ESTIMATION OF HEATING, VENTILATION AND AIR CONDITIONING(HVAC) NOISE LEVELS IN HOSPITALS

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ABSTRACT

ESTIMATION OF HEATING, VENTILATION AND AIR CONDITIONING(HVAC) NOISE LEVELS IN HOSPITALS

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The aim of this study is to predict occupied space sound levels originating from Heating Ventilation and Air Conditioning (HVAC) systems through air terminals and air outlets by using 2008 Standards of Air-Conditioning, Heating and Refrigeration Institute (AHRI) in order to provide hospital design information meeting acoustic goals with an emphasis onto low frequency noise termed as rumble. EXCEL Visual Basic for Applications (VBA) program is used for the development of software containing procedures of the AHRI Standard and evaluation of the predicted sound pressure level in terms of hospital space's defined Room Criteria (RC) level. Verification of the software is performed by making use of the example given in AHRI Standard. It is observed that software output gives the same results calculated by excel programming. Effectiveness of AHRI standard is evaluated by comparisons of the software results for total sound pressure levels due to designed HVAC system of four hospital private room with sound pressure level measurements in the built room.

Keywords: hospital acoustics, healthcare-building acoustics, hospital noise, hospital design, acoustical design, Heating, Ventilating and Air Conditioning (HVAC) System, HVAC noise.

ÖZ

HASTANELERDE ISITMA, HAVALANDIRMA VE İKLİMLENDİRME SİSTEMLERİNİN (HVAC) SES DÜZEYLERİNİN TAHMİNİ HESABI

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Kasım 2019, 142 sayfa

Bu çalışmada, akustik hedefleri karşılayan hastane tasarımı konusunda bilgi sağlamak amacıyla düşük frekansta gümbürtü şeklinde algılanan gürültüye dikkat çekerek, 2008 yılı İklimlendirme, Isıtma ve Soğutma Enstitüsü (AHRI) standardına göre; hava terminalleri ve hava çıkışlarına bağlı ısıtma, havalandırma ve iklimlendirme sistemlerinden kaynaklı ses düzeylerinin tahmini olarak hesaplanması amaçlanmıştır. EXCEL Visual Basic for Applications (VBA) programı, AHRI standartlarındaki yöntemleri ve hastane alanının belirlenmiş oda ölçütü/kriteri (RC) düzeylerine göre ses basıncı düzeyi değerlendirmelerini içeren yazılımın geliştirilmesinde kullanılmıştır. AHRI standardında verilen örnek kullanılarak yazılım doğrulanmıştır. Yazılım çıktısı ile hazırlanan jenerik Excel yazılımı ile elde edilen hesaplamaların aynı sonucu verdiği gözlemlenmiştir. AHRI standardının etkinliği, dört hastanenin özel odasındaki HVAC sistem tasarımının yazılım sonucunda elde edilen ses basıncı düzeyi ile odadaki ses basıncı düzeyi ölçümlerinin karşılaştırılmasıyla değerlendirilmiştir.

Anahtar Kelimeler: Hastane akustiği, sağlık hizmeti kurumları akustiği, hastane gürültüsü, hastane tasarımı, akustik tasarım, ısıtma, soğutma ve iklimlendirme sistemleri, ısıtma, soğutma ve iklimlendirme sistem gürültüsü.

To my lovely mother

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LIST OF ABBREVIATIONS

HVAC	Heating Ventilation and Air Conditioning
AHRI	Air-Conditioning, Heating and Refrigeration Institute
VBA	Visual Basic for Applications
RC	Room Criteria
SPL	Sound Pressure Level
US	United States
RT	Reverberation Time
SI	Speech Intelligibility
ICU	Intensive Care Unit
HCAHPS	Hospital Consumer Assessment of Healthcare Providers and Systems
EPA	Environmental Protection Agency
ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineers
HART	Hospital Acoustical Research Team
WHO	World Health Organization
AusHFG	Australasian Health Facility Guidelines
HTM	Health Technical Memorandum
UK	United Kingdom
SVDG	Sound & Vibration, Design Guidelines
AS/NZS	Australian/ New Zealand Standard

ARC	Acoustics Research Council
NC	Noise Criteria
PNC	Preferred Noise Criteria
RP	Research Project
ERL	End Reflection Loss
USARMRICD	United States Army Medical Research Institute of Chemical Defense

LIST OF SYMBOLS

L_{Aeq}	A-weighted equivalent sound pressure level
L_{eq}	Equivalent sound pressure level
L_{min}	Minimum sound pressure level
L_{max}	Maximum sound pressure level
L_{peak}	Peak sound pressure level
A_r	Duct outer surface area
A_i	Duct internal cross-sectional area
d_o	Outside diameter
d_i	Inside diameter
L	Length
L_{wi}	Sound power level at duct inlet
L_{wo}	Sound power level at duct outlet
TL_{out}	Transmission loss
a_i	Inner width
a_o	Outer width
b_i	Inner height
b_o	Outer height
a	Overall width
b	Overall height
A_s	Attenuation

c_o	Speed of sound
a_1	Dimensionless constant
a_2	Dimensionless constant
f	Octave band center frequency
V	Room volume
H	Ceiling height
N	Number of evenly spaced outlets in the room
S_A	Distributed ceiling array space effect
x	Ratio of the floor area served by each outlet to the square of the ceiling height
f_{co}	Cutoff frequency
c	Speed of sound in air
a	Larger cross-sectional dimension of rectangular duct
d	Diameter of round duct
TL	Transmission Loss
S_{out}	Plenum outlet area
S	Total plenum inside surface area minus plenum inlet and outlet areas
r	Distance between plenum's inlet and outlet centers
Q	Directivity factor, taken as 2 for opening near center of wall, or 4 for opening near corner of plenum
α_a	Average absorption coefficient of plenum lining

OAE	Offset angle effect
α_1	Sound absorption coefficient of plenum’s unlined inside surface area
S_1	Plenum’s unlined inside surface area
α_2	Sound absorption coefficient of plenum’s acoustically lined inside surface area
S_2	Plenum’s acoustically lined inside surface area
A_f	Surface area coefficient
W_e	Wall effect
C_1	Radiated and induction inlet sound power
D_1	Terminal discharge sound power
O_1	Outlet generated sound power
B	Duct breakout transmission loss
I	Insertion Loss
T	Duct elbow and tee loss
R	End reflection factor
P	Ceiling/space effect
S	Space effect
$S2$	Distributed array
F	Branch power division
PL	Plenum attenuation

CHAPTER 1

INTRODUCTION

1.1. SCOPE AND OBJECTIVE

There is a significant raise in environmental noise with the advances in technology and transportation industry and increase in population. Related to exterior noise augmentation, noise in interior spaces starts to be more challenging. It is possible to observe interior noise's exceeding design limits and accordingly recommendations. Hospitals are the special interior spaces where sick, helpless and sensitive individuals need to go to get medication. Therefore, healthcare environments require special attention and they should provide a place where people can get medication, recover, sleep, relax and get well. Moreover, every department in the healthcare building has multiple and different kinds of noise sources. Each department needs special acoustical design approaches according to the function of that department. Therefore, achieving acoustic comfort in hospitals is very challenging.

It is important to control temperature, humidity, air quality and the level of noise to have a comfortable living environment. Heating, ventilation, and air-conditioning (HVAC) system design is crucial for healthcare facilities to control the indoor environment and ensure a comfortable, hygiene, healthy and safe spaces for the hospital occupants [1]. Public demands for higher comfort levels and hygiene require use of more energy which results in higher levels of mechanical noise on hospital facades and interiors.

In Turkey, many new hospitals under the name Integrated Health Campuses are currently under planning and construction. The accumulated knowledge on much needed noise control and noise mitigation studies in hospitals will be service to the public. It is intended for this study to prepare software estimating HVAC noise levels in healthcare environment. With the development of estimation of HVAC system noises in hospitals, it can be possible to take necessary precautions in the design stage of HVAC system subjected to proven acoustical criteria. Air-Conditioning, Heating and Refrigeration Institute (AHRI) Standard 885 [2] a recent standard is for the prediction of HVAC system noise. This Standard is used when the acoustic performance of air terminals and/or outlets is known for the estimation of space sound pressure levels. For the calculation of sound pressure level of an enclosed area in a hospital with known acoustic performance and HVAC system design data, a user-friendly computer program by making use of Microsoft Visual Basic for Applications (VBA) Program is developed. For the validation of the program, the example with a known source, path and result data given in AHRI Standard Procedure document is used. Moreover, department's acoustical evaluation, by stating that it is within the limits designated by regulations or standards or not, is represented by the implemented software in VBA.

Consequently, the main aim of the study is to estimate HVAC system noise in hospitals by developing a computer program implementing requirements of AHRI Standard 885 and testing the HVAC design by measurements of sound levels and subsequent assessment of the procedure with respect to Turkish Hospitals.

1.2. OUTLINE OF THE THESIS

In Chapter 2, literature review about hospital acoustic is presented. This literature survey study is divided into six sub-sections: health effects of hospitals, historical noise levels in hospitals, occupant response to hospital noise, noise regulations and recommendations for hospitals and design guidelines for healthcare buildings.

In Chapter 3, detailed information about HVAC system noise is given. Formulas and tables presented in AHRI Standard 885, which is used in designed software, is included. Assumptions considered in the estimation are also stated.

In Chapter 4, methodology used in the thesis is mentioned. AHRI Standard 885 procedure is explained in detailed. Moreover, VBA program is briefly explained.

Detailed explanation is presented for the EXCEL program, named AHRI SPL Predictor. Four sub-parts exist for the clarification of AHRI SPL Predictor EXCEL document. These are listed as

- introduction to software,
- general view of the software,
- general workflow of the software,
- application of the software.

In Chapter 5, validation of the AHRI SPL Predictor is provided. Case studies are considered. One of them is imported from AHRI Standard 885. The example given in the standard is used in AHRI SPL Predictor and the same estimated value is obtained. The other ones are selected from real life examples. Four hospital rooms' HVAC system design data are used; and comparisons of measured and estimated values are supplied.

In the final chapter, conclusion of the study is presented. In addition, suggestions for the probable future study are mentioned.

CHAPTER 2

LITERATURE SURVEY

2.1. GENERAL

A soundscape is defined as “an atmosphere or environment created by or with sound [3].” Hospitals have unique and complex soundscape comprising of HVAC system noises, mechanical equipment noises, medical equipment noises and noises generated by humans. Therefore, hospitals have many different noise sources that must be controlled to reach recommended acoustic comfort. Acoustic comfort of a healthcare environment has an extreme significance on supporting safety, health, healing, and welfare for all occupants.

In this part, literature survey summary regarding healthcare building acoustic and prediction methods for HVAC noise is presented. In this respect, health effects of hospital noise, historical noise levels in hospitals, evaluation of hospital noise, occupant response to hospital noise and noise regulations and recommendations for hospitals are mentioned as a subsection of acoustics in healthcare building. Furthermore, some standards and existing studies related to HVAC system noise are reviewed and presented.

2.2. REVIEW OF LITERATURE SURVEY

2.2.1. Health Effects of Hospital Noise

It is scientifically supported that noise have many serious adverse health outcomes. Noise induced hearing impairment; interference with sleep communication; sleep disturbance [4-8]; cardiovascular effects [9, 10]; physiological and mental effects [10]; the effects of noise on performance [5] and residential behavior; and annoyance are some of the health effects with proven studies [11]. In addition, in a paper of Hsu et al. focusing on epidemiology of hospital noise pollution and its effects on patients, 36 studies were considered. It was concluded that there is no traced relationship between noise and some negative reactions in patients. While sleep arousal, cardiovascular response and hospital stay were strongly influenced by noise, there is not any clear evidence showing outcomes of noise on wound healing and pain management [12].

Noise induced hearing impairment is the most widespread permanent occupational danger in worldwide and universally 120 million people are estimated to suffer from hearing loss. It happens dominantly in the frequency range of 3000-6000 Hz, but 4000 Hz has the greatest effect. It is possible for this hazard to occur at harmonic at speech frequencies such as 2000 Hz with the increase in exposure time and A-weighted equivalent sound pressure level. Occupational noise exposure with high levels of energy at speech frequencies of 500 Hz to 2000 Hz may cause hearing damage over extended periods of exposure over the years. Clinical studies and research in the field has shown that the 8-hr equivalent A-weighted sound level (L_{Aeq},8h) must be higher than 75 dB. Hearing impairment can cause not understanding daily life speeches, which results harsh social defect. Some acoustical signals which are crucial for daily life can be masked by environmental noise. This speech interference also affects the social life negatively. Considering speech intelligibility, it is affected by speech level, speech pronunciation, distance between talker and listener, background sound level, hearing perception and attention level. If patients are not confident that they have complete privacy, potentially, they may hesitate to provide complete information about their medical conditions and/or concerns, potentially putting their health at greater risk [4].Therefore, medical errors can be reduced by maintaining speech privacy. Moreover, reverberation characteristics of a room influence the communication of people in that room. Reverberation time below 0,6s is preferred satisfactory speech intelligibly, or not to have speech discrimination and difficult speech perception. Those kinds of not clearly understood speeches can have terrible outcomes in personal life and behavior of a person who is struggling with this problem. Another problem that environmental noise causes is the sleep disturbance. To have good physiological and mental performance, uninterrupted sleep is necessary. Sleep disturbance is also associated primarily with difficulty in falling asleep; awakenings and alterations of sleep stages and depth; increased blood pressure, heart rate and finger pulse amplitude; vasoconstriction; changes in respiration; cardiac arrhythmia; and increased body movements. After effects are reduced perceived sleep quality; increased fatigue; depressed mood or well-being; and decreased performance. Focusing on physiological consequences of noise exposure, some irreversible problems such as hypertension and ischemic diseases may arise with prolonged exposure. Cardiovascular effects are also seen after long term noise exposure. On the other hand, mental illnesses can be affected by the environmental noise. High levels of such form of noise could cause neurosis. Performance of cognitive tasks can be also influenced in a way that better performance might be obtained for simple tasks while deteriorating performance on complex tasks. Strongly affected cognitive tasks are reading, attention, problem solving and memorization. Annoyance is another disturbing source of noise. Level of annoyance can vary depending on characteristic of noise and also non acoustical factors associated with social, psychological and economic environment [11].

2.2.2. Historical Noise Levels in Hospitals

Noise levels in healthcare facilities have been a critical concern for many years. In a paper of Ryherd et al., data from study by Busch-Vishniac et al. including years between 1960-2005 [13] and collected data from Hospital Acoustical Research Team (HART) [14-21], which is a collaboration of specialists in engineering, architecture, psychology, medicine, and nursing from various universities, medical facilities, and industry are mentioned with the data collected by authors [22]. It is concluded that there is an increasing trend of sound pressure levels in hospitals in United States (US); that is, sound pressure levels have risen significantly and consistently since 1960 [13].

Figure 2.1 shows A-weighted equivalent sound pressure levels as a function of year publication during daytime hours while Figure 2.2 showing nighttime hours. Linear line demonstrates that daytime levels have increased by 0.2 dB per year and nighttime levels have increased by 0.4 dB per year on the average.

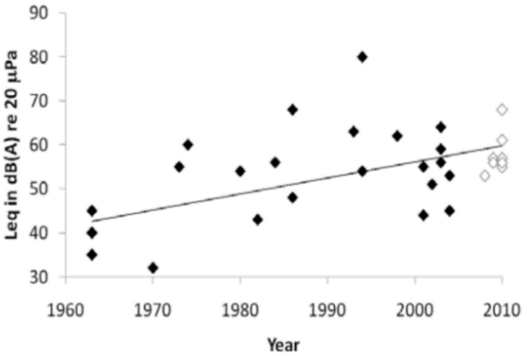


Figure 2.1. A-weighted equivalent sound pressure levels during daytime hours as a function of year [22]

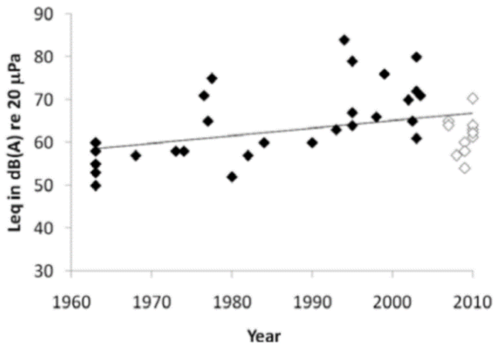


Figure 2.2. A-weighted equivalent sound pressure levels during nighttime hours as a function of year [22]

Another result presented in the paper by Ryherd et al. lists the ranges of levels published from 1960-2004 versus from 2005-2010. It can be seen in Table 2.1 that there exist large differences between years. This may be attributed hospitals' becoming more active and background noises' becoming more fluctuating. Moreover, more rigorous methodology, many measuring locations within individual units and relatively short averaging intervals were implemented for the collection of recent data [22]. Significant increase in the noise levels can also be observed from that study.

Table 2.1. *Ranges of Levels Published (1960-2004) versus from (2005-2010) [22]*

Daytime or Nighttime	**Publication or Measurement Date**	**Max range of Leq Published in dBA**	**Average Range of Leq Published in dBA**
Daytime	1960 – 2004	14	8
Daytime	2005 – 2010	32	27
Nighttime	1960 – 2004	12	8
Nighttime	2005 – 2010	33	28

2.2.3. Evaluation of Hospital Noise

Most of the studies have focused on characterizing overall noise levels. In this respect, equivalent (L_{eq}), minimum (L_{Min}), maximum (L_{Max}), and peak (L_{Peak}) sound pressure levels have been commonly reported. L_{Min} is the minimum rms-based noise level during a measurement period or noise event while L_{Max} is the maximum rms-based noise level during a measurement period or noise event. On the other hand, L_{Peak} is the actual peak of the pressure wave measured with a shorter time constant. This may be based on the practicality and convenience of these measurements, and also because they are incorporated into various guidelines such as the "Guidelines for Community Noise" document provided by World Health Organization (WHO). In a study of Okçu et al. it is stated that these overall sound pressure levels provide a good general overview of the sound environment but are limited in usefulness [23]. More detailed acoustic measures such as the statistical exceedance level (L_n), reverberation time (RT), speech intelligibility (SI), and frequency analysis or noise criteria indicators of spectral content that have been less commonly reported are necessary to better understand the complex soundscape of hospitals. This fact can be supported with the findings in Okçu et al paper. Even if traditional measures of overall A-weighted L_{eq} (L_{Aeq}), flat/unweighted L_{Max} (L_{Max}), A-weighted L_{Min} (L_{Amin}), and C-weighted L_{Peak} (L_{Cpeak}) of the two Intensive Care Units (ICUs) are similar, an ICU with higher mid-level transient sound occurrence rate and speech interference level is found to be louder and more annoying [23]. Need for studies better describing the environmental properties is also emphasized in paper by Waye et al. It is mentioned in that paper that some important points such as how often peak and maximum levels occur and how long time is allowed between maximum levels that can be used for the patients to restore or for the personnel to work without distraction are not mentioned in most of the studies [24].

2.2.4. Occupant Response to Hospital Noise

Healthcare environment can be problematic for all occupants in the hospitals: hospital personnel, patients, patient families and visitors. In a report on the Beryl Institute Benchmarking Study, noise reduction is in the top five priorities list for action identified in 2011; in fact, it is rated as the most crucial problem [25]. It is mentioned in that report as "The Beryl Institute is the global community of practice and premier thought leader on improving the patient experience. The Institute serves as a reliable resource for shared information and proven practices, a dynamic incubator of leading research and new ideas and an interactive connector of leaders and practitioners. The Institute is uniquely positioned to develop and publicize cutting-edge concepts focused on improving the patient experience, touching thousands of healthcare executives and patients." These findings are directly related to questions on Hospital Consumer Assessment of Healthcare Providers and Systems (HCAPS) survey. HCAHPS defined in a paper as "one of several national initiatives focused on patient-centered care that are challenging outdated assumptions that patient-reported data are less reliable and less valid than data obtained from abstraction, medical record review, and administrative claims [26].” HCAHPS data are currently available on approximately 3,900 hospitals nationwide, almost 90% of all eligible hospitals, and offer an unprecedented opportunity to analyze and compare aggregated hospital data at local, state, and national levels. It can be used alone or in conjunction with other measures (e.g., mortality rates, heart attack care, heart failure care, pneumonia care, surgical care improvement measures, and information on admitting condition [27-29]. It can contribute further informing health care policy and consumer decision making. HCAHPS serve as a national standard for collecting and publicly reporting information about patients’ experiences that permits valid comparisons across hospitals. This public reporting enables consumers to be informed while making decisions; complements the clinical information; encourages high quality and efficient healthcare delivery; and supports the transparency of quality information [26].

In a large study involving variety of patient care units in two hospitals, voices are found to be the most annoying for patients and hospital personnel in addition to noises generated by carts in the hall, footsteps in the hall, cardiac monitor alarms, overhead pages and pulse oximeter alarms [30]. Medical equipment noise is also found annoying by Intensive Care Unit (ICU) staff [31]. Moreover, noises from conversation, work environment problems, telephone calls and equipment can be distractive and interruptive for an operation theatre [32]. In a paper-based survey was administered to nurses working in a cancer unit and survey results can be seen on Figure 2.3 [22]. It shows nurse perception of various noise sources in a cancer unit. Noises from alarms, phone ringing, cleaning equipment, staff talking and rolling carts are the top five bothersome noise sources, respectively. HVAC noises found the least bothersome according to this survey results. Despite survey results, it is concluded in the paper that HVAC noises could serve as an underlying factor for increased stress or annoyance; e.g., ability to cope with other noise sources may be lessened if the HVAC noise is problematic.

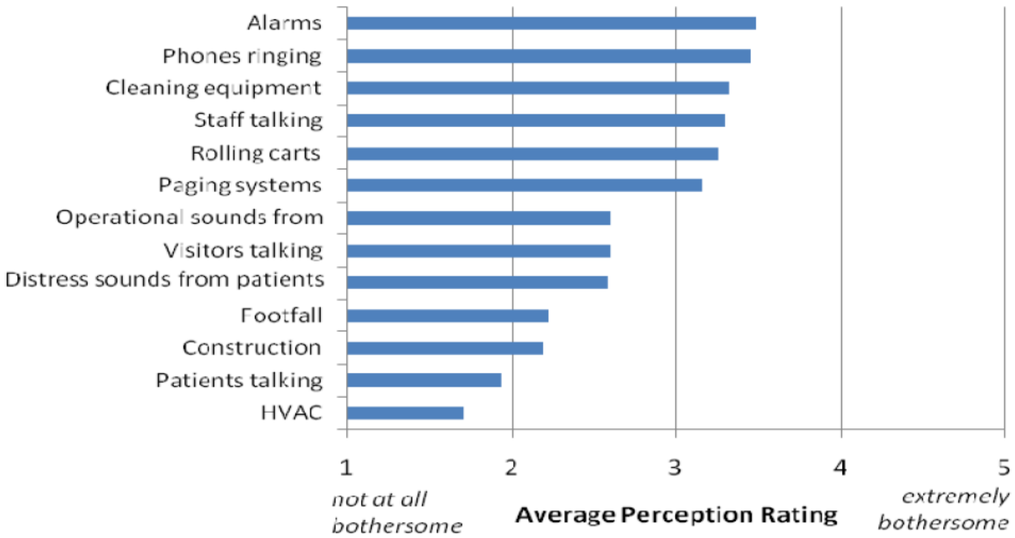


Figure 2.3. Nurse Perceptions of Various Noise Sources in a Cancer Unit [22]

2.2.5. Noise Regulations and Recommendations for Hospitals

WHO guidelines recommend a maximum Leq of 35 dBA in patient treatment and observation rooms and 30 dBA in ward rooms. [11]. On the other hand, Environmental Protection Agency (EPA) has established guidelines recommending noise levels not to exceed 45dBA in daytime and 35dBA at night in hospitals. [33]. American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) recommendation for hospitals and clinics are expressed as RC rating. It changes according to space. For private rooms and operating rooms of hospital, RC value should be between 25 to 35 while it should be between 30 to 40 for wards, corridors and public areas in the hospitals. [34]. Focusing on the figures constituted with data from study by Busch-Vishniac et al. including years between 1960-2005 [13] and collected data from Hospital Acoustical Research Team (HART) [14-21], which is a collaboration of specialists in engineering, architecture, psychology, medicine, and nursing from various universities, medical facilities, and industry, nearly all of the measured data exceed recommended values. Considering again Figure

2.1 and Figure 2.2 showing A-weighted equivalent sound pressure levels as a function of year publication during daytime hours and nighttime hours respectively, nearly all the measured data exceed recommended World Health Organization (WHO) and EPA values.

Formerly Turkish Regulation, originally Ministry of Environment and Forestry of Turkey specifies indoor limiting noise level values at the regulation of assessment and management of environmental noise. For health facilities, interior Leq limiting level for hospitals, dispensaries, polyclinics, residential facilities and more of the same is 35 dBA for window closed condition and 45 dBA for open condition. For rest and treatment rooms, it is 25 dBA for window closed condition and 35 dBA for open closed condition. [35].

2.2.6. Design Guidelines for Healthcare Buildings

Samuel Clarke [36] discusses acoustic design approaches of healthcare buildings in his paper and makes a short review of international design guidelines and compares these guidelines. Healthcare design guidelines mentioned in the paper are;

- Australasian Health Facility Guidelines Revision v4.0 (AusHFG) [37],
- Health Technical Memorandum (HTM) 08-01: Acoustics, United Kingdom
- (UK) Department of Health (HTM 08-01) [38],
- Sound & Vibration, Design Guidelines (SVDG) for Health Care Facilities,
- Version 2.0 [39],
- Australian/ New Zealand Standard (AS/NZS) 2107:2000 Acoustics-Recommended design sound levels and reverberation times for building interiors (AS2107) [40], and
- Green Building Council of Australia, Green Star- Healthcare v1 2009 (Green Star Healthcare) [41]

Considering Guidelines for Health Care Facilities [39], this guideline was constituted to be a reference document for architectural acoustics by the Acoustical Working Group, Acoustics Research Council, (ARC). It includes recommended minimum design requirements for all types of health facilities. These suggestions are proposed to have satisfactory acoustical and privacy environments. Considering the content of the guideline, it contains six sections: site exterior noise, acoustical finishes and details, room noise level, sound isolation performance of constructions, paging and call systems, clinical alarms, masking systems and sound reinforcement, and building vibration.

In the paper by Clarke [36], a brief summary of referenced guidelines is included in addition to mitigating factors. These factors are acquired upon consultation with users, infection control, hospitals - where activity and sleep collide, medical equipment and instrumentation, doors, emergency or standby plant, acoustic ceiling tiles and sound masking systems. Explanations about mitigating factors are as follows: Consultant should inform the client and/or users to take steps assuring their requirements. It is also important for the design to be flexible for the future. That is, it should be able to follow technological developments. For infection control, it is preferred to have smooth and moisture resistant finishes for cleaning purposes. Staff activity and equipment induced noise, which is not considered by design team, can affect sleep comfort of patient. These types of noise sources are difficult to control. Medical equipment and instrumentation which are necessary to be used in healthcare facilities can be very noisy. Performance of the partition is affected by the provision of doors. Frequency and duration requirements related to the testing of emergency and standby plant should be considered while applying a correction value. Sound absorptive ceiling tiles can be important in controlling noise generation in the space, improving speech intelligibility and even reducing noise intrusion. However, ceiling tiles in healthcare facilities is needed to meet some criteria such as humidity resistance, ability to be cleaned and infection control requirements. The last factor, sound masking is significant to improve acoustic privacy by introducing a continuous background noise. In addition, he gave a place to two case studies to demonstrate the difficulties that occur in design of real healthcare facilities. He concluded that healthcare design guidelines are beneficial as a starting point, but it is very important to be aware of the user groups and design constraints.

In Turkey, tender specifications exist as a design guideline for healthcare buildings; however, they cannot fulfill the needs. Necessary design strategies have been following in accordance with Turkish regulations. Having a general design guideline can be advantageous and helpful for preventing excessive discrepancies in terms of acoustic comfort in hospitals.

2.2.7. Low Frequency Noise Control

Low frequency noise is often considered as the frequency ranges from approximately 10 Hz to 200 Hz. It requires significant attention since it causes annoyance and extreme distress on people[42]. It is stated in WHO publication that “It should be noted that low frequency noise, for example, from ventilation systems can disturb rest and sleep even at low sound levels” [43]. Low frequency noise is attenuated less by structures such as walls and absorbed(dissipated) very little by building elements like wall coverings, furniture, and people. In fact, objects and walls can be rattled because of low frequency noise. Moreover, great distances can be crossed by low frequency noise without considerable energy dissipation with the help of atmospheric and ground attenuation [44].

Considering low frequency noise control strategies, implementing insulation techniques for the source, better maintenance of machinery such as HVAC system equipment or active sound absorption can decrease emission of low frequency noise [44]. Plenum chambers are often devised for reducing the ventilation system noise [45]. An HVAC plenum is usually a large sheet-metal box connected to a fan and ducted systems and it is used in supporting the distribution of ventilation or conditioned air. It is often used to attenuate sound, usually low frequency sound, within a ducted fan system [46], [47], [48]. Plenums can attenuate sound in three different ways. First of all, impedance produced is created at the plenum inlet with sudden area expansion. Second attenuation way is implementing an absorbing lining inside the plenum. Attenuation properties are enhanced with lining application, particularly at higher frequencies. The last one is minimizing turbulence. With this change, smooth airflow between upstream and downstream system components is achieved. It is obvious that noise reduction in plenums increases with the size enlargement of plenums but deciding the dimensions of the plenum is dependent on sufficient space to install, fan size, duct dimensions and required noise reduction measures [49]. In a paper, a significant noise reduction by 7dB in frequencies from 31.5 Hz to 500 Hz was observed by using a plenum. If lined plenum was implemented than noise reduction reaches to 11dB. Therefore, it was concluded that plenums are effective for noise reduction at low frequencies [50]. In addition, the amount or thickness of absorbent lining was founded as a main reason of decrease in noise levels at lower frequencies [51].

CHAPTER 3

HVAC SYSTEM NOISE

Considering historical background of HVAC noise control in general, Noise Criteria (NC) curves was constituted by Beranek to identify noise problems and to be able to specify the design goals in 1957 [52]. In addition, with these NC curves, indoor HVAC system noise could be rated in terms of NC level. Over the year, some shape problems in NC curves was found and then in 1971, Preferred Noise Criteria (PNC) curves were introduced [53] to cope with newly introduced preferred center frequencies of octave bands. Comparing PNC with the NC curves, gentler spectrum slopes below 250 Hz and sharper spectrum slopes about 1000 Hz was determined. Both of the rating curves only have level characteristic and it was found that there was a need to have quality aspect. Therefore, Room Criteria (RC) rating HVAC systems and having additionally quality feature was introduced in 1981 by Blazier [54].

It is aimed with HVAC systems that they control the indoor environment and present a safe, inexpensive, comfortable and healthy atmosphere for the building occupants at a minimum cost. However, hospital design in the light of this definition is different and more difficult than other spaces. In fact, the air- conditioning systems can contribute to the therapy of the patient and require special attention by virtue of health risks and hygiene considerations [1]. In addition, in the paper of Ghadge et al, HVAC system design is found crucial to have an optimum air quality and comfort level in hospitals [55].

In this chapter, noise sources and sound attenuation element covered in AHRI Standard 885; that is, acoustic design data used for the prediction of sound pressure levels in a conditioned occupied space for the application of air terminals and air outlets are explained in detail.

3.1. NOISE SOURCES DEFINED IN AHRI STANDARD 885

3.1.1. Air Terminal

Air Terminal is defined as a device that modulates the volume of air delivered to or removed from a defined space in response to an external demand [56]. The various types of air terminals defined in the AHRI 885 Standard are bypass terminal, integral diffuser, dual duct terminal, induction terminal, parallel flow fan-powered terminal, reheat terminal, series flow fan-powered terminal and single duct terminal [2].

There are three concerns while selecting the air terminals. They are occupant comfort, air quality and energy conservation. To fulfill all these three concepts, performance and design factors are considered. An air terminal's performance is affected by drop, throw, spread, pressure drop, and sound level of the air outlet. Firstly, drop is vertical distance which air jet stands below the ceiling. Drop can be reduced by decreasing supply air volume, increasing supply air temperature or utilizing surface effect of the ceiling; that is, locating the outlets near or in the ceiling. Secondly, Throw is the horizontal distance that the air is projected out from the outlet face. Throw is influenced by air velocity and it can be reduced by decreasing the airflow from the outlet or using an air outlet with high induction rate. Third factor is spread. Spread is the horizontal width of the air jet being discharged by the air outlet. To reduce the drop, air patterns are spread. On the other hand, size of the fan is affected from pressure drop in a way that higher pressure drops may require oversized fan. Lastly, air terminal should be selected to meet the specified air flow HVAC system noise level for the room type and function.

Design factors that must be considered while selecting the air terminal are function, location, air volume and natural convection. It is important to identify the function of air terminal as if it is to supply air to the room or return air from the room back to the air handling system. Moreover, air terminal can be installed in the floor, ceiling or side wall. Its location can be decided in accordance with desired performance and architectural or physical constraints. The path that the air takes from the supply outlet to the return outlet has a major effect on the comfort level of the space. Supply and return outlets must be chosen to provide the best possible performance in the space while satisfying the architectural constraints of the space. Generally, it is more difficult to handle larger volumes. On the other hand, natural convection is observed with the existence of air currents created by cold walls/ windows or localized heat sources and they should also be considered when planning room air motion.

Grilles, diffusers or registers are examples of air terminal units. It is not possible to attenuate the air terminal noise by the addition of downstream device because they are open into the room. Moreover, receiver is directly affected from the noise. Diffuser noise hinges upon the air velocity through the air terminal. In addition, addition of diffusers and the increase in size of the diffuser provide a decrease on velocity; accordingly, decrease on noise. Another factor influencing the diffuser noise is upstream flow conditions. Pressure equalizing grilles at the entry to the diffuser cause turbulence; thus, this enables diffuser noise to decrease. Moreover, there are three specific solutions recommended to reduce diffuser noise in AHRI Standard 885. First one is to be checking the diffuser inlet to be sure about the dampers condition as it is not almost fully closed and there is an acceptable duct connection. Secondly, it is important to verify whether diffuser sound is self-generated or not. To check this condition, removing diffuser core is required. If the diffuser sound is self-generated, adding additional diffusers must be considered to get a lower airflow per diffuser or another diffuser fulfilling the needs must be selected. Lastly, internally lined attenuation upstream of the diffuser should be added if the noise is caused mainly from duct not the diffuser. The reason why intentionally internal lining is preferred is that exterior lining effect on noise is less than interior lining [2].

3.1.2. Sound Sources Generated Aerodynamically

Aerodynamically sound is generated by flow induced noise resulting from pressure fluctuations induced by turbulence and unsteady flows [57]. At both gradual and abrupt changes in duct area can generate aerodynamic noise. Gradual transitions and low velocities generate less turbulence than abrupt transitions and high velocities. Noise generated in transition elements such as turns, elbows, junctions, and takeoffs can run 10 to 20 dB higher than the sound power levels generated in straight duct runs [58]. Moreover, they are generally in a proximity to the receiver; therefore, they often exceed fan sound which is the major sound source of HVAC system. Since AHRI uses sound-path-process for the estimation of sound pressure level of a closed area, aerodynamically generated sound must be included in the calculation as a path at the location of the element.

As stated before, transition elements create more significant pressure fluctuations through turbulence, mixing, vortex shedding, and other means compared to straight ducts since straight flow is generated in straight ducts. To illustrate, 90° bended elbows are about 10 dB noisier than straight ducts. Reducing the noise 8 to 10 dB at high and low frequencies can be provided by one or more turning vanes while increasing the noise 3 to 4 dB in the mid frequencies [59], [34].

3.1.3. Fan Noise

Different sound sources contribute to different sound levels in octave bands. Fan noise generally produce sound in lower frequency distributions, in the 16 to 250 Hz octave bands [34] . There are several mechanisms creating the fan noise. They are air pressure and velocity fluctuations created by fan blade motion, turbulent air flow, and physical movements of fan enclosure. Two types of component can be mentioned for aerodynamic noise component of all types of fans. Moreover, there are also non-aerodynamic noise sources. Considering the aerodynamic part, rotational part includes harmonic motion of fan blade while vortex part is associated with vortex shedding of fan blade. On the other hand, brush noise, magnetic noise, belt noise and some unbalanced parts or components can be sources of non-aerodynamic noise.

Fans are classified according to type of blade and air propelling mechanisms. Axial and centrifugal fans are the basic types of fans. Axial fans are also divided into two types as vane axial and tube axial. Fixed stator blades are used in vane axial fans whereas they are not used in tube axial fans. They are to provide straight flow of air after passing through the blades [34].

3.2. SOUND ATTENUATION ELEMENTS

Sound attenuation is the reduction of the intensity of sound as it travels from the source to a receiving location. Sound absorption is often involved as, for instance, in a lined duct. Spherical spreading and scattering are other attenuation mechanisms [56]. Eight sound attenuation mechanisms are explained and included in the resultant sound pressure level prediction in AHRI. They are duct breakout transmission loss, flow division noise reduction, duct insertion loss, manufacturer's attenuation element, ceiling/space effect, duct end reflection loss, space effect and duct elbow and tee loss.

3.2.1. Duct Breakout Transmission Loss

Airborne sound is the sound energy borne and transmitted through the air. This energy can be transmitted through the duct walls, depending on the duct geometry. Transmission path is termed duct breakout. Four types of duct are mentioned in the AHRI Standard: circular sheet metal duct and flexible duct, flat oval sheet metal duct and rectangular sheet metal duct.

Transmission loss for circular sheet metal ducts depends on cross sectional and surface areas of the duct. The calculation is as follows:

$$TL_{out} - 10\log\left(\frac{A_r}{A_i}\right) = L_{wi} - L_{wo} \tag{3.1}$$

$$A_r = \pi d_o L \tag{3.2}$$

$$A_i = \pi \frac{d_i}{4} \tag{3.3}$$

$$d_i = d_o \text{ (for single-wall ducts)} \tag{3.4}$$

where

A_r: Duct Outer Surface Area), in^2 [mm^2]

A_i: Duct Internal Cross-Sectional Area, in^2 [mm^2]

d_o: Outside Diameter, in [mm]

d_i: Inside Diameter, in [mm]

L: Length, in [mm]

L_{wi}: Sound Power Level at Duct Inlet, dB

L_{wo}: Sound Power Level Breaking Out of Ductwall, dB

T_{out}: Transmission loss, dB

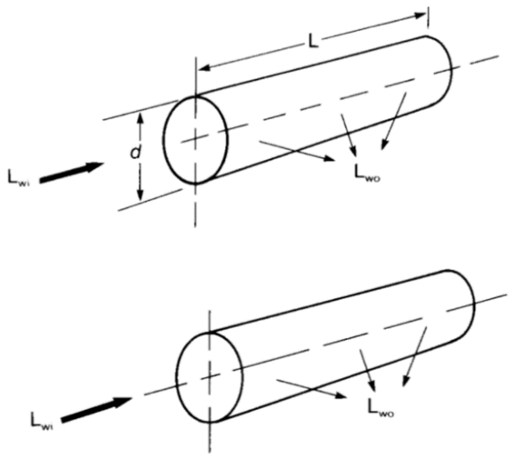


Figure 3.1. Circular Duct Breakout [2]

Table 3.1. *Duct Breakout Transmission Loss Value for Circular Metal Ducts in dB [2]*

Duct Diameter [mm]	Duct Type	Duct thickness [mm]	Duct Length [m]	Octave Band Center Frequency, Hz							
				63	125	250	500	1000	2000	4000	8000
200	long seam	0,55	4,5	45	53	55	52	44	35	34	26
350	long seam	0,7	4,5	50	60	54	36	34	31	25	38
550	long seam	0,85	4,5	47	53	37	33	33	27	25	43
800	long seam	0,85	4,5	51	46	26	26	24	22	38	43
200	spiral wound	0,55	3	48	64	75	72	56	56	46	29
350	spiral wound	0,55	3	43	53	55	33	34	35	25	40
650	spiral wound	0,7	3	45	50	26	26	25	22	36	43
650	spiral wound	1,6	3	48	53	36	32	32	28	41	36
800	spiral wound	0,85	3	43	42	28	25	26	24	40	45
350	long seam with two elbows	0,7	4,5	50	54	52	34	33	28	22	34

Considering the flexible ducts, radiated duct breakout for flexible duct is not directly proportional to length. Most breakout occurs in the first 1-2 ft [0.3 - 0.6 m] of the duct [34].Table 3.2 is given for 3m of length ducts; however, it can be used for duct length up to 3 m.

Table 3.2. *Duct Breakout Transmission Loss Value for Lined or Unlined Non-Metallic Flexible Duct in dB [2]*

Duct Diameter [mm]	Octave Band Center Frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
100	9	9	9	9	10	12	15	21
150	9	9	9	9	10	12	15	21
170	8	8	8	8	9	10	13	18
200	8	8	8	8	9	10	13	18
205	7	7	7	8	8	10	12	17
250	7	7	7	7	8	9	11	16
300	5	5	5	5	6	7	9	13
400	5	5	5	5	6	7	9	13

For flat oval duct, equations 3.1, 3.5 and 3.6 are used for the calculation of transmission loss

$$A_r = L[2(a_o - b_o) + \pi b] \quad (3.5)$$

$$A_i = b(a_i - b_i) + \pi \frac{b^2}{4}] \quad (3.6)$$

$$a_i = a_o \text{ (for single-wall ducts)} \quad (3.7)$$

$$b_i = b_o \text{ (for single-wall ducts)} \quad (3.8)$$

where

A_r: Duct Outer Surface Area in^2 [mm^2]

A_i: Duct Internal Cross Sectional Area, in^2 [mm^2]

a_i: Inner width, in [mm]

a_o: Outer width, in [mm]

b_i: Inner height, in [mm]

b_o: Outer height, in [mm]

Figure 3.2 and Table 3.3 are given for the flat oval duct transmission loss.

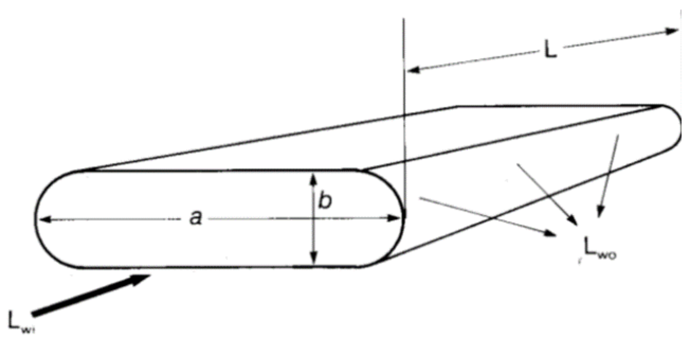


Figure 3.2. Flat Oval Duct Breakout [2]

Table 3.3. *Duct Breakout Transmission Loss Value for Flat-Oval Ducts in dB [2]*

Duct size [axb] [mm]	Thickness [mm]	Octave Band Center Frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
300x150	0,7	31	34	37	40	43	33	33	33
600x150	0,7	24	27	30	33	36	26	26	26
600x300	0,7	28	31	34	37	27	27	27	27
1200x300	0,85	23	26	29	32	22	22	22	22
1200x600	0,85	27	30	33	23	23	23	23	23
2400x600	1	22	25	28	18	18	18	18	18
2400x1200	1,3	28	31	21	21	21	21	21	21

The last duct type presented in AHRI Standard is rectangular sheet metal duct. Transmission loss is calculated with the equation 3.1 and cross-sectional areas is given below.

$$A_r = 2L(a + b) \qquad (3.8)$$

$$A_i = ab \qquad (3.9)$$

where

a: Overall width, inside any insulation, in [mm]

b: Overall height, inside any insulation, in [mm]

Figure 3.3 and Table 3.4 for rectangular sheet metal duct can be found below.

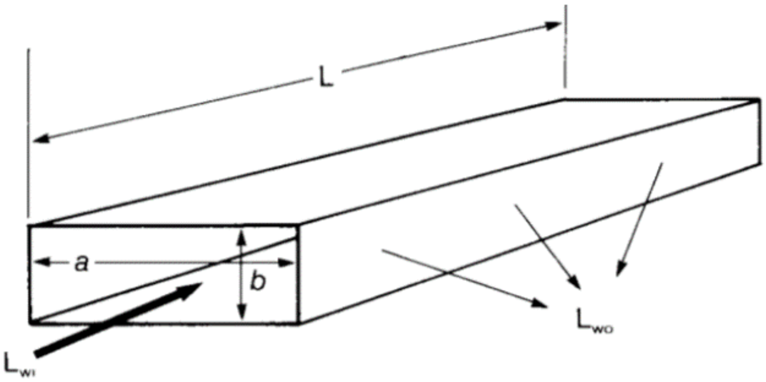


Figure 3.3. Rectangular Duct Breakout [2]

Table 3.4. *Duct Breakout Transmission Loss Value for Rectangular Ducts in dB [2]*

Duct size [axb] [mm]	Thickness [mm]	Octave Band Center Frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
300x300	0,7	21	24	27	30	33	36	41	45
300x600	0,7	19	22	25	28	31	35	41	45
300x1200	0,85	19	22	25	28	31	37	43	45
600x600	0,85	20	23	26	29	32	37	43	45
600x1200	1	20	23	26	29	31	39	45	45
1200x1200	1,3	21	24	27	30	35	41	45	45
1200x2400	1,3	19	22	25	29	35	41	45	45

3.2.2. Branch Power Division

Division of flow is observed at each junction and also acoustic energy is distributed between the branches at the branch takeoffs. This effect is reflected in the calculations as a ratio (B/T) of the branch cross-sectional areas (B) to the total cross-sectional area of all ducts leaving the takeoff (T). Thus, branch power division can be expressed by:

$$\text{Branch Power Division (dB)} = 10\log\left(\frac{B}{T}\right) \tag{3.10}$$

For the various cross-sectional areas Table 3.5 is given:

Table 3.5. *Duct Branch Sound Power Division [34]*

B/T	Division, dB	B/T	Division, dB
1	0	0.100	10
0.80	1	0.080	11
0.63	2	0.063	12
0.50	3	0.050	13
0.40	4	0.040	14
0.32	5	0.032	15
0.25	6	0.025	16
0.20	7	0.020	17
0.16	8	0.016	18
0.12	9	0.012	19

3.2.3. Duct Insertion Loss

Duct insertion loss is defined as difference between the octave band airborne Sound Power entering a duct section and the airborne Sound Power leaving the duct section. [56] It briefly refers to the noise that an equipment is removing. Three types of duct insertion loss are mentioned in AHRI Standard 885: lined circular sheet metal, lined rectangular or square sheet metal, and lined or unlined flexible duct.

Calculation for lined circular sheet metal yields:

Insertion loss=$A_s L = L_{wi} - L_{wo}$ (3.11)

where

A_s: Attenuation, dB/ft [db/m]

Table 3.6. *Insertion Loss Value for 25 mm Lined Circular Ducts in dB/m [34]*

Diameter [mm]	Octave Band Center Frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
150	0,38	0,59	0,93	1,53	2,17	2,31	2,04	1,26
200	0,32	0,54	0,89	1,5	2,19	2,17	1,83	1,18
250	0,27	0,5	0,85	1,48	2,2	2,04	1,64	1,12
300	0,23	0,46	0,81	1,45	2,18	1,91	1,48	1,05
355	0,19	0,42	0,77	1,43	2,14	1,79	1,34	1
410	0,16	0,38	0,73	1,4	2,08	1,67	1,21	0,95
460	0,13	0,35	0,69	1,37	2,01	1,56	1,1	0,9
510	0,11	0,31	0,65	1,34	1,92	1,45	1	0,87
560	0,08	0,28	0,61	1,31	1,82	1,34	0,92	0,83
610	0,07	0,25	0,57	1,28	1,71	1,24	0,85	0,8

Table 3.7. *Insertion Loss Value for 51 mm Lined Circular Ducts in dB/m [34]*

Diameter [mm]	Octave Band Mid frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
150	0,56	0,8	1,37	2,25	2,17	2,31	2,04	1,26
200	0,51	0,75	0,33	2,23	2,19	2,17	1,83	1,18
250	0,46	0,71	0,29	2,2	2,2	2,04	1,64	1,12
300	0,42	0,67	1,25	2,18	2,18	1,91	1,48	1,05
355	0,38	0,63	1,21	2,15	2,14	1,79	1,34	1
410	0,35	0,59	1,17	2,12	2,08	1,67	1,21	0,95
460	0,32	0,56	1,13	2,1	2,01	1,56	1,1	0,9
510	0,29	0,52	1,09	2,07	1,92	1,45	1	0,87
560	0,27	0,49	1,05	2,03	1,82	1,34	0,92	0,83
610	0,25	0,46	1,01	2	1,71	1,24	0,85	0,8
660	0,24	0,43	0,97	1,96	1,59	1,14	0,79	0,77
710	0,22	0,4	0,93	1,93	1,46	1,04	0,74	0,74
760	0,21	0,37	0,9	1,88	1,33	0,95	0,69	0,71
820	0,2	0,34	0,86	1,84	1,2	0,87	0,66	0,69
865	0,19	0,32	0,82	1,79	1,07	0,79	0,63	0,66
910	0,18	0,29	0,79	1,74	0,93	0,71	0,6	0,64
965	0,17	0,27	0,76	1,69	0,8	0,64	0,58	0,61
1020	0,16	0,24	0,73	1,63	0,68	0,57	0,55	0,58
1070	0,15	0,22	0,7	1,57	0,56	0,5	0,53	0,55
1120	0,13	0,2	0,67	1,5	0,45	0,44	0,51	0,52
1170	0,12	0,17	0,64	1,43	0,35	0,39	0,48	0,48
1220	0,11	0,15	0,62	1,36	0,26	0,34	0,45	0,44
1270	0,09	0,12	0,6	1,28	0,19	0,29	0,41	0,4
1320	0,07	0,1	0,58	1,19	0,13	0,25	0,37	0,34
1370	0,05	0,08	0,56	1,1	0,09	0,22	0,31	0,29
1420	0,02	0,05	0,55	1	0,08	0,18	0,25	0,22
1470	0	0,03	0,53	0,9	0,08	0,16	0,18	0,15
1520	0	0	0,53	0,79	0,1	0,14	0,09	0,07

Because of flanking paths, the duct attenuation in both round and rectangular ducts is limited to 40 dB. As with rectangular ducts, the unlined attenuation may be added to the lined attenuation. For circular ducts it is such a small contribution that it is usually ignored [34].

3.2.4. Manufacturer's Attenuation Element

Manufacturer's data includes lined boots, attenuators, or other silencing equipment added to the acoustic model. Location of a silencer is an important factor to benefit from the equipment. It is possible to confront with high velocities at the entrance of an air terminal with the attachment of a silencer directly to the discharge of the device. High air velocities results in high self-generated sound levels; thus, reduces effectiveness of a silencer. This fact may be observed in a partially closed air terminal damper, or a discharge mounted fan. A Silencer should be located at least three equivalent diameters downstream of the air terminal to avoid this condition.

3.2.5. Ceiling/Space Effect

A transfer function provided for the sound sources in the space is used for calculation of sound sources located in the ceiling cavity. Transfer function takes account of the effect of the absorption of the ceiling tile, plenum absorption and room absorption. This procedure is based on research conducted under ASHRAE Research Project RP-755. Project RP-755 focused on the interactions between terminal units (positioned above and close to a lay-in ceiling), the ceiling panels, the plenum and the room below [60].

Following conditions are considered for this procedure:

- The plenum is assumed to have 0.9 m deep at least.
- The plenum space is assumed to be lined or wide (over 9 m)
- The ceiling is assumed not to have considerable penetrations directly under the unit.

Below table including calculation of the total transfer function for three different sized Air Terminals is provided below in Table 3.8.

Table 3.8. *Attenuation Value for Uncorrected Ceiling/Space Effect in dB [34]*

Tile Type	Density [kg/m^3)	Thickness [mm]	Weight [kg/m^2]	Octave Band Center Frequency, Hz							
				63	125	250	500	1000	2000	4000	8000
Mineral Fiber	300	16	5	13	16	18	20	26	31	36	no data
Mineral Fiber	160	16	2,5	13	15	17	19	25	30	33	no data
Glass Fiber	40	16	0,7	13	16	15	17	17	18	19	no data
Glass Fiber	60	50	3	14	17	18	21	25	29	35	no data
Glass Fiber, TL Backed	60	50	3	14	17	18	22	27	32	39	no data
Gypsum Board Tiles	690	13	9	14	16	18	18	21	22	22	no data
Solid Gypsum Board	690	13	9	18	21	25	25	27	27	28	no data
Solid Gypsum Board	690	16	11	20	23	27	27	29	29	30	no data
Double Gypsum Board	700	25	18	24	27	31	31	33	33	34	no data
Double Gypsum Board	690	32	22	26	29	33	33	35	35	36	no data
Conceled Spline	300	16	5	20	23	21	24	29	33	34	no data

Table 3.9 is only valid for array of four diffusers having the same sound power level. It cannot be used for linear diffusers placed through a row. Data for four dissimilar room heights and three different outlet areas is presented in the table.

Table 3.9. *Sound Attenuation for an Outlet Array (4 Outlets) in dB [2]*

Area/Diffuser [m^2]	Ceiling Height [m]	Octave Band Mid Frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
20	2	1	2	3	4	5	6	7	8
30	2	2	3	4	5	6	7	8	9
40	2	3	4	5	6	7	7	8	9
20	3	2	3	4	5	6	7	8	9
30	3	3	4	5	6	7	8	9	10
40	3	4	5	6	7	8	8	9	10
20	3	3	4	5	6	7	8	9	10
30	3	4	5	6	7	8	9	10	10
40	3	5	6	7	7	8	9	10	11
20	3,6	5	6	6	7	8	9	10	11
30	3,6	6	6	7	8	9	10	11	12
40	3,6	6	7	8	9	10	11	12	12

3.2.6. Duct End Reflection Loss

End reflection loss is the reason of returning of considerable low frequency energy back into the attached ductwork resulted from sudden area change at the exit of an integral terminal unit or outlet. For instance, if HVAC design is arranged in a way that plane waves sound passing through a duct which is a small space flow into the room directly, a certain amount of sound is reflected into the duct. This fact is significantly decreasing low frequency sound. However, if a diffuser is located at the end of the ducting, end reflection loss is not seen. Because impedance transition between the duct and the room is smoothed due to diffuser. It is the difference between the octave band sound power incident on a duct end and the sound power transmitted out of the end of a duct [56].

Table 3.10, which is conducted under ASRAE Research Project RP-1314, Reflection of Airborne Noise at Duct Terminations is presented for the end reflection loss (ERL). ERL is a calculation added to the sound data obtained in a test chamber. ERL is a function of the size of the termination compared with the acoustical wavelength and the specific location of the duct termination within the room [61]. The formulation for this attenuation type is as follows:

$$ERL = 10\log(1 + \left(a_1 \frac{c_o}{\pi} f \frac{D}{12}\right)^{a_2}) \quad (3.12)$$

$$c_o = 1127 \quad (3.13)$$

$$a_1 = 0.7 \quad (3.14)$$

$$a_2 = 0.7 \quad (3.15)$$

where

c_o: speed of sound

a_1: flush-terminal duct, pink noise, full octave

a_2: flush-terminal duct, pink noise, full octave, rounded D in inches

f: octave band center frequency in Hz

Table 3.10. *End Reflection Loss/Per ASHRAE RP 1314 in dB [2]*

Diameter [mm]	Octave Band Mid frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
150	18	12	7	3	1	0	0	0
200	16	10	5	2	1	0	0	0
250	14	8	4	1	0	0	0	0
300	12	7	3	1	0	0	0	0
400	10	5	2	1	0	0	0	0
500	8	4	1	0	0	0	0	0
600	7	3	1	0	0	0	0	0
700	6	2	1	0	0	0	0	0
800	5	2	1	0	0	0	0	0
900	4	2	0	0	0	0	0	0
1200	3	1	0	0	0	0	0	0
1800	2	0	0	0	0	0	0	0

3.2.7. Space Effect

For spaces with no ceiling, sound source is a taken as a point source. Attenuation of radiated sound should be calculated using the below equation for It is crucial to consider the total space volume including the region where the source is located. The calculation of the Sound Pressure Level in rooms for the entering sound power can be accomplished using the Schultz equation [2]:

$$L_p = L_w - 10logr - 5logV - 3logf + 25 \tag{3.16}$$

where

r: Shortest distance from noise source to the receiver, m

V: Room volume, m^3

Table 3.11 is valid for a single sound source in the room. Calculation of sound levels of rooms with diffuser as a sound source takes in space effect. It is also valid for computing the sound traveling from an Air Terminal through the supply ductwork and entering the room through the diffuser.

Table 3.11. *Space Effect, Single Sound Source in dB [34]*

Room Volume [m^3]	Distance [m]	Octave Band Center Frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
60	1,5	4	5	6	7	7	8	9	10
60	3	7	8	9	10	11	11	12	13
60	4,6	9	10	10	11	12	13	14	15
69	1,5	4	5	6	7	8	9	10	11
69	3	7	8	9	10	11	12	13	14
69	4,6	9	10	10	12	13	14	14	15
80	1,5	5	6	7	7	8	9	10	11
80	3	8	9	10	10	11	12	13	14
80	4,6	10	10	11	12	13	14	15	16
100	1,5	6	7	8	9	9	10	11	12
100	3	9	10	11	12	12	13	14	15
100	4,6	11	12	12	13	14	15	16	17

The term $(L_p - L_w)$ can be considered as the effect of the space upon the entering sound power producing the resulting sound pressure level. Thus,

$$\text{Space effect}=(L_p - L_w) \tag{3.17}$$

$$S_A = (L_p - L_w) \tag{3.18}$$

$$S_A = 5logx + 28logh - 1.13logN + 3logf - 31 \tag{3.19}$$

where

S_A: Distributed Ceiling Array Space Effect
h: Ceiling height, m
N: Number of evenly spaced outlets in the room, minimum four
x: Ratio of the floor area served by each outlet to the square of the ceiling height, m

3.2.8. Duct Elbow and Tee Loss

Four types of elbow and tee loss are mentioned: round lined duct with 90 degrees elbow, round unlined duct with 90 degrees elbow, rectangular square elbows either mitered or without turning vanes (lined/unlined) and rectangular tee loss. For the round lined ducts, an empirical data exists, and it can be seen on Table 3.12.

Table 3.12. *Insertion Loss of Lined Round Elbows in dB [2]*

Diameter [mm]	Octave Band Center Frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
125 to 250	0	0	0	1	2	3	3	3
260 to 510	0	1	2	2	3	3	3	3
520 to 1020	0	2	2	3	3	3	3	3
1030 to 2030	1	2	3	3	3	3	3	3

For unlined round duct, Table 3.13 is given in the AHRI Standard.

Table 3.13. *Insertion Loss of Unlined Round Elbows in dB [2]*

Diameter [mm]	Octave Band Center Frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
100-250	0	0	0	1	2	3	3	3
260-700	0	1	2	2	3	3	3	3
710-1000	0	2	2	3	3	3	3	3
1010-2000	1	2	3	3	3	3	3	3

An approximate data is used for the Table 3.14 for lined or unlined rectangular square elbows mitered or without turning vanes.

Table 3.14. *Insertion Loss of Unlined and Lined Elbows in dB [2]*

	Insertion Loss of Unlined and Lined Elbows without Turning Vaned, dB								
	Width [mm]	Insertion Loss, dB-Octave Band Mid frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
Unlined	100-250	0	0	0	1	5	8	4	3
	260-700	0	1	5	5	8	4	3	3
	710-1000	0	5	5	8	4	3	3	3
	1010-2000	1	5	8	4	3	3	3	3
Lined	100-250	0	0	0	1	6	11	10	10
	260-700	0	1	6	6	11	10	10	10
	710-1000	0	6	6	11	10	10	10	10
	1010-2000	1	6	11	10	10	10	10	10
	Insertion Loss of Unlined and Lined Elbows with Turning Vaned, dB								
Unlined	100-250	0	0	0	1	4	6	4	4
	260-700	0	1	4	6	4	4	4	4
	710-1000	0	4	6	6	4	4	4	4
	1010-2000	1	4	6	6	4	4	4	4
Lined	100-250	0	0	0	1	4	7	7	7
	260-700	0	1	4	7	7	7	7	7
	710-1000	0	4	7	7	7	7	7	7
	1010-2000	1	4	7	7	7	7	7	7

3.2.9. Plenum Attenuation

Plenums are the attenuation elements reducing the mechanical noise by smoothing the turbulent air flow. They are generally located between fan and the ducting system. They are typically large rectangular enclosed spaces with an inlet and outlet. Frequency range, in-line inlet and outlet openings; and, in-line versus elbow configuration are the conditions affecting the plenum attenuation. Cutoff frequency is the frequency above which plane wave propagation in a duct is not possible[34]. Formulation for the cutoff frequency is as follows:

$$f_{co} = \frac{c}{2a} \text{ or} \tag{3.20}$$

$$f_{co} = 0.586\frac{c}{d} \tag{3.21}$$

where

f_{co}: cutoff frequency, Hz
c: speed of sound in air, m/s
a: larger cross-sectional dimension of rectangular duct, m
d: diameter of round duct, m

Transmission loss for the frequency ranges above cutoff frequency is given in 3.22 Cross or spinning modes of wave are observed in the duct at these higher frequencies.

$$TL = b[\frac{S_{out}Q}{4\pi r^2} + \frac{S_{out}(1-\alpha_a)}{S\alpha_a}]^n + OAE \tag{3.22}$$

$$b = 3.505 \tag{3.23}$$

$$n = -0.359 \tag{3.24}$$

$$\alpha_a = \frac{S_1\alpha_1 + S_2\alpha_2}{S_1 + S_2} \tag{3.25}$$

where

TL: Transmission loss, dB

S_{out}: Plenum outlet area, m^2

S: Total plenum inside surface area minus plenum inlet and outlet areas, m^2

r: Distance between plenum's inlet and outlet centers, m

Q: Directivity factor, taken as 2 for opening near center of wall, or 4 for opening near corner of plenum

α_a: Average absorption coefficient of plenum lining

OAE : Offset angle effect

α_1: Sound absorption coefficient of plenum's unlined inside surface area, m^2

S_1 : Plenum's unlined inside surface area, m^2

α_2: Sound absorption coefficient of plenum's acoustically lined inside surface area, m^2

S_2 : Plenum's acoustically lined inside surface area, m^2

Transmission loss of frequencies below than cutoff frequency is calculated by 3.26. It is noted that the maximum predicted transmission loss by equation 3.26 should be limited to 20 dB [34].

$$TL = 10.76 A_f S + W_e + OAE \qquad (3.26)$$

where

A_f: Surface area coefficient, dB/m^2

W_e: Wall effect, dB

Tables for commonly used types wall types, offset angle, sound absorption coefficients of general types of plenum materials are given in ASHRAE Handbook [34]. These tables are included in AHRI SPL Predictor for the calculation of plenum attenuation effect.

CHAPTER 4

METHODOLOGY

4.1. AHRI STANDARD 885 [2]

AHRI Standard was developed by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) to obtain a uniform industry procedure for predicting sound pressure levels in occupied spaces served by air terminals and/or outlets. It is beneficial to have such a standard for designers, engineers, consultants, building owners and other users to meet acoustic goals. This standard includes acoustical models and data of American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and recognized industry sources.

Source-Path-Receiver process is used in the AHRI Standard. Below table taken in AHRI Standard 885 shows this process: "A given *Source* travels over a given *Path* to an occupied space where a *Receiver* hears the sound produced by the *Source*." Symbolic representation is used in this standard as it can be seen from the Figure 4.1.

Source – Path – Receiver Process			
Process	Source →	Path →	Receiver
Description	Air Terminals and outlets are examples of *sound Sources*.	The sound travels over one or more *Paths* where attenuation takes place.	A person in the occupied spaces who hears the sound at the receiver location.
Symbols Used in this Standard	C A circle denotes a sound Source. The letter defines which Source.	P A triangle denotes an attenuation on the sound path. The letter defines the type of attenuation	1 A square denotes a sound Receiver. The number defines the sound path being considered.
Nature of Data	Octave band Sound Power Level	Octave band Path Attenuation	Octave band Sound Pressure Level
	(L_w) of Source in decibels (dB).	Sound reduction due to ducting, ceiling tile, etc.	(L_p) at receiver location. Often evaluated as Noise Criteria (NC) or Room Criteria (RC).
Sources of Data	Manufacturer's data tested in accordance with: • Air Terminals ASHRAE 130 • Air outlets ASHRAE 70	AHRI Standard 885, Appendix D.	Calculated by procedures in AHRI Standard 885.

Figure 4.1. Source-Path-Receiver Process of AHRI Standard 885 [2]

To estimate sound pressure levels by octave band, basically four steps are defined. First, sound source is obtained by referring air terminal or outlet sound power levels at specific unit operating points defined in manufacturer's data. Secondly, sound paths are evaluated by making use of acoustic model of the design. Thirdly, attenuation path factors for each path are determined from the tables and/or formulas in the appendix part of the standard. Last, overall sound pressure level is calculated by logarithmical addition of the acoustic contribution from each sound path of the design. For the first step, sound power levels specified in each octave band or band power levels presented in manufacturer's data are used. Each sound power value is written in associated octave band. Similarly, all other sound attenuation calculations are performed for associated octave band and logarithmic additions are done for each octave band. At the end, overall sound pressure levels calculated for each octave band values are obtained.

Three types of sound source is mentioned: casing radiated and induction inlet sound power, sound transmitted through the casing or through the induction port of an air terminal to the surrounding space, typically, a ceiling plenum; discharge sound power, airborne sound power transmitted through the ductwork from the outlet of an air terminal device; and outlet generated sound power, sound power generated by and transmitted from an air outlet into the surrounding space, typically the occupied space. They are calculated by subtracting environmental factor from the manufacturer's sound power data. This subtraction is to adjust manufacturer's data as in the real case since at low frequencies, real rooms are highly reverberant, and source radiates less low frequency noise.

There are eight sound paths defined in the standard. They are duct breakout transmission loss, lined or unlined; flow division noise reduction; duct insertion loss; manufacturer's attenuation element; ceiling/space effect; duct end reflection loss; space effect; and, duct elbow and tee loss. Sound attenuation values for these sound paths are given in the Standard in octave bands but for some specific designs, sizes or materials. It only includes the design in ASHRAE; however, for some octave band values, recognized industry sources are used. Sound path attenuation values for each path are available in the appendix part of AHRI Standard 885. For duct breakout transmission loss, there exist four types of design tables: circular sheet metal duct, non-metallic flexible duct & lined and unlined, flat oval ducts and rectangular ducts. Sound attenuation values are given for different specific size or type of ducts. Similarly, duct insertion loss of lined circular ducts, straight lined sheet metal ducts for rectangular and lined flexible ducts; round and rectangular duct elbow and tee loss; end reflection factor; ceiling; and space effect are presented for different duct design.

After calculation of sound attenuation for each path; in other words, including sound attenuation elements' contributions to each sound source, resultant sound pressure level at the receiver calculated along each path is obtained. By logarithmically adding these resultant sound pressure levels, resultant logarithmic sum of sound pressure levels at the receiver from all sound paths for a specific octave band can be calculated. NC or RC ratings could be used for convenience of calculated results with associated closed area.

AHRI Standard 885 for the estimation of occupied space sound levels in healthcare buildings in the application of air terminals and air outlets is one of the effective methods. Rumble due to mainly HVAC systems causes annoyance on people because of low frequency content. Since AHRI includes data available in the 63 Hz octave band, sound pressure levels of HVAC systems at low frequencies can be predicted.

4.2. VISUAL BASIC FOR APPLICATION

VBA (Visual Basic for Applications) is simply a programming language of Excel and other Office programs. The VBA programming is also defined as a built-in resource for Microsoft Office software that includes added codes performing specific procedures not originally built into the Excel software. Therefore, VBA remote control makes Excel more suitable. It is possible to have a user-friendly interface with VBA programming. Moreover, automation of tasks in Excel, writing macros, which is a computer program that gives automated instructions to the computer, is achievable [62].

Entering or inputting data is feasible with the application of Excel VBA Userform. Userform can be created by using the VBA toolbox. Toolbox has fifteen options: Label, TextBox, ComboBox, ListBox, CheckBox, OptionButton, ToggleButton, Frame, CommandButton, TabStrip, MultiPage, ScrollBar, SpinButton, Image, RefEdit. According to the users need, assigning a macro to any of the toolbox features enables a programmer to have an interactive and sophisticated user form. For example, by assigning a macro to a CommandButton, user only needs to click the design button to initiate automated task. In a study of Sipos et al, VBA was used to automate data capture and analysis for behavioral data management. It is stated in the study that using VBA program code for repetitive operations has resulted in a tremendous savings in both the time and manpower required to reliably capture, analyze and plot data from research protocols at the United States Army Medical Research Institute of Chemical Defense (USARMRICD). Another advantage reached in the study with the implementation of VBA is that fewer errors while entering data and increase productivity is observed with the usages of VBA macros for repetitive data manipulations [63]. VBA is also used in the article of Rossato [64] which is about data entry system for dietary surveys. Like the Sipos's study, repetitive data entry management is accomplished. In addition to that, to force users to interact with different forms and arrangements and to record and format the data in the data bank, VBA programming is used.

The reason why Microsoft Excel VBA is preferred for this thesis is that it has a simple language; therefore, VBA programming is much easier than programming with other programs. Another benefit of using VBA for programming is that there are many resources such as internet, books, and online learning sources to learn the VBA program. Since it is planned for this project to have a user-friendly interface which user can enter the HVAC design data and then understand if design is within the limits, NC or RC ratings, VBA program is found to be an effective method.

4.3. SOUND PRESSURE LEVEL ESTIMATION SOFTWARE BY AHRI STANDARD 885 ON EXCEL

4.3.1. Introduction to Software

This software is developed to estimate occupied space sound pressure level in the application of air terminals and air outlets. Procedures mentioned in AHRI Standard 885 are the basis of the software. The programming language is EXCEL Visual Basics for Application.

AHRI standard includes sound levels of some specific components of air distribution system. Air Terminals, air outlets and the low-pressure ductwork which connects them are considered as sound sources. It does not take into consideration of sound level contributions from the central system fan, ductwork upstream of the Air Terminal, equipment room machinery or exterior ambient sound.

It is assumed that all HVAC system equipment and components are installed properly; that is, there is not leakage in the ducting system. Moreover, metric system is used in the program. Therefore, user must select the appropriate metric system value for each HVAC design element. Accordingly, user must also be an expert on the acoustic design to correctly enter and choose the values.

AHRI uses source-path-receiver procedure for the prediction of sound pressure level. Sound source or sources are selected, and manufacturer's sound power data is entered by the user. As it is mentioned before, user select the true data reflecting the HVAC design for the calculation.

A user-friendly interface is designed for the ease of handling. User can get the result without difficulty by just entering and selecting the accurate values. Since this software is designed for the estimation of hospital sound levels, software provides user the information of design's validity; that is, if the design is within the specified limits or not. Therefore, the user is able to take actions about the legitimacy of the design with little effort.

Since estimation method based only on AHRI Standard 885, software is named as "AHRI SPL Predictor".

4.3.2. General View of The Software

The user encounters an informative form given below right after opening the AHRI SPL Predictor EXCEL document. It is designed to inform the user about the software. It includes the information on the purpose of the software and a crucial note stating that this software only evaluates healthcare buildings' HVAC design.

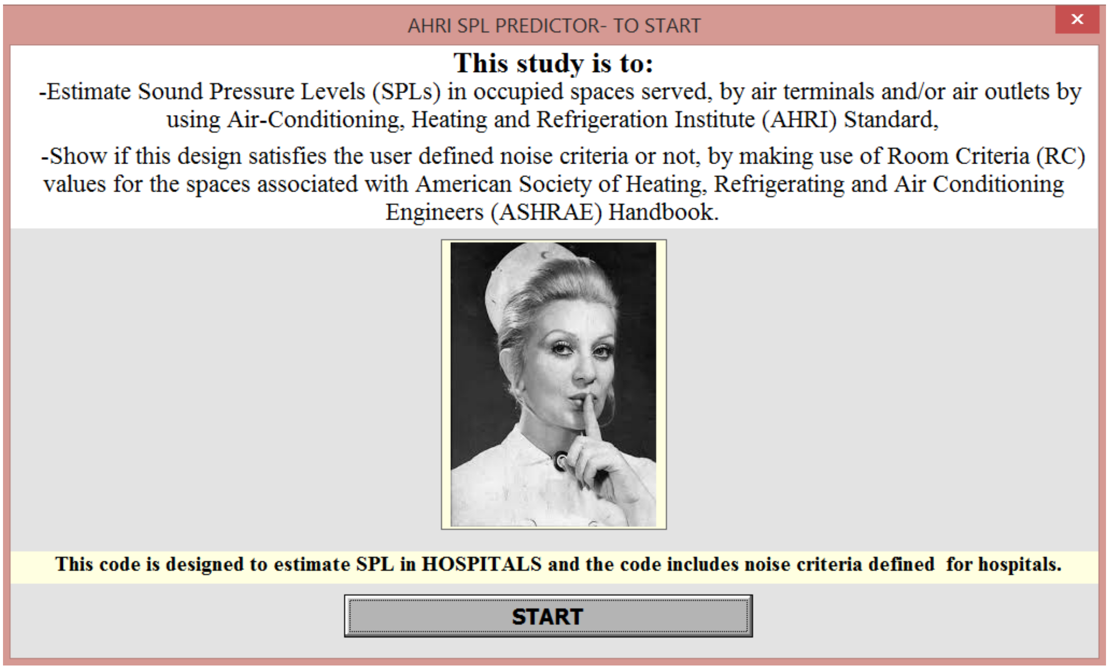


Figure 4.2. AHRI SPL Predictor informative user form

There exist only two clicking options for the user. The first one is closing button positioned right corner of the form and enables user to close the form. Second one is the start button which allows starting of the sound pressure level estimation procedure and opening the other user form.

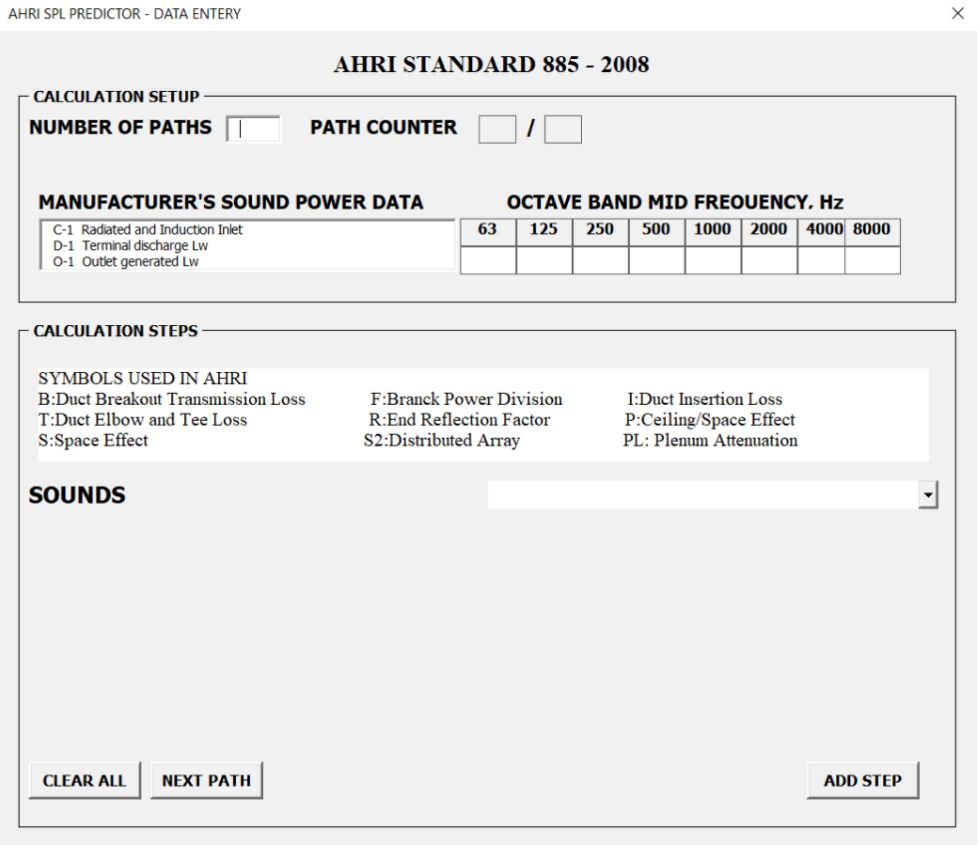


Figure 4.3. AHRI SPL Predictor main user form including data entering

After clicking the "START" button another user form, which is the main user form, comes up. It can be seen in figure. User must enter the number of paths principally. After that, manufacturer's source sound power must be selected and corresponding decibel values at associated in octave bands must be entered for the first path. By this process, user finishes the source part of "Source-Path-Receiver" process of AHRI Standard for the first path. Then, the path process must be finished. It is done by selecting the appropriate attenuation type and corresponding data defined in "CALCULATION STEPS" part of the form. After finishing selection, if there is another attenuation element by clicking "ADD STEP" button all selections will be cleared for the next selection. User must do this process until the last attenuation element along the duct length. Then, if there is more than one path user must click

“NEXT PATH” button and then similar sound power data selection and attenuation element selection process must be completed for all paths. On the other hand, there is a button for the false selections to restart the estimation process again. That is “CLEAR ALL” button.

If user selects “PL” as a path attenuation element which is available in the combo box of “SOUNDS”, another user form displayed in Figure 4.4 comes up. It is necessary to fill or select dimensional or material information of plenum used in the HVAC system design. After finishing all the filling and selecting process “DONE” button must be clicked. Then, plenum attenuation form is closed, and user is directed to main user form.

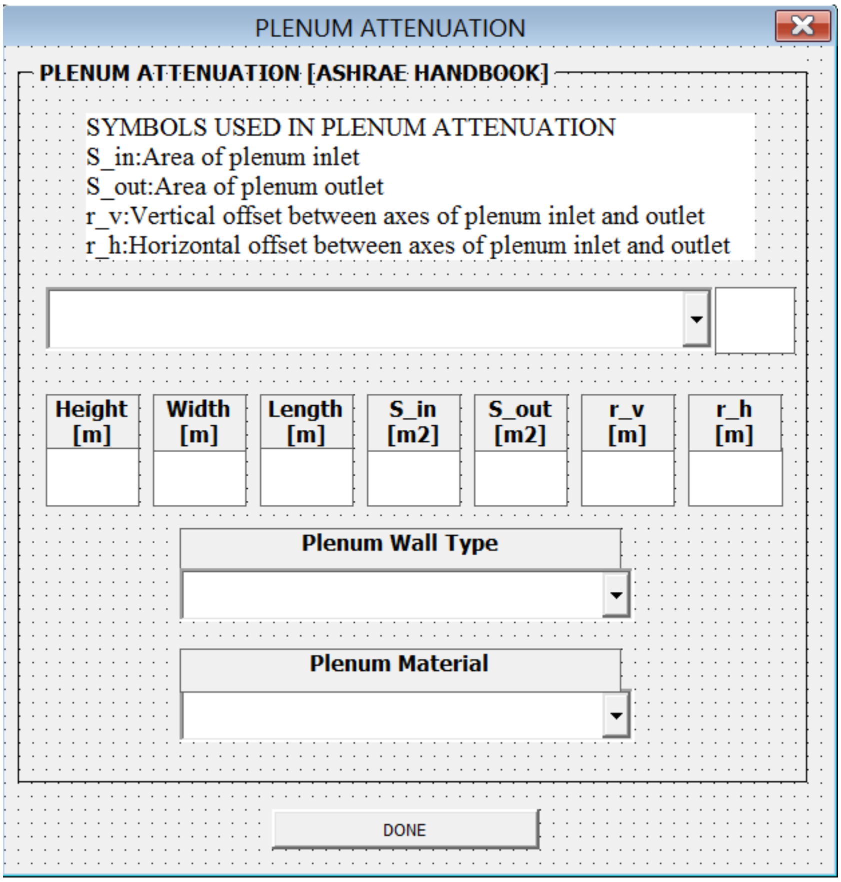


Figure 4.4. AHRI SPL Predictor plenum attenuation user form

According to user defined path number, user sees the “FINISH” button instead of “NEXT PATH” button. Upon completion of entering all acoustic design parameters/variables user must click on this button. Afterwards, another form which can be seen in Figure 4.5 opens. This is the form showing total estimated sound pressure levels at a receiver location. In addition, the user must enter as an input of select type of space where HVAC design is to be installed or located. With this selection, the user will be able to learn if the acoustic design is within the limits or not from the note at the end of the form. Allowable sound pressure levels for the selected space are also presented in a tabulated form. It includes Room Criteria (RC) values for the spaces associated with hospitals defined in ASHRAE Handbook [34]. For private rooms and operating rooms, specified sound criteria values range between RC 25 to RC 35, while wards, corridors and public areas are rated between RC 30 to RC 40 is noted. Considering the note appears for the assignment of total predicted sound pressure levels according the RC criteria defined for the selected space, it appears in the orange-colored area in the form after selection of the space. User can also observe the allowable sound levels for the corresponding space. Moreover, the user can also see the evaluation results with respect to Noise Rating (NR) curves. For private rooms and operating rooms, sound levels should not exceed NR 30 level. On the other hand, NR 35 levels are defined as maximum allowable levels for corridors and public areas [65].

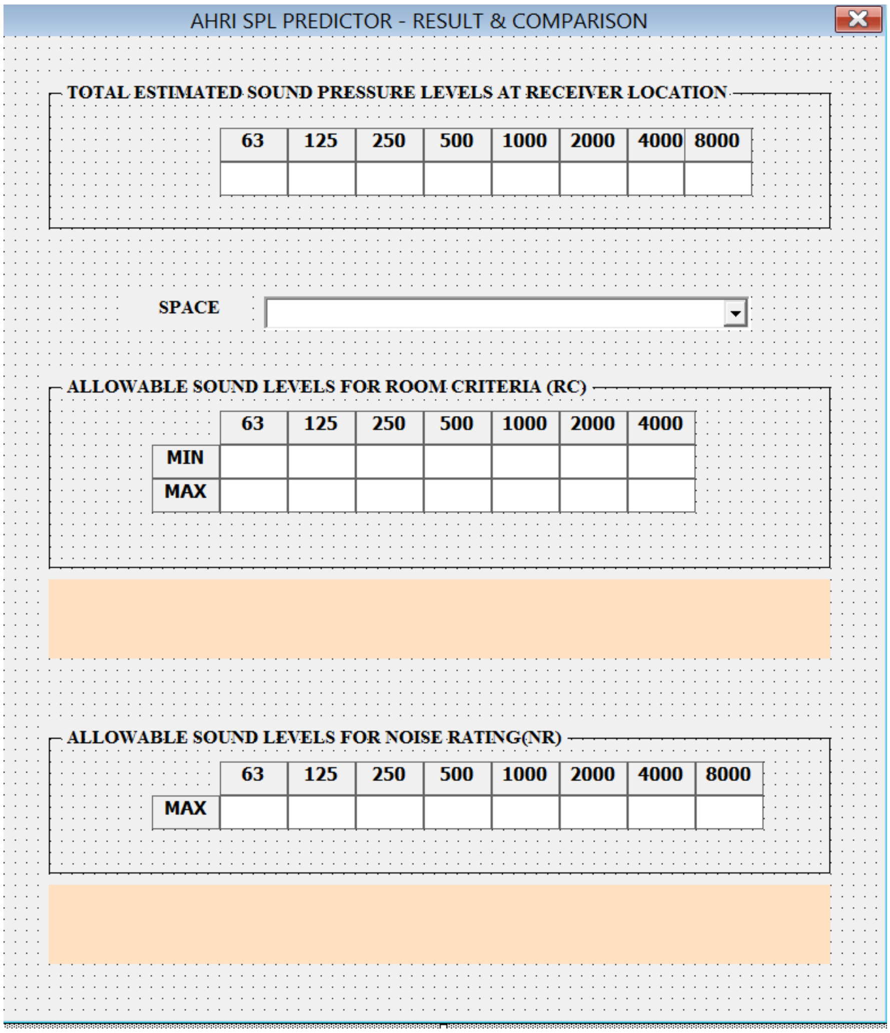


Figure 4.5. AHRI SPL Predictor user form presenting total SPL level and entered HVAC design evaluation note according to selected space

4.3.3. General Workflow of The Software

AHRI SPL Predictor EXCEL document has six sheets which are "DATABASE", "CONSTANT", "VALUE", "RESULT", "ALLOWED RANGE" and "PLENUM". Moreover, it contains three user forms as shown in part 4.3.2. Considering the "DATABASE" sheet, first twenty-three columns includes data of

HVAC design elements and the following eight columns contain sound attenuation values in dB for each octave band from 63 Hz to 8000 Hz.

For the first user form, there exist only two codes. One of them functions to open the informative user form right after opening the AHRI SPL Predictor EXCEL document. The other one serves to open the main user form when the user clicks the start button and at the same time hides the informative user form.

In the main user form, there are two frames: calculation setup and calculation steps. The specified path number in the calculation setup is assigned to second path counter label. The first path counter label is assigned by default to "1" initially, but it is required to increase the path counter whenever the user finishes the associated path selection; that is, whenever the user clicks "NEXT PATH" button. The code executed for the "NEXT STEP" button is referred to specified requirement. "VALUE" sheet is used to store values of variables. List box tool is used for the selection of the manufacturer's sound power data. Three types of source power data are defined in associated list box initializing code. The path number entering is necessary to select the sound power data type. Otherwise, a warning message of "Please Enter Path Number!" appears. Similarly, it is not possible to enter sound power data to the associated octave band before selecting sound power data type. Another warning messages of "First Select the Sound Value" shows up for these this case. If statements with the condition depending upon path number value or sound power data value defining is used for that purpose. Entered sound power data values are stored in "VALUE" sheet for the future calculations. Upon completion of entering path number and sound power data; in other words, fulfilling the calculation setup part of main user form, sound attenuation element and corresponding design data selection is required. Selection option of sound attenuation element is available for the first combo box since attenuation elements defined in letters listed in the user form is attained to combo box initializing procedure. With the selection of first combo box value, first column including sound attenuation values in "DATABASE" sheet is filtered according to the selected data. "CONSTANT" sheet is used for storing all combo box selections including labels of these selections. At the end, first row of "CONSTANT" sheet includes filtered HVAC design data. Moreover, associated dimensions or types are listed below the corresponding HVAC design data. Considering in detail, a conditional statement is defined for each sound attenuation element and also for the next HVAC element selection. First, sound attenuation element is filtered from "DATABASE" sheet and stored in the "CONSTANT" sheet. Then, a conditional statement decides the next filtering element. According to the selected sound attenuation element, the next filtering column is selected and all visible cells in that column are copied. After that, these values are pasted to the defined column in "CONSTANT" sheet. In addition to that, label for second combo box, which is below the "SOUNDS" label, is also present in that conditional statement. These conditional statements are written for each sound attenuation element and attained to first combo box. Another conditional statement controls second combo box which consists of required data, such as dimensions or types. Necessary dimensions are taken from the "CONSTANT" sheet since they are written in the "CONSTANT" sheet in the first conditional statement. Similar structure is defined for other combo boxes. After completion of combo box selection, sound attenuation value of HVAC design element in each octave band is filtered onto "DATABASE" sheet. "ADD STEP" button is created to include this sound attenuation value into the estimation by storing these values onto the "VALUE" sheet. As stated before, sound power data is also stored onto that sheet. Additionally, environmental adjustment factor for each octave band is also written in the space below associated sound power level data in the sheet. After the row of environmental effects, attenuation values belonging to the first sound attenuation elements in each octave band are presented. Therefore, "VALUE" sheet contains ordered "DATABASE" sheet filtered sound attenuation values of a path starting with sound power data and including environmental effect. Considering the "NEXT STEP" button; coding for increasing the number provided for path counting, get the "VALUE" sheet to be ready for the next path by clearing all the values in it and writing current path result onto the "RESULT" sheet are embedded in this button. In addition, a conditional statement to check whether the last path is in view or not exists to change the label of “NEXT PATH” to “FINISH”. Whenever user selects “PL” as a sound source, another user form to calculate the plenum attenuation appears. According to the user defined values or selections, associated values written in the “PLENUM” sheet is used in the formula classified for plenum attenuation. Clicking “DONE” button enables to hide the plenum attenuation calculation form and also write calculated plenum attenuation values for each octave band to the “VALUE” sheet as it is performed for all sound path attenuations. Clicking “FINISH” button calls some functions which account for logarithmically adding each path resultant sound pressure levels to each other for octave bands and presenting the total sound pressure level in the next user form in related text box. The remaining button is “CLEAR ALL”. As it can be understood from the name, it clears all labels, combo boxes and removes filters; in short, it resets the main user form.

The last user form has only one user-defined part and it is a combo box. According to selected combo box value, allowable sound levels for room criteria and noise rating tables are filled with the numbers existing in “ALLOWED_RANGES” sheet. Moreover, with the change of combo box selections, a conditional statement compares the total estimated sound pressure level with the allowable sound level for each octave band and a message comes up according to this statement.

4.3.4. Application of Software

For the simplicity and convenience of use, one main form displaced in Figure 4.3 exists for the clarification of all sources and path elements.

First, number of paths must be defined. User must enter the value into the empty box near the "NUMBER OF PATHS" text. Secondly, user must have sound sources' data to fill manufacturer's sound power level section. At the beginning, type of sound source of the path must be selected, then sound power values taken from manufacturer for each frequency band must be entered the empty boxes positioned for each center frequency. Next, each sound attenuation element from the sound source to the receiver must be entered to the main user form respectively.

There are many symbols used in AHRI and accordingly in the AHRI SPL Predictor program. They are stated in the beginning of "Calculation Step" part and, user confronts with these symbols while selecting the sound path element whose selection box is positioned next to "SOUNDS" text. By choosing the suitable sound path new selection box appears. Considering each sound path separately, duct breakout transmission loss shown as "B" notation needs duct type information after the selection of this sound path. There exist four options for this part: circular sheet metal duct, non-metallic flexible duct, flat oval duct and rectangular duct. Each of these types requires different data such as duct material type, duct size, duct thickness, duct length and duct diameter. For circular sheet metal ducts, duct material type, duct diameter, duct thickness and duct length information are needed. For non-metallic flexible duct, only diameter information is required to get the sound attenuation value for each frequency. On the other hand, duct size and duct thickness must be entered for flat oval ducts. The final one is the rectangular duct. It has boxes for duct size and duct thickness for user to select the proper value, like flat oval duct case.

Second sound path is duct insertion loss, showed with the symbol “I”. With the selection of this path, duct type selection box appears. User must select one of the three types of duct types: lined circular duct, straight lined sheet metal duct and lined flexible duct. Like the duct breakout transmission loss; according to duct type selection, some specific duct information is required. Lining thickness and duct diameter for lined circular duct, duct dimension or cross-sectional area for straight lined sheet metal duct and duct diameter and duct length for lined sheet metal duct are the selection boxes for the duct insertion loss sound path.

Third sound path that user can be able to choose is duct elbow and tee loss. It is denoted as the symbol “T”. Three types of ducts are defined. They are round lined duct-90° elbow, round unlined duct-90° elbow, and rectangular square elbows either mitered or without turning vanes, lined and unlined. Diameter value is enough to obtain associated sound attenuation data for lined and unlined round ducts. On the other hand, turning information, width of the duct and lining information is needed to get correct attenuation value for rectangular ducts.

End reflection factor, demonstrated with “R” symbol, is the fourth sound path. There is only one filtering element or selection option. User must only select the proper duct diameter for the addition of end reflection factor’s contribution to the total calculation.

Other sound path is ceiling/space effect. Its symbol is “P”. User must choose the tile type initially. There are seven types of tiles: mineral fiber, glass fiber, glass fiber (TL backed), gypsum board tiles, solid gypsum board, double gypsum board and concealed spline. After that, corresponding density, thickness and weight must be pickedSpace effect is another sound path included in the form. It is denoted as “S” symbol. It requires different specifications. They are room volume and distance.

Distributed array showed as “S2” symbol is one of the sound paths. User must perform some calculations for this step since it requires area/diffuser value. In addition to that, ceiling height is also needed.

Another sound path defined in the form is branch power division. User must also do calculations for this part. Required calculation is the division of branch cross-sectional areas (B) to the total cross-sectional area of all ducts leaving the takeoff (T).

Plenum attenuation having the symbol “PL” is the last sound attenuation path. User encounters another user form when “PL” is selected. Upon inputting diameter of round duct or larger cross-sectional dimension of rectangular duct, plenum wall type and plenum material should be selected. Moreover, height, width, length, area of inlet section, area of outlet section; and vertical and horizontal offset between axes of plenum inlet and outlet information must be written. Finally, “DONE” button must be click after completion of input variables for the plenum attenuation.

AHRI SPL Predictor only has data defined in AHRI Standard 885. It is the reason for designing the form in a way that user select the proper values instead of entering the values. It is not possible to obtain sound attenuation values for different specifications; that is, designs not in the AHRI Standard 885. It is recommended to make choices to be in the safe side.

CHAPTER 5

VALIDATION

5.1. AHRI SPL PREDICTOR VALIDATION

Validation of the program is performed by using the example given in AHRI Standard 885. Acoustical design given in the standard can be inspected in Figure 5.1 and symbolic representation of sound paths with its elements is presented in Figure 5.2.

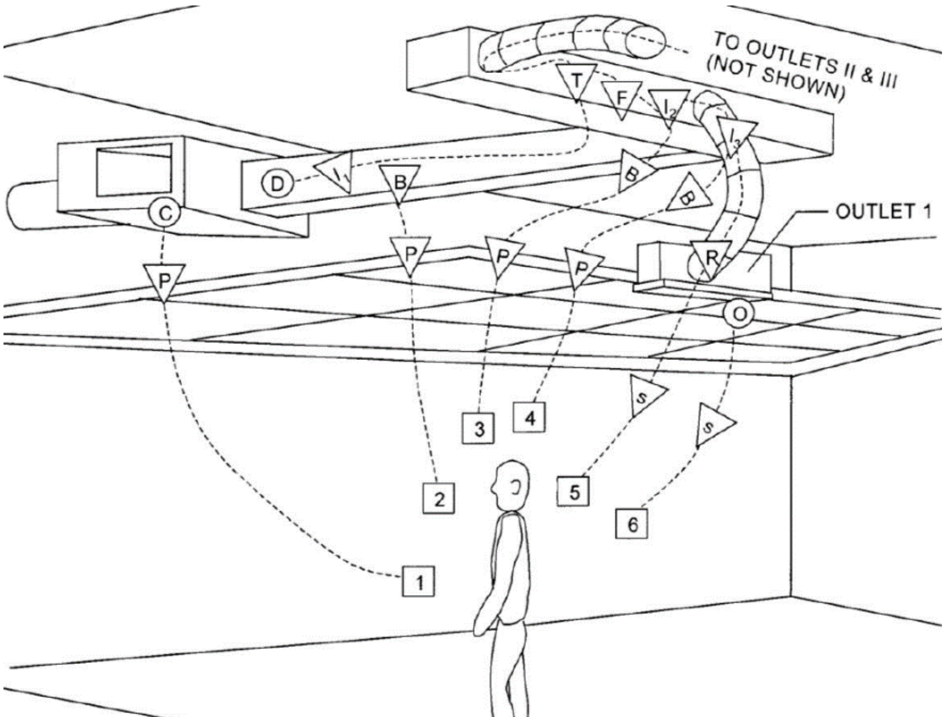


Figure 5.1. HVAC design example [2]

Sound Sources and Paths in Acoustic Model		
Sound Source	Path Attenuation Factor	Sound Receiver/Path
C	P	= 1
D	I_1 - B - P	= 2
D	I_1 - T - F - I_2 - B - P	= 3
D	I_1 - T - F - I_2 - I_3 - B - P	= 4
D	I_1 - T - F - I_2 - I_3 - R - S	= 5
O	S	= 6

Figure 5.2. Sound Sources and paths in HVAC design example [2]

Six sound paths were identified for this problem. The first path includes effects of sound source inside a ceiling space with mineral tile type. Values given or defined for manufacturer's sound data, environmental adjustment factor and ceiling/space effect are considered for the calculation of sound pressure level at the specified receiver location. The second sound path is a duct breakout including the effect of sound traveling through a lined rectangular duct inside the mineral tile type ceiling. Distributed duct breakout sound is identified as the third sound path. A rectangular tee and a branch exist along this path. Therefore, their attenuation characteristics are also considered in the calculation of sound pressure level contribution at the receiver. In addition to duct attenuation effects before and after the branch; duct transmission loss and ceiling/space effect are also considered as in the previous path. The fourth sound path is associated with the flexible duct transmission loss path. Flexible duct design is made available in this path in addition to the third path; that is, it is the continuation of the third path with the addition of flexible duct work. Discharge sound path is the fifth sound path. Instead of including duct transmission loss after the flexible duct work, both duct end reflection loss and space effect are considered. It is the path through the outlet. The last path is outlet generated path. It includes only the space effect.

Table 5.1 shows the detailed information of each path; that is, attenuation elements' type, size and dimensions are included with the corresponding sound attenuation values in dB. These sound attenuation values are taken from the tables in the appendix part of AHRI Standard 885 for each element.

Table 5.1. *Sound Path Details for the HVAC Example*

Sound Path		Octave Band Mid Frequency, Hz							
Path No	Name	63	125	250	500	1000	2000	4000	8000
1	**Radiated and Induction Inlet**								
	Radiated and induction inlet Lw (from manufacturer's data)	no data	64	60	57	58	55	52	no data
	Environmental adjustment factor	4	2	1	0	0	0	0	0
	Ceiling/space effect, type1, mineral tile, density:300kg/^3, thickness: 16mm, weight:5 kg/m^2	13	16	18	20	26	31	36	no data
2	**Duct Transmission Loss**								
	Terminal dischange Lw (from manufacturer's data)	no data	66	65	62	62	62	60	no data
	Environmental adjustment factor	4	2	1	0	0	0	0	0
	1.5m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	2	6	16	40	40	25	15
	Duct transmission loss, size:300mm x 300mm, thickness:0,7mm	21	24	27	30	33	36	41	45
	Ceiling/space effect, type1, mineral tile, density:300kg/^3, thickness: 16mm, weight:5 kg/m^2	13	16	18	20	26	31	36	no data
3	**Distribution Duct Transmission Loss**								
	Terminal dischange Lw (from manufacturer's data)	no data	66	65	62	62	62	60	no data
	Environmental adjustment factor	4	2	1	0	0	0	0	0
	3m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	2	6	16	40	40	25	15
	Rectangular tee attenuation entering brach duct, elbows without turning vanes, lined duct, width:300mm	0	1	6	6	11	10	10	10
	Branch power division 50% split	3	3	3	3	3	3	3	3
	1.5m length, unlined rectangular duct	0	0	0	0	0	0	0	0
	Duct transmission loss, size:300mmx300mm, thickness:0,7mm, 3m long	21	24	27	30	33	36	41	45
	Ceiling/space effect, type1, mineral tile	13	16	18	20	26	31	36	no data

Table 5.1. continued

Sound Path		Octave Band Mid Frequency, Hz							
Path No	Name	63	125	250	500	1000	2000	4000	8000
4	**Flexible Duct Transmission Losss**								
	Terminal dischange Lw (from manufacturer's data)	no data	66	65	62	62	62	60	no data
	Environmental adjustment factor	4	2	1	0	0	0	0	0
	3m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	2	6	16	40	40	25	15
	Rectangular tee attenuation entering brach duct, elbows without turning vanes ,lined duct, width:300mm	0	1	6	6	11	10	10	10
	Branch power division 50% split	3	3	3	3	3	3	3	3
	Duct insertion loss, 1.5m length, unlined rectangular duct	0	0	0	0	0	0	0	0
	Duct insertion loss, 0.9m lined 200mm diameter non-metallic flexible duct	2	3	7	14	14	16	8	6
	Duct transmission loss, 200mm diameter non-metallic flexible duct	8	8	8	8	9	10	13	18
	Ceiling/space effect, type1, mineral tile	13	16	18	20	26	31	36	no data
5	**Discharge Path**								
	Terminal dischange Lw (from manufacturer's data)	no data	66	65	62	62	62	60	no data
	Environmental adjustment factor	4	2	1	0	0	0	0	0
	3m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	2	6	16	40	40	25	15
	Rectangular tee attenuation entering brach duct, elbows without turning vanes, lined duct, width:300mm	0	1	6	6	11	10	10	10
	Branch power division 50% split	3	3	3	3	3	3	3	3
	Duct insertion loss, 1.5m length, unlined rectangular duct	0	0	0	0	0	0	0	0
	Duct insertion loss, 1.5m lined 200mm diameter non-metallic flexible duct	4	5	10	18	19	21	12	7
	End reflection factor 200mm diameter	16	10	5	2	1	0	0	0

Table 5.1. continued

	Space Effect, distance:1.5m, room volume:60 m^3	4	5	6	7	7	8	9	10
6	**Outlet #1 Generated**								
	Outlet generated Lw (from manufacturer's data)	no data	40	43	46	46	44	42	no data
	Environmental adjustment factor	4	2	1	0	0	0	0	0
	Space Effect, distance:1.5m, room volume:60 m^3	4	5	6	7	7	8	9	10

Some reasonable values are assumed for the missing or unavailable data written as “no data” in the Table 5.2. As explained before, for the calculation of sound pressure levels at receiver location sound attenuation values defined for each frequency is subtracted from the sound source data. Table 5.2 shows the estimated data and calculation of sound pressure level of each path with respect to octave bands. There exist results lower than zero. That means noise source was attenuated excessively at that specific frequency for associated the path. They were not included in the overall sound pressure level calculation; that is, all negative levels are treated as zero dB in the calculation of the overall levels.

Table 5.2. *Step-By-Step Calculation for the HVAC Example*

Sound Path		Octave Band Center Frequency, Hz							
Path No	**Name**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1	**Radiated and Induction Inlet**								
	Radiated and induction inlet Lw (from manufacturer's data)	65	64	60	57	58	55	52	50
	Environmental adjustment factor	-4	-2	-1	0	0	0	0	0
	Ceiling/space effect, type1, mineral tile, density:300 kg/m^3, thickness:16mm, weight:5 kg/m^2	-13	-16	-18	-20	-26	-31	-36	-36
	Lp at receiver location:	**48**	**46**	**41**	**37**	**32**	**24**	**16**	**14**
2	**Duct Transmission Loss**								
	Terminal dischange Lw (from manufacturer's data)	67	66	65	62	62	62	60	58
	Environmental adjustment factor	-4	-2	-1	0	0	0	0	0
	1.5m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	-2	-6	-16	-40	-40	-25	-15
	Duct transmission loss, size:300mm x 300mm, thickness:0,7mm	-21	-24	-27	-30	-33	-36	-41	-45
	Ceiling/space effect, type1, mineral tile, density:300 kg/m^3, thickness:16mm, weight:5 kg/m^2	-13	-16	-18	-20	-26	-31	-36	-36
	Lp at receiver location:	**29**	**22**	**13**	**-4**	**-37**	**-45**	**-42**	**-38**
3	**Distribution Duct Transmission Loss**								
	Terminal dischange Lw (from manufacturer's data)	67	66	65	62	62	62	60	58
	Environmental adjustment factor	-4	-2	-1	0	0	0	0	0
	3m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	-2	-6	-16	-40	-40	-25	-15
	Rectangular tee attenuation entering brach duct, lined duct, elbows without turning vanes, width:300mm	0	-1	-6	-6	-11	-10	-10	-10
	Branch power division 50% split	-3	-3	-3	-3	-3	-3	-3	-3
	1.5m length, unlined rectangular duct	0	0	0	0	0	0	0	0
	Duct transmission loss, size:300mmx300mm, thickness:0,7mm, 3m long	-21	-24	-27	-30	-33	-36	-41	-45
	Ceiling/space effect, type1, mineral tile	-13	-16	-18	-20	-26	-31	-36	-36
	Lp at receiver location:	**26**	**18**	**4**	**-13**	**-51**	**-52**	**-58**	**-51**

Table 5.2 continued

Sound Path		Octave Band Center Frequency, Hz							
Path No	**Name**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
4	**Flexible Duct Transmission Losss**								
	Terminal dischange Lw (from manufacturer's data)	67	66	65	62	62	62	60	58
	Environmental adjustment factor	-4	-2	-1	0	0	0	0	0
	3m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	-2	-6	-16	-40	-40	-25	-15
	Rectangular tee attenuation entering brach duct, lined duct, elbows without turning vanes, width:300mm	0	-1	-6	-6	-11	-10	-10	-10
	Branch power division 50% split	-3	-3	-3	-3	-3	-3	-3	-3
	Duct insertion loss, 1.5m length, unlined rectangular duct	0	0	0	0	0	0	0	0
	Duct insertion loss, 0.9m lined 200mm diameter non-metallic flexible duct	-2	-3	-7	-14	-14	-16	-8	-6
	Duct transmission loss, 200mm diameter non-metallic flexible duct	-8	-8	-8	-8	-9	-10	-13	-18
	Ceiling/space effect, type1, mineral tile	-13	-16	-18	-20	-26	-31	-36	-36
	Lp at receiver location:	**37**	**31**	**16**	**-5**	**-41**	**-48**	**-35**	**-30**
5	**Discharge Path**								
	Terminal dischange Lw (from manufacturer's data)	67	66	65	62	62	62	60	58
	Environmental adjustment factor	-4	-2	-1	0	0	0	0	0
	3m length, lined rectangular duct 300mm x 300mm, 25mm thickness	0	-2	-6	-16	-40	-40	-25	-15
	Rectangular tee attenuation entering brach duct, lined duct, elbows without turning vanes, width:300mm	0	-1	-6	-6	-11	-10	-10	-10
	Branch power division 50% split	-3	-3	-3	-3	-3	-3	-3	-3
	Duct insertion loss, 1.5m length, unlined rectangular duct	0	0	0	0	0	0	0	0
	Duct insertion loss, 1.5m lined 200mm diameter non-metallic flexible duct	-4	-5	-10	-18	-19	-21	-12	-7
	End reflection factor 200mm diameter	-16	-10	-5	-2	-1	0	0	0
	Space Effect, distance:1.5m, room volume:60 m^3	-4	-5	-6	-7	-7	-8	-9	-10
	Lp at receiver location:	**36**	**38**	**28**	**10**	**-19**	**-20**	**1**	**13**
6	**Outlet #1 Generated**								
	Outlet generated Lw (from manufacturer's data)	40	40	43	46	46	44	42	40
	Environmental adjustment factor	-4	-2	-1	0	0	0	0	0

Table 5.2 continued

	Space Effect, distance:1.5m, room volume:60 m^3	-4	-5	-6	-7	-7	-8	-9	-10
	Lp at receiver location:	**32**	**33**	**36**	**39**	**39**	**36**	**33**	**30**

Resultant sound attenuation value is calculated with the logarithmically adding each path's resultant sound pressure level at the receiver location. It is represented in Table 5.3.

Table 5.3. *Combination of Path Results Using Logarithmic Addition*

Sound Path		**Octave Band Center Frequency, Hz**							
Path No	**Description**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1	Radiated and Induction Inlet	48	46	41	37	32	24	16	14
2	Duct Transmission Loss	29	22	13	0	0	0	0	0
3	Distribution Duct Transmission Loss	26	18	4	0	0	0	0	0
4	Flexible Duct Transmission Losss	37	31	16	0	0	0	0	0
5	Discharge Path	36	38	28	10	0	0	1	13
6	Outlet #1 Generated	32	33	36	39	39	36	33	30
	Total Lp at receiver location	**49**	**47**	**42**	**41**	**40**	**36**	**33**	**30**

The same HVAC design problem is considered in AHRI SPL Predictor program. Number of paths and sound source data of first path is entered initially to the program. Entered data is written at the same time to the "VALUE" sheet of the EXCEL. Ceiling/space effect symbol "P" in the selection box of "SOUND" is selected. After that, tile type, density, thickness and weight selections were completed accordingly. Add step button was clicked to include this element to the calculations. With the completion of attenuation element selection of first path, next path button was clicked to continue with the second path. Figure 5.3 shows entered manufacturer's data while Figure 5.4 showing the selected first path attenuation element data.

For the second path, first sound power data is selected and its value for each corresponding frequency band copied from manufacturer's sound power data. Then, necessary information for the first attenuation element, duct insertion loss is selected.

As in the first path, “ADD STEP” button is clicked. The same procedure is followed for the other four attenuation elements and upon completion of second path’s attenuation elements, “NEXT PATH” button is clicked. Figures 5.5, 5.6, 5.7 and 5.8 are presented for the selections of attenuation elements of second path.

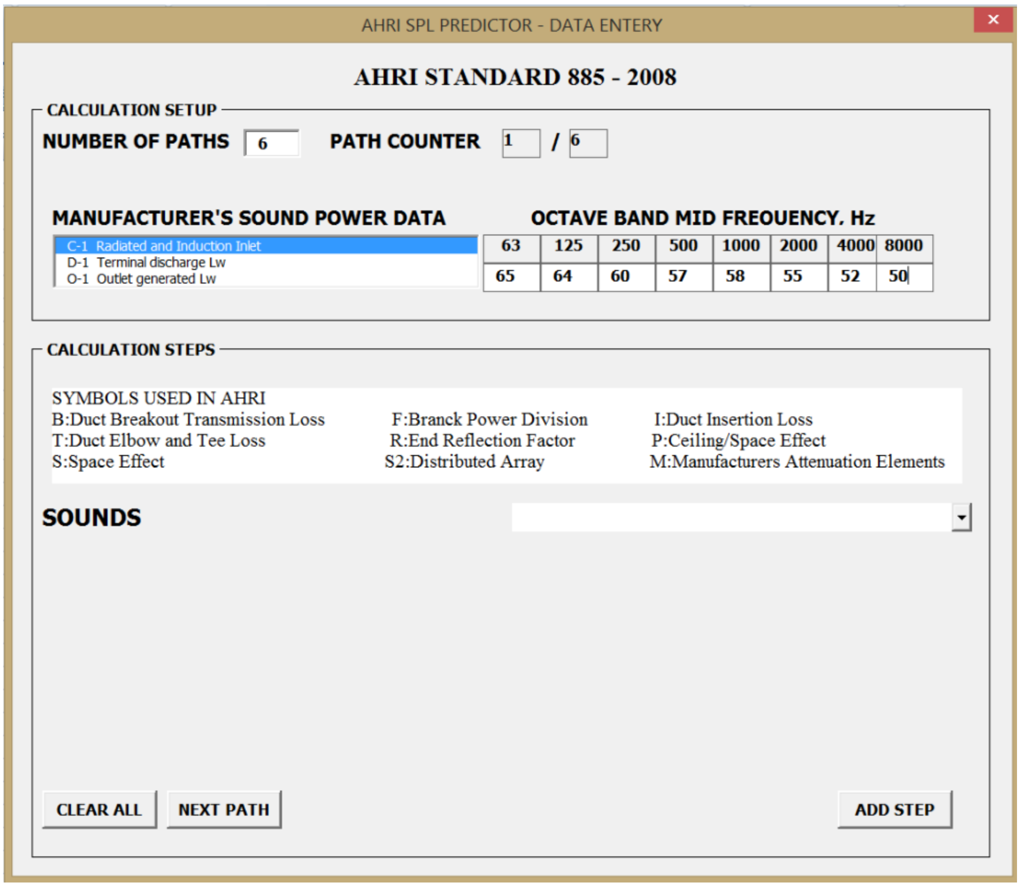


Figure 5.3. AHRI SPL Predictor, First Path Manufacturer’s Data

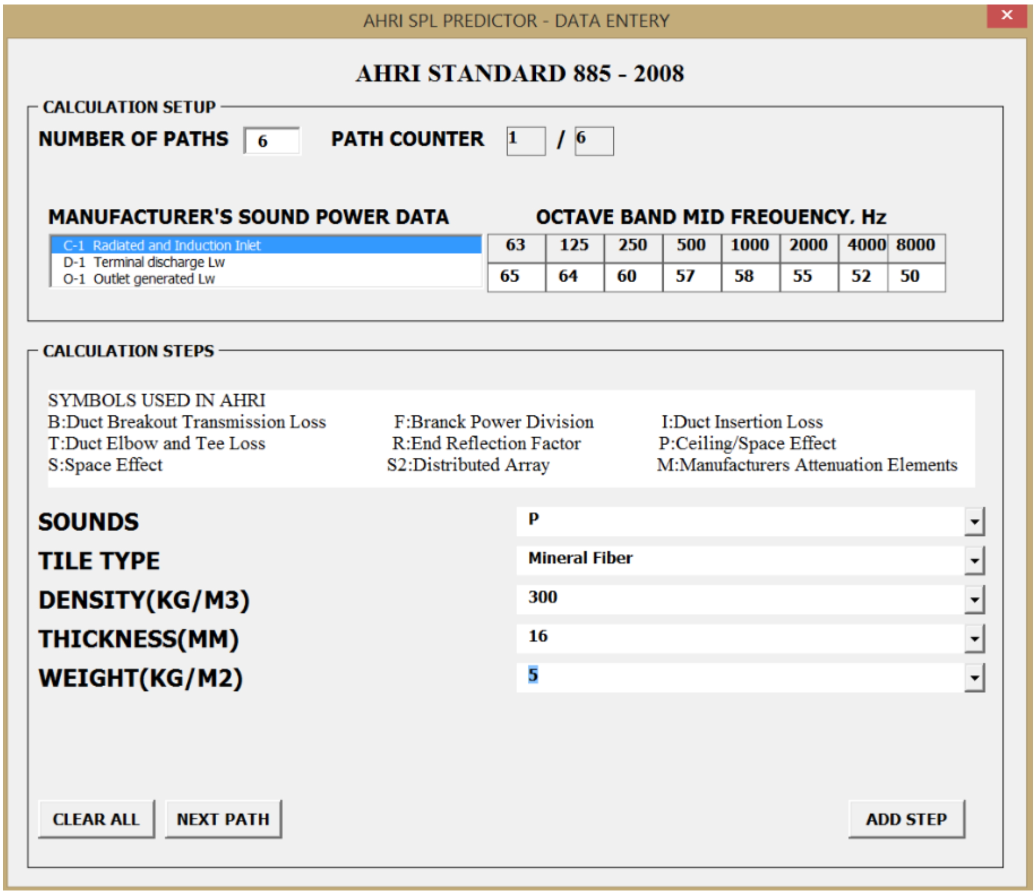


Figure 5.4. AHRI SPL Predictor, First Path Attenuation Element, Ceiling/space effect

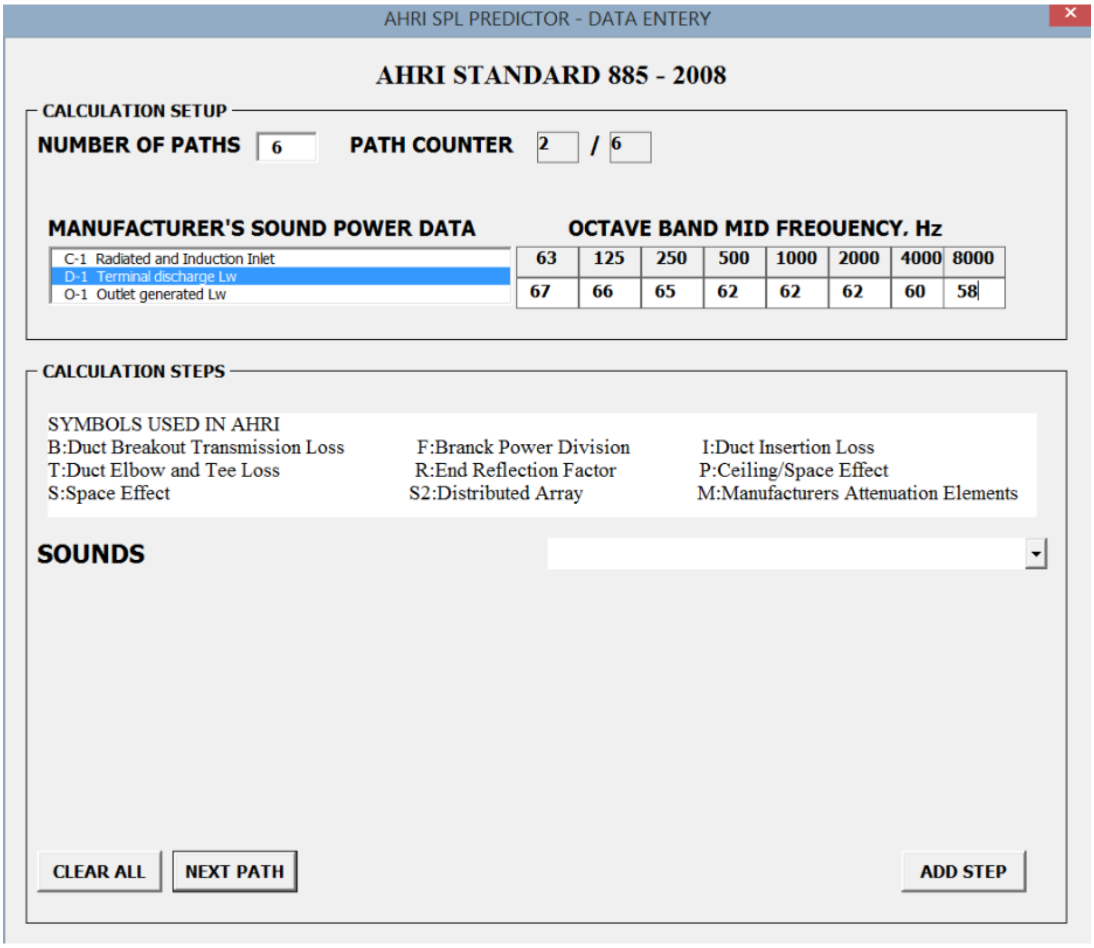


Figure 5.5. AHRI SPL Predictor, Second Path Manufacturer' Data

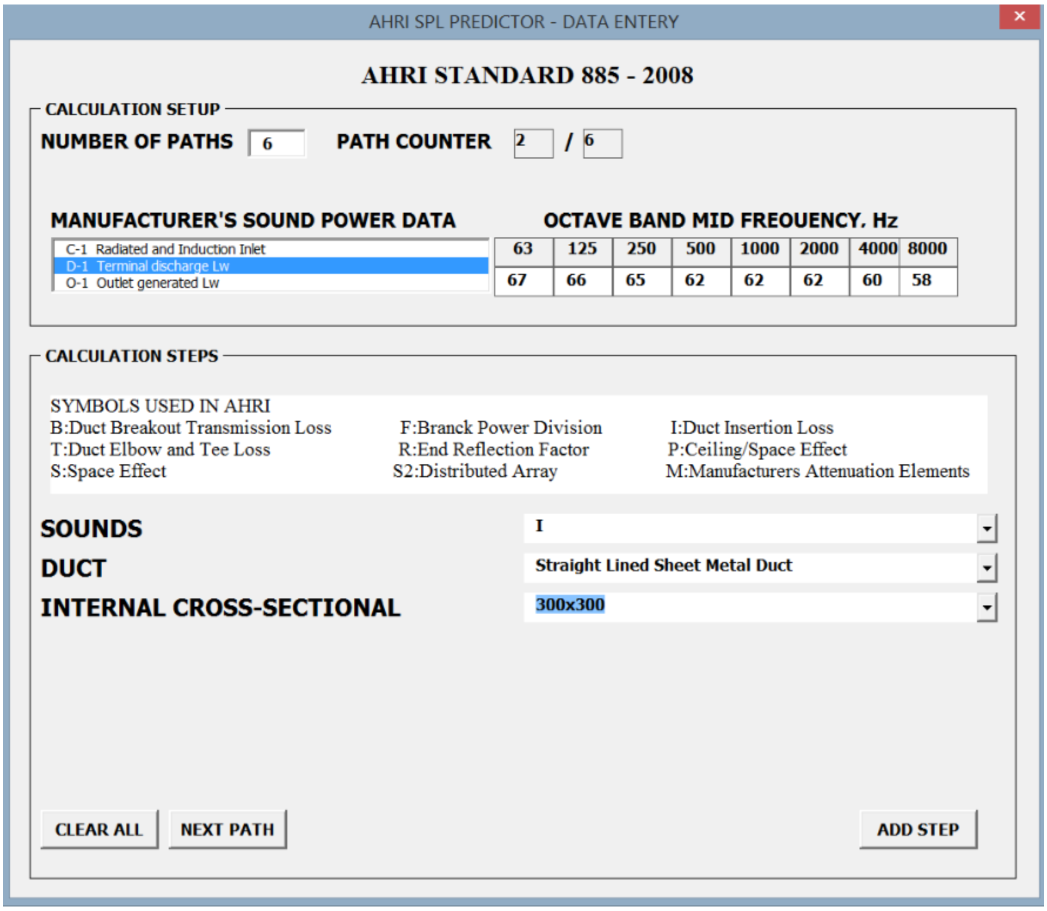


Figure 5.6. AHRI SPL Predictor, First Attenuation Element of Second Path

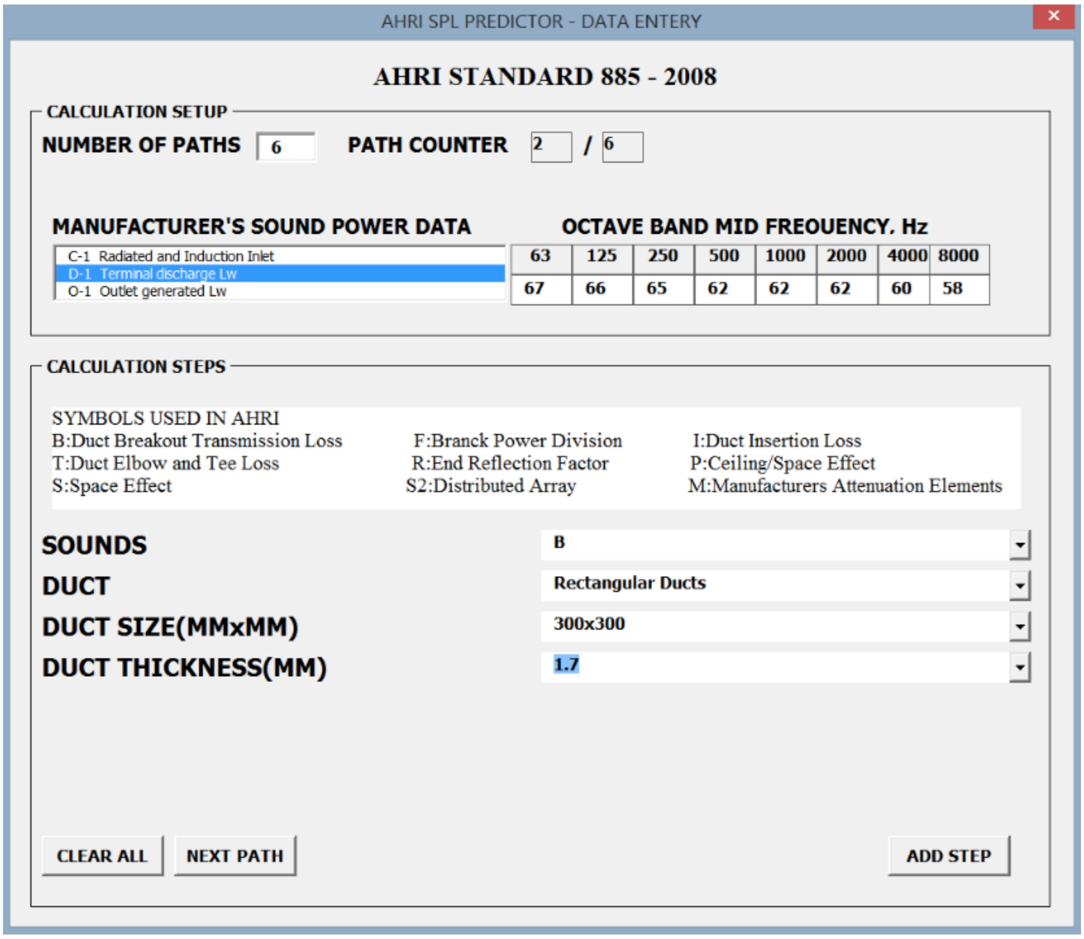


Figure 5.7. AHRI SPL Predictor, Second Attenuation Element of Second Path

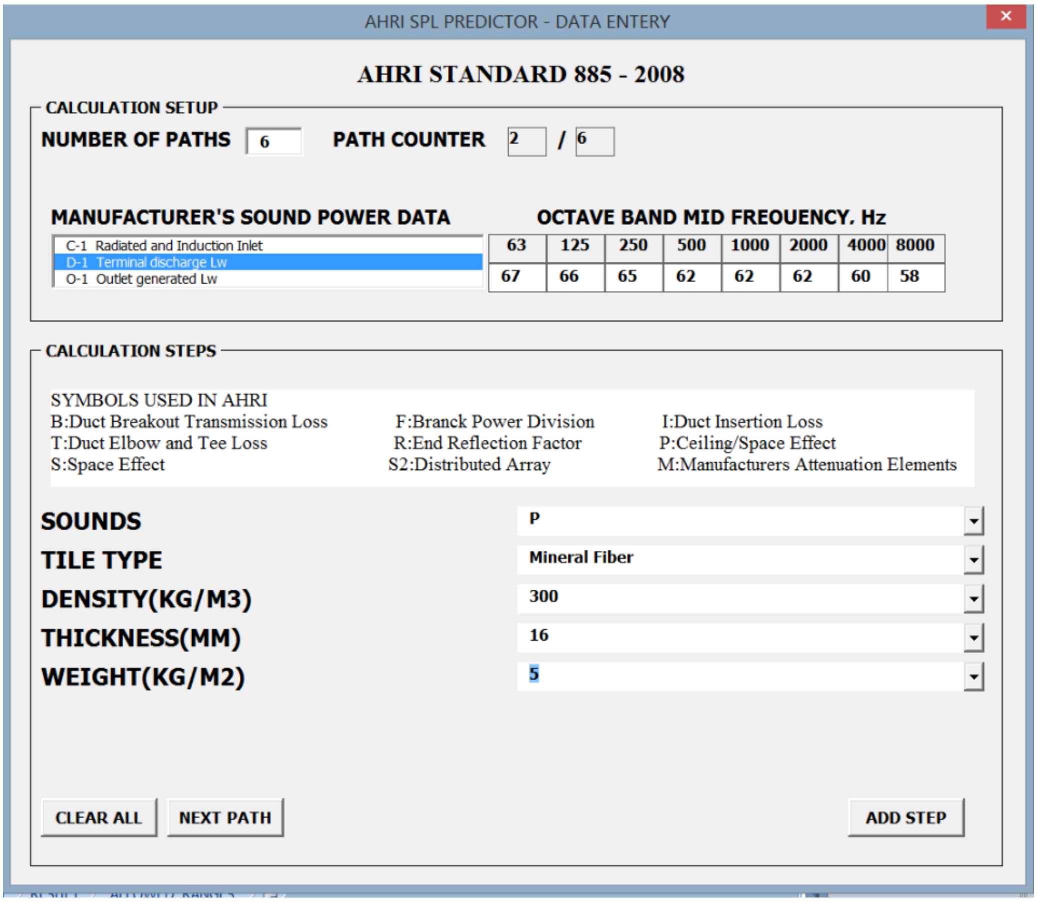


Figure 5.8. AHRI SPL Predictor, Last Attenuation Element of Second Path

At the end of inputting all the acoustical design data into the program, another user form presenting the total estimated sound pressure level of entered acoustical model is reached. It can be seen on Figure 5.9. With the selection of HVAC design space, program informs the user that the defined HVAC design is out of limits for all hospital areas as seen on Figures 5.10, 5.11, 5.12 and 5.13.

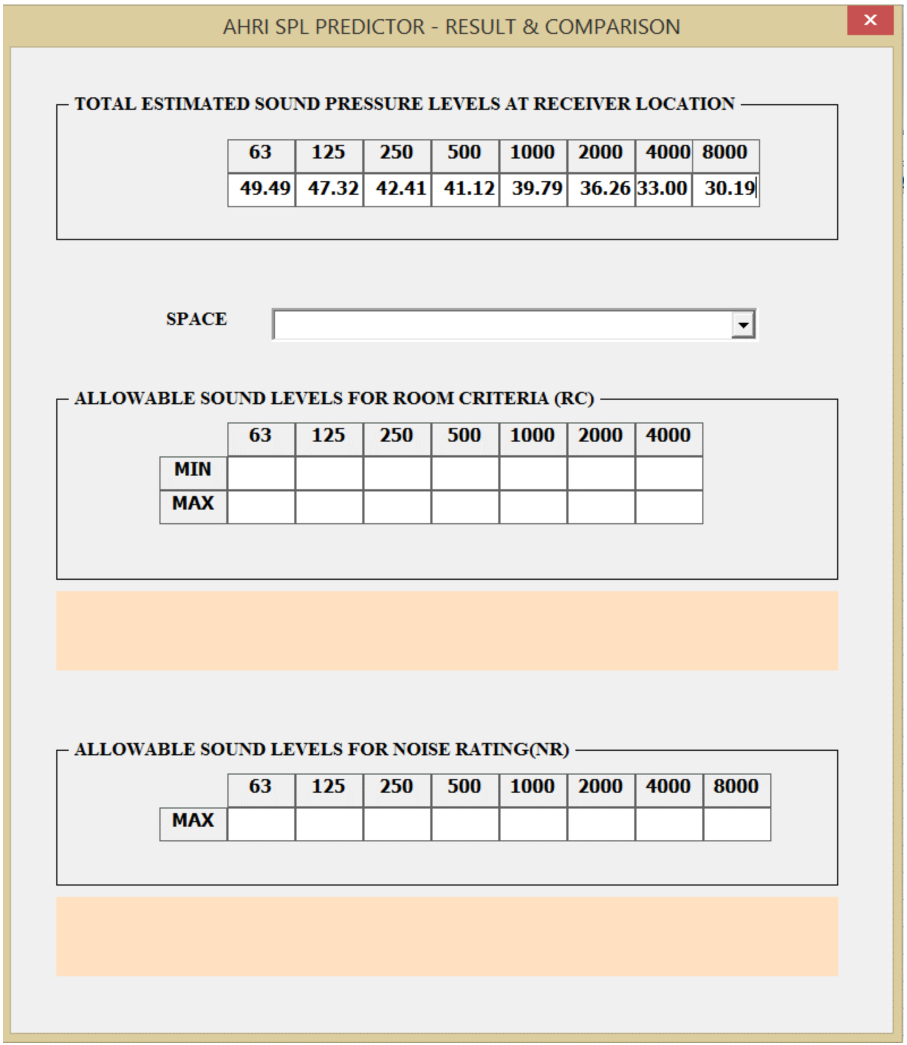


Figure 5.9. AHRI SPL Predictor, Total Estimated Sound Pressure Levels at Receiver Location

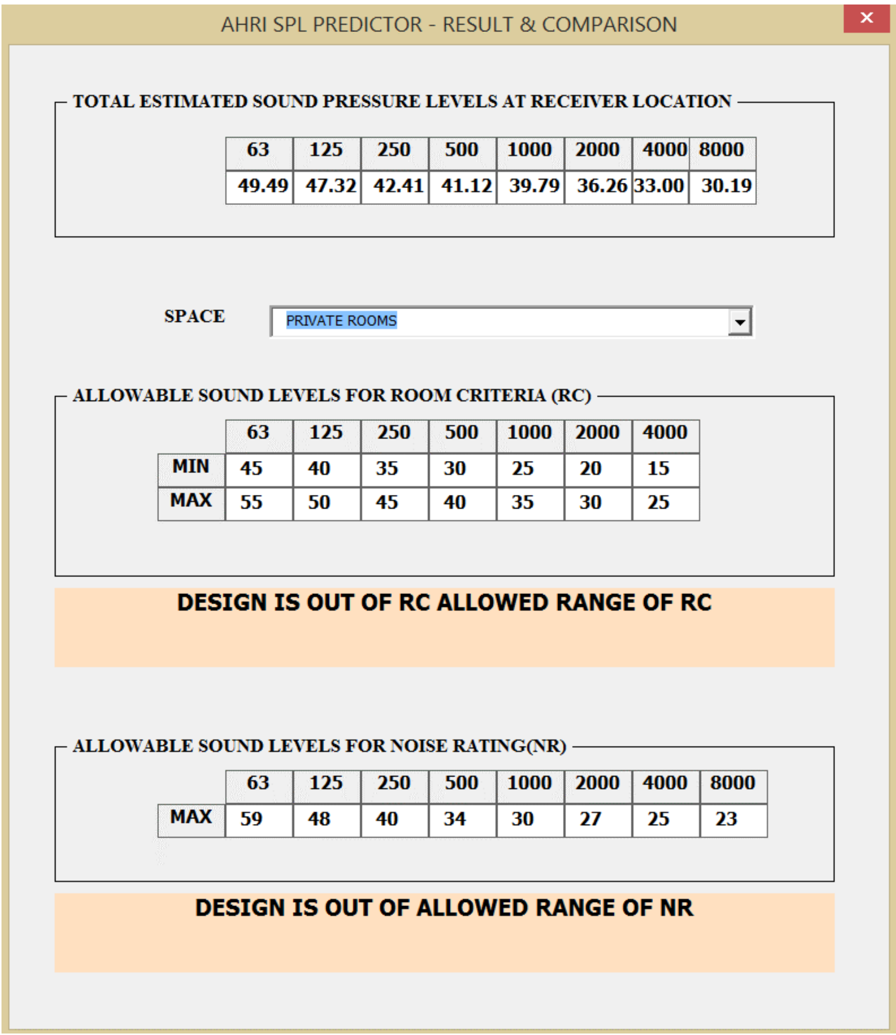


Figure 5.10. AHRI SPL Predictor, Validity of HVAC Design According to RC and NR Criteria

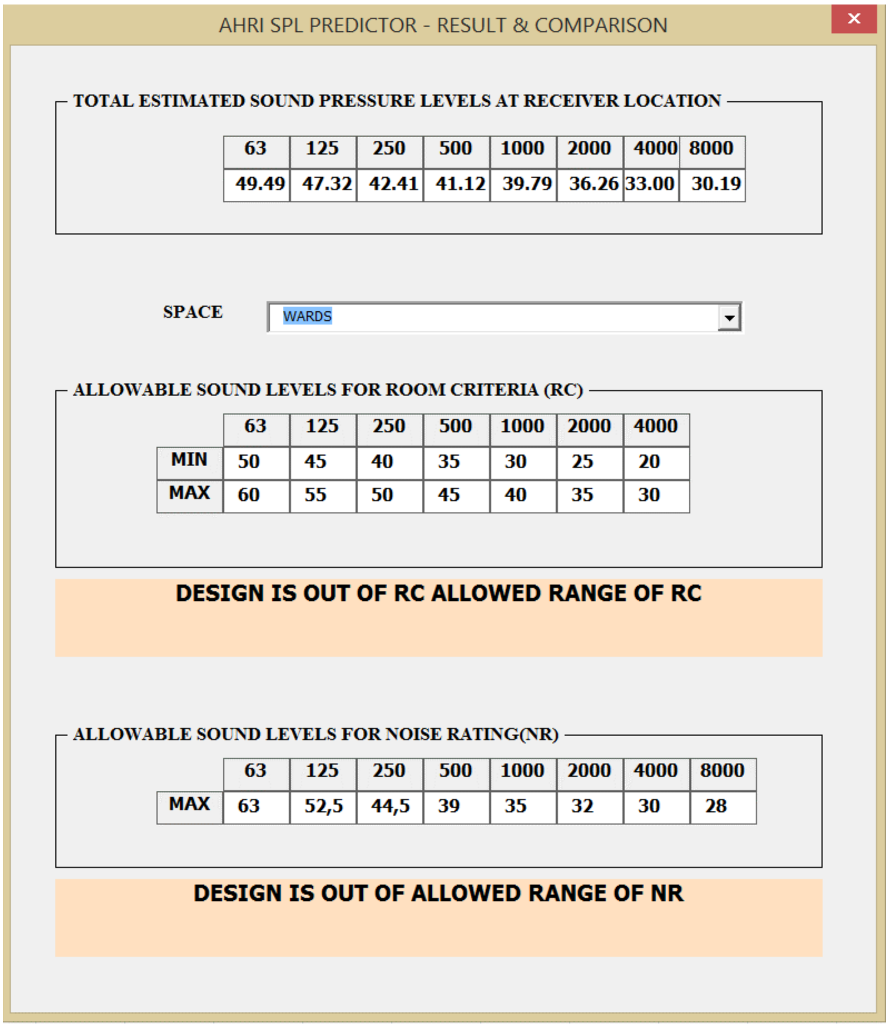


Figure 5.11. AHRI SPL Predictor, Design Validity for Wards

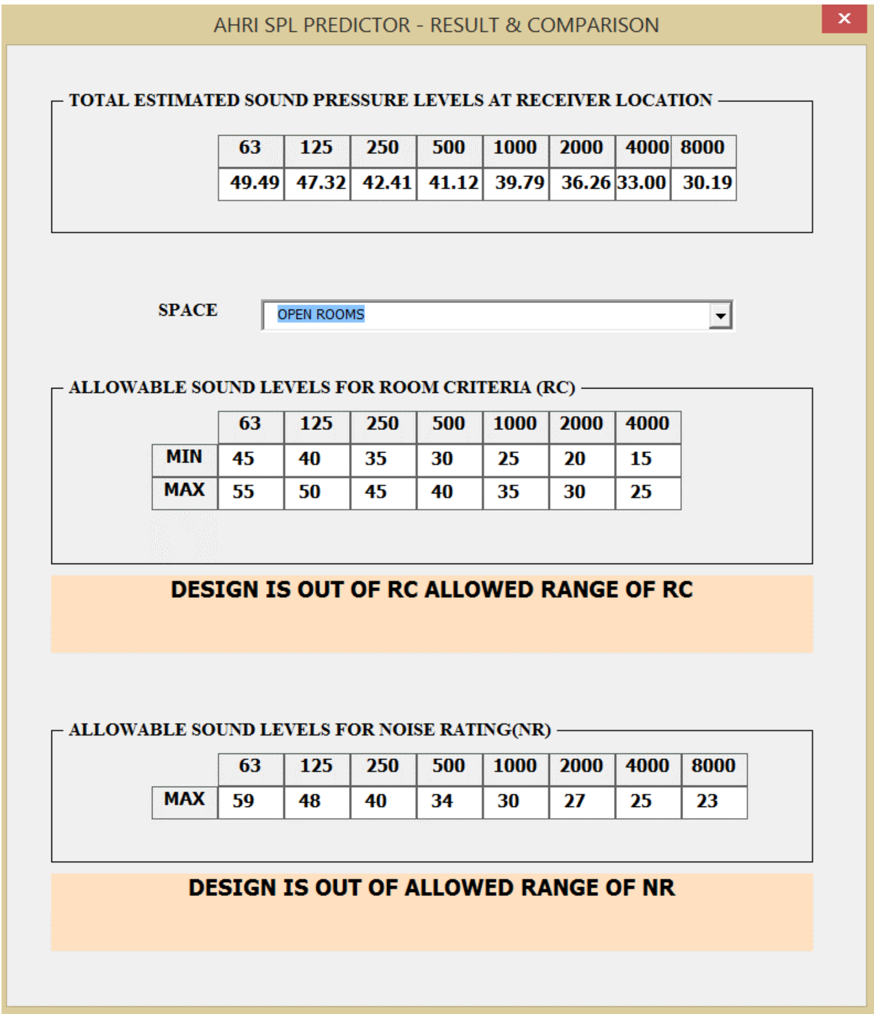


Figure 5.12. AHRI SPL Predictor, Design Validity for Open Room

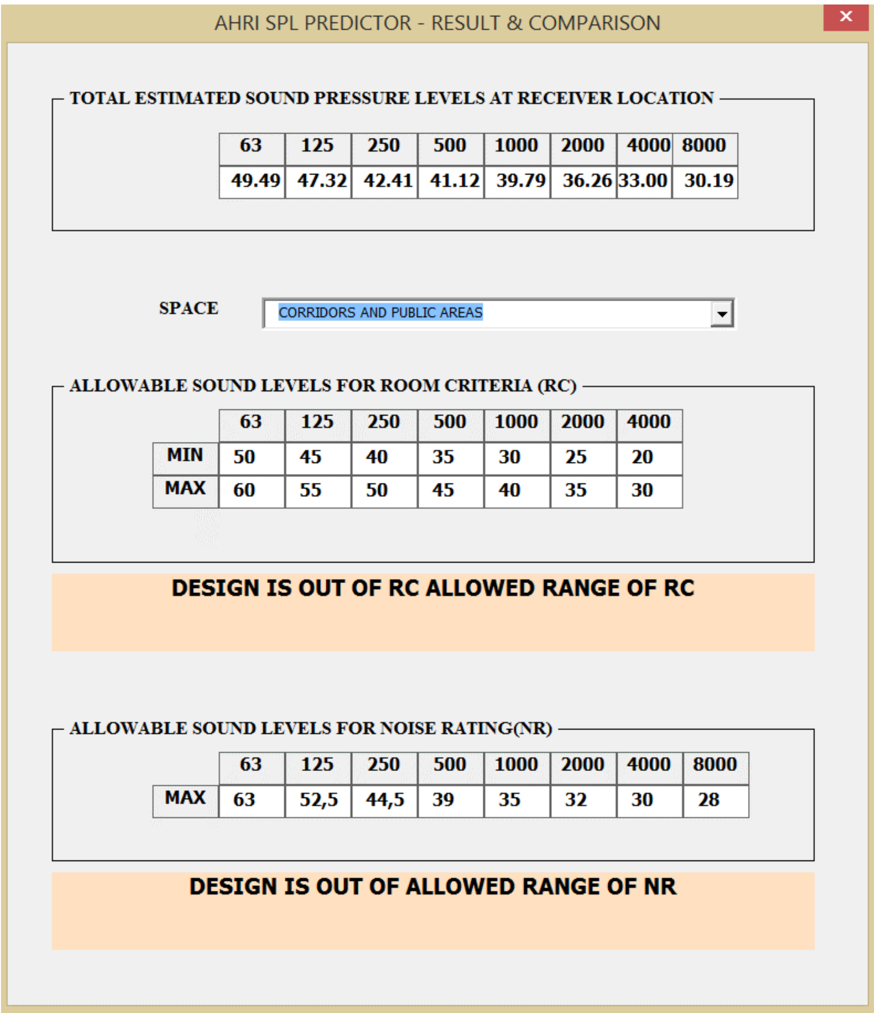


Figure 5.13. AHRI SPL Predictor, Design Validity for Corridors and Public Areas

5.2. AHRI STANDARD 885 VALIDATION

5.2.1. AHRI SPL Predictor Evaluation of The Hospital Private Rooms

AHRI Standard 885 validation was performed by comparing the measured SPL data with the AHRI SPL Predictor Program prediction. Private rooms of three different hospitals in Ankara were considered. The fist hospital was still under construction; therefore, the room was not furnished. However, other hospitals are in service with fully furnished rooms. HVAC system designs of the rooms were examined in detail and AHRI SPL Predictor program was used to calculate estimated sound pressure levels of each private room in these hospitals.

5.2.1.1. AHRI SPL Predictor Result of the Hospital Private Room #1

Plan view of the first hospital private room with HVAC design is shown on Figure 5.14 while its section view of the room can be seen on Figure 5.15.

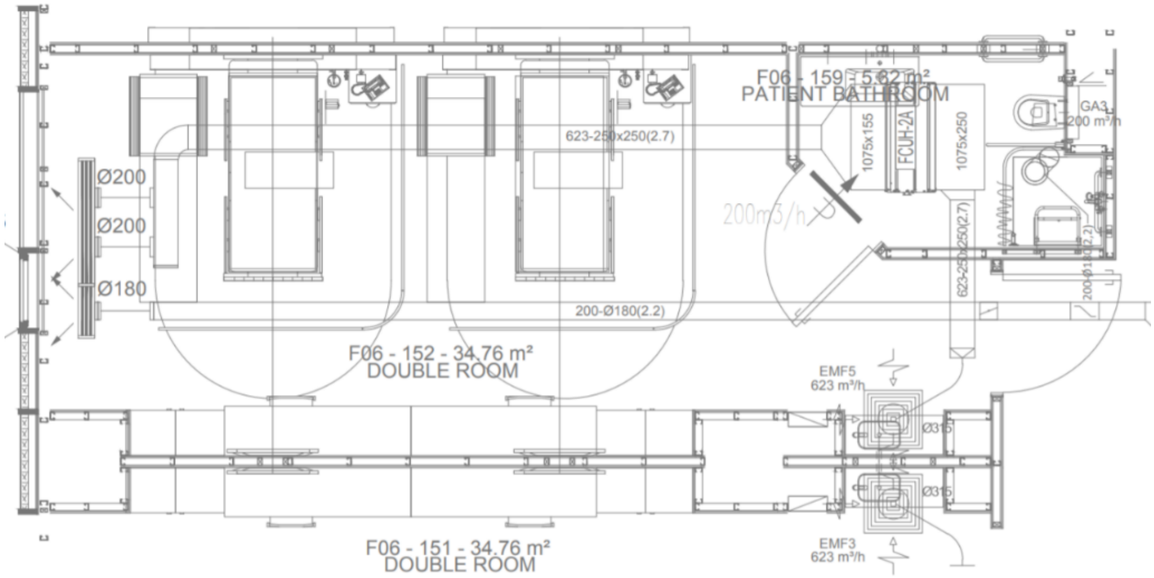


Figure 5.14. Top View of the Hospital Private Room

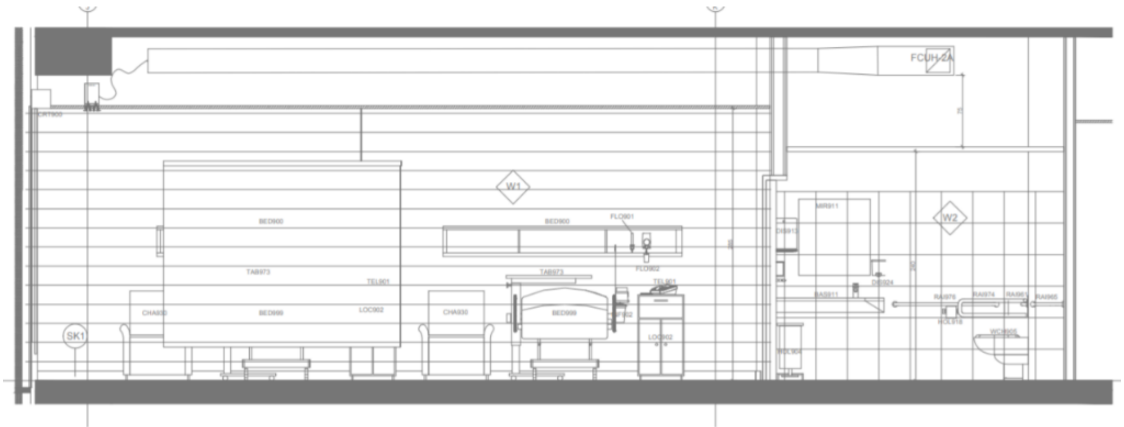


Figure 5.15. Section View of the Hospital Private Room

Considering the HVAC design shortly, there exist an FCU as a sound source and it is positioned in a ceiling at the bathroom. Rectangular ducting preferred through the air suction and blow lines. Moreover, flexible ducting exists before the outlets. To use AHRI SPL Predictor, detailed approach is necessary. In addition, manufacturer's sound power data is required. Manufacturer provided an average sound power data and it is used as a sound source for all paths. However, there is not any defined value for 63 Hz. An assumed value of 65 dB is used at that octave band. It is known that we must have higher sound power value for 63 Hz than sound power value given in 125 Hz. To be in safe side, a higher value of 65 dB is assumed. All paths are tabulated including their attenuation elements in Table 5.4. In Figure 5.16, supply line is drawn in red while return line drawn in green. These two airlines of FCU are considered in detailed.

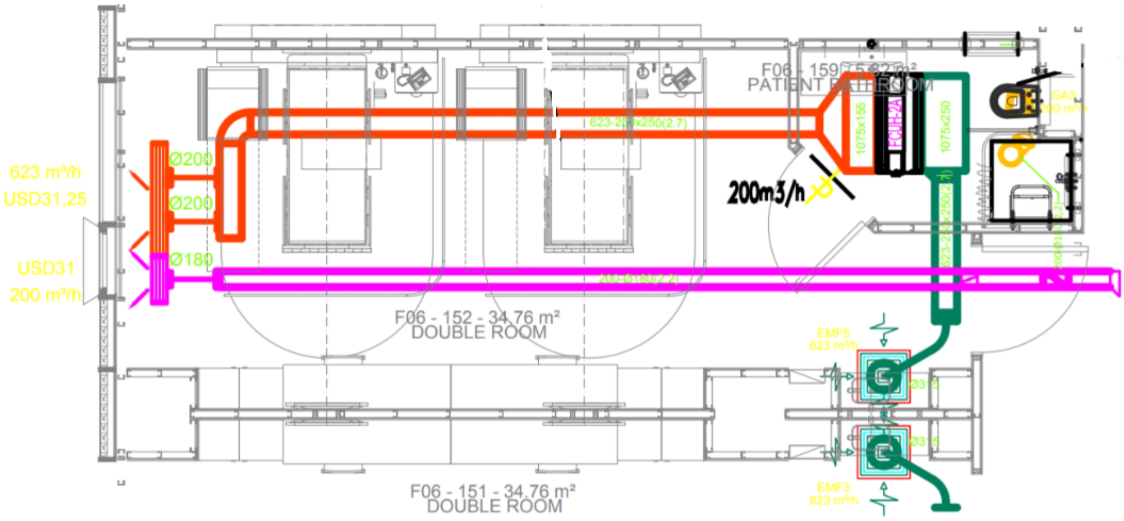


Figure 5.16. E HVAC System Design of the Hospital Private Room#1

Table 5.4. *Sound Path details of the Hospital Private Room#1*

Path No	Sound Path Element
1	FCU-Sound source
	Unlined Rectangulat Duct 1075 mm x250 mm, 0.3m long
	Rectangular Duct Reducer
	Insertion Loss-Rectangular Duct 250 mm x250 mm, 6,45 m long
	Transmission Loss-Rectangular Duct 250 mm x250 mm, 6,45 m long
	Ceiling/Space Effect-Gypsum Board Tile
2	FCU-Sound source
	Unlined Rectangulat Duct 1075 mm x250 mm, 0.3m long
	Rectangular Duct Reducer
	Insertion Loss-Rectangular Duct 250 mm x250 mm, 6,45 m long
	90 degrees Elbow 250mm x 250 mm
	Branch Power Division
	Insertion Loss-Flexible Duct 203mm diameter, 1m long
	Transmission Loss-Flexible Duct 203mm diameter, 1m long
	Ceiling/Space Effect-Gypsum Board Tile

Table 5.4 continued

Path No	Sound Path Element
3	FCU-Sound source
	Unlined Rectangulat Duct 1075 mm x250 mm, 0.3m long
	Rectangular Duct Reducer
	Insertion Loss-Rectangular Duct 250 mm x250 mm, 6,45 m long
	90 degrees Elbow 250mm x 250 mm
	Branch Power Division
	Insertion Loss-Flexible Duct 203mm diameter, 1m long
	End Reflection Factor- Outlet 1,3 m x 2 m
	Space effect- Room Volume: 99.066m^3
4	FCU-Sound source
	Unlined Rectangulat Duct 1075 mm x250 mm, 0.5 m long
	Rectangular Duct Reducer
	Insertion Loss-Rectangular Duct 250 mm x250 mm, 1,51 m long
	Transmission Loss-Rectangular Duct 250 mm x250 mm, 1 m long
	Ceiling/Space Effect-Gypsum Board Tile
5	FCU-Sound source
	Unlined Rectangulat Duct 1075 mm x250 mm, 0,5 m long
	Rectangular Duct Reducer
	Insertion Loss-Rectangular Duct 250 mm x250 mm, 1,51 m long
	Insertion Loss-Flexible Duct 315 mm diameter, 1m long
	Transmission Loss-Flexible Duct 315 mm diameter, 1m long
	Ceiling/Space Effect-Gypsum Board Tile
6	FCU-Sound source
	Unlined Rectangulat Duct 1075 mm x250 mm, 0,5 m long
	Rectangular Duct Reducer
	Insertion Loss-Rectangular Duct 250 mm x250 mm, 1,51 m long
	Insertion Loss-Flexible Duct 315 mm diameter, 1m long
	End Reflection Factor- Outlet 595mm x 595 mm
	Space effect- Room Volume: 99.066m^3

There are some points to mention about radiated and induction inlet path. It accounts radiated sound through the ceiling space. It is noted in the design that ceiling is metal clip-in type which consists of 60mm square parts. It is required to select the most similar type of attenuation element from the AHRI Standard and accordingly AHRI SPL Predictor. Since clip-in panels can be filled by mineral fiber board, mineral fiber type is selected [66]. Moreover, type 1 is selected because it has higher density. Clip-in tiles are mostly aluminum, or steel and they have higher density than the ones written in AHRI Standard. As stated, before FCU is placed in bathroom; therefore, we did not include effect of this path to the calculations since room is focal point.

First path is rectangular duct breakout path of blow side. Unlined rectangular duct with sizes of 1075mm and 155mm is not included since its length is very short, approximately 0,3m and it is unlined. As stated before, insertion loss data stated in AHRI Standard 885 is for 3m long duct. Therefore, its effect is not added to the calculations. There is a rectangular reducer at the end of unlined rectangular duct. It is placed to have proper air flow at the exit, and it does not have a significant effect in terms of sound attenuation. Thus, reducers are not included in AHRI. Then we have a square ducting with size of 250mm. It is about 2,7m. Insertion loss data provided for 250mm width, 250mm length and 3m long rectangular duct is used for this element. After including insertion loss, breakout effect is added to the calculation. Since all off the mentioned HVAC design elements are behind the ceiling, ceiling effect is also included to the calculations. For this room, gypsum board tile type is used; therefore, data for gypsum board in AHRI is used for this room.

Second path is flexible duct breakout path of supply side. Air blowing side is continuing with 90 degrees of elbow after square ducting. Then, design is divided into branches. Flexible duct having 1m length and 203 mm diameter is placed after branch division. 200mm diameter flexible duct data is used in calculations. Insertion loss and transmission loss data for the flexible ducting is added for this path. As in the second path, calculations ended up with ceiling effect.

Third path is discharge path. Flexible duct mentioned in second path connected to an outlet with sizes of 1,3m and 2m. End reflection factor is included for this design and after that space effect is included with room values of 99,066 m3 volume. AHRI Standard 885 data for spaces with 100m3 volume and 1,5m distance is used for this hospital room.

Fourth path is rectangular duct breakout path of return side. There exist 0,5 lengths rectangular duct with sizes of 1075mm and 250mm. Similar to supply side this duct and a reducer behind it are not included in the calculations. After that another rectangular duct whose sizes are 250mm is placed. While calculating the transmission losses of this duct, it is seen that some portion of it is in bathroom and other portion is in the room. Since we focus on the room not the bathroom, only room side transmission loss is included.

Fifth path is flexible duct breakout path of return side. At the end of 250mm width and length rectangular duct, there is 315mm diameter and 1m long flexible duct. Flexible duct insertion loss and transmission loss are included in the calculations. Then, as in the previous paths ceiling effect is added at the end of this path's estimation.

Sixth and the last path is discharge path of return side. After flexible duct, a square outlet with dimension of 595mm is positioned. 300mm diameter flexible duct data given in AHRI is used in end reflection loss calculations. Then, space effect is added to the calculations of this path.

Table 5.5 shows sound data used in AHRI SPL Predictor to estimate sound pressure level of the hospital private room; that is, assumed sound attenuation elements of HVAC design of hospital private room.

Table 5.5. *AHRI SPL Predictor Data for Hospital Private Room#1*

Path No	Sound Path Element
1	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Duct Breakout Loss-Rectangular Duct 300 mm x300 mm
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
2	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Branch Power Division, B/T=0,4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	Transmission Loss-Non metalic Flexible Duct 200mm diameter
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
3	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Branch Power Division B/T=0.4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	End Reflection Factor- 200mm diameter duct
	Space effect- Room Volume: 100m^3, 1,5 m distance
4	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Duct Breakout Loss-Rectangular Duct 300 mm x300 mm
	Ceiling/Space Effect-Gypsum Board Tile, Type 6

Table 5.5 continued

Path No	Sound Path Element
5	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Insertion Loss-Flexible Duct 300 mm diameter, 0.9m long
	Transmission Loss-Non metalic Flexible Duct 300mm diameter
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
6	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Insertion Loss-Flexible Duct 300 mm diameter, 0.9m long
	End Reflection Factor- 300mm diameter duct
	Space effect- Room Volume: 100m^3, 1,5 m distance

AHRI SPL Predictor ended up with the result shown in Figure 5.17. It can be concluded by looking this estimated total sound pressure levels assessment regarding to RC criteria that the space is overdesigned, since all of the sounds at frequencies higher than 500 Hz is attenuated. This is deduced from the results below than zero. These levels are taken as zeros. It is expected to have higher sound pressure level for lower frequencies since fan noise generally produce sound in lower frequency distributions, in the 16 to 250 Hz octave bands [34]. However, attenuation of all sounds in higher frequencies is questionable. The underlying reason of having such a result is in assumptions. In insertion loss calculations, rectangular and flexible ducts were taken as lined even if there is not any specified lining for that ducts. As stated before, there was not any discrete data for manufacturer's sound power data. Given averaged data was used for all types of sound source. Dimensional limitations of AHRI Standard were also mentioned before and this is another cause for the estimations. All these assumptions strictly affect the calculations. On the other hand, design is within the limits for NR criteria since estimated sound pressure levels are less than sound pressure levels specified by NR criteria. However, considering maximum sound pressure level of NR criteria, it can be concluded that overdesigning condition occurs. This is deduced from the comparison of sound pressure levels. Estimated sound pressure levels are much less than the maximum sound pressure level defined by NR criteria. Therefore, the same result is obtained for both criteria.

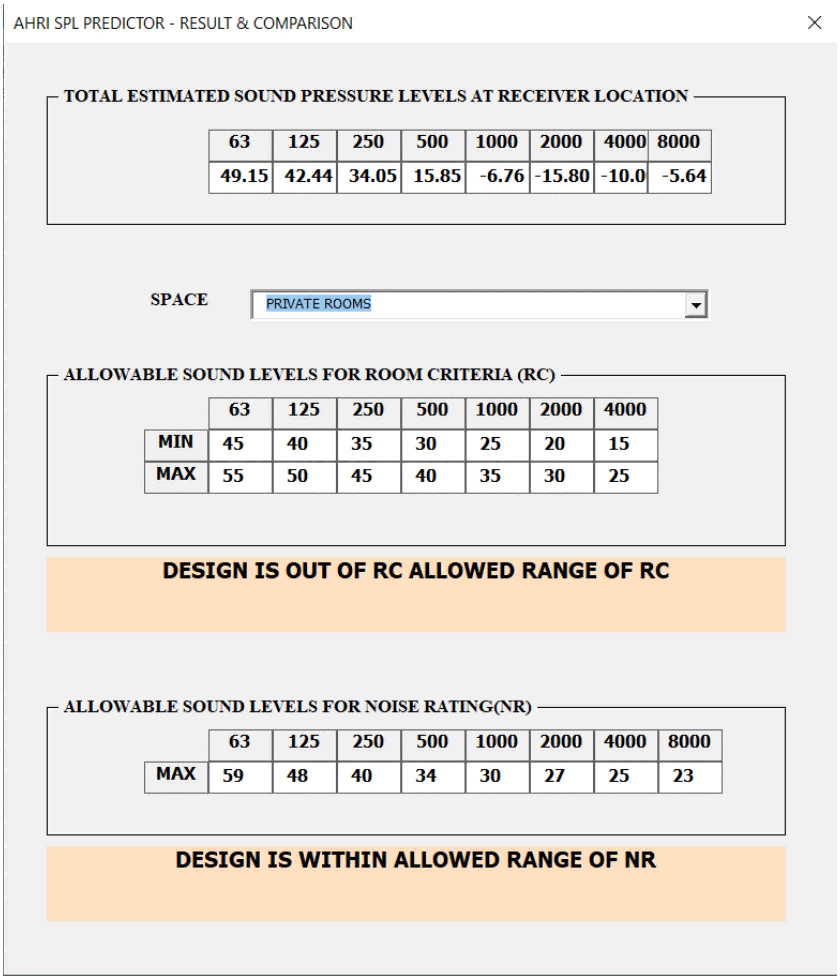


Figure 5.17. Estimated Total Sound Pressure Level of the Hospital Private Room Including Evaluation of the Room

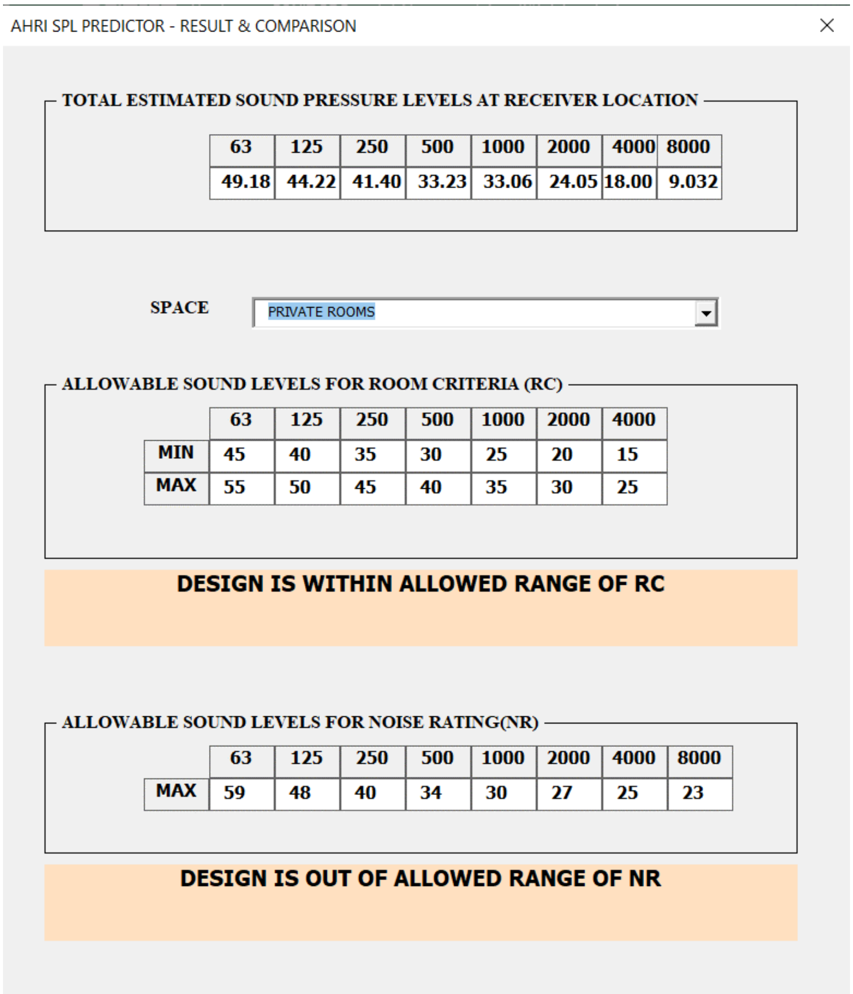
It is stated in the AHRI Standard that insertion loss of unlined sheet metal ducts is taken as negligible due to lack of documented data [2]. With this logic, rectangular duct work in return side is taken as unlined and insertion loss of this ducting is assumed as zeros for all octave band. Table 5.6 and Figure 5.18 are presented to show the effect of lining practices in the HVAC design.

Table 5.6. *AHRI SPL Predictor Data for Hospital Private Room Having Unlined Rectangular Duct Work in Return Side*

Path No	Sound Path Element
1	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Duct Breakout Loss-Rectangular Duct 300 mm x300 mm
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
2	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Branch Power Division, B/T=0,4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	Transmission Loss-Non metalic Flexible Duct 200mm diameter
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
3	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 250 mm x250 mm, 3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Branch Power Division B/T=0.4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	End Reflection Factor- 200mm diameter duct
	Space effect- Room Volume: 100m^3, 1,5 m distance
4	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Duct Breakout Loss-Rectangular Duct 300 mm x300 mm
	Ceiling/Space Effect-Gypsum Board Tile, Type 6

Table 5.6 continued

Path No	Sound Path Element
5	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Flexible Duct 300 mm diameter, 0.9m long
	Transmission Loss-Non metalic Flexible Duct 300mm diameter
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
6	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Flexible Duct 300 mm diameter, 0.9m long
	End Reflection Factor- 300mm diameter duct
	Space effect- Room Volume: 100m^3, 1,5 m distance



AHRI SPL PREDICTOR - RESULT & COMPARISON

TOTAL ESTIMATED SOUND PRESSURE LEVELS AT RECEIVER LOCATION

63	125	250	500	1000	2000	4000	8000
49.18	44.22	41.40	33.23	33.06	24.05	18.00	9.032

SPACE PRIVATE ROOMS

ALLOWABLE SOUND LEVELS FOR ROOM CRITERIA (RC)

	63	125	250	500	1000	2000	4000
MIN	45	40	35	30	25	20	15
MAX	55	50	45	40	35	30	25

DESIGN IS WITHIN ALLOWED RANGE OF RC

ALLOWABLE SOUND LEVELS FOR NOISE RATING(NR)

	63	125	250	500	1000	2000	4000	8000
MAX	59	48	40	34	30	27	25	23

DESIGN IS OUT OF ALLOWED RANGE OF NR

Figure 5.18. Estimated Total Sound Pressure Level of the Hospital Private Room Having Unlined Rectangular Duct Work in Return Side Including Evaluation of the Room

It can be seen from the Figure 5.18 that design is within the RC while exceeding NR limits at 250Hz, 500 Hz and 1000 Hz. There is only 1 dB exceeding at frequencies 250 Hz and 500 Hz; however, estimated sound pressure level is 3 dB higher than it should be according to NR criteria at 1000 Hz. It is in user design to taking one of or both criteria into consideration.

By considering the previous case which all rectangular ducts were taken as lined, lining implementation of rectangular ducting of return side caused over design. Moreover, it is seen that duct lining is very effective in the noise control. It is especially very effectual for higher frequencies. Focusing on the Table 5.17 and Table 5.18 together, lining implementation does not have a considerable effect in the noise reduction at frequencies 63 Hz and 125 Hz. However, 7 dB reduction is observed at 250 Hz and noise reduction level increases as frequencies getting higher. In addition, effect of lining practices according to octave band frequencies can be observed from Table 3.14. Insertion loss of unlined and lined elbow are slightly differed from each other at lower frequencies while the difference reaches 7 dB for higher frequencies. Therefore, duct lining practices can be advantages method for reducing the HVAC system noise levels except for lower frequencies. There are different methods the lower frequency induced rumble noise. Plenum implementation can be used for the HVAC design that lower frequency noise is dominant.

5.2.1.2. AHRI SPL Predictor Result of the Hospital Private Room #2

HVAC system design of the second hospital private room was considered. Top view of the room with HVAC system design can be seen in Figure 5.19.

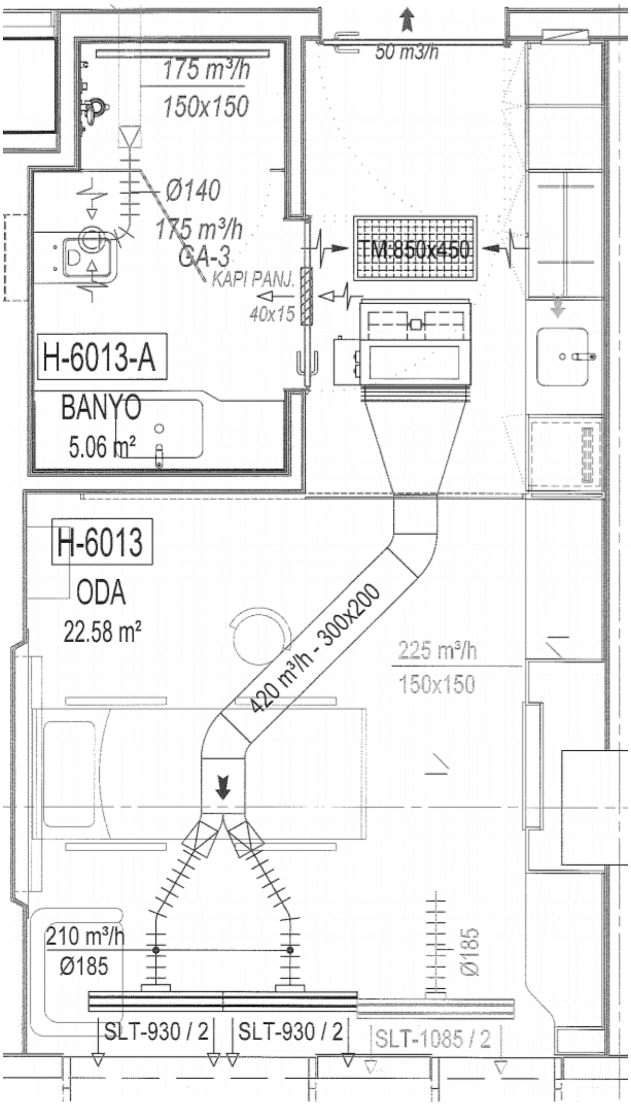


Figure 5.19. HVAC System Design of the Hospital Private Room#2

An FCU is positioned in the entrance of the room in a ceiling. Rectangular ducting exists for the blow side while there is not any ducting system for the suction side. Suction procedure is performing free form the ducting system; that is, air suctioning is performed in a closed region where FCU positioned inside the ceiling. HVAC system details of the room used in the AHRI SPL Predictor program can be seen in Table 5.7

Table 5.7. *AHRI SPL Predictor Data for Hospital Private Room#2*

Path No	Sound Path Element
1	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
2	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 0,3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 2 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 0,6 m long
	Branch Power Division B/T=0.4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	End Reflection Factor- 200mm diameter duct
	Space effect- Room Volume: 100m^3, 1,5 m distance
3	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 0,3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 2 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 0,5 m long
	Branch Power Division B/T=0.4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	Transmission Loss-Non metalic Flexible Duct 200mm diameter
	Ceiling/Space Effect-Gypsum Board Tile, Type 6

Table 5.7 continued

Path No	Sound Path Element
4	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 0,3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 2 m long
	Duct Breakout Loss-Rectangular Duct 300 mm x300 mm
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
5	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 0,3 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 2 m long
	Tee Loss-Unlined Elbows with Turning Vanes 250 mm
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 300 mm x200 mm, 0,5 m long
	Duct Breakout Loss-Rectangular Duct 300 mm x300 mm
	Ceiling/Space Effect-Gypsum Board Tile, Type 6

First path is to calculate sound transmitted through the casing to the ceiling plenum. Manufacturer's casing radiated sound power data is necessary for that path. However, manufacturer provided only averaged sound power data. Therefore, this sound power data is used for in the estimation. Moreover, FCU is positioned in a ceiling. Ceiling effect is included in the path.

Second path is discharge path because of the rectangular air outlets with dimensions 930cm and 100cm positioned at the end of flex ducting having a diameter of 185cm. Starting from the sound source, insertion loss of three different length rectangular ducts with 300 mm width and 200 mm height. There are elbows between ducts; therefore, tee losses of these elbows are also included. There is a branch after 0.6m long rectangular duct. Brach power division is added to the calculation. After that, insertion loss of flex ducting is considered. Space effect of the room having approximately 95 m3 volume is included after end reflection source since sound transmitted through the room after leaving the air outlet.

Third, fourth and fifth sound path are transmission paths. 0.3 m long rectangular ducting's transmission loss is neglected since duct length is too small; therefore, its contribution is to sound attenuation is not effective. Third path includes flex duct's breakout sound while fourth and fifth path including transmission loss of rectangular ducts with length of 2 m and 0.5 m accordingly.

As it can be seen from the Figure 5.20 design is out of RC and NR limits. According to RC criteria, overdesign case was observed for lower frequencies. On the other hand, considering NR, sound pressure level is over the limit at 500 Hz. If the estimated data at 500 Hz is one decibel lower, then the design would be within the NR limits.

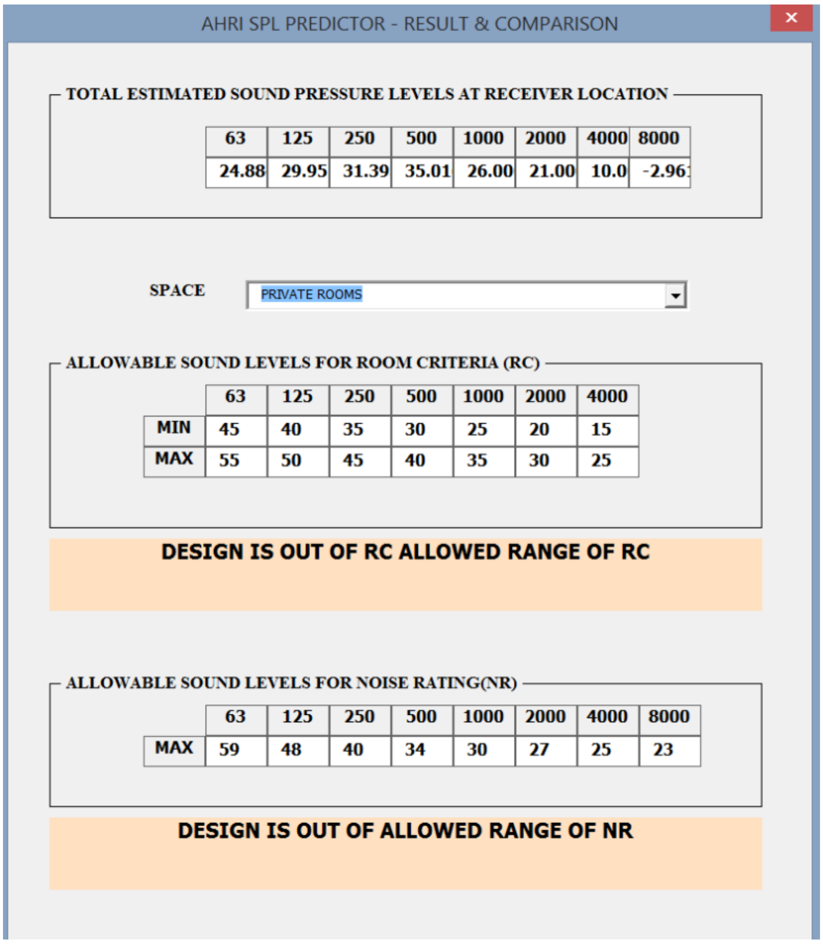


Figure 5.20. AHRI SPL Predictor Outcome of the HVAC Design Hospital Private Room#2

5.2.1.3. AHRI SPL Predictor Result of the Hospital Private Room #3 & 4

Third and fourth hospital private rooms have the same room geometry and accordingly the same HVAC system design. Therefore, only one sound pressure level estimation procedure on AHRI SPL Predictor program was performed for these two rooms. Table 5.8 shows the HVAC system design details of the rooms. HVAC system design of those rooms is very similar to the second hospital private room HVAC system design. FCU is positioned in the entrance of the rooms and rectangular ducting exists only for the blow side.

Table 5.8. *AHRI SPL Predictor Data for Hospital Private Room#3 & 4*

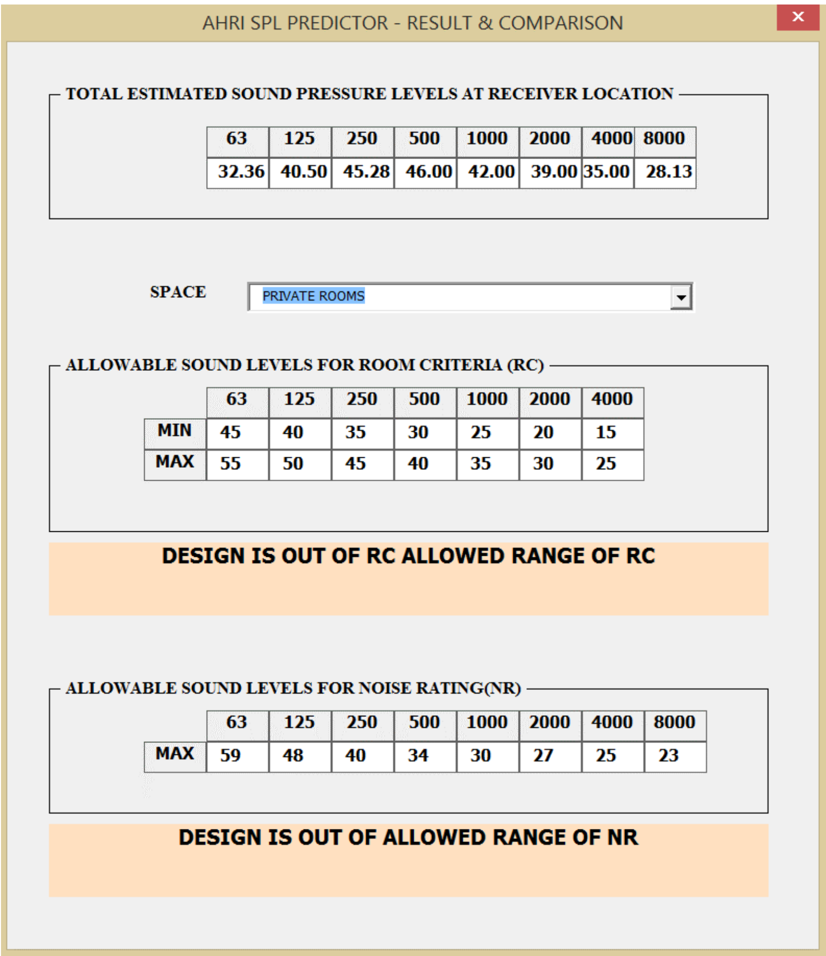
Path No	Sound Path Element
1	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
2	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 450 mm x250 mm, 2,8 m long
	Branch Power Division B/T=0.4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	End Reflection Factor- 200mm diameter duct
	Space effect- Room Volume: 68m^3, 1,5 m distance
3	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 450 mm x250 mm, 2,8 m long
	Branch Power Division B/T=0.4
	Insertion Loss-Flexible Duct 200mm diameter, 0.9m long
	Transmission Loss-Non metalic Flexible Duct 200mm diameter
	Ceiling/Space Effect-Gypsum Board Tile, Type 6
4	Manufacturer Sound Power Data
	Environmental Adjustment Factor
	Insertion Loss-Straight Lined Sheet Metal Rectangular Duct 450 mm x250 mm, 2,8 m long
	Duct Breakout Loss-Rectangular Duct 450 mm x 250 mm
	Ceiling/Space Effect-Gypsum Board Tile, Type 6

As in the second hospital room, first path is casing radiated sound path. Casing radiated sound power data provided by manufacturer is required; however, manufacturer averaged sound power data is available. Therefore, the averaged sound power data is used in the calculations. Since FCU is positioned in a ceiling, ceiling effect is added in the estimation.

Air outlets are used after the flex ducting in the room. Second path includes end reflection loss of air outlets with dimensions of 950mm and 100mm. Before air terminals, insertion loss of 2.8 m rectangular duct having width of 450mm and height of 250mm and also insertion loss of flexible duct with 200mm diameter. Moreover, there is a branch before flexible ducting; therefore, its effect is included. Space effect is also included for the hospital private rooms of approximately 105 m3.

Third and fourth path are rectangular and flexible duct transmission loss paths. Since all of the ducting is placed in the ceiling, ceiling space effect is included after addition of transmission losses.

Estimated sound pressure levels by AHRI SPL Predictor can be seen in Figure 5.21 HVAC design is out of allowable ranges of RC and NR. Noise reduction is necessary for all frequencies. According to NR limitation, design has expectable sound pressure levels at lower frequencies; 63 Hz and 125 Hz. However, estimated sound pressure levels are higher than allowable levels for other frequencies. On the other hand, estimated levels are higher than the RC limitation for all frequencies except for 63 Hz. Overdesign condition occurs at 63 Hz.



63	125	250	500	1000	2000	4000	8000
32.36	40.50	45.28	46.00	42.00	39.00	35.00	28.13

	63	125	250	500	1000	2000	4000
MIN	45	40	35	30	25	20	15
MAX	55	50	45	40	35	30	25

	63	125	250	500	1000	2000	4000	8000
MAX	59	48	40	34	30	27	25	23

Figure 5.21. AHRI SPL Predictor Outcome of the HVAC Design Hospital Private Room#3 & 4

5.2.2. Hospital Private Room Measurements

Sound level meter defined by Standard International Electrotechnical Commission (IEC) 61672 with Class1 performance category is used and it is equipped with octave band filtering capability will be used to measure sound levels. IEC 61672 Standard covers three kinds of sound measuring device and provides electro acoustical performance specifications of these instruments. They are time-weighting sound level meter, integrating-averaging sound level meter and integrating sound level meter. Exponential time-weighted and frequency-weighted sound levels are measured by time-weighting sound level meters while time-averaged and frequency-weighted sound levels are measured by integrating-averaging sound level meters. On the other hand, frequency-weighted sound exposure levels are measured by integrating sound level meters. There exist two performance categories: class 1 and class 2. Even if these performance categories have the same design goals, their tolerance limits and the range of operational temperature can be different from each other. The tolerances for Class 1 are tighter than for Class 2. Lower levels can be measured by Class 1 sound level meter since microphone capsule of this sound level meters is more sensitive [67]. Therefore, they are suitable for the measurements areas where low frequency noise dominates. Hospitals are one of the places where sound in lower frequency distributions is generally produced by hospital sound sources.

ISO 1996-1 and-2 measurement standards were followed for noise level measurements whereas ISO 16283-1 and -2 were taken as references for measurement of sound isolation characteristics of partitions and floors. ISO 1996 series provides an international harmonization of description methods, environmental noise measurement and assessment from all sources. ISO 1996-1 describes methods and basic assessment procedures applicable for various noise sources, separate or in combination [68]. Determination of sound pressure levels are explained in ISO 1996-2. It is generally used for outdoor measurement, but it can also be used as guidance for indoor measurements as well. It is also applicable for all kinds of sound sources [69]. ISO 16283-1:2014 identifies actions for the airborne sound insulation determination between two rooms in a building by sound pressure level measurements. These procedures are valid for room volumes in the range from 10 m3 to 250 m3 in the frequency range from 50 Hz to 5 000 Hz [70].

Considering the sound level meter used in the measurements in detail, handheld analyzer type 2250, which is a single channeled and general-purpose hand-held analyzer was used. Frequency analyses template was chosen to get 1/3 octave band distribution of sound pressure level measurement of HVAC system noise. A-weighting frequency weighting is used since the response of human ear at medium-range levels is resembled better with these weighing and international and national standards, and guidelines specifies the associated sound levels in A-weighting [71]. It is suggested by EPA that a microphone should be 1.2 to 1.5 meters high from the ground or floor, located at least 1.2 meters from any acoustically reflecting surface, and placed on a tripod or held at arm's length to avoid reflections [72]. Turkish Noise Legislation has fixed the microphone height at 1.5 m since 2005.

Focusing on the calculations made for the measurements, total sound pressure level of HVAC system is calculated by logarithmically subtracting measured background noise data from averaged value of the two measurements performed after HVAC system is powered. Equation 5.1 represents the calculation.

$$L_{HVAC} = 10\log(10^{\frac{L_{total}}{10}} - 10^{\frac{L_{background}}{10}}) \tag{5.1}$$

$$L_{total} = \frac{L_1+L_2}{2} \tag{5.2}$$

where

L_{HVAC}: HVAC sound pressure level at a specific frequency

L_{total}: Total measured sound pressure level at a specific frequency

$L_{background}$: Measured background sound pressure level at a specific frequency

L_1: First measured sound pressure level at a specific frequency

L_2: Second measured sound pressure level at a specific frequency

5.2.2.1. Measurement of Hospital Private Room #1

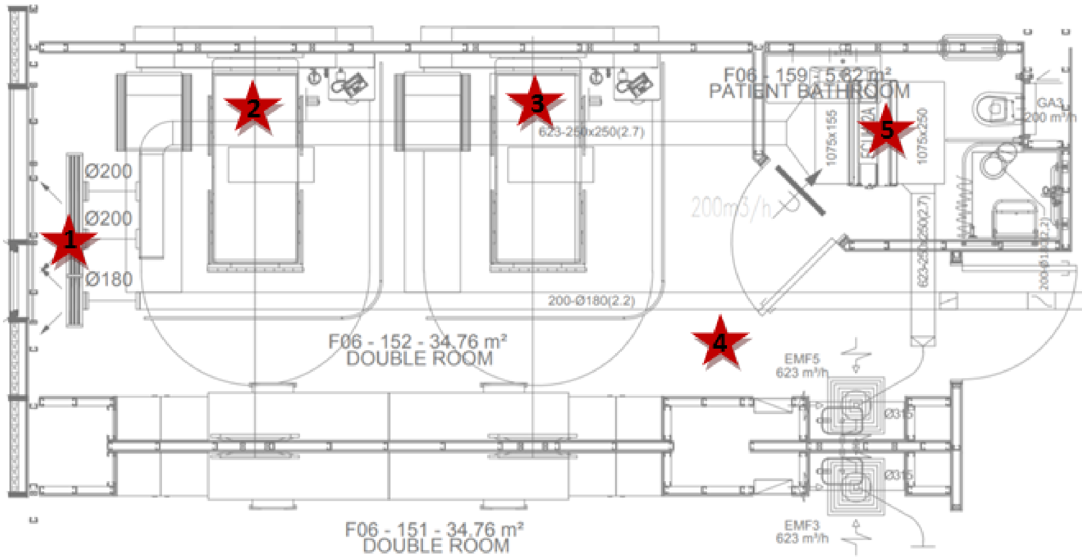


Figure 5.22. Measurement point of Hospital Private Room#1

HVAC sound pressure level measurements of a hospital private room were held on 22nd of August 2019, hours in between 11:00 -12:30. Measured room was not furnished. Only the suspended ceiling was in existence. Therefore, it was a controlled atmosphere and suitable space to measure HVAC noise. Moreover, measurements were performed at five points in the room as illustrated in Figure 5.22. Microphone was kept approximately 1.5 meters high from the floor level and 1 meter away from the walls. All recordings lasted thirty seconds. Firstly, background noise was measured at these five points. Then, FCU was energized to work at maximum power. One after the other of two measurements was held at these five points. Measurements taken from all points and shots of room photos are given in the appendix part. Point 3 shown in Figure 5.22 is chosen for the comparison procedure since it is the place where receiver or the patient is located. Therefore, the calculations, measurements held at that point was used.

Table 5.9. *Measured and Estimated HVAC Sound Pressure Level in Hospital Private Room#1*

Octave Band Center Frequency [Hz]	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Measured HVAC System Noise Levels [dB]	41,62	36,87	40,05	39,54	37,85	30,64	23,99	13,12	6,08
Estimated HVAC Sound Levels [dB]	-	49	44	41	33	33	24	18	9
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

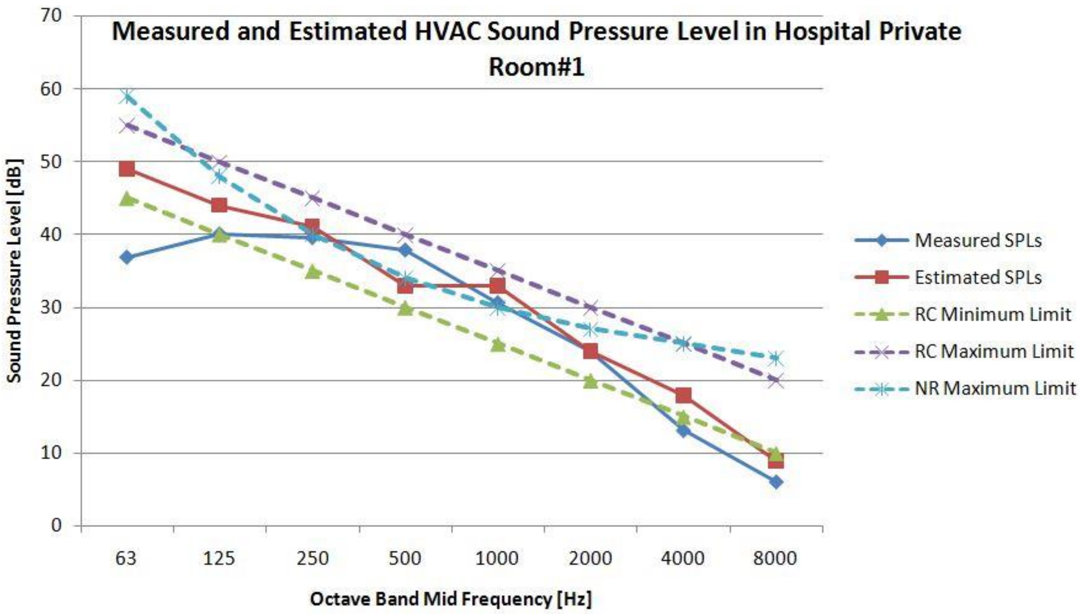


Figure 5.23. Measured and Estimated Sound Pressure Level of Hospital Private Room#1

Table 5.9 and Figure 23 show the measured and estimated HVAC sound pressure levels of the hospital private room. It is stated in AHRI Standard 885 that uncertainties of less than 5 dB are generally seen when AHRI is used [2]. This statement is observed for all frequencies except for 63 Hz. Even if there are many assumptions including manufacturer's sound power data at 63 Hz, the difference between the results is worth considering and requires more comprehensive study.

AHRI Standard 880, which is the previous sound pressure estimation standard before AHRI Standard 885 is published, does not have any data for 63 Hz; that is, does not estimate sound pressure level at 63 Hz. Data for 63 Hz is newly added to AHRI Standard 885; therefore, data's being new and not mature enough could be one of the effective factors of having considerable difference between measured and estimated data at 63 Hz.

Measured sound pressure levels at five points can be seen from Table 5.10. It is expected to have higher sound pressure levels at point 5 since this point is right below the sound source, FCU. Sound pressure levels at other points are similar to each other comparing the measured data at point 5.

Table 5.10. *Measured Sound Pressure Level in Hospital Private Room#1*

Octave Band Center Frequency [Hz]	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Measured HVAC System Noise Level at point 1[dB]	39,71	32,08	39,23	39,81	38,19	31,56	24,98	13,18	2,54
Measured HVAC System Noise Level at point 2[dB]	39,71	32,08	39,23	39,81	38,19	31,56	24,98	13,18	2,54
Measured HVAC System Noise Level at point 3[dB]	41,76	36,87	40,05	39,54	37,85	30,64	23,99	13,12	6,08
Measured HVAC System Noise Level at point 4[dB]	41,13	39,29	39,90	40,52	37,51	30,87	24,48	12,74	3,21
Measured HVAC System Noise Level at point 5[dB]	42,13	43,89	51,16	48,41	43,98	38,35	33,40	22,94	13,32
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

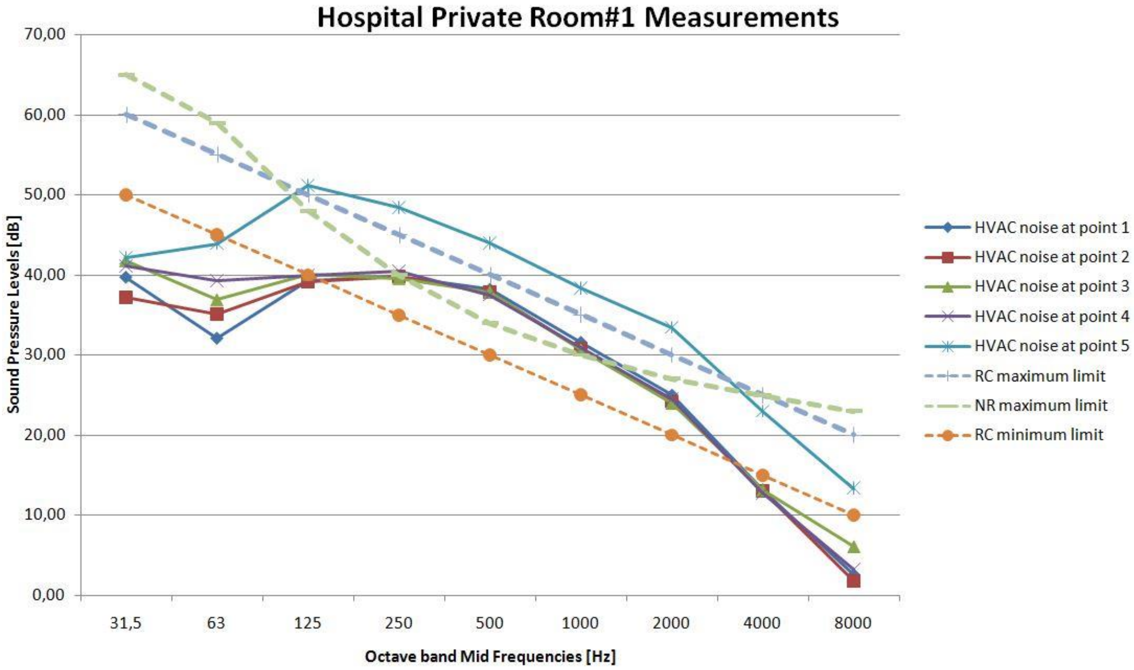


Figure 5.24. Hospital Private Room#1 Measurements

5.2.2.2. Measurement of Hospital Private Room #2

Sound pressure level measurements of another hospital private room were held in 15th September 2019, hours in between 12:00 -13:30. In this case, a hospital private room in service was considered. Therefore, different from the other case, room was furnished including bed, sofas, curtains and TV. Room photos can be seen in appendices. In addition, remarkable background noise generated by traffic, human walking, human talking, door closing, phone or equipment beeping existed. Similar measurement procedures were followed. Measurements were performed at five points marked in the Figure 5.23 Microphone position was also the same: approximately 1.5 meters high from the ground level and 1 meter away from the walls. Firstly, background noise is measured at these five points for thirty seconds. Then, HVAC system was energized at maximum power and two serial measurements is held at these five points for thirty seconds. There existed too many background noise sources strictly affecting the measurements. Moreover, considering the time of the measurements, it was lunch time when background noise could reach its maximum values. Therefore, another thirty seconds measurement for the background noise was performed after lunch time by shutting down the ventilation system. Another important point observed in the measurements that corridor HVAC system noise was remarkably high, in fact; it could be heard from the room while the door was closed. Therefore, this noise contributed the low frequency noise content of the room and felt rumble noise in the room could be more disturbing than estimated.

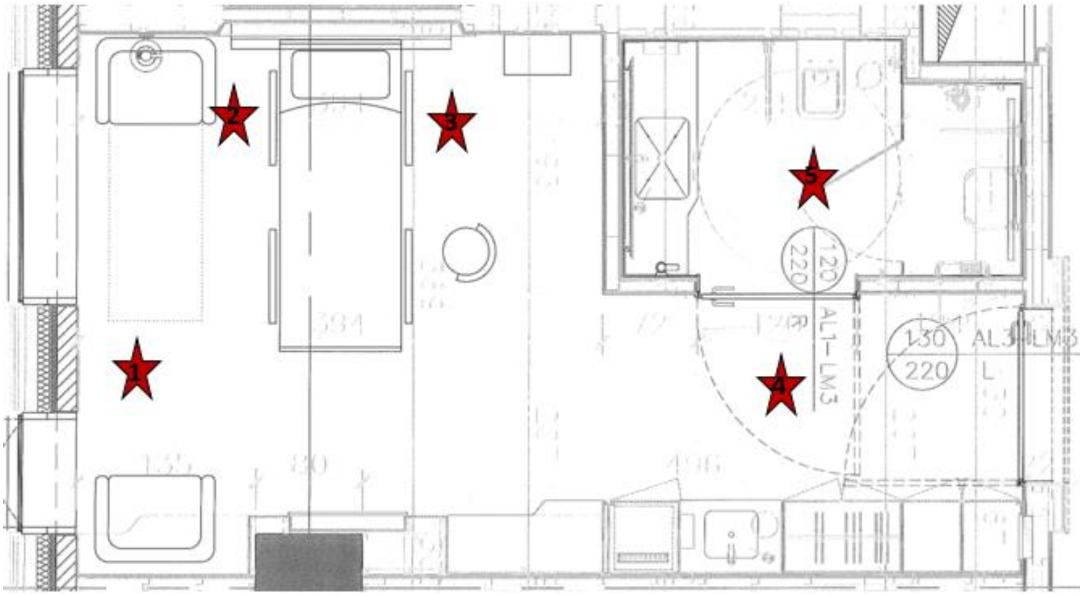


Figure 5.25. Measurement point of Hospital Private Room#2

Point 2 shown in Figure 5.25 was selected for the comparative evaluation procedure since it is the place that patient is in the room. Measurements held at that point were used for validation. For the selection of background noise, all of the measured data was considered. Point 2 measurements, together with the point 3 measurements were used for background noise. Total sound pressure level of HVAC system was calculated by using Equation 5.1 and 5.2 as in the hospital private room#1 calculations.

Table 5.11 shows estimated and measured sound pressure levels in the hospital private room while Table 5.12 showing all measurements held in the room. Considering Table 5.11, more than 5 dB differences were observed for some frequencies. Approximately 9 dB differences were noted at 63 Hz and there are 7 dB differences between estimation and measurement at 500 Hz. Estimated sound pressure level at 63 Hz is 9 dB lower the measurement at 63 Hz. However, estimation is 7 dB higher than the measurement at 500 Hz. The explanation stated for the differences between data at 63 Hz for the hospital private room#1 is valid for this hospital private room.

Manufacturer’s sound power data has its maximum value at 500 Hz. The information on the name of manufacturer and model of FCU was taken from the building technicians; and, available internet source was used for the manufacturer’s sound power data. Therefore, sound power data of FCU used in that room was not taken directly from the company. There may be differences between the current data and the one available on the internet, which could result in more than 5 dB differences between measured and estimated value.

Focusing on the Figure 26 showing measured and estimated sound pressure levels with NR and RC criteria, design is not exceeding allowable limits defined by NR criteria according to the measurements. Moreover, measurements are below the minimum allowable sound pressure levels of RC criteria. Therefore, overdesign condition occurs by looking the measurements.

Figure 27 represents sound pressure levels measurements at five points in the room and allowable sound pressure levels defined by RC and NR criteria. Measured levels are very close except for point 4 where FCU is right below on it. Measurements held at point 4 where maximum sound pressure levels are obtained are not exceeding NR criteria. Therefore, it is not expected to have annoyance on patients and hospital because of HVAC system noise since sound pressure levels are tolerable by comparing measurements with the NR criteria.

Table 5.11. *Measured and Estimated HVAC Sound Pressure Level in Hospital Private Room#2*

Octave Band Center Frequency [Hz]	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Measured HVAC System Noise Levels [dB]	42,14	35,86	31,42	31,86	28,11	22,30	15,93	13,15	5,3
Estimated HVAC Sound Levels [dB]	-	24.88	29.95	31.39	35.01	26.00	21.00	10.00	0
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

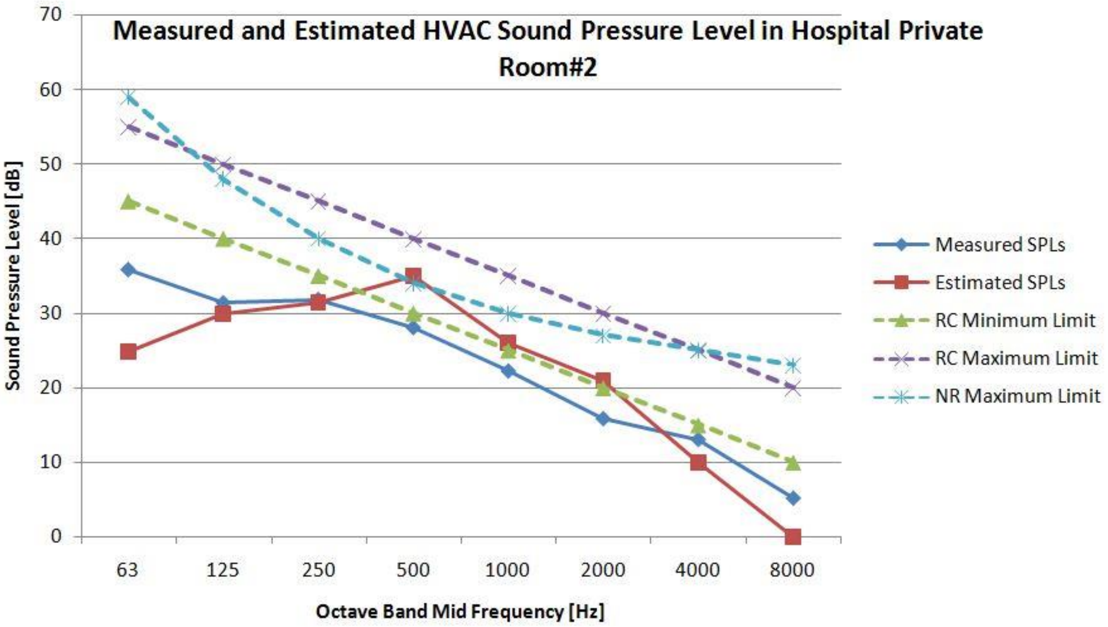


Figure 5.26. Measured and Estimated Sound Pressure Level of Hospital Private Room#2

Table 5.12. *Measured Sound Pressure Level in Hospital Private Room#2*

Octave Band Center Frequency [Hz]	31,5	63	125	250	500	1000	2000	4000	8000
Measured HVAC System Noise Level at point 1[dB]	46,76	33,24	33,83	29,86	28,11	22,19	19,16	11,37	3,28
Measured HVAC System Noise Level at point 2[dB]	42,14	35,86	31,42	31,86	28,11	22,30	15,93	13,15	5,31
Measured HVAC System Noise Level at point 3[dB]	42,83	35,23	33,79	32,37	29,34	22,68	16,88	13,17	6,50
Measured HVAC System Noise Level at point 4[dB]	49,49	36,68	38,37	36,59	33,56	28,03	21,88	19,37	13,24
Measured HVAC System Noise Level at point 5[dB]	43,97	39,42	33,26	33,31	30,16	24,56	18,02	14,07	7,58
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

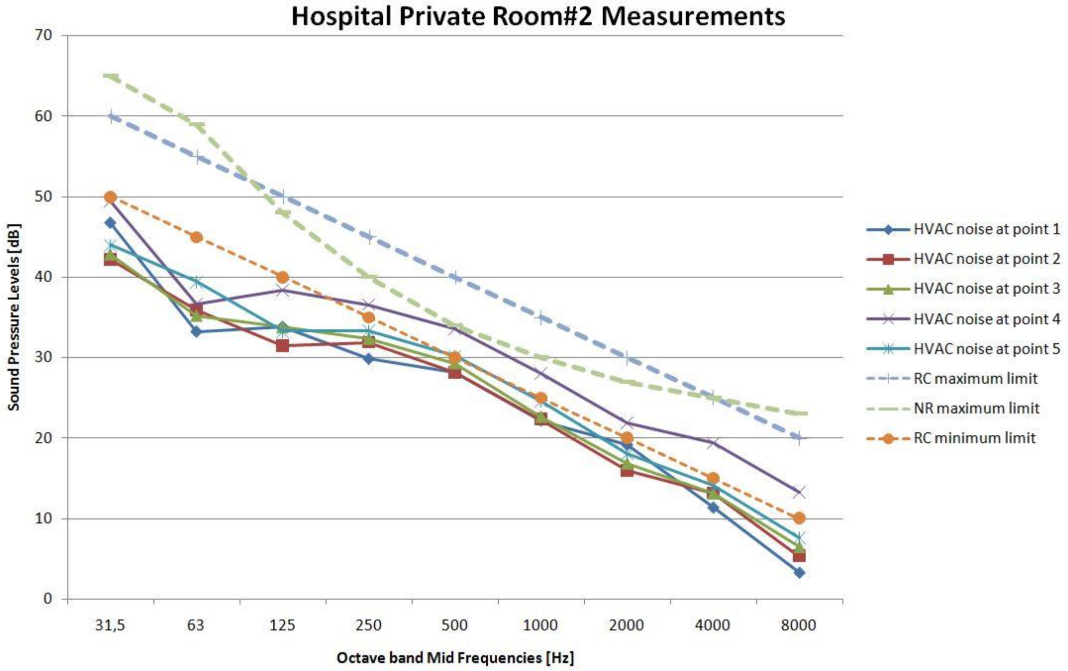


Figure 5.27. Hospital Private Room#2 Measurements

5.2.2.3. Measurement of Hospital Private Room #3

The third hospital private room where sound pressure level measurements were held on 28th September 2019, between at 12:30 -13:00 hours. It is an in-service hospital private room; that is, furnishing exists in the room. However, the floor that the room placed was empty. Therefore, controlled environment was reached, and measurements can be held easily. Room photos were illustrated in appendices. Similar measurement procedures were followed as in the other measurements. Measurements performed at five points. Measurement points are the same as in the hospital private room#2, Figure 5.25. Point 3 was selected for the comparison measured and estimated of the sound pressure levels at the receiver location. Table 5.13 shows these values. Disparity of less than 5 dB was observed for all frequencies except for the 63 Hz. Estimated sound pressure level is approximately 14 dB lower than the measurements at 63 Hz.

Figure 28 shows measured and estimated sound pressure levels, and design criteria of NR and RC. Measurements are exceeding the design limits for all frequencies except for lower frequencies. It can be concluded that HVAC design of that room can cause annoyance on patients and hospital staff since measured sound pressure levels significantly exceed design limits.

Table 5.14 demonstrates measurement result at five points. The nearest point to FCU is point 4. Because of that reason, considerably high values were obtained at that point. This can also be seen in Figure 29. Point 4 measurements are much higher than the measurements held at other points.

Table 5.13. *Measured and Estimated HVAC Sound Pressure Level in Hospital Private Room#3*

Octave Band Center Frequency [Hz]	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Measured HVAC System Noise Levels [dB]	50,64	47,00	40,30	40,25	42,52	42,56	40,12	33,30	25,80
Estimated HVAC Sound Levels [dB]	-	32,36	40,50	45,28	46,00	42,00	39,00	35,00	28,13
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

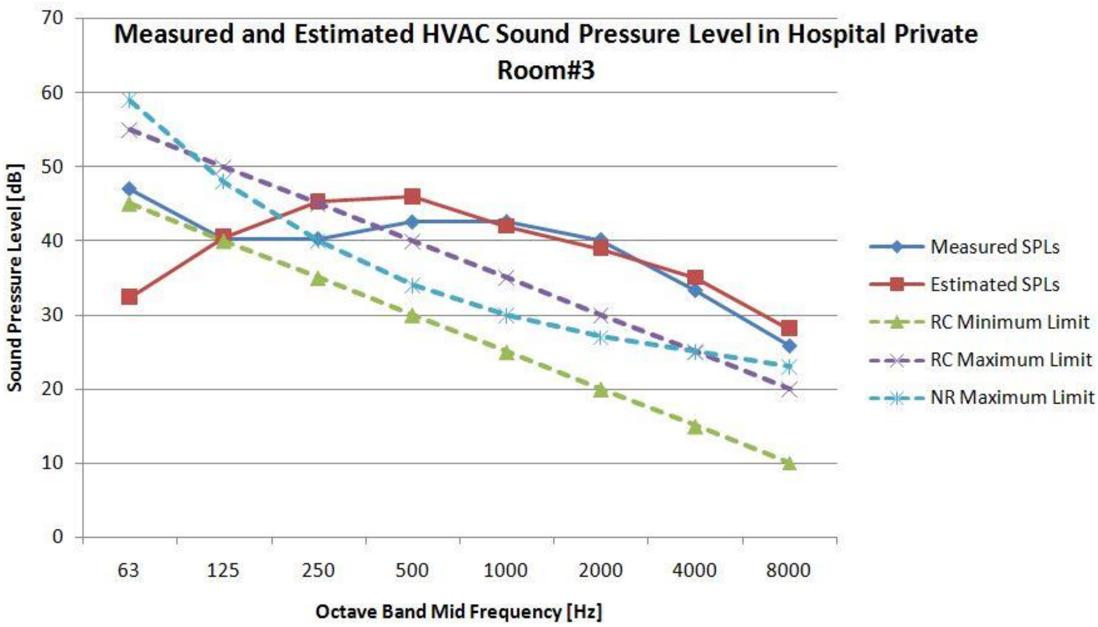


Figure 5.28. Measured and Estimated Sound Pressure Level of Hospital Private Room#3

Table 5.14. *Measured Sound Pressure Level in Hospital Private Room#3*

Octave Band Center Frequency [Hz]	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Measured HVAC System Noise Level at point 1[dB]	50,75	49,39	43,05	40,45	43,60	41,45	39,63	32,85	24,61
Measured HVAC System Noise Level at point 2[dB]	52,40	41,90	41,46	41,52	40,16	42,89	38,54	32,93	24,92
Measured HVAC System Noise Level at point 3[dB]	50,64	47,00	40,30	40,25	42,52	42,56	40,12	33,30	25,80
Measured HVAC System Noise Level at point 4[dB]	48,32	44,58	47,18	46,99	45,26	46,07	42,76	34,88	27,15
Measured HVAC System Noise Level at point 5[dB]	47,41	41,71	40,95	38,30	42,70	42,74	38,27	31,29	23,62
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

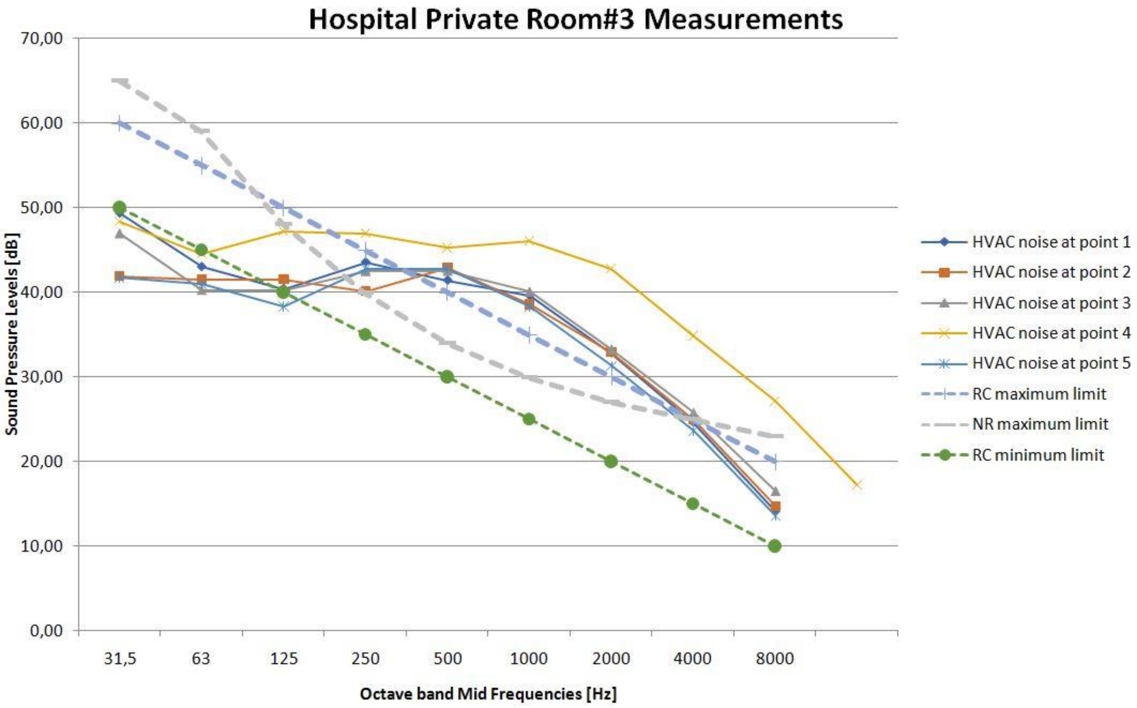


Figure 5.29. Hospital Private Room#3 Measurements

5.2.2.4. Measurement of Hospital Private Room #4

Sound pressure level measurements of fourth hospital private room were held on the 28th of September 2019, hours in between 13:30 -14:00. This hospital private room has the same geometrical dimensions as the hospital private room #3. However, it was an occupied floor. Room photos can be seen in appendices. The same measurement procedures were followed. Measurements were performed at five points as in the hospital private room #3.

Measured and estimated values are presented in Table 5.15 and Figure 30. Like other hospitals, there are significant differences between values at 63 Hz. Measured sound pressure level is approximately 12 dB higher than the estimation. Since this hospital room has the same room geometry and HVAC system design with the hospital private room#3, the same evaluations and conclusions can be made.

Table 5.16 and Figure 31 demonstrate measurement results at five points. Higher levels are observed at point 4 where FCU is positioned above it.

Table 5.15. *Measured and Estimated HVAC Sound Pressure Level in Hospital Private Room#4*

Octave Band Center Frequency [Hz]	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Measured HVAC System Noise Levels [dB]	48,29	44,89	42,35	41,62	44,20	42,68	41,16	37,61	29,67
Estimated HVAC Sound Levels [dB]	-	32,36	40,50	45,28	46,00	42,00	39,00	35,00	28,13
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

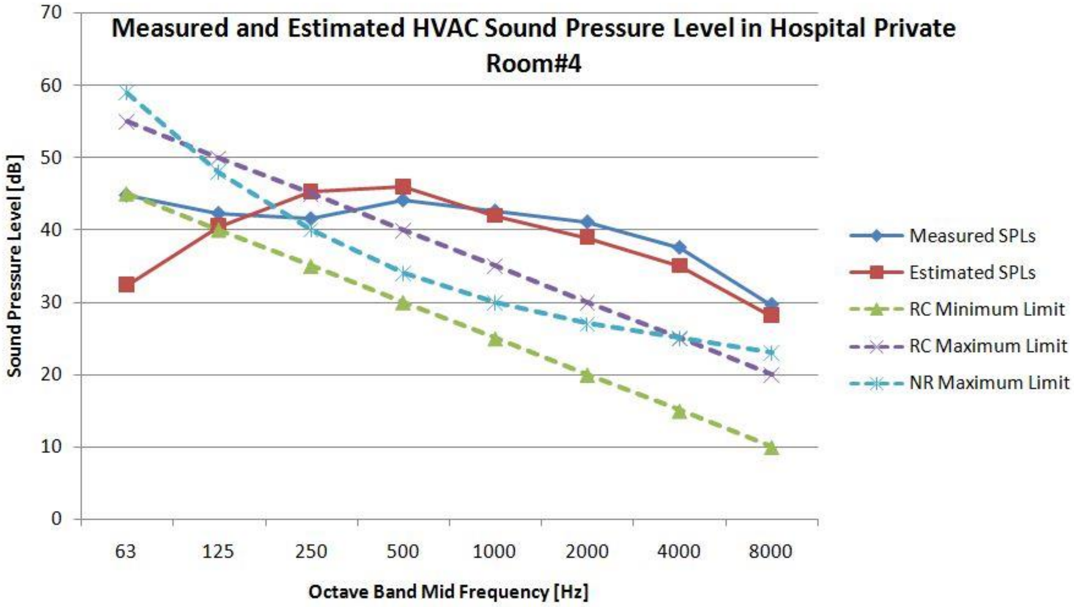


Figure 5.30. Measured and Estimated Sound Pressure Level of Hospital Private Room#4

Table 5.16. *Measured Sound Pressure Level in Hospital Private Room#4*

Octave Band Center Frequency [Hz]	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Measured HVAC System Noise Level at point 1[dB]	54,51	50,01	47,38	40,69	46,94	42,15	39,89	36,13	28,12
Measured HVAC System Noise Level at point 2[dB]	51,54	44,00	48,47	45,15	42,36	42,01	39,96	36,84	28,99
Measured HVAC System Noise Level at point 3[dB]	48,29	44,89	42,35	41,62	44,20	42,68	41,16	37,61	29,67
Measured HVAC System Noise Level at point 4[dB]	50,94	46,98	49,33	50,08	47,60	44,43	44,24	40,90	33,67
Measured HVAC System Noise Level at point 5[dB]	53,70	44,06	41,89	41,08	43,57	41,10	40,65	37,06	29,18
NR Criteria Maximum Allowable SPL [dB]	-	59	48	40	34	30	27	25	23
RC Criteria Minimum Allowable SPL [dB]	-	45	40	35	30	25	20	15	10
RC Criteria Maximum Allowable SPL [dB]	-	55	50	45	40	35	30	25	20

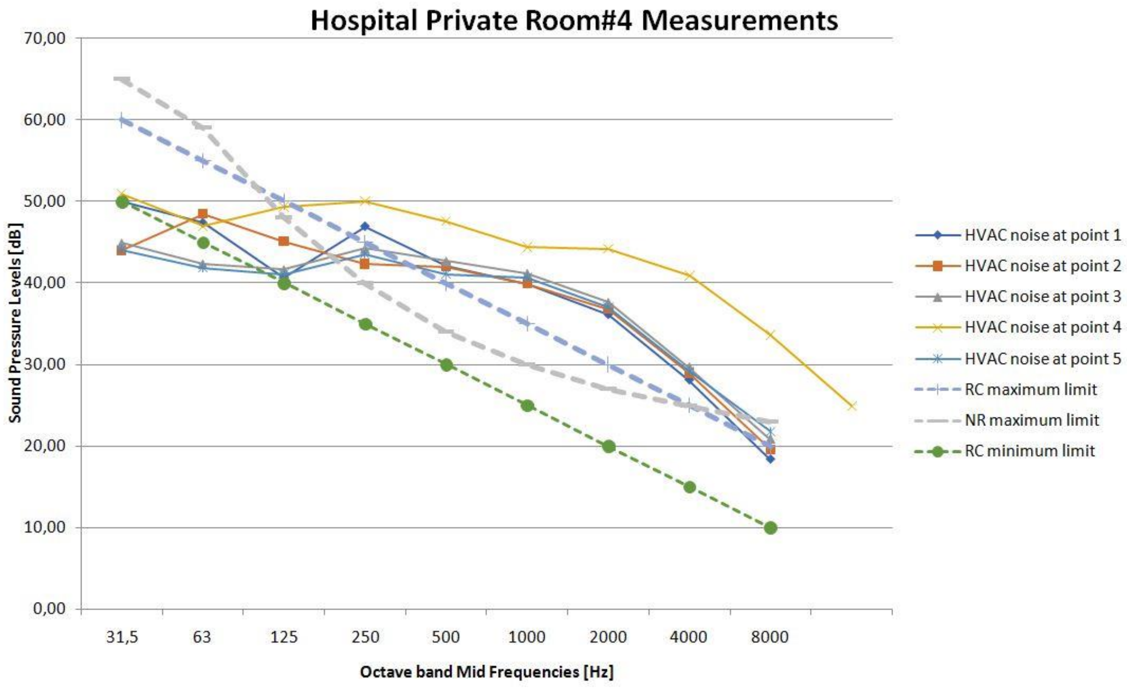


Figure 5.31. Hospital Private Room#4 Measurements

It can be deduced by looking all the four hospital private room measurements that it is quite possible for hospital staff to be disturbed by rumble noise due to low frequency content of HVAC system noise. Criticality of lower frequency content of HVAC system noise can also be seen in Figure 5.24, 5.27, 5.29 and 5.31, showing all measured sound pressure levels at five points with allowable limits defined by NR and RC criteria in the same graphic. There are not any sharp increases or decreases at any frequencies in the figures. Therefore, room modes of hospital private rooms, which have non-rectangular shapes, were not observed at the measured five points. Moreover, the measured point directly performed below the FCU has the highest noise levels and it could be easily separated from the other measurements. Considering the figures, point 5 in the hospital private room#1 and point 4 in the others are the nearest point to the FCU and they have considerable higher sound pressure levels comparing with the other measured points.

Focusing on the Figure 5.23, 5.26, 5.28 and 5.30, estimated sound pressure level at 63 Hz is considerably lower than the measured sound pressure level at 63 Hz except for the hospital private room#1 measurements. As mentioned before first hospital private room did not have any furniture. This condition did not take into consideration in the estimation of sound pressure levels at the receiver location since space effect defined in AHRI Standard only counts in room volume and shortest distance from noise source to the receiver. Inconsistency of between measured and estimated values at 63 Hz; that is, only first hospital private room's having higher measured sound pressure level at 63 Hz, results from not counting the reverberation effect in that room. For reflective unfurnished rooms, classical diffuse-field equation is used. This theory estimates that sound pressure level initially decreases at the rate of 6 dB per doubling of distance with the increase in distance between sound source and point of observation. Reverberant sound field starts to dominate at some point, then sound pressure level remains at a constant level [34]. Considering the space effect in AHRI Standard, doubling the distance results in 3 dB increase in attenuation. It is stated in ASHRAE project, RP755, the reduction in level with increasing distance for a source in the room was found to depend on the inverse of the room reverberation time [73]. The approximate relationship for 250Hz and above is as follows

$$attenuation = 0.9/RT + 0.5dB/distance\ doubling \qquad (5.3)$$

where

RT: reverberation time

Furnished rooms have usually reverberation time about 0.5s [73]. Therefore, estimated sound pressure levels at lower frequencies must be lower than the ones predicted by using AHRI Standard.

Amongst other four measurements, highest sound level was mostly observed at 31,5 Hz. It can be deduced that lower frequency noise is dominant in the measured noise. Considering these case studies held on hospital private rooms, primary sound sources generally used in hospitals have high sound power levels at lower frequencies;

that is, rumble noise due to low frequency content of noise levels are primary noises in the hospitals. Moreover, sound attenuation strategies implemented to have a design within the limits for the HVAC system could end up with over design case for higher frequencies. Therefore, effective estimation method is crucial to have a cost-effective HVAC design which also does not disturb any patient or negatively affect any hospital personnel.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1. CONCLUSIONS

Healthcare buildings are complex interior spaces in terms of maintaining acoustic comfort since there is a considerable increase in environmental noise and hospitals possess many kinds of noise sources which require to be analyzed separately. In addition, healthcare buildings must function as places where people recover and rest comfortably.

HVAC design has an important role in controlling temperature, humidity, air quality and noise level of an interior space. With the construction of new hospitals named Integrated Health Campuses, noise control in hospitals is taken as a serious task to comply with legislative limits stated. In this dissertation, a user-friendly program was developed to predict occupied space sound levels in hospitals by using 2008 Standards of AHRI. VBA program was devised for the reason of its simplicity and availability. User even with a limited knowledge in acoustics performance and HVAC system design data can benefit from AHRI SPL Predictor program by selecting the accurate HVAC system values such as size, length, type and thickness of a duct. At the end, user obtains total estimated sound pressure level and by selecting the design space, an informative message stating whether the design is within or without the limits is presented. It is possible with this program to take measures in the design stage. Therefore, design engineers can utilize this program to be sure about spaces' validity and economy, since over attenuation is costly. Determination of the acoustical requirements of a space provides an efficient HVAC system design.

Validation of program was performed by using the example given in AHRI Standard 885 with some assumptions. The same result calculated by EXCEL program was reached with the software for all octave bands. Hospital space's design limit evaluation was performed in AHRI SPL Predictor program. Therefore, AHRI SPL Predictor correctly estimated and evaluated HVAC system noise in healthcare buildings by using procedure and data of AHRI Standard 885. Effectiveness of AHRI Standard 885 in predicting HVAC noise levels was evaluated by comparing AHRI SPL Predictor total sound pressure level outcome of four hospital private rooms with the measurements performed in those rooms. Uncertainty of more than 5 dB at 63 Hz was observed for all hospital. Low frequency noise is dominant for healthcare building and rumble noise due to low frequency cause annoyance on people, detailed and sophisticated effort is necessary for AHRI Standard 885 to be more beneficial for the hospitals HVAC system design estimation. In addition, there were cases of having more than 5 dB differences between measured and estimated data for other frequency bands, which could be attributed to the validity of the assumptions made in the estimation procedure.

To conclude, AHRI SPL Predictor can be used for the HVAC system design of hospitals in order to have a cost-effective design within in the specified hospital design limits by taking necessary precautions or changes at the design stage. More attentive data is required for the prediction of sound pressure levels at lower frequency distributions for healthcare buildings where the most annoying and effective noise is resulted from the low frequency content.

6.2. RECOMMENDATION FOR FUTURE WORK

There might be several implementations for this study. It is observed with the comparison of measured and estimated sound pressure levels that AHRI Standard 885 lacks the accuracy to estimate noise level at 63 Hz. More comprehensive study on low frequency data in AHRI Standard 885 would be beneficial for the places where lower frequency distribution is leading to noise levels. Moreover, there is not any practical procedure to predict the noise level below than 63 Hz. Considering the measurements held in hospital private rooms, remarkable noise was noted at 31,5 Hz. Apart from reliability of these measurements, inconsistencies at low frequencies can arise due to interactions of measurements with room acoustical modes. Therefore, rumble noise is the leading noise and it is probably to be annoying for the hospital occupants. There is a necessity of having estimation methods for lower frequencies to account for the acoustical modal behavior of hospital spaces. Since rumble noise is a consequence of pressure differences between supply and return ducts, it is essential to have a noise prediction method of HVAC design. Measurement of low frequency noise, ranging from approximately 10 Hz to 200 Hz, presents difficulties and constraints on the equipment as well as methodology.

AHRI SPL Predictor program only includes healthcare building spaces to evaluate. Therefore, interface is designed to serve this purpose. It could be possible to include other spaces or specialize it for different spaces. Additional coding and user form modifications are required. AHRI SPL Predictor can serve as a starting point or suggestion stage for the user interface part for other spaces.

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APPENDICES

HOSPITAL PRIVATE ROOM MEASUREMENTS AND ROOM PICTURES

Table 0.1. *A. Hospital Private Room#1 Measurements*

Measurement Points	**Laeq [dBA]**	**Elapsed time[s]**	**Octave Band Center Frequency, Hz**							
			63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Background noise, point1	26,92	32	18,63	23,79	23,6	20,38	15,34	12,87	9,99	8,19
Background noise, point2	24,96	31	21,94	22,27	17,59	15,7	17,07	12,3	9,41	8,97
Background noise, point3	23,83	31	19,57	21,59	16,17	13,27	15,45	11,86	9,25	8,25
Background noise, point4	24,96	31	24,25	20,54	19,62	13,94	14,64	13,89	10,55	10,95
Background noise, point5	24,83	30	15,99	13,4	13,9	15,38	17,73	13,04	9,12	8,17
Total noise, point1-1st measurement	43,55	30	32,59	39,33	40,39	38,61	31,92	25,38	14,83	9,1
Total noise, point1-2nd measurement	43,23	30	31,95	39,37	39,43	37,91	31,4	25,09	14,93	9,37
Total noise, point2-1st measurement	43,23	30	31,95	39,37	39,43	37,91	31,4	25,09	14,93	9,37
Total noise, point2-2nd measurement	42,4	32	38,66	39,01	40,25	37,81	30,51	23,83	14,17	10,07
Total noise, point3-1st measurement	42,52	34	37,01	40,01	39,99	37,95	30,89	23,97	14,61	10,1
Total noise, point3-2nd measurement	42,44	31	36,9	40,21	39,13	37,79	30,64	24,52	14,62	10,52
Total noise, point4-1st measurement	43,16	32	39,57	39,57	40,55	37,75	31,27	25,07	15,49	11,3
Total noise, point4-2nd measurement	42,9	30	39,27	40,33	40,57	37,31	30,67	24,61	14,1	9,01
Total noise, point5-1st measurement	50,3	31	44,13	51,19	48,36	43,68	38,27	32,98	22,63	15,32
Total noise, point5-2nd measurement	50,58	31	43,67	51,14	48,46	44,3	38,5	33,9	23,61	13,63

Table 0.2. *B.* *Hospital Private Room#2 Measurements*

Measurement Points	Laeq [dBA]	Elapsed time[s]	Octave Band Center Frequency, Hz							
			63	125	250	500	1000	2000	4000	8000
Background Noise at point 1	29,62	61	43,01	34,83	28,28	32,5	30,65	20,55	16,8	15,51
Background Noise at point 2	33,99	60	43,42	35,23	27,68	32,23	32,03	28,67	23,14	19,69
Background Noise at point 3	30,95	60	40,76	43,74	32,57	34,63	24,88	19,44	17,72	17,8
Background Noise at point 4	35,86	61	41,2	39,87	37,46	35,27	35,47	25,11	22,25	22,65
Background Noise at point 5	31,1	61	43,97	36,82	31	24,73	24,66	23,46	20,59	15,27
Background Noise at point 1, measurement#2	29,63	31	49,16	33,9	27,46	35,72	26,15	19,25	16,29	14,41
Background Noise at point 1, measurement#3	35,33	32	44,7	34,71	26,93	33,54	29,41	18,02	15,82	14,4
Background Noise at point 2, measurement #2	35,53	30	43,99	33,72	27,38	31,37	27,37	20,31	18,53	16,06
Background Noise at point 3, measurement#2	35,03	31	42,9	31,83	32,04	34,48	24,29	17,32	17,85	15,87
Background Noise at point 4, measurement#2	34,94	30	44,93	40,9	36,95	36,59	28,76	18,92	18,67	17,79
Background Noise at point 5, measurement#2	35,28	31	51,26	36,51	28,03	31,25	26,72	21,61	18,74	14,18
Total noise, at point 1	35,39	31	52,72	46,95	33,56	36,9	32,34	27,97	22,56	20,96
Total noise, at point 1, measurment #2	39,14	30	52,47	47,1	34,74	36,5	32,96	29,07	23,62	19,86
Total noise, at point 2	39,09	30	44,53	42,81	36,36	34,24	33,18	28,83	23,15	18,22
Total noise, at point 2, measurement #2	37,14	30	45,14	42,64	36,41	34,57	33,18	28,2	23,22	18,27

Table 0.2. B.

Total noise, at point 3	37,1	30	43,43	43,13	35,79	35,84	33,85	29,69	23,06	17,99
Total noise, at point 3, measurement #2	29,46	31	43,57	43,53	35,86	35,67	33,27	29,61	23,92	19,66
Total noise, at point 4	29,29	30	45,41	49,18	36,98	39,2	36,95	33,61	28,68	22,79
Total noise, at point 4, measurement #2	29,74	30	45,04	50,02	37,26	39,12	37,22	33,74	27,89	22,4
Total noise, at point 5	31,93	30	52,76	45,02	28,47	35,76	34,03	30,89	25,41	19,45
Total noise, at point 5, measurement #2	30,8	31	53,07	44,35	28,71	35	34,32	30,56	25,73	19,6

Table 0.3. *C. Hospital Private Room#3 Measurements*

Measurement Points	**Laeq [dBA]**	**Elapsed time[s]**	**Octave Band Center Frequency, Hz**							
			63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Background noise, point1	39,16	30	44,14	43,3	36,81	33,33	30,57	30,07	34,54	19,83
Background noise, point2	38,13	31	43,25	37,28	39,64	36,3	26,37	28,67	34,31	19,54
Background noise, point3	38,32	30	42,54	42,94	30,32	33,55	28,1	27,81	34,23	18,93
Background noise, point4	39,21	30	47,65	39,46	39,88	31,6	31,21	29,29	34,61	19,78
Background noise, point5	36,76	30	52,32	39,32	33,79	32,59	27,47	26,09	33,07	16,68
Total noise, point1-1st measurement	48,76	30	51,43	50,19	42,78	40,71	43,38	41,97	41,02	32,95
Total noise, point1-2nd measurement	48,56	30	51,78	50,5	45,17	41,73	44,24	41,54	40,59	33,18
Total noise, point2-1st measurement	48,23	30	52,73	43,25	43,78	43,1	40,48	42,97	39,75	33,02
Total noise, point2-2nd measurement	48,37	30	53,07	43,13	43,53	42,23	40,2	43,14	40,11	33,23
Total noise, point3-1st measurement	48,85	30	51,42	47,84	40,89	41,1	42,28	42,49	40,91	33,27
Total noise, point3-2nd measurement	49,3	30	51,11	49,03	40,54	41,09	43,07	42,92	41,32	33,65
Total noise, point4-1st measurement	51,49	30	50,86	45,98	47,69	46,97	45,56	46	43,62	35,08
Total noise, point4-2nd measurement	51,43	30	51,16	45,51	48,16	47,26	45,3	46,33	43,14	34,94
Total noise, point5-1st measurement	48,08	30	53,56	43,49	41,3	39,53	42,8	42,64	39,44	31,47

Table 3. *C. continued*

Total noise, point5-2nd measurement	48,08	30	53,51	43,89	42,12	39,13	42,86	43,03	39,39	31,4

Table 0.4. *D. Hospital Private Room#4 Measurements*

Measurement Points	**Laeq [dBA]**	**Elapsed time[s]**	**Octave Band Center Frequency, Hz**							
			63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Background noise, point1	32,83	30	51,46	44,94	35,74	26,9	27,38	29,47	22,72	16,18
Background noise, point2	31,79	30	49,25	40,61	37,21	30,82	25,77	24,72	21,66	18,59
Background noise, point3	31,07	30	46,87	45,45	31,29	26,83	26,73	24,24	21,62	16,27
Background noise, point4	31,28	30	48,92	43,76	37,83	27,9	27,79	25,79	22,19	15,36
Background noise, point5	31,12	30	55,8	46,78	33,82	27,84	28,66	27,16	20,03	13,14
Total noise, point1-1st measurement	49,62	30	56,51	51,41	47,68	40,7	47,04	42,71	40,22	36,19
Total noise, point1-2nd measurement	49,45	30	56,01	50,96	47,65	41,04	46,94	42,05	39,73	36,16
Total noise, point2-1st measurement	49,34	30	53,94	45,33	48,54	45,16	41,99	42,89	39,77	36,92
Total noise, point2-2nd measurement	49,24	30	53,17	45,94	49,03	45,46	42,91	41,3	40,27	36,89
Total noise, point3-1st measurement	50,23	30	50,62	48,01	42,72	41,79	44,18	42,81	41,31	37,59
Total noise, point3-2nd measurement	50,15	30	50,68	48,37	42,63	41,73	44,37	42,67	41,11	37,69
Total noise, point4-1st measurement	53,49	30	53,39	48,68	49,71	49,95	47,78	44,42	43,73	40,71
Total noise, point4-2nd measurement	53,67	30	52,72	48,66	49,55	50,27	47,52	44,55	44,8	41,11
Total noise, point5-1st measurement	49,82	30	57,61	48,52	42,21	41,09	43,64	41,37	40,73	37
Total noise, point5-2nd measurement	49,81	30	58,16	48,76	42,83	41,47	43,77	41,17	40,64	37,16

Figure 0.1. E. Picture#1 of Hospital Private Room #1

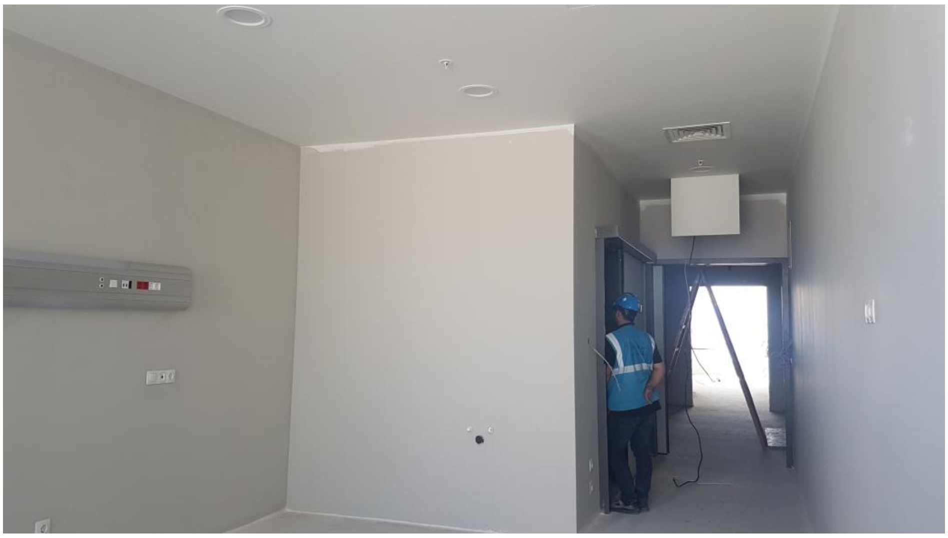

Figure 0.2. E. Picture#2 of Hospital Private Room #1

Figure 0.3. E.	Picture#3 of Hospital Private Room #1

Figure 0.4. E. Picture#1 of Hospital Private Room #2

Figure 0.5. E. Picture#2 of Hospital Private Room #2

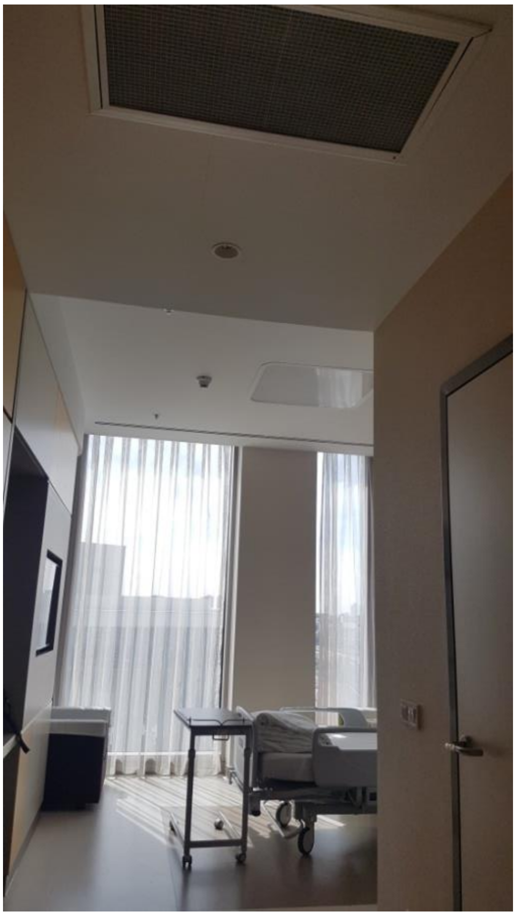

Figure 0.6. E. Picture#3 of Hospital Private Room #2

Figure 0.7. E.	Picture#4 of Hospital Private Room #2

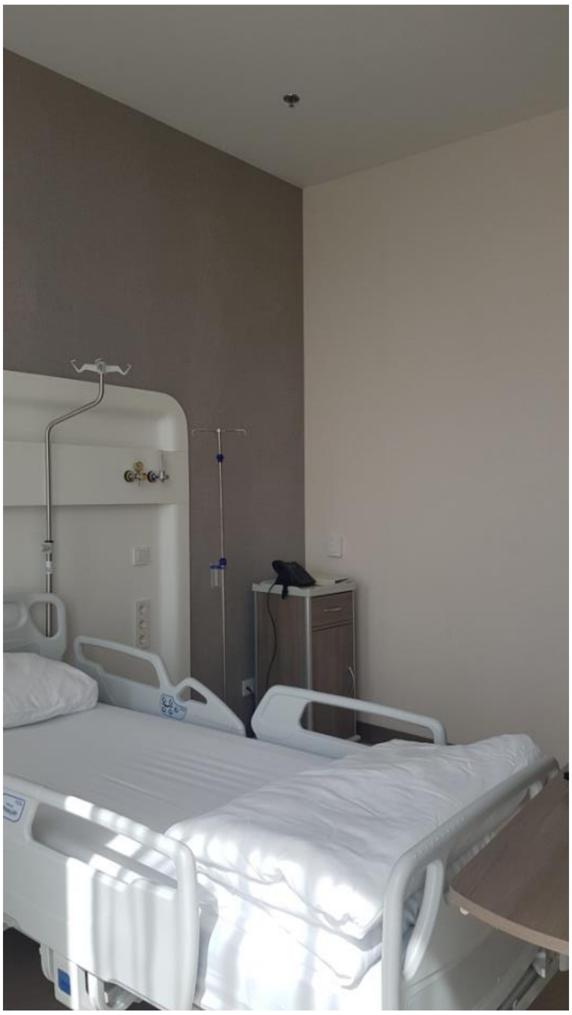

Figure 0.8. E.	Picture#5 of Hospital Private Room #2

Figure 0.9. E. Picture#1 of Hospital Private Room #3

Figure 0.10. E. Picture#2 of Hospital Private Room #3

Figure 0.11. E. Picture#3 of Hospital Private Room #3

Figure 0.12. E. Picture#4 of Hospital Private Room #3

Figure 0.13. E. Picture#1 of Hospital Private Room #4

Figure 0.14. E. Picture#2 of Hospital Private Room #4

Figure 0.15. E. Picture#3 of Hospital Private Room #4