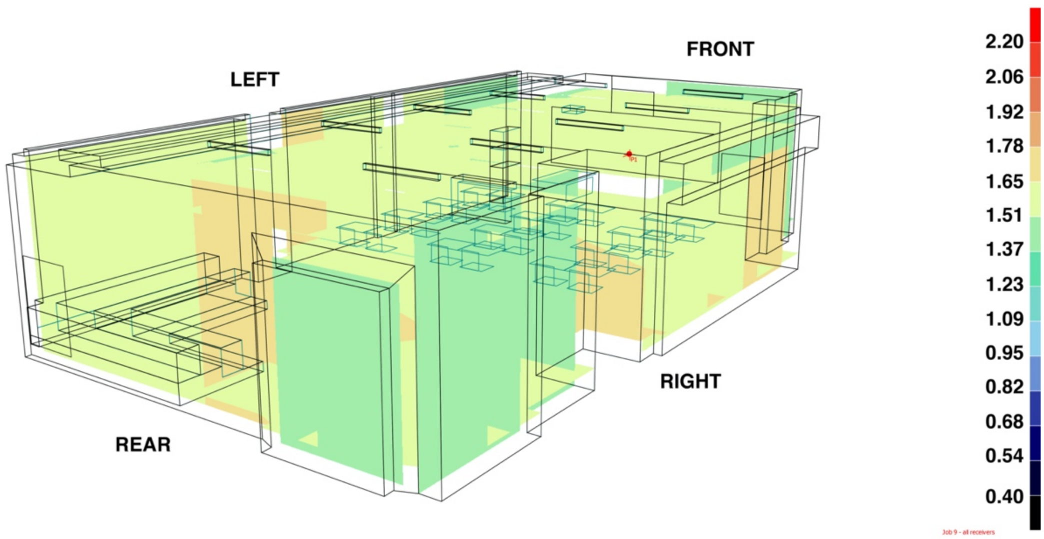


1000 Hz

Figure 4.2.2 T30 parameter grid analyses result of the middle school multipurpose music classroom with 2 m grid receiver distance

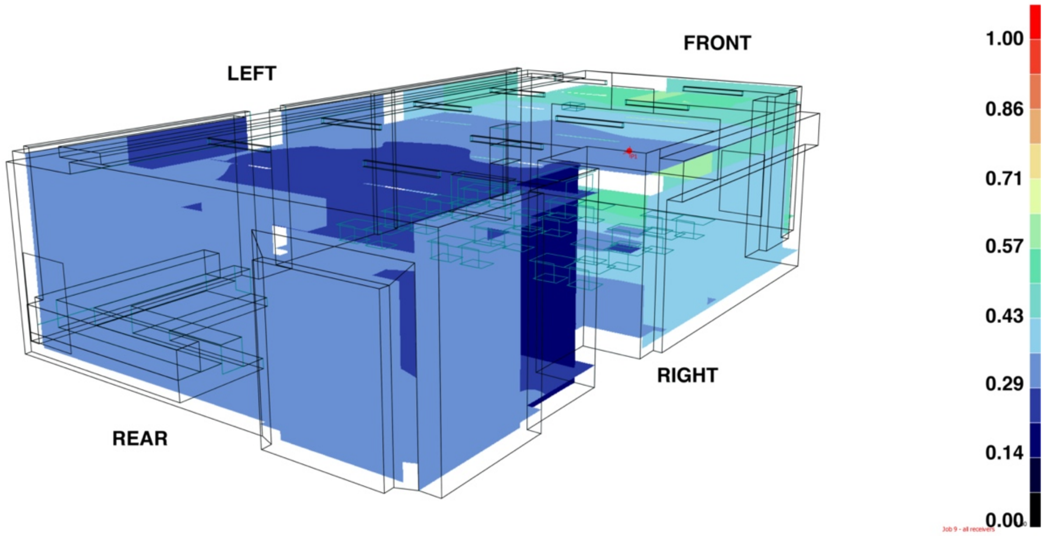


500 Hz

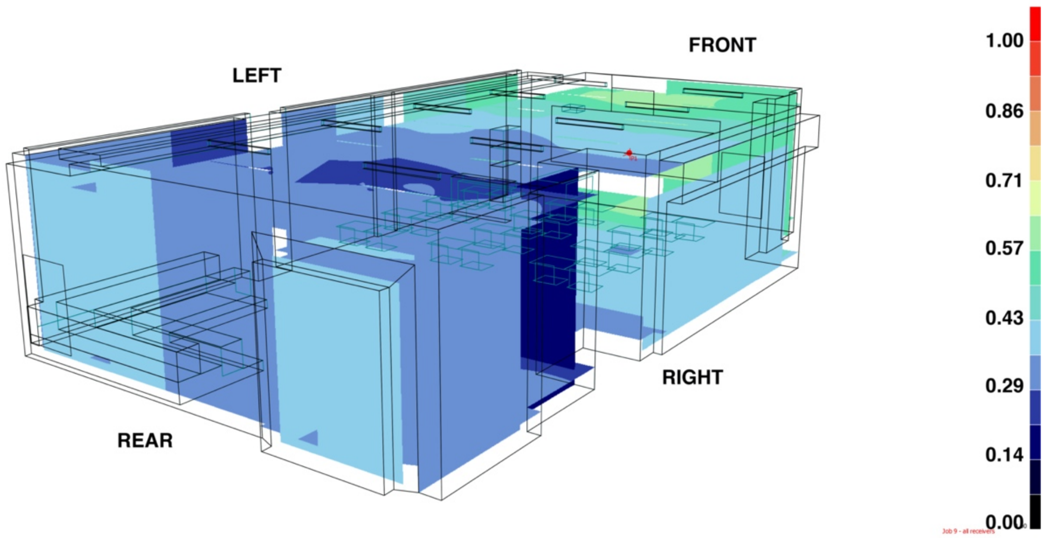


1000 Hz

Figure 4.2.3 EDT parameter grid analyses result of the middle school multipurpose music classroom with 2 m grid receiver distance

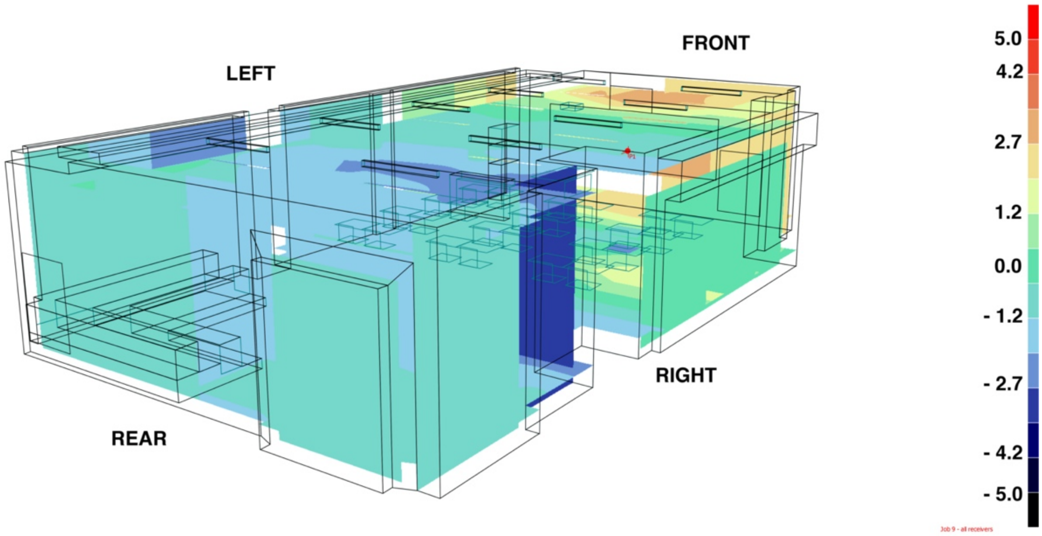


500 Hz

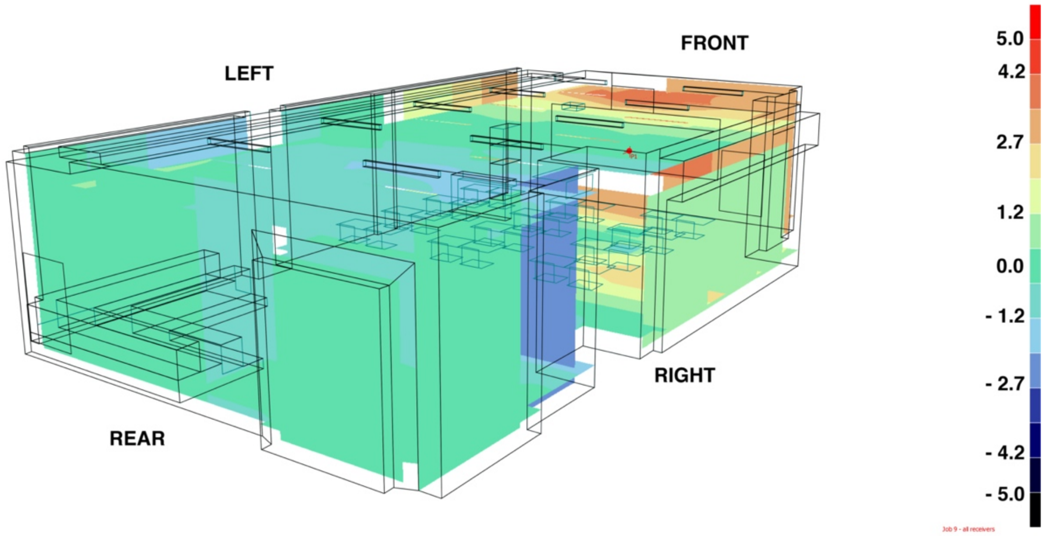


1000 Hz

Figure 4.2.4 D50 parameter grid analyses result of the middle school multipurpose music classroom with 2 m grid receiver distance



500 Hz



1000 Hz

Figure 4.2.5 C80 parameter grid analyses result of the middle school multipurpose music classroom with 2 m grid receiver distance

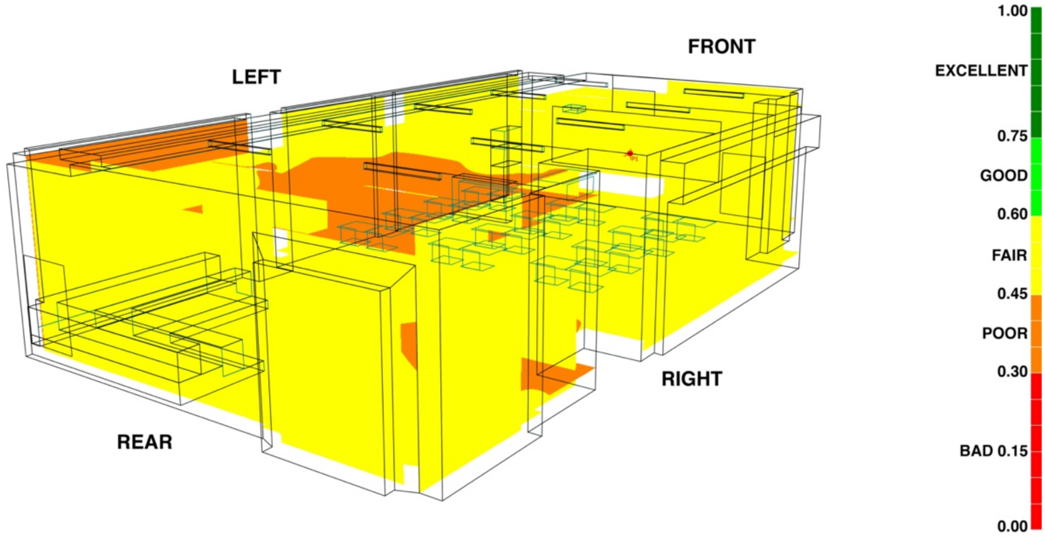
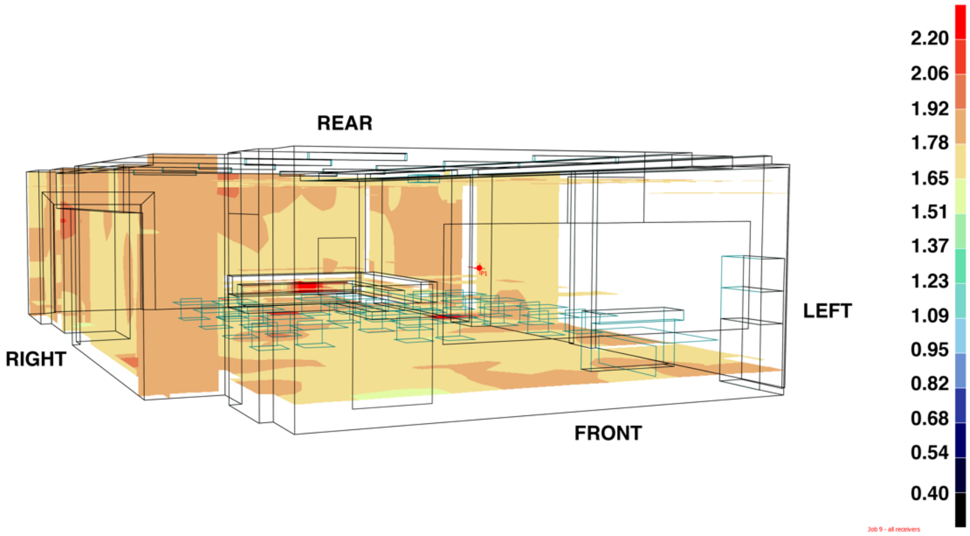
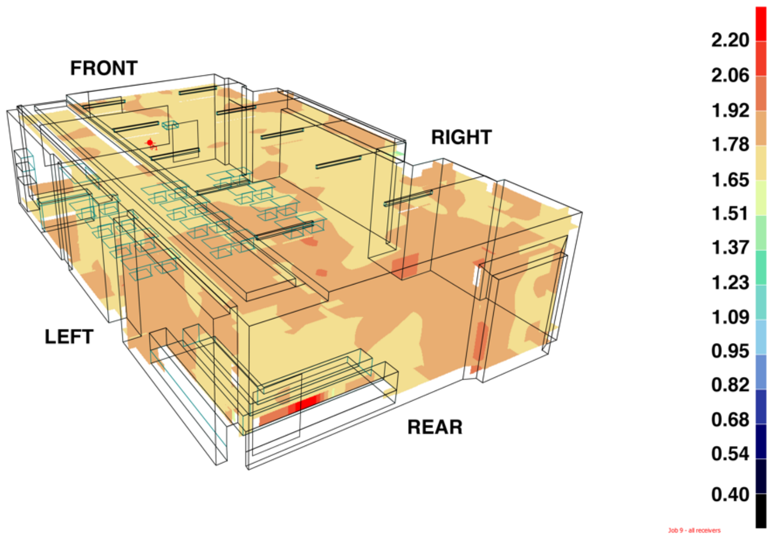


Figure 4.2.6 STI parameter grid analyses result of the middle school multipurpose music classroom with 2 m grid receiver distance

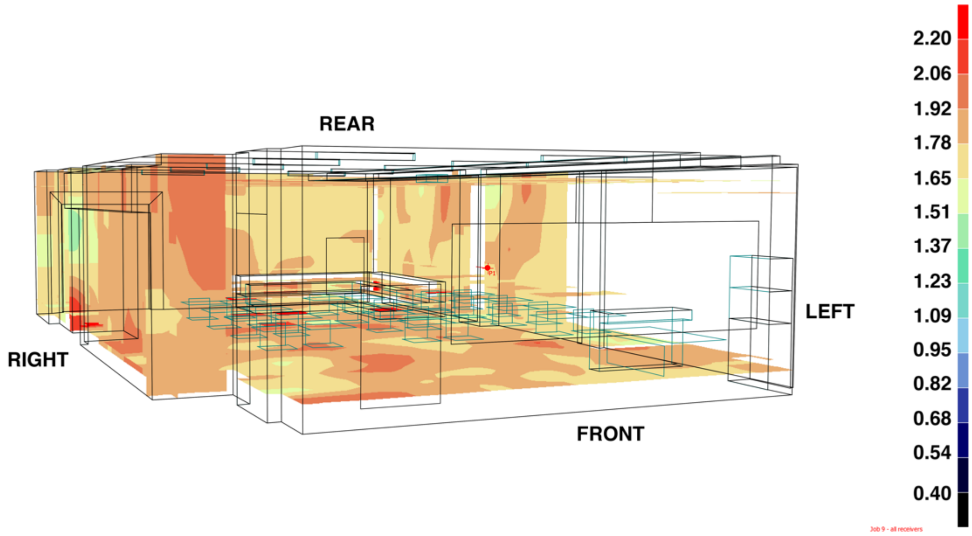
In the first phase of the case study, the surfaces of the classroom are analyzed in terms of the T30, EDT, D50, C80, and STI parameters. The grid responses demonstrate homogeneous reverberation characteristics for the T30 parameter in mid-frequencies. However, the rear doors, rear parts of the right wall, glass surfaces of the rear-left windows, rear parts of the ceiling, various parts of the floor, choral platform, and student desks demonstrate slightly higher reverberation, between 1.8 and 2.0 seconds. High EDT values are determined in the front-right, middle-right and rear walls, and windows at middle-right, middle-left and rear-left sides of the classroom with 1.8 – 1.9 s. Also, various parts on the floor and horizontal surfaces of the student desks demonstrate high EDT values with 1.9 – 2.2 s. The rear-right wall, rear-left windows and rear surfaces of the ceiling have D50 values below 20 percent. The C80 parameter is within the appropriate limits of music function throughout the classroom. However, various parts of the rear-right wall and rear-left windows and rear-right parts of the ceiling have values between -3 dB and -2 dB. The area where the student desks are located corresponds to fair result in terms of STI. However, various parts on the rear surfaces demonstrate poor STI results. The surfaces mentioned above are analyzed in detail with reduced grid sizes of 1 m and 0.5 m respectively. Since the results with 1 m grids are close to the results with 0.5 m grids, the results of 1 m grids are not discussed in the study. The results at 500 Hz and 1000 Hz are in compliance. Therefore, only the 500 Hz results are shown in the second phase of the case study. The grid analysis results of the room acoustic parameters at 500 Hz with 0.5 m receiver distance are shown in Figures 4.2.7 – 4.2.11.

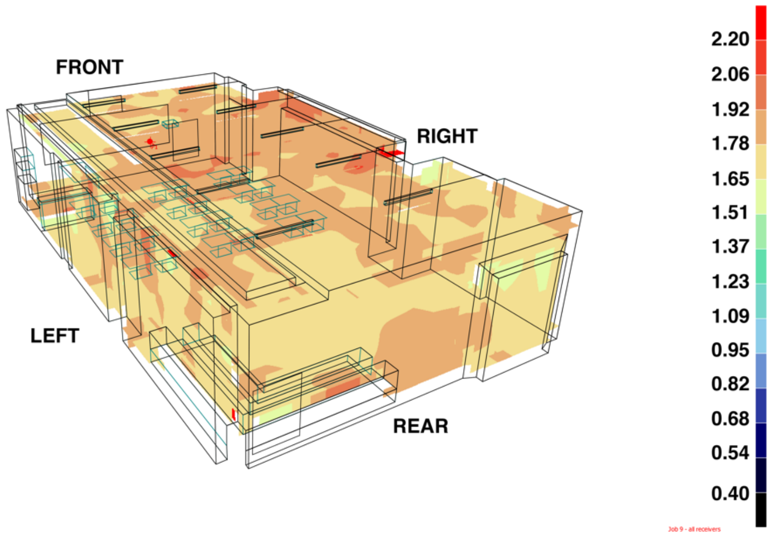




500 Hz

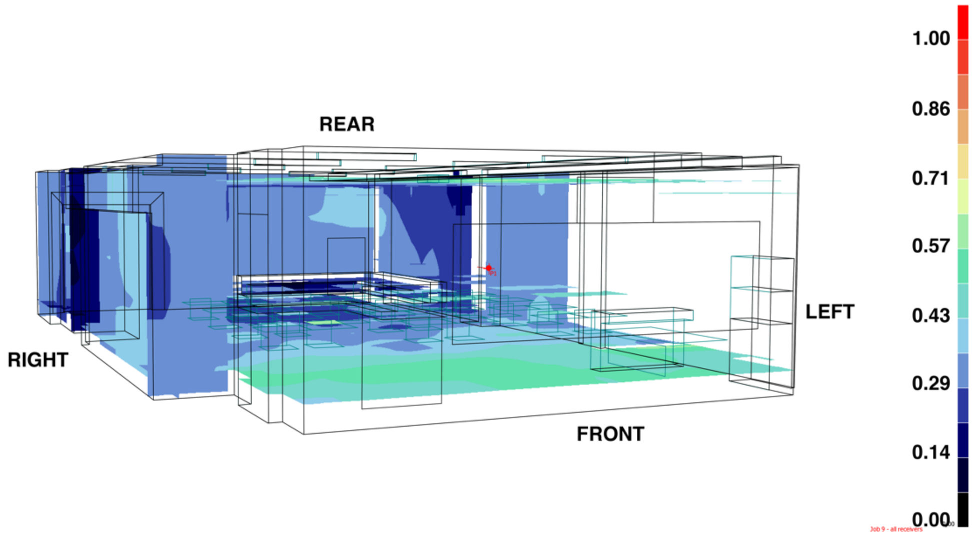
Figure 4.2.7 T30 parameter grid analyses result of the middle school multipurpose music classroom with 0.5 m grid receiver distance

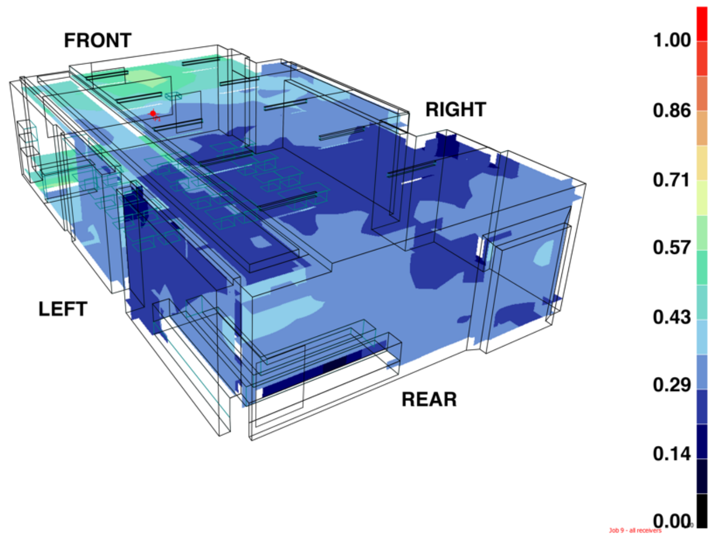




500 Hz

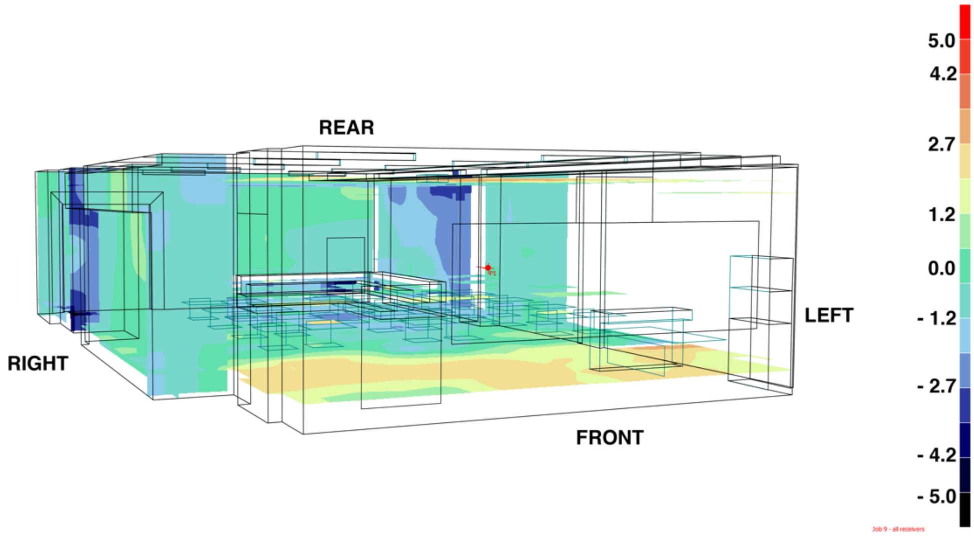
Figure 4.2.8 EDT parameter grid analyses result of the middle school multipurpose music classroom with 0.5 m grid receiver distance

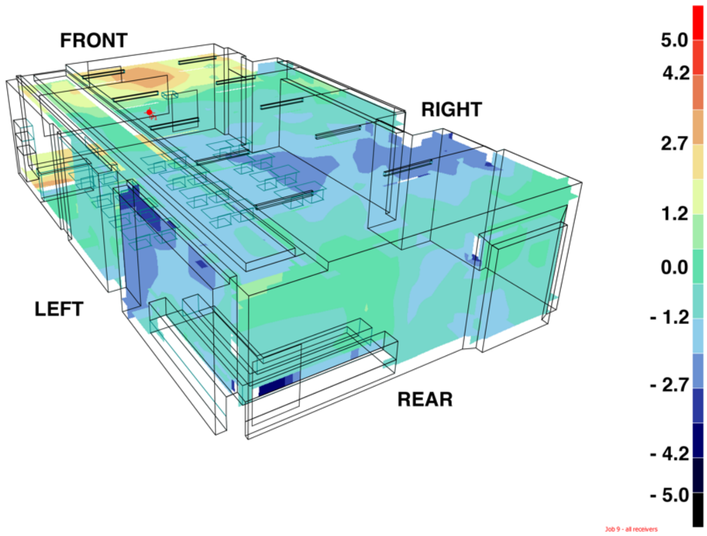




500 Hz

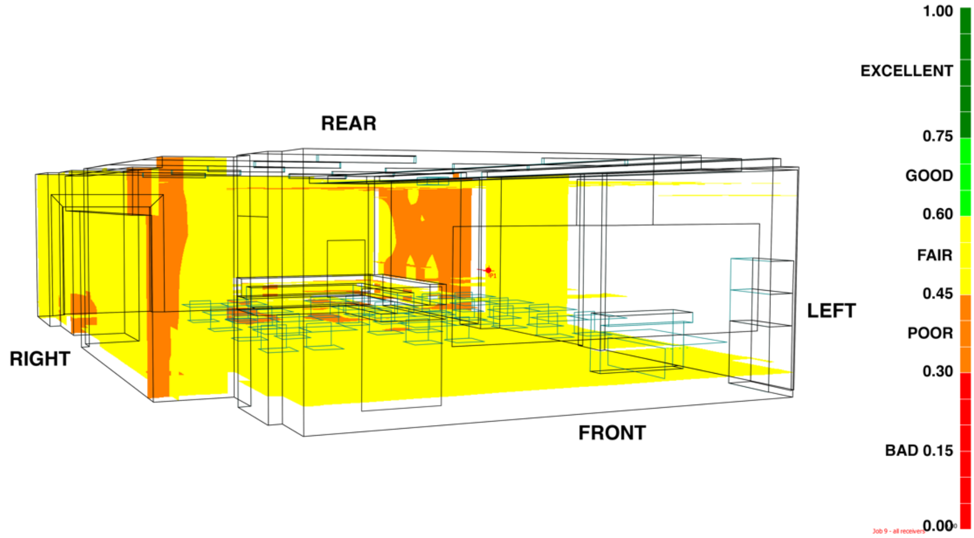
Figure 4.2.9 D50 parameter grid analyses result of the middle school multipurpose music classroom with 0.5 m grid receiver distance

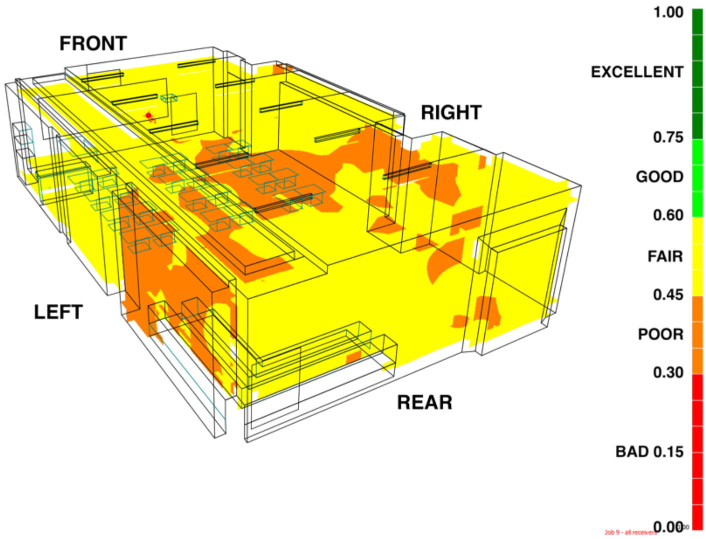




500 Hz

Figure 4.2.10 C80 parameter grid analyses result of the middle school multipurpose music classroom with 0.5 m grid receiver distance





Broad Band

Figure 4.2.11 STI parameter grid analyses result of the middle school multipurpose music classroom with 0.5 m grid receiver distance

The results of the second phase of the case study identified the worst parts of the surfaces in terms of acoustical problems. In this phase, the ceiling, floor, and the middle and rear parts of the walls and windows were investigated through grids with 0.5 m receiver distance. The results of the room acoustic parameters examined in the middle school multipurpose music classroom demonstrate that:

- T30 values are high in the rear-right, middle-left and middle-right parts of the classroom. The middle and rear parts of the ceiling (plastered gypsum over rockwool) have values of 1.8 – 2.0 s (appropriate ranges are 0.45 – 0.80 s and 0.95 – 1.40 s for speech and music, respectively). The front-right parts of the walls (paint and plaster over gypsum) and rear-left parts of the windows (6 – 8 mm thick double glass) have results between 1.9 – 2.0 s. Various parts of the choral platform demonstrate values even above 2.2 s. According to the evaluation, the surfaces mentioned are the most problematic surfaces of the classroom in terms of T30.
- EDT results are the highest at the middle-right parts of the ceiling, middle-right parts of the walls, front parts of the floor (PVC material), rear-left parts of the windows, and horizontal surfaces of various student desks (werzalit material). The results at these parts are in a range of 1.9 – 2.2 (reference values are EDT < 1.00 s for speech and EDT > 1.00 s for music.
- According to the D50 graph, the rear parts of the ceiling and floor have values between 0.15 and 0.30 (reference range is: D50 > 50%). Also, the rear-left windows and middle-right walls have results below 0.20. This indicates that the rear surfaces of the classroom display the lowest D50 results. However, this situation would not affect the definition of speech during theoretical classes, since the rear part is only used for music purposes and the speech function is held in the front of the classroom.
- The C80 parameter values are higher in the front and decrease through the rear end of the classroom. However, the middle parts of the ceiling, floor, walls, and windows have the worst results of C80 in a range between -3 dB and -1.5 dB (-1 dB > C80 > +3 dB is the reference range for music). This indicates that the clarity of music is lowest in the middle parts of the classroom. Also, various parts of the choral platform have values below -1.5 dB.

- STI results are parallel with D50 results. The rear parts of the floor ceiling, rear-left windows and rear-right walls have results correspond to poor in terms of STI. The rest of the classroom have fair results. In this case, the parts with poor STI are not crucial since the students are located in the front and middle part of the classroom when the theoretical classes are being taught.

4.3. Case Study III: High School Multipurpose Music Classroom

The high school multipurpose music classroom is evaluated with grid analyses in terms of acoustical problems. Potential sources of the acoustical problems are identified through the surfaces. The identification is based on the reference criteria given in Table 3.4.1. Mid-frequencies (500 – 1000 Hz) are investigated through grid responses defined on the surfaces of the classroom. The grid sizes are reduced from 2 m to 1 m and 0.5 m in a systematic order (see Figure 4.3.1). The omni-directional sound source used in the section 3.2 is used in the same position with identical acoustic properties. In the first phase of the case study, the T30, EDT, D50, C80, and STI parameters are analyzed with a 2 m grid receiver distance. The results of the first phase are provided in Figures 4.3.2 – 4.3.6. The second phase of the study includes analyses results with 0.5 m grid receiver distance. The results of the analyses with 1 m and 0.5 m grid sizes are converged. Therefore, the results of 1 m grid sizes are not included. The most problematic parts of the surfaces in the classroom are identified in the first phase of the study, while the next phases of the study focused only on these surfaces in order to narrow down the investigation.

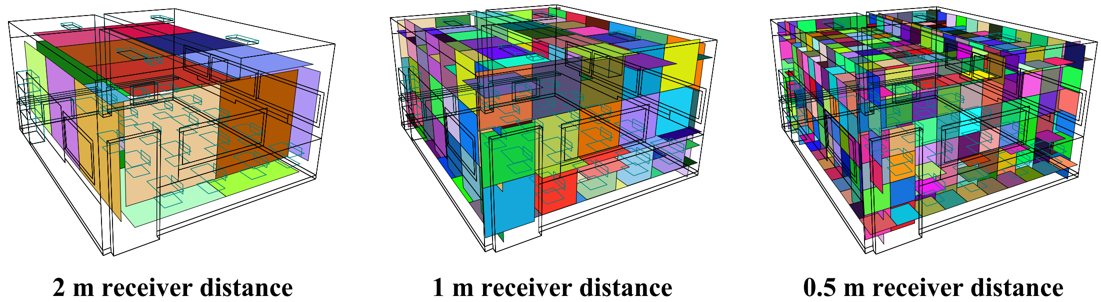
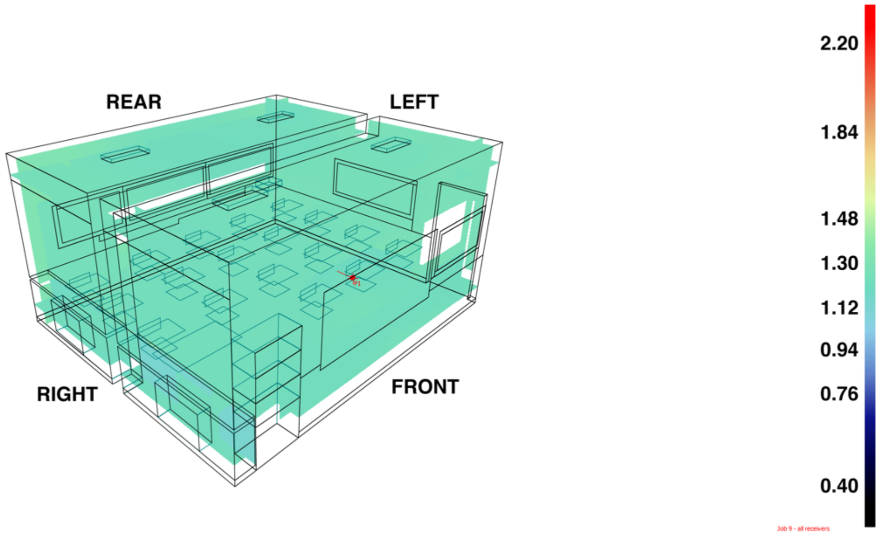
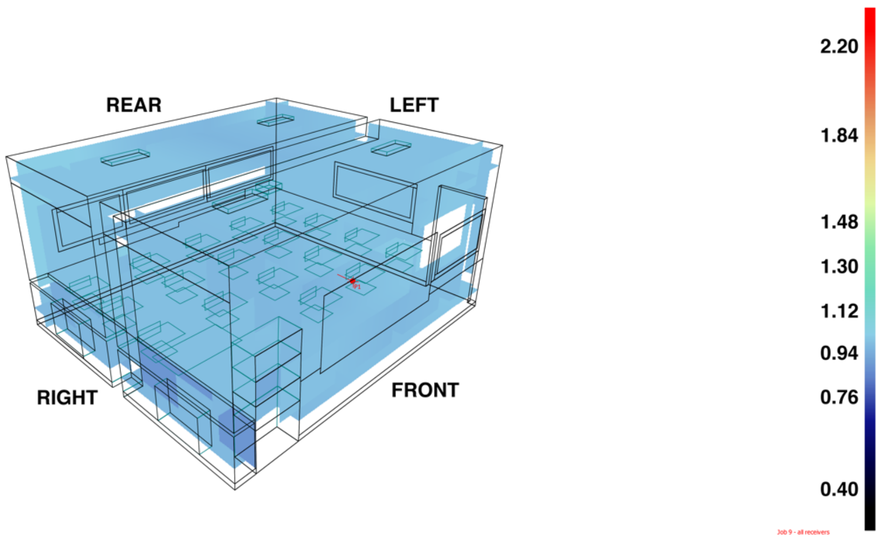


Figure 4.3.1 Grid sizes according to the receiver distances determined for Case Study III.

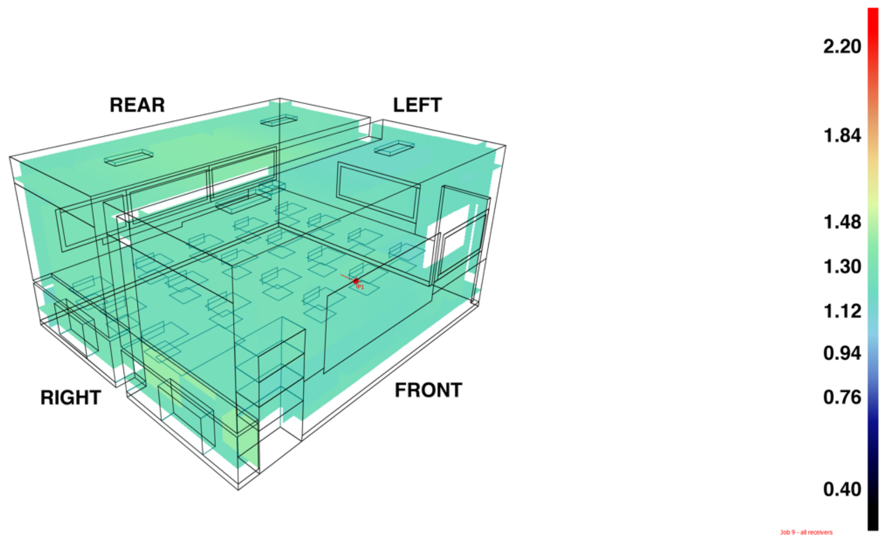


500 Hz

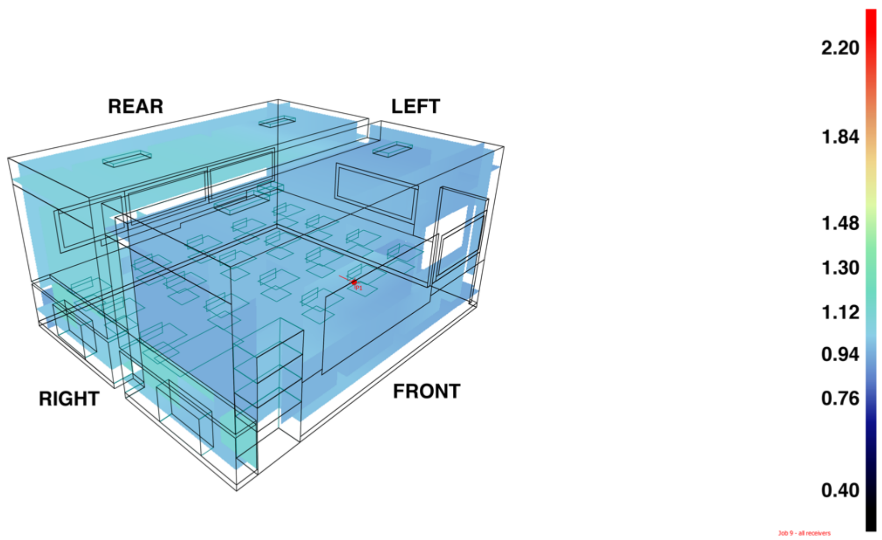


1000 Hz

Figure 4.3.2 High school multipurpose music classroom grid analyses results of T30 parameter with 2 m grid receiver distance

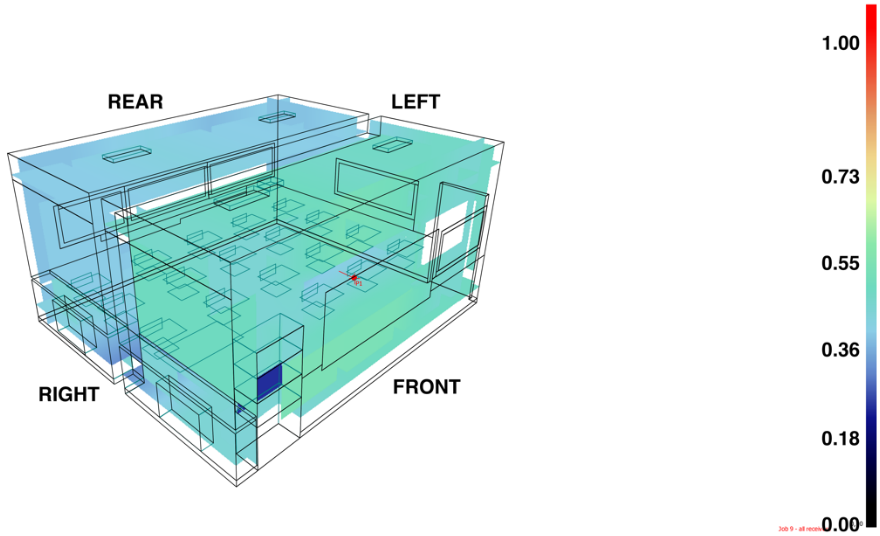


500 Hz

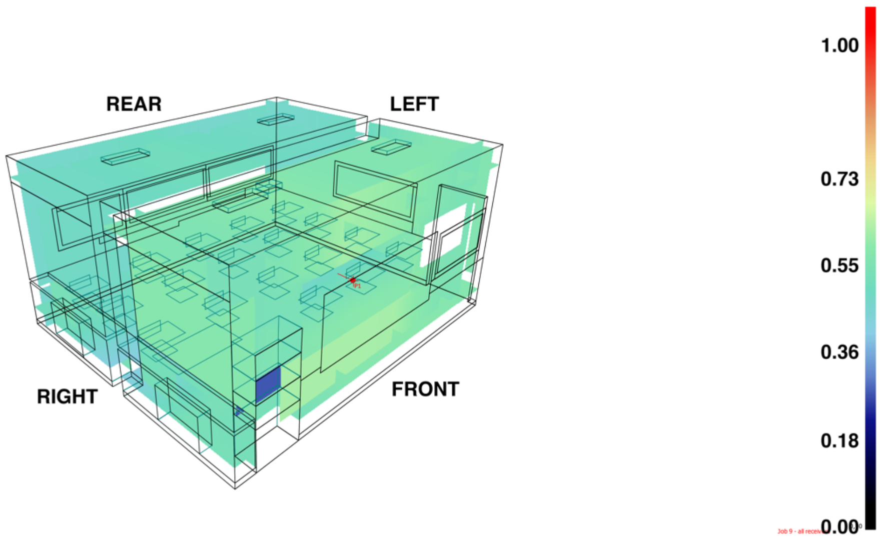


1000 Hz

Figure 4.3.3 High school multipurpose music classroom grid analyses results of EDT parameter with 2 m grid receiver distance

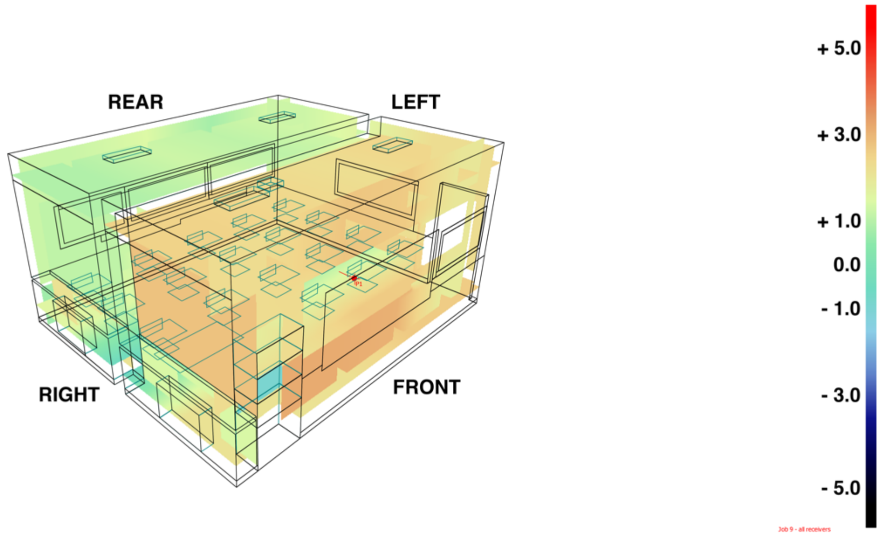


500 Hz

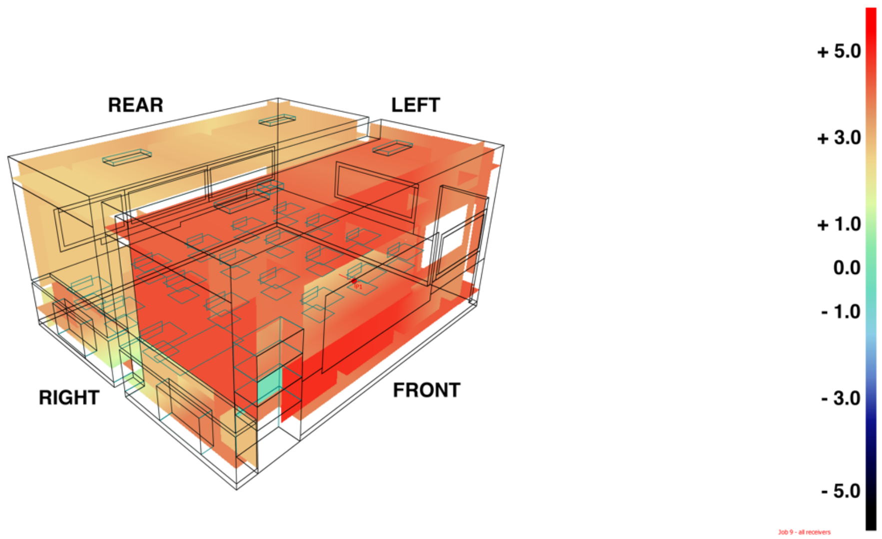


1000 Hz

Figure 4.3.4 High school multipurpose music classroom grid analyses results of D50 parameter with 2 m grid receiver distance



500 Hz



1000 Hz

Figure 4.3.5 High school multipurpose music classroom grid analyses results of C80 parameter with 2 m grid receiver distance

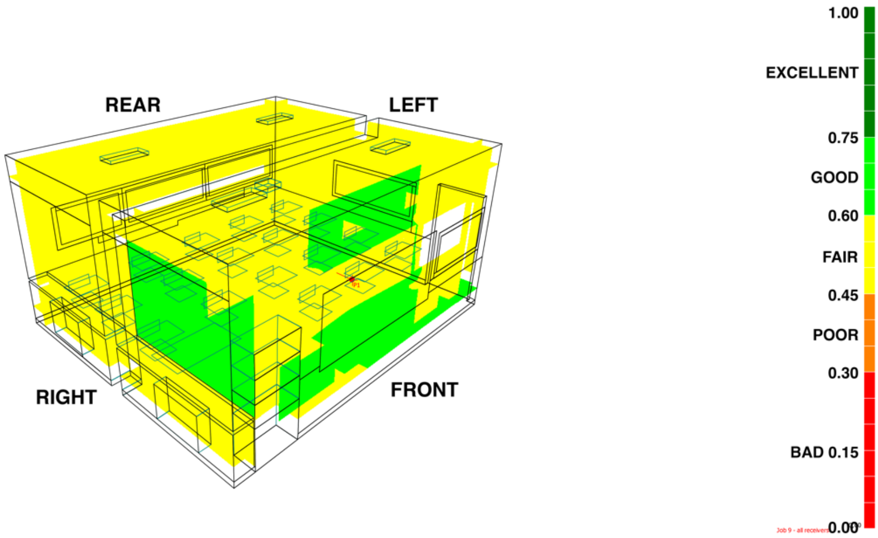
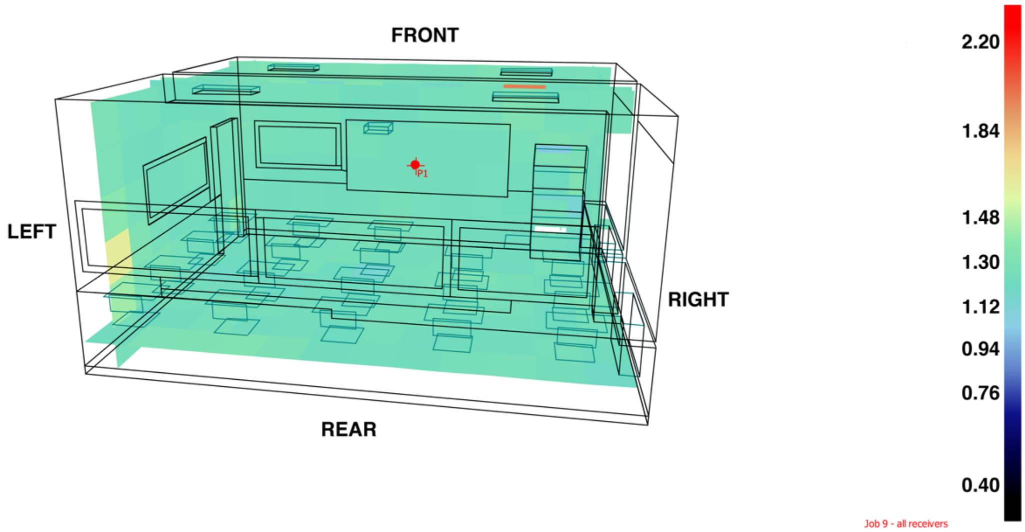
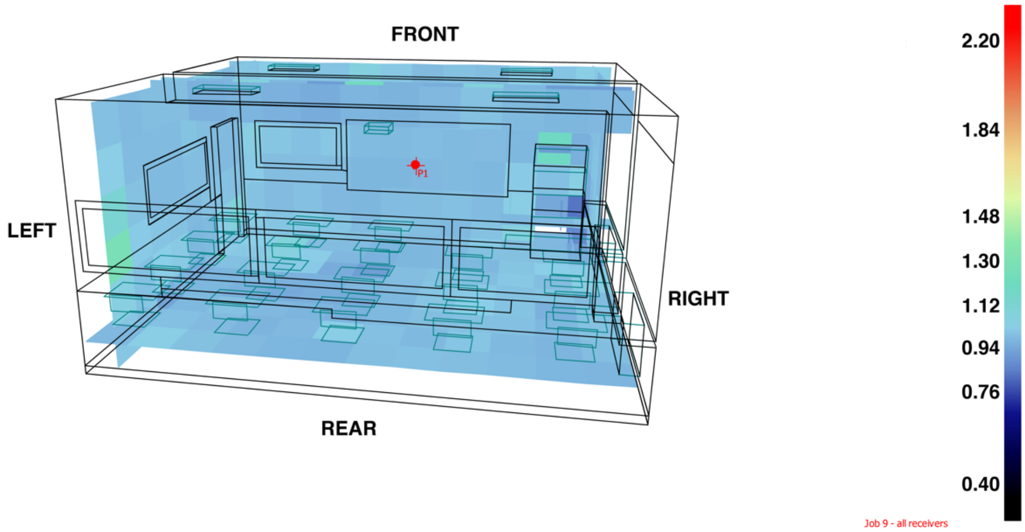


Figure 4.3.6 High school multipurpose music classroom grid analyses results of STI parameter with 2 m grid receiver distance

The analyses carried out with 2 m grid sizes are examined in the first phase. The results indicate that the reverberation characteristics are uniform in terms of the T30 and EDT parameters. The results of the T30 values are 1.00 s and 1.30 s at 500 Hz and 1000 Hz, respectively. The EDT values are varying in 0.90 s and 1.30 s at mid-frequencies. The D50 values are above the appropriate limit, which is 50 percent in the front end of the classroom. However, the D50 values on the rear surfaces of the classroom are below 50 percent. The C80 values are in the reference range, which is between -1 dB and +3 dB for 500 Hz. However, the middle and front parts of ceiling and floor, front-right wall, front-left window, front wall, and writing board have C80 values above the reference range with results of +3 dB – +8 dB. The results of the STI parameter is good in the various surfaces located in the front of the classroom. However, the middle and rear parts are in a fair condition in terms of the STI parameter. The front side of the ceiling, left and front walls and floor are included in the second phase investigation alongside the surfaces of the writing board, wall boards and bookshelves. These surfaces are analyzed in detail with a receiver distance of 0.5 m. The results of the second phase are given in Figures 4.3.7 – 4.3.11.

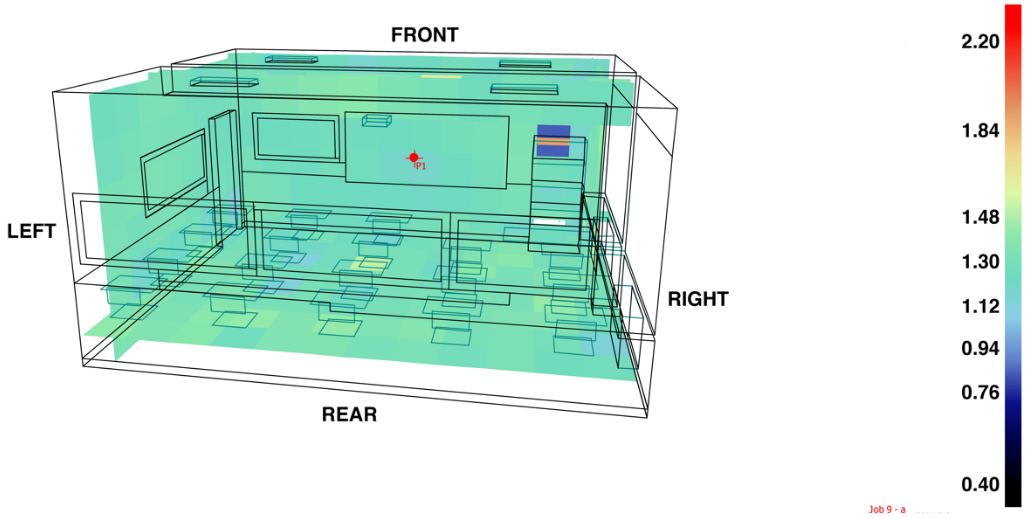


500 Hz

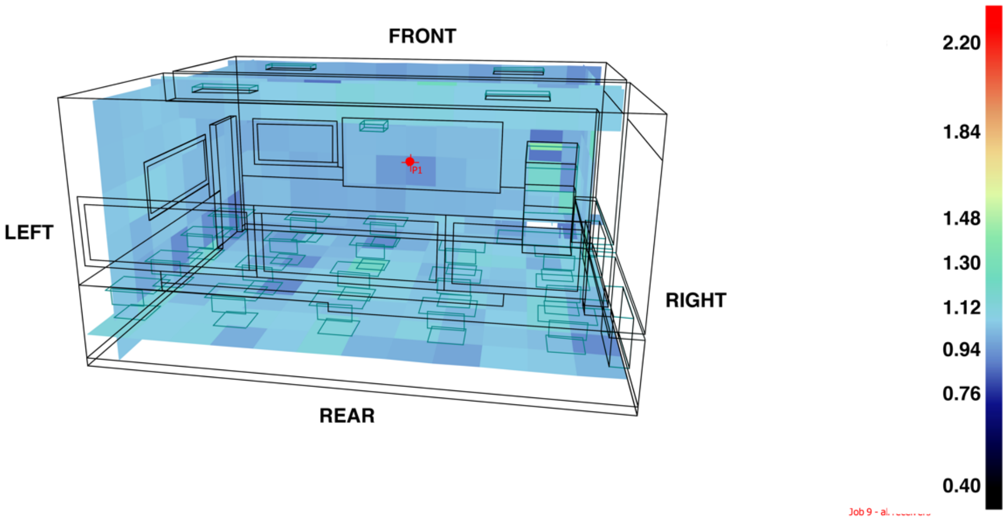


1000 Hz

Figure 4.3.7 High school multipurpose music classroom grid analyses results of T30 parameter with 0.5 m grid receiver distance

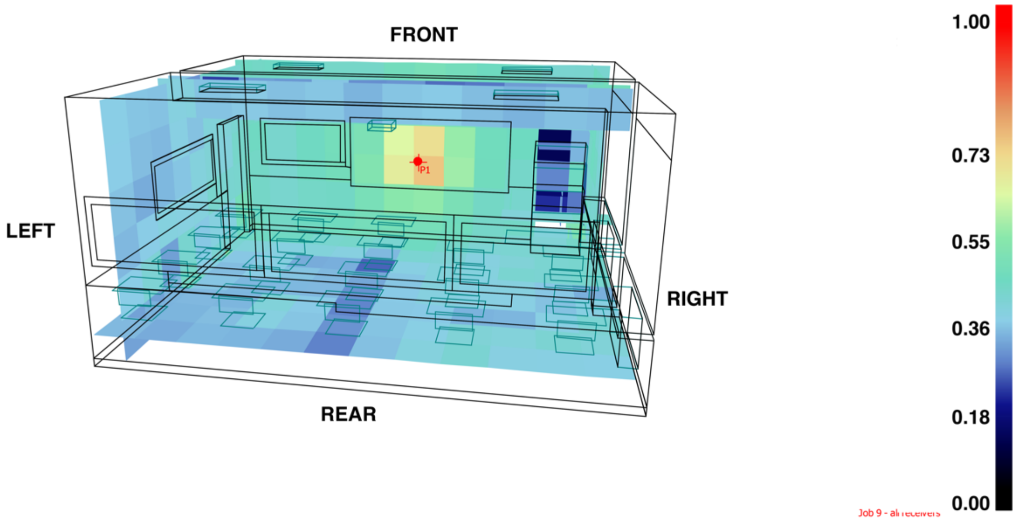


500 Hz

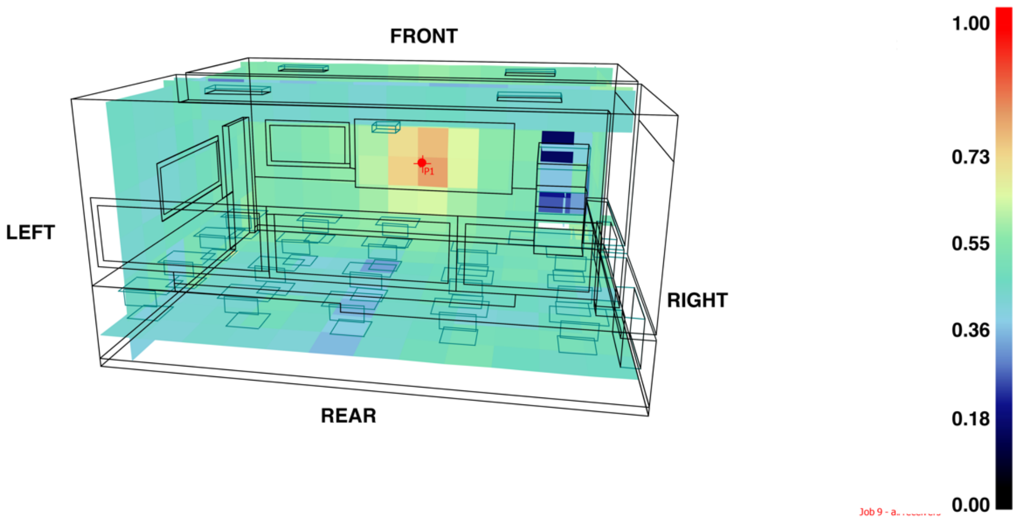


1000 Hz

Figure 4.3.8 High school multipurpose music classroom grid analyses results of EDT parameter with 0.5 m grid receiver distance

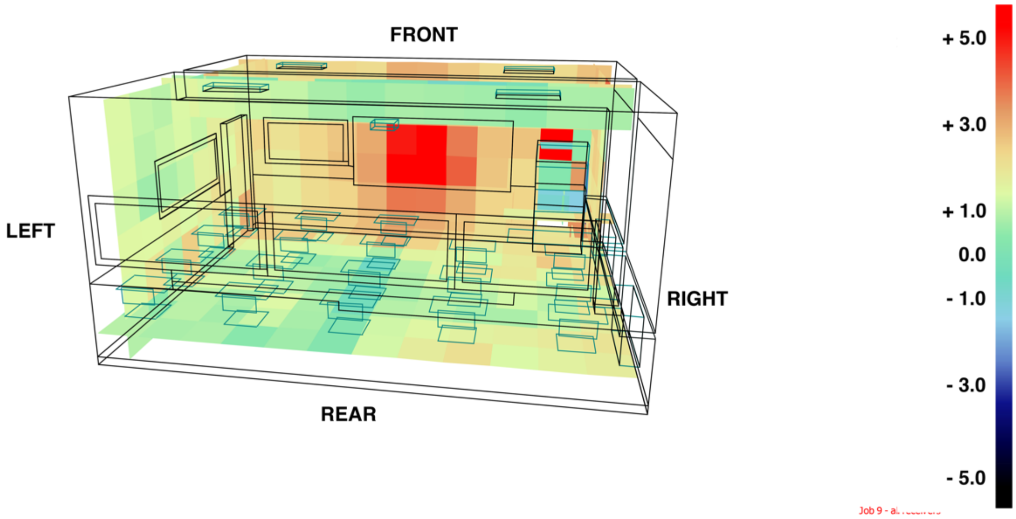


500 Hz

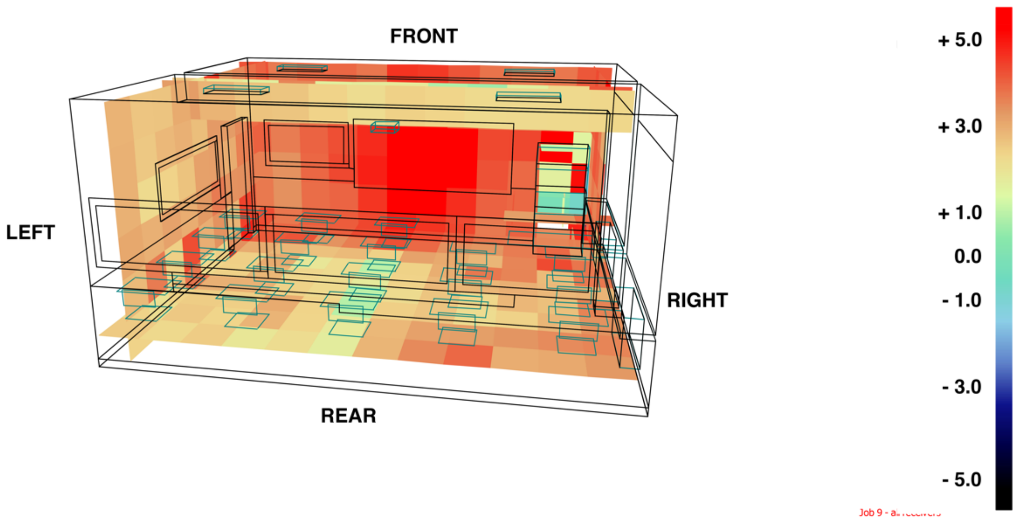


1000 Hz

Figure 4.3.9 High school multipurpose music classroom grid analyses results of D50 parameter with 0.5 m grid receiver distance



500 Hz



1000 Hz

Figure 4.3.10 High school multipurpose music classroom grid analyses results of C80 parameter with 0.5 m grid receiver distance

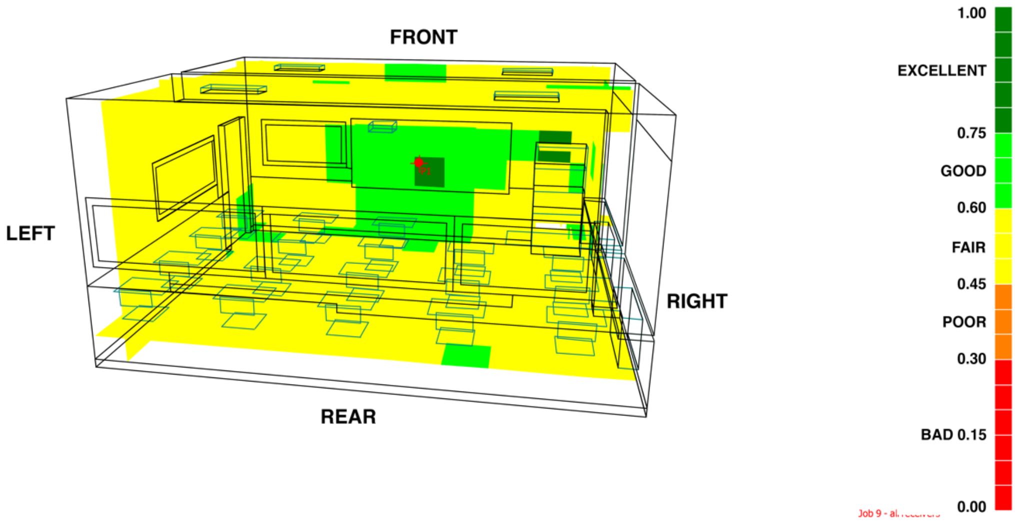


Figure 4.3.11 High school multipurpose music classroom grid analyses results of STI parameter with 0.5 m grid receiver distance

The values that are not in the reference limits are identified in the second phase of the case study. The worst parts of the investigated surfaces are determined in terms of acoustical problems. The distance between the receiver grids are 0.5 m in the second phase. According to the results of the case study:

- The T30 parameter values are in the range of 1.00 – 1.30 s, which are above the reference range for the speech function but in the reference range of music function (reference ranges are 0.45 – 0.80 for speech and 0.95 – 1.40 for music). The reverberation characteristics of the classroom are homogeneous throughout the classroom. Therefore, the EDT parameter is investigated along with T30 in order to locate the worst surfaces.
- EDT results are in the range of 1.00 – 1.30 s. The EDT values are parallel with the T30 values. The investigated surfaces are almost equivalent in terms of sourcing the acoustical problems due to the uniform characteristics of the EDT parameter throughout the classroom.

- The D50 parameter is in the reference limit in the front side of the classroom. The D50 values of the writing board and front wall are within the range of 0.50 – 0.80 (allowable values are: D50 > 0.5). The rear parts of the ceiling (plaster over concrete) and floor (PVC material), rear-right windows (6 – 8 mm thick double glass), rear-left wall (plaster over brick wall) and interior surfaces of the bookshelves (18 mm chipboard material) have D50 values below 0.40. Therefore, these surfaces are identified as root causes of acoustical problems in terms of D50.
- The clarity is in the appropriate range in the middle and rear parts of the classroom within a range of 0 dB - +3 dB. However, C80 is above the appropriate limits on the surfaces of the front-right windows (double glass), the front wall (plaster over brick wall), writing board (laminate surface), and in the front parts of the ceiling and floor (appropriate range of C80 is -1 dB - +3 dB for music).
- The STI parameter is in the good range and even excellent range in various surfaces in the front of the classroom. The remainder of the surfaces indicate fair results throughout the classroom.

4.4. Comments & Discussion on the Case Studies

The root causes of the acoustical problems are identified in the Case Studies I, II and III. Grid analyses of the T30, EDT, D50, C80, and STI parameters are conducted in the three multipurpose music classrooms. Surfaces are investigated in detail by reducing the grid sizes systematically. The identification studies are conducted in mid-frequencies (500 – 1000 Hz) since the reference criteria in Section 3.4 are provided in the mid-frequencies. For some parameters, the values of all surfaces fall outside the reference limits. In the current study, the worst parts are determined among the surfaces in terms of acoustical problems. The identification study of the root causes of the acoustical problems indicates that:

- In the elementary school multipurpose music classroom, the rear parts of the ceiling and middle to rear parts of the floor surfaces are the sources of the primary acoustical problems among the building elements in terms of acoustical parameters. The interior surfaces of the open bookshelves are also root causes in terms of acoustical problems. In this classroom, the values of the T30 and EDT parameters are parallel and the values of D50 and C80 decrease as the receiver grids get further from the sound source. STI is uniform in the entire classroom.

- The root cause surfaces of the acoustical problems in middle school multipurpose music classroom are identified as: the rear parts of the floor, middle and rear parts of the ceiling, rear-left window, middle-right wall, middle parts of the rear wall, and the horizontal parts of the student desks. The locations of the most problematic T30 and EDT values are in line throughout the classroom, although the EDT results are higher at various points, since the first 10 dB decay is considered. The worst surfaces of the D50, C80 and STI parameters are almost in identical parts of the relevant surfaces. Therefore, the primary sources of the acoustical problems are identified at certain locations all over the classroom.
- As for the high school multipurpose music classroom, the worst surfaces in terms of acoustical problems are identified as: the middle to rear parts of the ceiling and floor, rear parts of the left and right walls, and the rear-right windows. These surfaces are mainly determined based on the results of the D50 and STI parameters since the T30 and EDT results are uniform and almost identical throughout the classroom. However, the C80 parameter results reveal a contrasting graph in terms of identifying the root causes. The C80 values are above the reference range in the front to middle parts of the classroom, while the rear parts are better in terms of clarity of music and speech. This is considered to be due to the fact that the front surfaces are in close proximity to the sound source on the front.

The surfaces identified in the study are the primary root causes of the acoustical problems. The determination process of the acoustical problems is carried out by narrowing down the scope of the investigation to localize the most relevant surfaces. The identification process should be repeated after primary root causes of the acoustical problems have been resolved. Primary problems and root causes in the new situation should be investigated with the procedure explained in the Case Studies I, II and III. The aim of this research procedure is to identify the root causes of the acoustical problems and bring the acoustical performance of the classroom closer to the reference range, step-by-step. In order to resolve the acoustical problems of the classrooms, materials with appropriate absorption coefficients can be applied instead of the problematic surfaces. Therefore, the values of the acoustical parameters can be matched to the reference criteria in each step of the investigation. Also, extra surfaces can be applied on the existing surfaces of the classrooms. Supportive materials with appropriate absorption coefficients can be applied. These surfaces can be adjacent to the existing surfaces or arranged as a supportive layer placed in a distance to the parent surfaces.

In the elementary school, the sources of the acoustical problems are the rear parts of the ceiling and middle to rear parts of the floor, in terms of building elements. Acoustical materials with higher sound absorption coefficients can be applied to these parts to match the acoustical performance of the classroom to the reference criteria. Also, cabinet doors can be provided in front of the open bookshelves. In this way, trapping of the sound waves inside the surfaces of the shelves can be prevented.

Materials with higher absorption coefficients can be applied to the relevant parts of the floor and ceiling surfaces in the middle school music classroom. Also, demountable panels of various sizes and absorption properties can be applied to the vertical surfaces identified. These panels can be applied according to the functions and needs. The material of the table top of student desks can be changed with a more absorptive material or a supportive layer can be applied on top of the existing desks.

The high school music classroom can be considered as two separate parts, front and rear. According to this separation, materials with lower absorption coefficients can be applied on the surfaces of the front part of the classroom in order to increase the reverberation. Since reverberation is inversely proportional to the clarity values, the front end of the classroom can then be matched to the reference limits. The rear parts of the classroom can be supported with the application of surfaces with higher absorption capabilities. In this way, low STI and D50 values can be increased in this section. However, in these applications, the balance between the different parameters of the room acoustics should be considered accurately. The improvement of one parameter can deteriorate another parameter, due to the inversely proportional relations.

Chapter 5

Conclusions and Future Prospects

5.1. Conclusions

In the current study, the acoustical performance of three multipurpose music classrooms are investigated with experimental and computational methods in terms of the T30, EDT, D50, C80, and STI parameters. The conclusions of the study are as follows:

- The background noise levels of the multipurpose music classrooms are measured. The elementary and middle school multipurpose music classrooms are in the appropriate Noise Criterion (NC) limits. However, the NC level of the high school classroom is above the reference NC limits.
- The initial results of the acoustical simulations are incompatible with results of the measurements of room acoustic parameters. Therefore, the materials defined on the surfaces of 3D models are updated with compatible absorption coefficients at various octave bands.
- Synthesis of the measurements and simulations is administered according to the Just Noticeable Difference (JND) criteria provided in the ISO 3382-1 standard and 3D models of the classrooms are calibrated.
- According to the synthesized results of experimental and computational studies, the values of the T30, EDT, D50, C80, and STI room acoustic parameters are evaluated for the speech and music functions in each classroom. Values that are not within reference limits are determined for each room acoustic parameter.
- Grid analyses are conducted to identify the root causes of acoustical problems in the classrooms. To locally diagnose the worst surfaces in terms of acoustical problems, grid sizes are reduced systematically and root causes are identified.
- According to the identification, some promising countermeasures to the acoustical problems are discussed. It is concluded that modifiable acoustic solutions can be used for typical multipurpose music classrooms to meet the acoustical performance criteria for both speech and music functions.

- A procedure is developed to examine the acoustical performance of multipurpose music classrooms and identify the acoustical problems.

5.2. Future Prospects

The current study analyzes the acoustical performance of multipurpose music classrooms according to the functions of speech and music. The acoustical performance of the multipurpose music classrooms is determined in terms of room acoustic parameters. Experimental and computational studies are synthesized and the root causes of the acoustical problems are identified and localized through systematic grid analyses. A similar study can be planned to improve the acoustical performance of the multipurpose music classrooms. Using the conclusions of the current study, modification proposals can be developed. Also, it is possible to come up with sustainable countermeasures to acoustical problems using the procedure proposed in the current study.

To improve the acoustical performance of the classrooms, surfaces with values that fall outside the reference limits of acoustical parameters should be primarily considered. In some classrooms, all of the surfaces are problematic in terms of the room acoustic parameters. In the identification study, the worst surfaces in terms of acoustical problems are determined. The acoustical performance of the classrooms can be brought closer to the reference limits by replacing the materials of the determined surfaces with materials that have compatible absorption coefficients. In subsequent studies, the root causes of the acoustical problems should be identified in the current conditions of the classrooms. The materials of the relevant surfaces should be replaced to lead the results to the reference limits step-by-step.

The replacement of the surface materials can be done through various approaches. Changing the materials of the relevant surfaces of the building elements can improve the acoustical performance (e.g. problematic parts of the floor and ceiling surfaces can be replaced with materials that have higher absorption to reduce the reverberation time). Instead of structural renovations, acoustical panels can be applied in front of the relevant surfaces. Therefore, it is possible to develop acoustical solutions by preserving the surface materials preferred in the original design of the classroom. Since the surfaces in these two suggestions are stationary, it is not possible to fulfill the requirements of two functions in general. The reference ranges are different for the speech and music functions, and providing appropriate conditions for one may produce incompatible results for the other. Also, one can provide proper acoustical quality for a room acoustic parameter while deteriorating values of the other parameters, since some of the acoustical parameters are in conflict with each other. At this point, modifiable acoustical design solutions can result in appropriate acoustical performance for different functions. Once the room acoustic parameter values are approximated to the reference limits to some extent, modifiable acoustical designs can be applied. In this way, it is possible to adjust the acoustical conditions for the reference range of each room acoustic parameter. For example, panels that have multiple faces with different acoustical properties (one face is diffusive and the other face is absorptive) can be used. Also, curtain systems can be applied to surfaces with high reverberant characteristics. Music instructor(s) can control the configuration of the panels and curtain systems according to the functions of the classroom.

One of the primary concerns of any modification should be the sustainability of the proposals. In this respect, modification proposals are discussed in terms of sustainability. It is possible to design modifications without changing the original form and architectural design of the music classrooms. This can be done by using acoustical panels and modifiable acoustical solutions to the original building elements in classrooms. In the future, the solutions should be demountable, in case the usage characteristics and acoustic requirements of the spaces change. In this manner, the original design and materials of the classrooms can be preserved while the acoustical performance is maintained at the appropriate levels. This is especially important when the classroom under study is located in a building with historical significance. Another concern in the modification proposals is the trade-off between the acoustical quality of classrooms and the financial cost of the modifications. The costs of the solutions proposed should be kept as affordable as possible. It is important to consider the issues mentioned above while developing solution proposals for acoustical performance of multipurpose music classrooms in terms of sustainability.

BIBLIOGRAPHY

American National Standards Institute. (1994). American National Standard - Acoustical Terminology (ANSI Standard No. S1.1-1994). https://webstore.ansi.org/standards/asa/ansis11994r2004

American National Standards Institute/Acoustical Society of America. (1997). American National Standard – Methods for Calculation of the Speech Intelligibility Index (ANSI/ASA Standard No. S3.5-1997). https://webstore.ansi.org/standards/asa/ansiasas31997r2017

American National Standards Institute/Acoustical Society of America. (2010). Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 1: Permanent Schools (ANSI/ASA Standard No. S12.60-2010). https://webstore.ansi.org/Standards/ASA/ANSIASAS12602010Part

Adams, T. (2016). Sound materials. Frame Publishers

Astolfi, A., Perino, M., & Piccaluga, A. (2001). A procedure to improve speech intelligibility in university classrooms, 17th International Congress on Acoustics (ICA), Classroom Acoustics, Rome

Barron, M. (2010). Auditorium Acoustics and Architectural Design. Spon Press

Bassuet, A. (2011). New Acoustical Parameters and Visualization Techniques to Analyze the Spatial Distribution of Sound in Music Spaces. *Building Acoustics,* 18(3-4), 329–347. https://journals.sagepub.com/doi/10.1260/1351-010X.18.3-4.329

Bayazıt, N. T. (1999). *Dikdörtgen Kesitli Konser Salonlarının Akustik Değerlendirmesi İçin Bir Tasarım Yöntemi* [Doctoral dissertation, Istanbul Technical University]. Istanbul Technical University Thesis and Dissertations Archive. https://polen.itu.edu.tr/xmlui/handle/11527/11919

Beranek, L. (1996). Concert and Opera Halls: How They Sound. Acoustical Society of America, New York.

Bistafa, S. R. & Granado, M. V. (2005) A survey of the acoustic quality for speech in auditoriums. *Electronic Journal Technical Acoustics,* 15, 1 - 16

Bork, I. (2000). A comparison of room simulation software - The 2nd round robin on room acoustical computer simulation. *Acta Acustica,* 86(6), 943-956.

Bradley, J. S. (1986). Predictors of speech intelligibility in rooms. *The Journal of the Acoustical Society of America*, 80, 837-845. https://asa.scitation.org/doi/pdf/10.1121/1.393907

Bradley, J. S. (2002). Optimising sound quality for classrooms. XX Encontro da SOBRAC, II Simpósio Brasileiro de Metrologia em Acústica e Vibrações–SIBRAMA.

Cavanaugh, W. J., Wilkes, J. A., & Gregory, C. T. (1999). *Architectural Acoustics Principles and Practice*. NY: John Wiley.

Christensen, C. L., Koutsouris, G., Rindel, J. H. (2013). The ISO 3382 parameters: Can we measure them? Can we simulate them? *International Symposium on Room Acoustics, Toronto.*

Cirrus Research plc. (2013). Calculation of NR & NC Curves in the optimus sound level meter and the NoiseTools software. UK. https://www.cirrusresearch.co.uk/library/documents/technical_papers/TN31_Calculation_of_NR_and_NC_Curves_in_the_optimus_sound_level_meter_and_NoiseTools_software.pdf

Cunha, I. B., Mattos, T., & Bertoli, S. R. (2013). Sound Quality in Small Music Classrooms. *The Journal of the Acoustical Society of America.* https://doi.org/10.1121/1.4800249

Daloğlu, C. (2019). Özel Dersliklerin Akustik Performans Sınıfları ve Aksutik Proje Tanımları Kapsamında Değerlendirilmesi: İzmir B.B Müzik Sanat Atölyeleri Örneği, [Master's thesis, Dokuz Eylül University]. Ulusal Tez Merkezi Repository. https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp

Department of Education and Science. (1975). Building Bulletin 51, Acoustics in Educational Buildings.

Deutsches Institut für Normung (2004). Acoustic Quality in Rooms – Specifications and Instructions for The Room Acoustic Design. (DIN Standard No. 18041:2004) https://www.din.de/en/wdc-beuth:din21:243375201

Duman, T. (1991). Türkiye'de Ortaöğretimde Öğretmen Yetiştirme-Tarihi Gelişimi. İstanbul: MEB Basımevi.

Eargle, J., & Foreman, C. (2002). JBL Audio Engineering for Sound Reinforcement. Hal Leonard Corporation

Egan, M. D. (1988). Architectural Acoustics. New York: McGraw-Hill.

Ermann, M. (2015). Architectural Acoustics Illustrated. John Wiley and Sons,Inc.

Escobar G. V., & Morillas B. J. M., (2015). Analysis of Intelligibility and Reverberation Time Recommendations in Educational Rooms, *Applied Acoustics, 96,*1-10. https://doi.org/10.1016/j.apacoust.2015.03.001

Everest, F. A., & Pohlmann, K. C. (2009) Master Handbook of Acoustics. McGraw-Hill

Galster, J. A. (2007) The Effect of Room Volume on Speech Recognition in Enclosures with Similar Mean Reverberation Time [Doctoral dissertation, Vanderbilt University]. Vanderbilt University Theses and Dissertations Archive. https://etd.library.vanderbilt.edu/available/etd-12062007-131834/unrestricted/galster_dissertation.pdf

Ginn, K. B. (1978). Architectural Acoustics. Brüel & Kjaer.

Gürel, N. (2007). İlköğretim Okullarının Akustik Açıdan İncelenmesi, [Master's thesis, Istanbul Technical University]. Istanbul Technical University Thesis and Dissertations Archive. https://polen.itu.edu.tr/xmlui/handle/11527/8171

Güven, İ. (2012). Eğitimde 4+ 4+ 4 ve fatih projesi yasa tasarısı= reform mu? *İlköğretim Online*, *11(3),* 556-577.

Hodgson, M. (1999). Experimental investigation of the acoustical characteristics of university classrooms. *Journal of the Acoustical Society of America,* 106, 1810 – 1819. https://asa.scitation.org/doi/10.1121/1.427931

Houtgast, T., Steeneken, H.J.M., & Plomp, R. (1980). Predicting speech intelligibility in rooms from the modulation transfer function. I. General room acoustics. Acta Acustica, 46, 60-72.

Houtgast, T. & Steneken, H.J.M. (1984). A multi-language evaluation of the RASTI-method for estimating speech intelligibility in auditoria. *Acoustica, 54 (4)*, 185-199(15).

International Electrotechnical Commission. (2003). Sound system equipment - Part 16: Objective rating of speech intelligibility by speech transmission index (IEC Standard No. 60268-16:2003). https://webstore.iec.ch/publication/14399

International Organization for Standardization. (2009) Acoustics – Measurement of Room Acoustic Parameters, Part 1: Performance Spaces (ISO Standard No. 3382-1:2009). https://www.iso.org/standard/40979.html

Karaman Yılmaz, Ö., & Üçkaya Berber N. (2015). Eğitim Mekânlarında Akustik Konfor: Dokuz Eylül Üniversitesi Mimarlık Fakültesi Örneği, *Megaron, 10 (4),* 503-521. 10.5505/MEGARON.2015.58076

Knudsen, V. O., & Harris, C. M. (1951). Acoustical designing in architecture (2th ed.). John Wiley and Sons,Inc.

Kurra, S. (2009). Çevre Gürültüsü ve Yönetimi I, Bahçeşehir Üniversitesi, İstanbul.

Kuttruff, H. (2009). Room acoustics (5th ed.). NY: Spon Press.

Laitinen, H., & Poulsen, T. (2008). Questionnaire investigation of musicians' use of hearing protectors, self reported hearing disorders, and their experience of their working environment. *International journal of audiology, 47(4),* 160–168. https://doi.org/10.1080/14992020801886770

Long, M. (2006). Architectural Acoustics. Elsevier Academic Press.

Maekawa, Z., Rindel, J. H., & Lord, P. (2011). Environmental and Architectural Acoustics. (2nd ed.). Spon Press.

Mehta, M., Johnson J., Rocafort J. (1999). *Architectural Acoustics.* Prentice Hall Inc.

Meriç, I. (2009). *A Model for the Evaluation of Speech Intelligibility in Elementary School Classrooms.* [Master's thesis, İstanbul Technical University]. Ulusal Tez Merkezi Repository. shttps://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp

Ministry of National Education. (2018). Müzik Dersi Öğretim Programı [Music Lesson Teaching Program]. Ministry of National Education of Turkey. http://mufredat.meb.gov.tr/Dosyalar/2018129173048695-1-8%20M%C3%BCzik%20%C3%96%C4%9Fretim%20Program%C4%B1%2020180123.pdf

Mommertz, E., & Müller-BBM. (2009) Acoustics and sound insulation: Principles, planning, examples. Aumüller Druck.

Odeon (2020). ODEON room acoustics software user's manual, version 15. Denmark. https://odeon.dk/download/Version15/OdeonManual.pdf

Official Newspaper, 27601. (2010, June 4). Çevresel Gürültünün Değerlendirilmesi ve Yönetimi Yönetmeliği [Regulation of Assessment and Management of Environmental Noise]. Official Newspaper of Turkey. https://www.resmigazete.gov.tr/eskiler/2010/06/20100604-5.htm

Osman, R. (2010). *Designing Small Music Practice Rooms for Sound Quality.* Proceedings of 20th International Congress on Acoustics (ICA), Sydney, Australia.

Ozgencil, Y. (2015). *Konservatuar Prova Odalarının Aksutik İncelenmesi ve Akustik Tasarımın İyileştirilmesi,* [Master's thesis, Bahçeşehir University]. Ulusal Tez Merkezi Repository. https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp

Özçevik, A. (2005). Mimari Tasarım Stüdyolarında İşitsel Konfor Gereksinimleri ve Bir Örnek, [Master's thesis, Anadolu University]. Ulusal Tez Merkezi Repository. https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp

Özgüven, H. N. (2008). *Gürültü Kontrolü.* Türk Akustik Derneği.

Paek, H., Siebein, G. W., & Kim, B. (2003). Case Studies of Acoustical Design of Rooms for Music Instruction In Schools. *In INTER-NOISE and NOISE-CON Congress and Conference Proceedings* (Vol. 2003, No. 1, pp. 492-504). Institute of Noise Control Engineering.

Peters, R. J., Smith, B. J., & Hollins M. (2011) Acoustics and noise control. Routledge

Rayleigh, J. W. S. B. (1945). *Theory of sound.* Dover Publication.

Rossing, T. D. (2007). Springer handbook of acoustics: With 91 tables. Springer

Rindel, J. H., Christensen C. L., Gade, A. C. (2012, August 19-22). *Dynamic sound source for simulating the Lombard effect in room acoustic modeling software.* Internoise 2012, p: 19-22, New York, USA.

Sala, E., & Viljanen, V. (1995). Improvement of Acoustic Conditions for Speech Communication in Classroom. Applied Acoustics 45, p:81-91 https://doi.org/10.1016/0003-682X(94)00035-T

Seep, B., Glosemeyer, R., Hulce, E., Linn, M., & Aytar, P. (2000). Classroom Acoustics: A resource for creating environments with desirable listening conditions. *Acoustical Society of America, 451697,* p:17.

Tang, S. K. (2008). Speech related acoustical parameters in classrooms and their relationships. *Applied Acoustics, 69*, 1318-1331. https://doi.org/10.1016/j.apacoust.2007.08.008

Vocational Qualifications Authority. (2015). Türkiye Yeterlilikler Çerçevesi [Turkey Qualifications Framework]. Vocational Qualifications Authority of Turkey. https://www.myk.gov.tr/images/articles/editor/130116/TYC_teblig_2.pdf

World Health Organization, (1999). *Guidelines for Community Noise.* http://www.who.int/peh/

Wroblewska, D. (2010). Acoustical standards used in design of school spaces. Acoustic and Biomedical Engineering, vol 118, 186 -189.

Xiang, N. (2017) Architectural acoustics handbook. J. Ross Publishing.

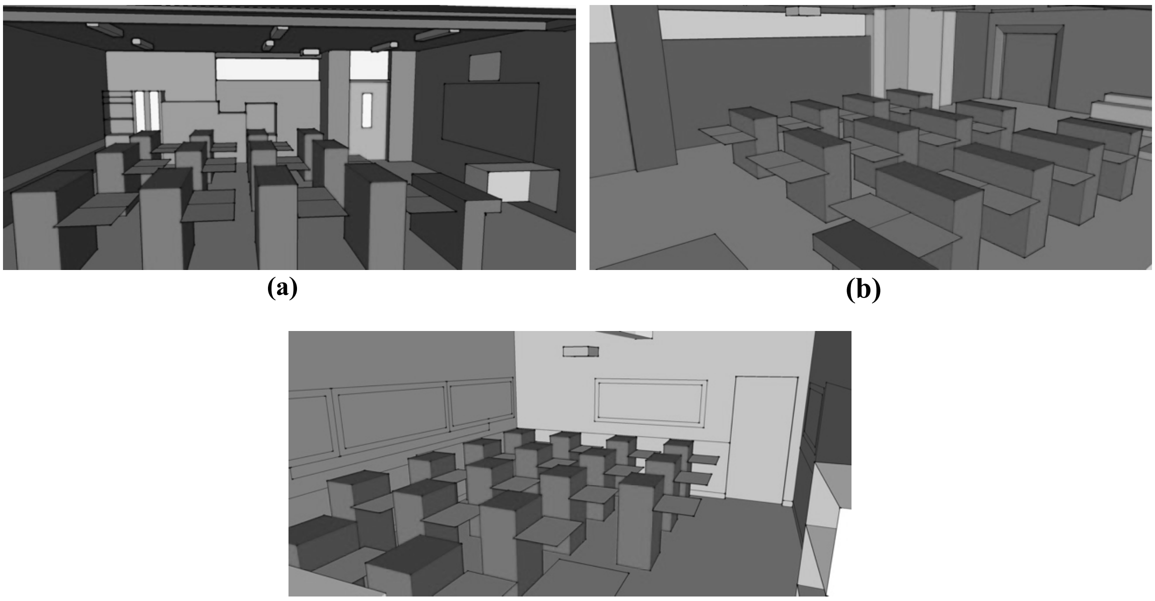
Zannin, P. H. T., Fiedler, P. E. K., & Bunn, F. (2013). Reverberation time in classrooms – Case study: When an administrative decision changes acoustic quality. *Journal of Scientific & Industrial* Research, 72, 506-510. http://nopr.niscair.res.in/handle/123456789/20254

Zhu, P., Mo, F., Kang, J., & Zhu, G. (2015). Comparisons between simulated and in-situ measured speech intelligibility based on (binaural) room impulse responses. *Applied Acoustics 97*, 65–77. https://doi.org/10.1016/j.apacoust.2015.04.005.

APPENDIX

6.1. Simulation of Occupied Condition of Classrooms

The experimental and computational studies were conducted according to the procedures described in ISO 3382-1. In this respect, the unoccupied state of the classrooms was investigated. However, the functions described in the previous sections take place under the occupied states of the classrooms. Since the 3D models of classrooms are calibrated, the potential effects of the students' being present on the acoustical performance have been investigated. Students are represented as rectangular prisms and are added to the calibrated models. The dimensions of each prism that represents a student are 40 cm in length, 52 cm in width and 100 cm in height (see Figure 6.1.1). The rest of the parameters remained as they were described in the Section 3.2 and they include: the properties of surfaces, positions of source and receivers and computation settings. The results of the simulations, taking into account the presence of the students, are given in Tables 6.1.1 – 6.1.3. The results are the average values of the receiver points R1 – R7 that were determined in the classrooms. The absorption coefficient data of the prisms that represent the students are given in Table 6.1.4.



(a) (b) (c)

Figure 6.1.1 Prisms that represent the presence of students in elementary (a), middle (b) and high (c) school classroom models.

Elementary School Music Classroom						
EDT (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,04	1,69	1,03	1,64	0,96	0,87
Maximum	1,09	1,79	1,10	1,78	1,03	0,95
Average	1,06	1,73	1,07	1,68	0,99	0,90
T30 (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,07	1,74	1,05	1,68	0,96	0,89
Maximum	1,13	1,81	1,10	1,79	1,02	0,93
Average	1,10	1,77	1,08	1,74	0,99	0,91
D50						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	0,42	0,27	0,42	0,29	0,46	0,49
Maximum	0,56	0,41	0,57	0,43	0,60	0,63
Average	0,48	0,33	0,48	0,34	0,51	0,54
C80 (dB)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,7	-1,3	1,7	-1,0	2,3	3,1
Maximum	3,7	0,6	3,7	0,7	4,2	5,0
Average	2,5	-0,6	2,6	-0,3	3,1	3,8
STI						
Minimum	0.55					
Maximum	0.59					
Average	0.56					

Table 6.1.1 Elementary school multipurpose music classroom room acoustic parameter values with presence of the students.

Middle School Music Classroom						
EDT (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,31	1,67	1,19	1,60	1,06	0,99
Maximum	1,50	1,87	1,34	1,77	1,27	1,20
Average	1,41	1,77	1,27	1,67	1,17	1,10
T30 (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,50	1,89	1,37	1,70	1,26	1,16
Maximum	1,59	1,98	1,43	1,78	1,32	1,19
Average	1,53	1,94	1,40	1,73	1,29	1,18
D50						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	0,31	0,24	0,33	0,25	0,36	0,37
Maximum	0,54	0,45	0,57	0,47	0,60	0,61
Average	0,43	0,35	0,46	0,37	0,49	0,50
C80 (dB)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	0,0	-1,6	0,6	-1,2	0,8	1,2
Maximum	3,3	1,4	3,8	2,0	4,3	4,7
Average	1,6	-0,2	2,1	0,3	2,7	3,0
STI						
Minimum	0.47					
Maximum	0.57					
Average	0.52					

Table 6.1.2 Middle school multipurpose music classroom room acoustic parameter values with presence of the students.

High School Music Classroom						
EDT (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,03	1,57	0,75	0,99	0,55	0,51
Maximum	1,14	1,67	0,84	1,16	0,65	0,58
Average	1,07	1,61	0,78	1,06	0,59	0,54
T30 (s)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,04	1,58	0,77	1,02	0,60	0,53
Maximum	1,11	1,64	0,80	1,08	0,62	0,56
Average	1,08	1,61	0,79	1,05	0,61	0,55
D50						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	0,42	0,29	0,52	0,40	0,62	0,66
Maximum	0,58	0,44	0,68	0,59	0,77	0,81
Average	0,49	0,36	0,60	0,49	0,70	0,73
C80 (dB)						
Octave Band	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Minimum	1,9	-0,9	4,1	1,7	6,3	7,2
Maximum	4,2	1,4	6,6	4,3	9,2	10,3
Average	2,9	0,1	5,4	3,0	7,7	8,7
STI						
Minimum	0.62					
Maximum	0.66					
Average	0.64					

Table 6.1.3 High school multipurpose music classroom room acoustic parameter values with presence of the students.

	Sound Absorption Coefficient					
Surface Material	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Children, seated in plastic or metal chairs (per child) (Department of Education and Science, 1975).	0.28	0.00	0.33	0.00	0.37	0.37

Table 6.1.4 Sound absorption coefficient data of the material assigned to prisms representing the students.

A comparison of the unoccupied and occupied states of each classroom in terms of the room acoustic parameters is given in Table 6.1.5. According to the results, the T30 parameter values decreased in each classroom since the students behave like absorbers. In the elementary school, the mid-frequency average value of T30 in the occupied state is still above the reference limits speech function. However, it is just above the reference limit of music function with 0.01 s. Therefore, it can be considered appropriate for the music function. As for the middle school music classroom, the T30 values decreased by 0.12 s. The reverberation time is still beyond the reference limits. The T30 values are in the reference range of the music function in the unoccupied state of the high school music classroom. However, the unoccupied state is slightly below the reference range for the music function with 0.03 s, which is negligible in this case.

The EDT parameter decreased in parallel with T30 in all three classrooms. For the elementary and middle school music classrooms, the EDT is shortened and is still appropriate for the music function in terms of reference limits. This is not the case for the high school where the change in the EDT value results in an inappropriate condition for the music function. When it comes to the speech function, it is observed that the EDT value is appropriate in the high school for the occupied state, even though it is not so for the music function.

With the presence of students, the D50 parameter remains almost unchanged in the elementary and middle schools. The D50 value increased by 0.05 in the high school music classroom. The results of the occupied state in the high school are within the appropriate limits of the D50 parameter (appropriate limits: D50 > 50%).

The values of C80 parameter is slightly increased in elementary and middle school music classrooms by 0.2 and 0.1 dB, respectively. However, in the high school, the clarity increased by 1.65 dB. The C80 value is in the reference range in the unoccupied state, with 2.55 dB (reference range of C80 is between -1 dB and +3 dB for music). In the occupied state, the clarity is above the reference range with 4.2 dB. This is due to the inversely proportional relation between clarity and reverberation.

The results of the STI parameter is slightly increased for elementary and middle school multipurpose music classrooms in the occupied state. The values are still in the range of fair. In the high school with the increase of total absorption in the space, the STI resulted at 0.64, which corresponds to good range.

The results indicate that the presence of students can affect the acoustical performance of multipurpose music classrooms in the five room acoustic parameters investigated. Acoustical performance is improved for some of the acoustical parameters and the results move closer to the reference values. However, in room acoustics, some of the parameters are conflict with each other, which means that improving one of the parameters may result in disabling the others. Regarding the occupied state of the elementary and middle school music classrooms, the results are slightly improved for both the speech and music functions in general. The acoustical performance of the high school music classroom is considerably improved in terms of the speech function and decreased for the music function.

	Elementary School		**Middle School**		**High School**	
	Unoccupied Result	**Occupied Result**	**Unoccupied Result**	**Occupied Result**	**Unoccupied Result**	**Occupied Result**
T30 (500-1000 Hz avg.)	1.67 s	1.41 s	1.68 s	1.56 s	1.15 s	0.92 s
EDT (500-1000 Hz avg.)	1.66 s	1.37 s	1.62 s	1.47 s	1.14 s	0.92 s
D50 (500-1000 Hz avg.)	0.40	0.41	0.41	0.41	0.49	0.54
C80 (500-1000 Hz avg.)	0.95 dB	1.15 dB	1.1 dB	1.2 dB	2.55 dB	4.2 dB
STI	0.51	0.56	0.50	0.52	0.58	0.64

Table 6.1.5 Comparison of the acoustics of unoccupied and occupied conditions of multipurpose music classrooms.

Publications

Aslan, A., Metin, B., & Oktav, A. (2020). Computational Investigation of Acoustical Performance of Multipurpose Music Classrooms. *III. International Symposium on Engineering Natural Sciences and Architecture (ISENSA)* (pp. 44-53). Kocaeli, Turkey.