

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**A MODEL FOR THE EVALUATION OF SPEECH INTELLIGIBILITY IN
ELEMENTARY SCHOOL CLASSROOMS**

**M.Sc. Thesis by
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**Programme : Environmental Control and
Building Technology**

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**İLKÖĞRETİM OKULU SINIFLARINDA KONUŞMANIN
ANLAŞILABİLİRLİĞİ DERECESİNİN TAHMİNİ İÇİN
KULLANILABİLECEK BİR MODEL**

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FOREWORD

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May 2009

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ABBREVIATIONS

AI	: Articulation Index
ALcons	: Articulation Loss of Consonants
ANSI	: American Standards Institute
ASA	: Acoustical Society of America
BEM	: Boundary Element Method
dB	: Decibel
DI	: Directivity Index
EDT	: Early Time Decay
FEM	: Finite Element Method
FDTD	: Finite Difference Time Domain
Hz	: Hertz
IACC	: Interaural Cross Correlation
ISO	: International Standards Institute
LEF	: Lateral Energy Fraction
MTF	: Modulation Transfer Function
NC	: Noise Criterion
NCB	: Balanced Noise Criterion
PNC	: Preferred Noise Criterion
R	: Room Constant
RASTI	: Rapid Speech Transmission Index
RC	: Room Criterion
RT	: Reverberation Time
SEA	: Statistical Energy Analysis
SN	: Signal to Noise Ratio
SPL	: Sound Pressure Level
SPSS	: Statistical Package for the Social Sciences
STI	: Speech Transmission Index

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A MODEL FOR THE EVALUATION OF SPEECH INTELLIGIBILITY IN ELEMENTARY SCHOOL CLASSROOMS

SUMMARY

Verbal communication is very important in education. Teachers usually transfer their knowledge to students by speech. The acoustical environment defines the speech intelligibility which affects the teaching and the learning activities in a classroom.

Many researches have done to develop metrics for speech intelligibility. Some of the metrics are based on modulation transfer function while others are based on acoustical energy ratios. Subjective evaluations derived from speech tests under various conditions are used to create qualification scales for the metrics of speech intelligibility.

The speech intelligibility in a classroom can be predefined by the the acoustical and geometrical characteristics of the classroom. Depending on this, a model for the evaluation of speech intelligibility is developed for the architects to acoustically design a classroom.

The model in the thesis is an integrated model which combines a simulation based model and a formula based graphic model. In the first sub-model, computer simulations are done to observe the acoustical quality of classrooms in different conditions. Background noise conditions were introduced later to the simulation outputs. Depending on different frequencies, classroom dimensions, ceiling materials, background noise levels, source and receiver combinations, 97200 data is statistically analyzed to develop a regression formula for the STI metric which will be used to determine the acoustical quality in a classroom. In the second sub-model, a graphic method is developed depending on theory to estimate the signal level at a receiver point in a classroom. Then, by combining the two sub- models, a final model is formed. STI is estimated by using the final model. According to the model, a qualification is done to evaluate the speech intelligibility in a designed classroom. If the result is not acceptable, the architect should change one or more decisions he made in the model.

The model is an easy to use method to evaluate the speech intelligibility in elementary school classrooms during their design process.

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ÖZET

Konuşma bilgi aktarım araçlarının en önemlilerinden biridir. Özellikle sınıflarda, bilgi aktarımı genellikle sözel olarak gerçekleştirilir. Bu yüzden sınıflardaki konuşmanın anlaşılabilirliği derecesi eğitim ve öğretimi ciddi yönde etkiler.

Günümüze değin, sınıf akustiği konusunda pek çok araştırma yapılmıştır. Konuşmanın anlaşılabilirliği bu araştırmalarda geçen belli başlı konulardan biridir. Bir ortamdaki konuşmanın anlaşılabilirliği derecesinin saptanabilmesi amacıyla araştırmacılar tarafından bir takım ölçütler geliştirilmiştir. Bu ölçütlerin bir kısmı modülasyon transfer fonksiyonuna dayanırken, diğerleri akustik enerji oranına dayanmaktadır. Konuşma testleriyle elde edilen subjektif değerlendirmeler bu ölçütlerin derecelendirilmesinde kullanılmıştır.

Bir sınıf ortamındaki konuşmanın anlaşılabilirliği derecesi, tasarımda oluşturulan geometrik ve akustik özelliklerle belirlenebilir. Bu görüşe dayanarak, tez çalışması kapsamında tasarım aşamasındaki bir sınıfta elde edilebilecek konuşmanın anlaşılabilirliği derecesinin tahminine yönelik bir model tasarlanmıştır.

Geliştirilen model iki alt modelin kombinasyonu ile oluşturulmuştur. Birinci alt modelde, olası sınıf tipleri değişik malzemelerle modellenerek simüle edilmiştir. Bu simülasyonlara arka plan gürültüsü de ilave edilerek, oluşabilecek çeşitli durumların benzeri yaratılmıştır. Bu işlemlerden elde edilen veriler istatistik programında analiz edilerek, STI ölçütünü verecek bir regresyon denklemi oluşturulmuştur. İkinci alt modelde, sınıftaki seçilebilecek bir alıcı noktasındaki sinyal seviyesinin saptanabilmesi için grafiklere dayanan bir yöntem geliştirilmiştir. Bu alt modelden elde edilen sinyal seviyesi ile kabul edilebilir arka plan gürültüsü, sinyal gürültü oranı elde edilmesinde kullanılmıştır. Daha sonra bu sinyal gürültü oranları simülasyonlara dayanan ilk alt modelden elde edilen regresyon denklemine yerleştirilerek, sınıf içinde belli bir alıcı noktasında oluşabilecek STI değeri hesaplanmıştır. Modelin son aşamasında elde edilen STI değerinin, sınıf için kabul edilebilir bir seviyede olup olmadığı ölçüt değerlendirme metoduyla sınanmıştır.

Geliştirilen model tasarım aşamasında mimarların kolayca kullanabileceği ve değişik tasarım seçimlerini içeren, istatistiksel analizlere ve teorik kuramlara dayanan bir değerlendirme modelidir.

1. INTRODUCTION

Environmental comfort is one of the leading subjects in architectural world. Although, it has been so far integrated to design process at many stages, today it becomes a separate scientific field. Architectural acoustics is a main topic in environmental control. It is the science of controlling sound within buildings. According to its function, each building needs a different acoustic treatment. Educational buildings are the ones in which acoustical comfort should highly be considered.

Acoustically uncomfortable environments affect teaching and learning activities negatively. Students and teachers face various problems in such conditions. Harmful effects show up as hearing loss, motivation and concentration problems, reduced memory, and reduced ability to carry out various tasks at the same time, stress responses and vocal fatigues. [1]

Noise is the main acoustical problem of many schools in Turkey. The researches conveyed in Istanbul show that classroom activities are not only disturbed by the exterior noise. Also interior noise coming through corridors and adjacent rooms may cause degraded acoustic quality in the classrooms. On the other side, students might be a noise source by themselves [1,2,3]. While designing a classroom, architects should take the inputs of both outdoor and indoor noise conditions into the account of their design proposals. These proposals should regard appropriate decisions on both sound insulation and planning of anticipated noisy sections of the schools.

Another important study that should be carried out is about the acoustical character of the rooms in educational buildings. Particularly classrooms are the places where the education is going on by verbal communication. Classrooms should be detailed according to achieve optimum speech intelligibility conditions.

The content of the thesis is about the speech intelligibility in classrooms. Noise insulation and planning strategy upon noise is off the point in the thesis.

Many studies in the subject of classroom acoustics concentrate on speech intelligibility in classrooms. Some intelligibility metrics are created for the estimation of speech intelligibility in enclosed spaces. Researchers examined the acoustical conditions and the other effective factors to find out the acceptable conditions for speech intelligibility [4, 5, 6].

However, without much knowledge of acoustics, it is not very practical for architects to acoustically design a classroom. Recommendations about the reverberation time and the acceptable background noise levels in a classroom clarify the content partially. The architect should know how to adjust the reverberation and the background noise levels and decide the amount of absorptive material and its placement.

Decisions given during design process about geometry and materials defines the room character so that the degree of speech intelligibility in that room. From this perspective, the objective stated below is tried to be achieved in this study.

- To develop a model that can be used by architects to predict the speech intelligibility in a classroom in the early stages of its design process.

The objective of the thesis is realized as a step by step approach which includes the factors (capacity, area per student, distance to source, NRC ceiling and background noise level) affecting the speech intelligibility in a classroom. Speech transmission index metric is used to define the acoustical quality of the predesigned classroom within the selected limits of the parameters and conditions.

This thesis is organized as follows: Chapter 2 gives a brief information about the concepts in room acoustics, explains the factors affecting speech intelligibility and the metrics used to measure the speech intelligibility in an enclosure. In Chapter 3, previous researches done about the speech intelligibility subject and regulations about classrooms are briefly summarized. Chapter 4 is the part in which the developed model to predict speech intelligibility is explained in detail. Chapter 5 draws the conclusion of the thesis.

2. BASICS OF THE CLASSROOM ACOUSTICS

Especially in classroom acoustics, speech intelligibility is the most studied subject. The speech intelligibility in enclosures is defined by various metrics. Every metric have different approaches to the speech intelligibility subject, on the other hand they use same inputs in different levels. Before introducing the speech intelligibility parameters, some knowledge must be gained about these inputs.

2.1 Sound Field Theory

Sound radiated from a source gets a different character at the receiver point. The character of sound at the end of its path is defined with the direct sound and the reverberant sound fields. Figure 2.1 [7] illustrates the behaviour of sound in an enclosure.

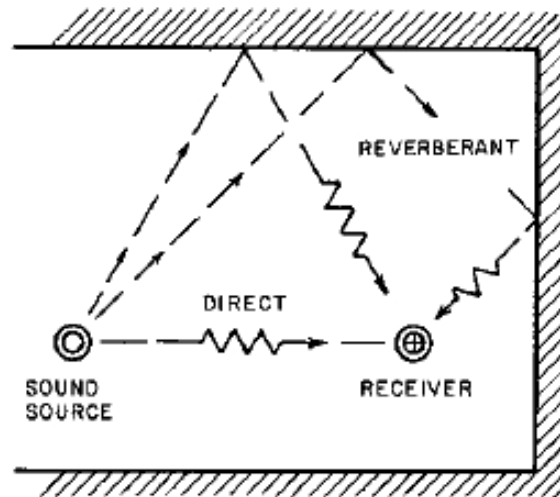


Figure 2.1 : The reverberant and direct sound fields [7]

2.1.1 Direct Sound Field

Direct sound is the acoustical energy travelled with sound waves which directly comes to the receiver point without striking surfaces in the room. The acoustic energy density that associates with the direct sound field is given in Eq. 2.1 [7].

$$E_d = \frac{QW}{4\pi(r)^2 c} \quad (2.1)$$

E_d : Energy density (Ws/m²)

Q : Directivity factor

W : Source power (W)

r : Distance from receiver to source (m)

c : Speed of sound in the air (m/sec.)

Directivity factor of a sound source is defined as the ratio of the intensity of a sound radiator at a certain distance r , to the intensity that would be produced at the same distance by a spherical source radiating the same total acoustic energy [7].

Directivity of a source is also specified by the directivity index. The relation between the directivity factor and directivity index is given in Eq. 2.2 [7].

$$DI = 10 \log_{10}(Q) \quad (2.2)$$

DI : Directivity Index

The directivity index is expressed in decibel (dB). Directivity depends on the source position. The directivity factor and the directivity index according to various source locations is given in Table 2.1 [7, 8, 9].

Table 2.1: Directivity factor and DI of a source in various locations [7, 8, 9].

Source Location	Directivity Factor	Directivity Index
Free field	1	0
On a flat plane	2	3
At junction of two perpen.	4	6
At junction of three perpen.	8	9

2.1.2 Reverberant Sound Field

The reverberant sound field is associated with the sound waves that have been reflected one or more times from various surfaces in the room. In room acoustics, the reverberant sound field is assumed as uniform and diffuse for every location in a room. Sound waves that have struck surfaces lose its energy depending on the

absorption of that surfaces. According to diffuse field theory, this decrease of energy is uniform for all around the room.

The energy density in a reverberant field is explained as Eq. 2.3 [7].

$$E_R = \frac{4W}{cR} \quad (2.3)$$

E_R : Reverberant sound energy density (W/m^3)

W: Sound power

c: Speed of sound (m/s)

R: Room constant

The room constant is the energy attenuation in the room air and expressed as in Eq. 2.4 [7].

$$R = \frac{\bar{\alpha} \cdot S_0}{1 - \bar{\alpha}} \quad (2.4)$$

R: Room Constant

S_0 : Total Surface Area

$\bar{\alpha}$: Total Absorption Coefficient

The distance, which reverberant field conditions become in charge, is called critical distance (reverberation radius) of the source. Critical distance is figured by equalizing the direct and reflected sound energy density. Equation 2.5 shows the formula of the critical distance [9].

$$r_c = \sqrt{\frac{QA}{16\pi(1 - \alpha_{mean})}} \quad (2.5)$$

The total sound energy density in a room is found by adding the direct and the reverberant sound energy densities [7].

$$E_T = E_D + E_R \quad (2.6)$$

Then, the steady state sound pressure is found from Eq. 2.7 [7].

$$p^2 = W \cdot \rho \cdot c \cdot \left(\frac{Q}{4\pi \cdot r^2} + \frac{4}{R} \right) \quad (2.7)$$

p^2 : Sound pressure (Pa)

ρ : Density of the air (kg/m³)

The sound pressure is commonly expressed as level. The conversion to “level” is done by taking $\log_{10}$ of both sides and multiplying through by 10 [7].

$$L_p = L_w + 10 \log_{10} \left(\frac{Q}{4\pi \cdot r^2} + \frac{4}{R} \right) \quad (2.8)$$

L_p : Sound pressure level (dB)

L_w : Sound power level (dB)

Human perception of the magnitude of sound is different from the existing sound conditions. Because of the intentions to characterize this effect, in the 1920's and 30's scientists at Bell Laboratories develop loudness-level contours, which is also known as Fletcher-Munson curves [7,9]. On the other hand, the use of these curves with an analogue sound level meter was complex. To overcome this problem, electrical weighting filters were designed. Apart from other filters, the A weighting curve resembles the response of human ear for a sound pressure level of 40dB at all frequencies and is widely used as a single measure of noise annoyance.

Table 2.2: Weighting factors for the A-Scale [7]

Octave band centre frequency, Hz	A-scale CFA
31	-39,4
63	-26,2
125	-16,1
250	-8,9
500	-3,2
1000	0
2000	+1,2
4000	+1,0
8000	-1,1
16000	-6,6

If the sound pressure level spectrum is known, the A weighted sound level is calculated as in Eq.2.9 where the summation is carried out for all octave bands [7].

$$L_A = 10 \log_{10} \left(\sum 10^{(L_p + CFA)/10} \right) \quad (2.9)$$

2.2 Factors Affecting Speech Intelligibility

Speech intelligibility is the main acoustic consideration in classrooms. A good intelligibility will increase the quality of education and avoid the fatigues encountered by the teachers and the students. Room geometry, size and reverberant character, ambient background noise and speech levels are the factors that affect speech intelligibility in a classroom.

2.2.1 Room geometry and size

The direct sound from the speaker to the listener must be strong enough to conserve the intelligibility of speech. The sound intensity is reduced and the level decreases by 6 dB as the distance between speaker and listener is doubled. For adequate intelligibility of sound, also the direct path of the sound should not be obstructed [10].

The sightline of listeners is important because sound is weakened while it passes over seated people at grazing incidence. Seats on a rake may ensure this order but in most of the schools, the flat seating plan is in use. In a case like this, a platform which the speaker raised on may obtain the clearance [10].

The useful amount of reflections coming through the surfaces of a room have a strengthening effect on the direct sound if the time delay is less than 50 milliseconds. Early reflections especially are useful at the furthest seat[10].

Figure 2.2 shows the principles which should be considered to ensure sufficient speech intelligibility in a classroom.

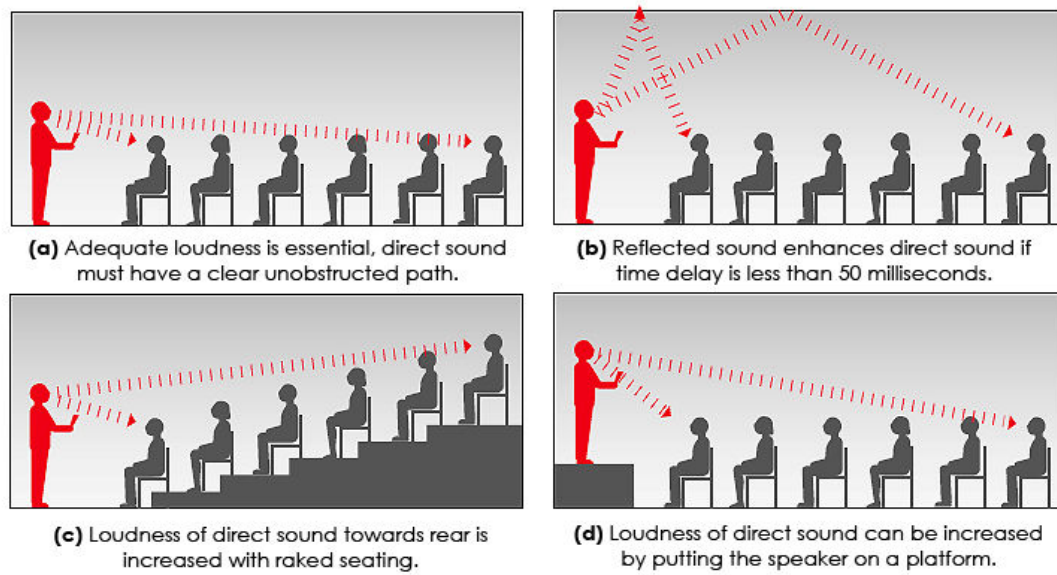


Figure 2.2 : Effect of room geometry and size to speech intelligibility.[10]

Moreover, there shouldn't be any focusing effect of room geometry. This effect is observed if the room has a curved rear wall, a shallow hipped roof or a barrel vault (see Figure 2.3).

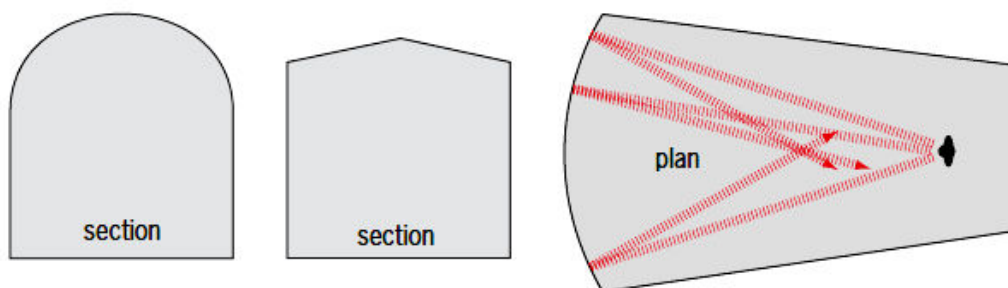


Figure 2.3 : Room geometries that sound focussing observed [10]

2.2.2 Reverberation time

The reverberation time depending on the volume and the total absorption in a room affect the speech intelligibility. Absorption of the materials and their amount are the decisions taken in the design period. It is very important to decide how much absorption is going to be used in a room. Absorption in a room can reduce reverberation and late arriving energy which have a detrimental effect on speech intelligibility, on the other hand it will also reduce early beneficial reflections and may lead to a decrease in speech levels [11].

Sound waves need an environment to travel from one point to another. For speech transmission in an enclosure, we consider air as the transition path of the sound. After coming out of source, apart from the sound waves that are directly coming to our ears, some of them go to other directions and encounter with surfaces made from different materials. When the sound waves hit these surfaces, they can reflect or absorbed by these materials. Absorption percentage of the sound energy gives the absorption or the reflection coefficient of the surface. If the total energy is taken as one, sum of the absorption and the reflection coefficients must be equal to the total energy, one, as seen in Eq 2.10 [9].

$$\alpha_{\theta} + \alpha_r = 1 \quad (2.10)$$

α_{θ} : Absorption coefficient

α_r : Reflection coefficient

Mean absorption coefficient of the materials can be found by dividing the total absorption by the total surface area as shown in Eq 2.11 [12].

$$\alpha_{mean} = \frac{A}{S_{tot}} = \frac{\alpha_1 S_1 + \alpha_2 S_2 + \dots + \alpha_n S_n}{S_1 + S_2 + \dots + S_n} \quad (2.11)$$

S_1, S_n : Surface areas of the materials (m^2)

α_1, α_n : Absorption coefficients of the materials

α_{mean} : Mean absorption coefficient of a relevant frequency

Absorption coefficients of the materials are frequency depended, so mean value of the absorption coefficients is defined by the absorption coefficients of the materials in a specific frequency.

W. Sabine was a pioneer in defining the absorption of sound and also he was the one who comes up with the theory of reverberation time. According to the experiments he made, he defined the reverberation time as the required time for the sound pressure level to decrease by 60dB and he proposed a formula for the reverberation time. The reverberation time formula is given in Equation 2.12 [9].

$$RT = \frac{0,161.V}{A} \quad (2.12)$$

V : Volume of the room (m^3)

A : Total absorption (m^2sabin)

The reverberation time formula which was modulated and presented by Eyring is given below in Equation 2.13 [9].

$$RT = \frac{0,161.V}{-S_{tot} \cdot \ln(1 - \bar{\alpha}_{mean})} \quad (2.13)$$

Many researches have done to determine the optimum reverberation times for classrooms. Also many country define an acceptable reveberation time for classrooms by standards or regulations. Detailed information about the acceptable reverberation time for classrooms will be given in Chapter 3.

2.2.3 Signal to Noise Ratio

Signal-to-noise (SN) ratio or sometimes called speech-to-noise ratio is respected as a descriptive metric of speech intelligibility and shows the difference between the signal and noise pressure levels. Equation 2.14 is used to calculate SN values.

$$SN = L_{signal} - L_{noise} \quad (2.14)$$

Signal level at the receiver point is related with the vocal effort of the speaker. In classrooms, the natural tendency of teachers is to raise their voice levels to overcome the masking of background noise. This effect is called Lombard effect. An example to this situation is given in Figure 2.4. The upper panel of the figure shows the level distribution of a male teacher talking in a classroom when the overhead projector with a noisy fan was in use. The teacher naturally talked louder to overcome the masking noise of the projector. The lower panel of the figure shows the situation when the projector is turned off [13].

The vocal effort of the teacher helps up to a certain limit. The background noise should be taken under a value that the signal to noise ratio is enough to achieve the agreeable conditions for speech intelligibility.

Although there are many speech intelligibility or speech recognition tests, the best results in tests are taken when signal to noise ratios are 15 dB or greater [13]. For example, in their studies, Nabelek and Pickett observed the highest scores in mean

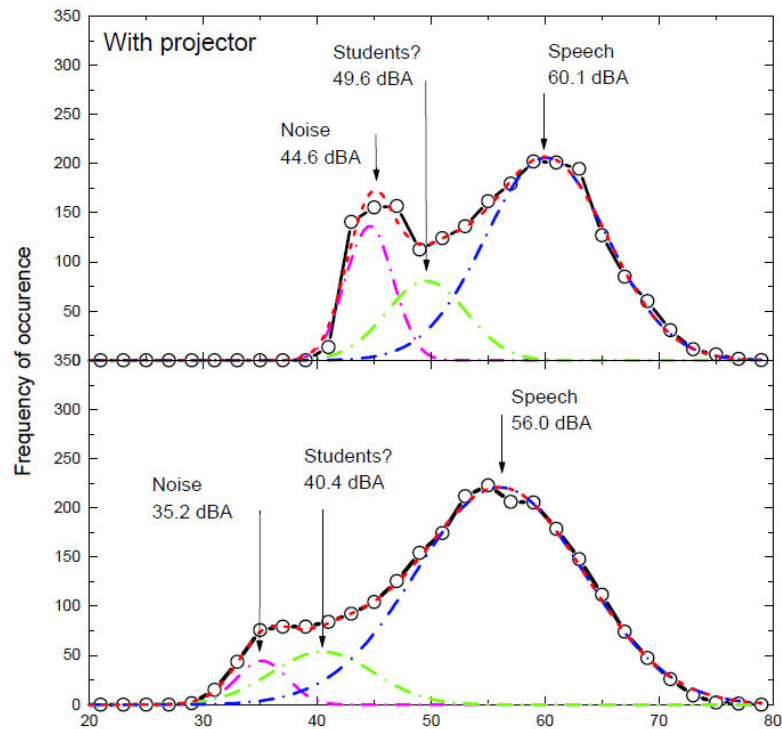


Figure 2.4 : The effect of noise on teachers vocal effort (Upper panel when overhead projector was in use, lower panel projector off) [13]

word recognition tests for normal listeners when the reverberation time 0.3 and 0.6s and SN ratios are above 10dB, close to 15dB [14]

2.2.4 Ambient Noise Level

Ambient noise is a determining factor for teaching spaces. For optimum speech intelligibility, teachers' voice should be heard above the background noise [10].

Noise in a classroom may originate from external or internal noise sources. Traffic around the school site and playground activities are major external noise sources. The student traffic at indoor corridors can also be counted as an external noise source. Students sometimes create noise in the classroom during classtimes. They can become an internal noise source. Ventilation systems and the electronic equipment running inside the classroom such as computers are the other possible internal noise sources [2, 3, 5, 15]

Noise rating systems are developed to assess steady industrial and communal noise. Beranek introduced Noise Criteria (NC) curves in 1957 for the evaluation of noise problems in various interior spaces Later, after it is detected that background noise that fitted to NC curves was not entirely neutral, Preferred Noise Criterion (PNC)

curves were developed. In 1989, NC curves were superseded by Balanced Noise Criterion (NCB) curves [12]. In Figure 2.5, NCB curves graphic is given.

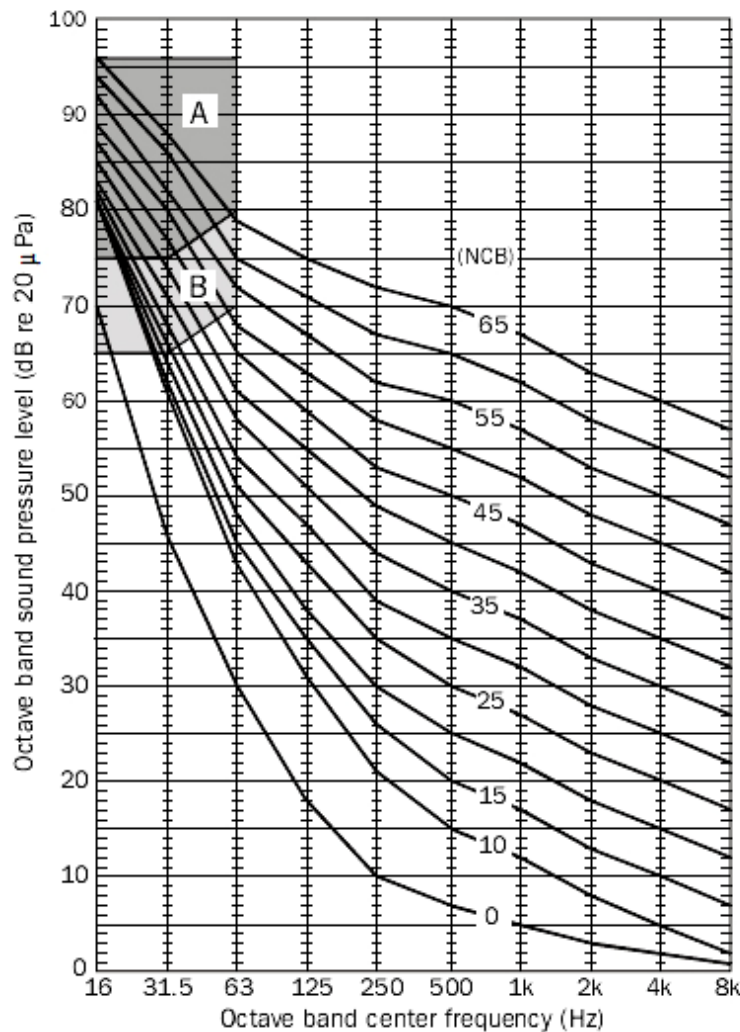


Figure 2.5 : Balanced Noise Criterion (NCB) curves. Region A represents exceedence of criteria for readily noticeable vibrations and Region B represents exceedence of criteria for moderately (but not readily) noticeable vibrations [12]

There are some suggested NCB rating for various activities and different interior spaces. The NCB rating from 30 to 40 is a recommended steady background noise interval for the rooms that good listening conditions are required such as classrooms, private offices, libraries, etc.

Another system that is widely used is Noise Rating (NR) curves which is adopted by The International Standards Organization. Including NR curves, some of the other noise rating system graphics are given in Appendix A [12].

A number of criteria, standard and regulation about acceptable background noise levels in classrooms are set by countries. The acceptable levels that are defined for classrooms are explained in Chapter 3. In most of the regulations, acceptable background noise levels are given as A-weighted pressure levels. Frequency distributions of the levels are not given. So that, noise criterion curves are taken into consideration if a frequency depended analysis is in question.

2.2.5 Speech levels

Information transfer in education mostly eventuates by oral communication. Thus, speech plays an important role in educational facilities, especially inside classrooms. Teachers are the main signal source.

The speech levels of the teachers changes according to the ambient background noise. If the noise level is higher than the speech level, the teacher starts to speak with a higher level to be audible in the classroom. The room volume also affects the speech levels. In small rooms (300m^2), people tend to speak with a normal voice level but as the room volume increases, they expect to use a 'raised' voice level. Pearsons et al. determined long term average speech levels for talkers at various levels of vocal effort. In Figure 2.5, Pearson's male and female speech spectra are given [9]

The frequencies of sound in speech are changing between below 125Hz to above 8kHz. Vowels have more sound energy than consonants, on the other hand consonants carry more information and gives us the detail in speech. The energy of consonants which is the key factor of speech intelligibility, is commonly concentrated towards the higher frequency end of the speech spectrum between 2000Hz and 4000Hz frequency range [16].

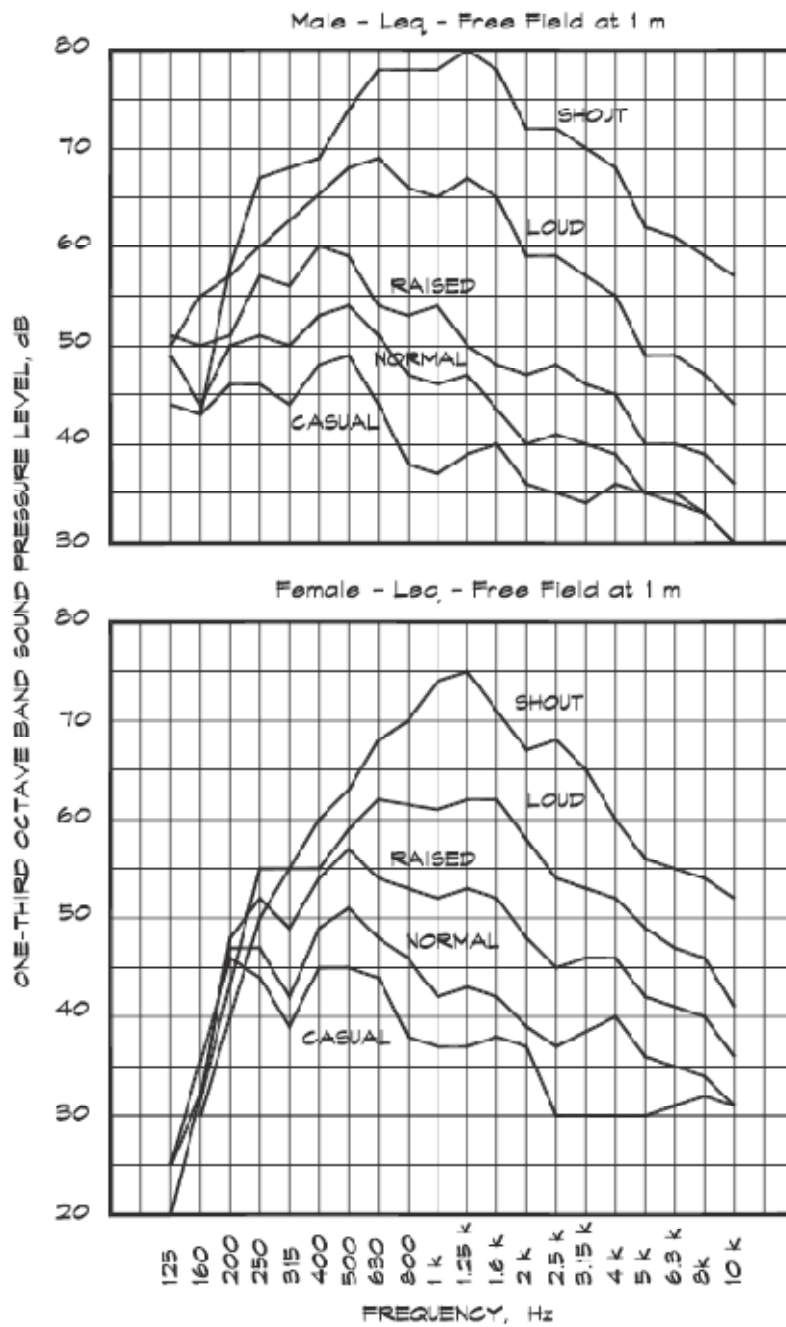


Figure 2.6 : Male and Female Speech Spectra [9]

2.3 Metrics of Speech Intelligibility

Under this title, some of the speech intelligibility metrics will be explained briefly. The speech intelligibility metrics are divided into two headings: metrics based on acoustical energy ratio and metrics based on modulation transfer function.

2.3.1 Metrics based on acoustical energy ratio

Speech intelligibility metrics like Definition (D), Clarity (C) and Useful to Detrimental Energy Ratio (U) are based on the acoustical energy ratio concept. This concept was firstly introduced by Aigner and Strutt in 1930s. They proposed a ratio, R_{EL} , which compares early to late sound energy. In their studies, Aigner and Strutt defined the early reflections as the reflections which arrive not more than 62 ms after the direct sound. In Equation 2.15 the early to late ratio proposed by Aigner and Strutt is given [4].

$$R_{EL} = \frac{(E_d + E_e)}{(E_l + E_n)} \quad (2.15)$$

E_d : Direct sound energy

E_e : Energy of useful part of the reflected sound which comes to ears not later than $1/16^{\text{th}}$ sec. after sound was issued

E_l : Energy of reflected sound which comes later than $1/16^{\text{th}}$ sec.

E_n : Energy of the noise

If $1/16^{\text{th}}$ second is written as 62ms, we can use a slightly different notation for the early and late energy:

$$R_{EL} = \frac{(E_d + E_{0 \rightarrow 62})}{(E_{62 \rightarrow \infty} + E_n)} \quad (2.16)$$

The reason to examine early to late sound energy is that early reflections of a speech in a room have a strengthening effect on speech signals. Intelligibility is increased by the early arriving reflections but decreased by late arriving ones. An illustration about early and late reflections on speech intelligibility is given in Figure 2.6 [17].

After Aigner and Strutt, many researchers took 50ms as the limiting time for the early, useful reflections. 50ms time limit actually wasn't a new concept because this beneficial effect was determined a long time ago, in 1850s by Joseph Henry.



Figure 2.7 : Simulation of different effect of early and late ratio [17]

On the other hand, many researchers refer to Haas for their understanding of the importance of early reflections [13].

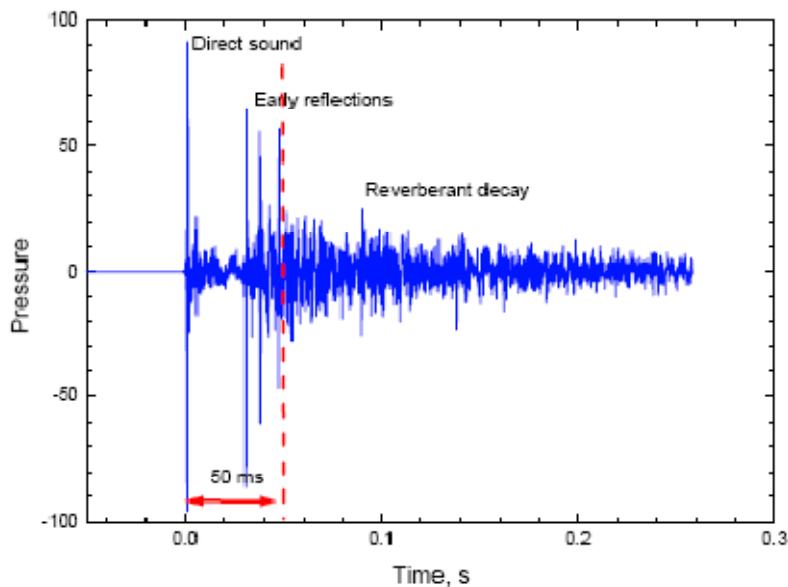


Figure 2.8 : Example of room impulse response showing the direct sound, early reflections and later-arriving reflections [13].

Recently, Yang and Hodgson [18] performed various tests to find the most proper early time limit for speech intelligibility. They found that higher scores in speech intelligibility tests for normal hearing subjects were achieved for the early time limit of 50ms.

Speech intelligibility metrics, D, C and U, depending on different acoustical energy ratios, are explained below:

Definition (Deutlichkeit) – Useful to total sound energy ratio:

This acoustical energy ratio concept was improved by others. Thiele suggested an acoustical energy ratio which compares early part of the acoustical energy with the total acoustical energy as in Equation 2.17a. Detrimental effect of background noise is not considered in the definition of D_{50} so that, it is not a widely used metric for determining the quality of speech intelligibility in classrooms as background noise always expected in [4].

$$D_{50} = \frac{E_d + E_{0 \rightarrow 50}}{E_t} \quad (2.17a)$$

E_d : Direct sound energy

$E_{0 \rightarrow 50}$: Energy within the first 50ms

E_t : Total energy consists of both direct and reflected sound energy

The ratio of early to total acoustical energy D_{50} is also written as in Equation 2.17b [4].

$$D_{50} = \frac{\frac{Q}{4\pi.r^2} + \frac{4(1-\alpha)}{A} \left(1 - e^{\frac{-0.69}{T}} \right)}{\frac{Q}{4\pi.r^2} + \frac{4(1-\alpha)}{A}} \quad (2.17b)$$

T : Reverberation time (sec.)

r : Distance between the source and the receiver (m)

In much literature both numerator and denominator are divided by $4(1-\alpha)/A$, so we find [4];

$$D_{50} = \frac{\left(\frac{r_c}{r} \right)^2 + \left(1 - e^{\frac{-0.69}{T}} \right)}{\left(\frac{r_c}{r} \right)^2 + 1} \quad (2.17c)$$

Clarity – Early to Late Sound Energy Ratio:

The metric which is the logarithmic ratio of early arriving sound to late arriving sound as shown in Equation 2.18a, is called clarity, C_{50} [4, 19].

$$C_{50} = 10 \log \left(\frac{E_d + E_{0 \rightarrow 50}}{E_{50 \rightarrow \infty}} \right) \quad (2.18a)$$

This metric also does not consider the effect of background noise, it is only related with the speech source energy. C_{50} can be calculated through the Equations 2.18b [4].

$$C_{50} = 10 \log \left(\frac{\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)}{A} \left(1 - e^{\frac{-0,69}{T}} \right)}{\frac{4(1-\alpha)}{A} \left(e^{\frac{-0,69}{T}} \right)} \right) \quad (2.18b)$$

If both numerator and denominator are divided by $4(1-\alpha)/A$, the other expression for Equation 2.18b will be,

$$C_{50} = 10 \log \left(\frac{\left(\frac{r_c}{r} \right)^2 + \left(1 - e^{\frac{-0,69}{T}} \right)}{e^{\frac{-0,69}{T}}}} \right) \quad (2.19c)$$

Useful to Detrimental Sound Energy Ratio:

This metric is taking into account not only the sound source's early and late acoustical energies but also the energy of noise source. Apart from the simplified version, U_{50} , Lochner and Burger first introduced a complicated version of U ratio with an early time limit of 95sec [20]. Yang and Hodgson determined the best predicting early time limit for the expression of U . They used 20 to 120 seconds for the early time limit. For each early sound field configuration, regression analyses were made on the mean speech intelligibility scores. U_{50} was the most accurate

metric at speech intelligibility predictions in classrooms for normal hearing listeners [18].

The detrimental part of the ratio consist the late part of the source acoustic energy and the SN ratio which introduces the effect of noise into the expression. In the denominator of the U_{50} equation, noise disturbance effect upon the source's useful energy discussed together with the late part of the source energy as shown in Equation 2.20a [4,13,19].

$$U_{50} = 10 \log \left(\frac{E_d + E_{0 \rightarrow 50}}{E_{50 \rightarrow \infty} + E_n} \right) \quad (2.20a)$$

Equation 2.11a is also written as in Equation 2.20b.

$$U_{50} = 10 \log \left(\frac{\frac{Q}{4\pi.r^2} + \frac{4(1-\alpha)}{A} \left(1 - e^{\frac{-0.69}{T}} \right)}{\frac{4(1-\alpha)}{A} e^{\frac{-0.69}{T}} + \frac{4(1-\alpha)}{A} \cdot 10^{\frac{-SN}{10}}} \right) \quad (2.20b)$$

When divided two sides by $4(1-\alpha)/A$, the formula in Equation 2.20c is obtained.

$$U_{50} = 10 \log \left(\frac{\left(\frac{r_c}{r} \right)^2 + \left(1 - e^{\frac{-0.69}{T}} \right)}{e^{\frac{-0.69}{T}} + 10^{\frac{-SN}{10}}} \right) \quad (2.20c)$$

2.3.2 Metrics based on modulation transfer function

Modulation Transfer Function (MTF) concept was introduced by Houtgast and Steeneken in the field of room acoustics in 1973 [21]. A special index, speech transmission index, STI derived from MTF was found highly correlated with the speech intelligibility test scores which were obtained for different laboratory setups including interfering noise, reverberation and single echoes. In this approach, the sound field at a listener's position may consist of direct field, reverberant field and in interfering noise and the characteristics depending on source-to-receiver distance, reverberation time, volume and signal-to-noise ratio. A scheme is given in Figure 2.8 which is showing the steps in estimating speech intelligibility by MTF [6].

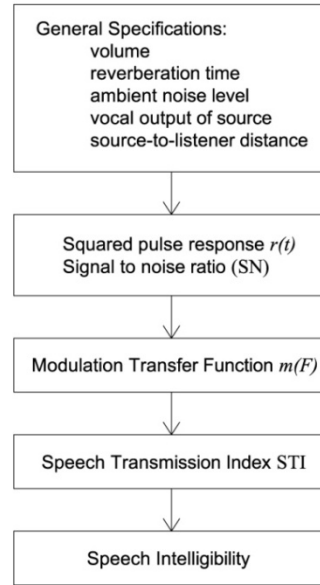


Figure 2.9 : General scheme for estimating speech intelligibility in a room for a given set of design specifications

In an enclosure, the temporal variations in the envelope of the speech are preserved at the listener's position. Preserving of the temporal variations in the envelope means that the intensity modulations produced at the speaker's position still exist at the listener's position. In reverberant conditions under the effect of an interfering noise, modulation intensity decreases [6]. The Figure 2.9 shows the change in a signal when it passes through an enclosure. The basis of the STI method is that the better we can hear the differences in modulations, the better we are able to understand speech.

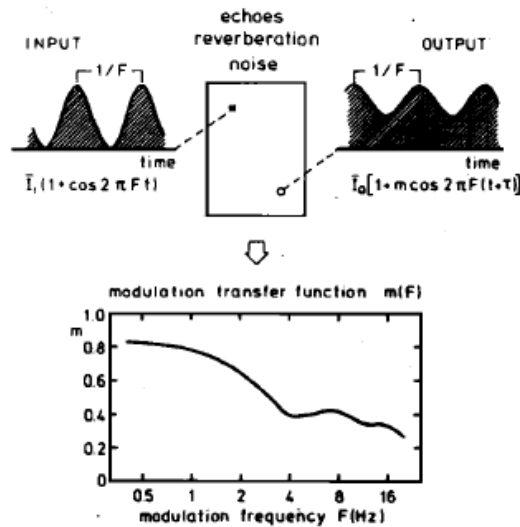


Figure 2.10 : The change in a signal when it passes through an enclosure [6, 21]

The MTF is found by the ratio of modulation reduction factor, m_F , to $(1-m_F)$ for a relevant modulation frequency. The equation 2.21 shows the MTF formula.

$$MTF = \frac{m_F}{1 - m_F} \quad (2.21)$$

m_F : Modulation reduction factor for a relevant modulation frequency, F.

Modulation transfer function is used to find an apparent signal to noise ratio for a specific modulation frequency as shown in Equation 2.22 [6].

$$SN_{app,F} = 10 \log_{10} \left(\frac{m_F}{1 - m_F} \right) \quad (2.22)$$

$SN_{app,F}$: Appearant signal to noise ratio for a relevant modulation frequency, F

This apparent signal to noise ratio is calculated for modulation frequencies of a specific range. This range generally consist 14 modulation frequencies. So that, there will be 14 different signal to noise ratio depending on 14 different m value.

After the 14 m values converted into 14 apparent signals to noise ratios, the mean values of $SN_{app,F}$ is found after each value is clipped according to the rules below:

If $SN_{app,F} > 15\text{dB} \rightarrow SN_{app,F} = 15\text{dB}$,

If $SN_{app,F} < -15\text{dB} \rightarrow SN_{app,F} = -15\text{dB}$

After clipping the mean value is calculated as [10];

$$\overline{SN}_{app,k} = \frac{1}{14} \sum_{F=0,6}^{12,5} SN_{app,F} \quad (2.23)$$

$\overline{SN}_{app,k}$: Mean appearant signal to noise ratio for a relevant octave band frequency

The mean signal to noise ratio achieved from 14 m values is only representing one octave band frequency. The same calculations must be done for the 7 octave band frequencies changing from 125Hz to 8000Hz frequency.

	Octave band frequencies						
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
f ₁ = 0,63Hz							
f ₂ = 0,8Hz							
f ₃ = 1,0Hz							
f ₄ = 1,25Hz							
f ₅ = 1,6Hz							
f ₆ = 2,0Hz							
f ₇ = 2,5Hz							
f ₈ = 3,15Hz							
f ₉ = 4,0Hz							
f ₁₀ = 5,0Hz							
f ₁₁ = 6,3Hz							
f ₁₂ = 8,0Hz							
f ₁₃ = 10Hz							
f ₁₄ = 12,5Hz							

Figure 2.11 : Matrix for the calculation results [22]

After getting the results of mean SN_{app} values for every octave band frequency, Speech Transmission Index, STI, for each frequency is calculated as shown below [10].

$$STI_k = \frac{\overline{SN}_{app,k} + 15}{30} \quad (2.24)$$

STI_k : Speech transmission index for a relevant octave band frequency

The results obtained for each octave band frequency are weighted to achieve a mean value. Weighting factors, proposed by Steeneken and Houtgast according to frequencies are given in Table 2.3 [6].

Table 2.3: Weighting factors for STI values on each octave frequency [6]

Center Frequency - Hz	Weighting factor
125	0,13
250	0,14
500	0,11
1000	0,12
2000	0,19
4000	0,17
8000	0,14

The final result is a single number calculated as in Equation 2.25.

$$STI = \frac{1}{7} \sum_{k=125}^{8000} w_k STI_k \quad (2.25)$$

W_k : STI weighting factor for a relevant octave band frequency

The relation between STI and speech intelligibility are designated by the speech intelligibility test results. Intelligibility scores obtained for a wide range of conditions, comprising combinations of various SN ratios, reverberations times and echo-delay times are used to create a qualification scale for STI values. Houtgast and Steeneken qualify STI values as excellent (1.00-0.75), good (0.75-0.60), fair (0.60-0.45), poor (0.45-0.30) and bad (0.30-0.00) [6].

STI developers also provided a prediction method to estimate the modulation reduction factor for a room while it is still in its design stage. The formula to calculate modulation reduction factor is given in Equation 2.26 [6].

$$m_F = \left[1 + \left(2\pi \cdot F \cdot \frac{T}{13,8} \right)^2 \right]^{-1/2} \left[1 + 10^{(-SN/10)} \right]^{-1} \quad (2.26)$$

T: The reverberation time of the room

F: Modulation frequency

SN: The signal to noise ratio at the receiver point

The first term in brackets reflects the signal intensity in a reverberant enclosure. The second term is used when there is an interfering noise in this enclosure.

Rapid Speech Transmission Index

Rapid speech transmission index RASTI is a simplified version of STI. Other than using TI values from all center band frequencies, only TI values of 500Hz and 2000Hz frequencies are used in the calculation of Rapid Speech Transmission Index [4].

The modulation frequencies used for 500Hz octave band are 1, 2, 4, 8 Hz and for 2 kHz octave band are 0.7, 1.4, 2.8, 5.6 and 11,2 Hz. Qualification scale for RASTI values are similiar with STI qualification scale just with a difference between bad and poor scale. The interval, 0.00-0.325, indicates bad values of RASTI and the interval 0,325-0,45 indicates poor values of RASTI [23].

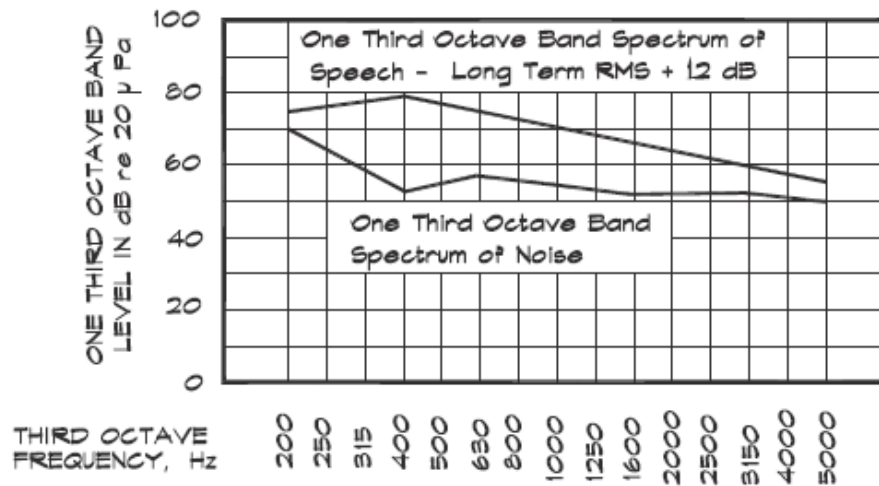
	Octave band frequencies						
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
$f_1 = 0,63\text{Hz}$							
$f_2 = 0,8\text{Hz}$							
$f_3 = 1,0\text{Hz}$							
$f_4 = 1,25\text{Hz}$							
$f_5 = 1,6\text{Hz}$							
$f_6 = 2,0\text{Hz}$							
$f_7 = 2,5\text{Hz}$							
$f_8 = 3,15\text{Hz}$							
$f_9 = 4,0\text{Hz}$							
$f_{10} = 5,0\text{Hz}$							
$f_{11} = 6,3\text{Hz}$							
$f_{12} = 8,0\text{Hz}$							
$f_{13} = 10\text{Hz}$							
$f_{14} = 12,5\text{Hz}$							

Figure 2.12 : The modulation frequencies for RASTI [23]

2.3.3 Articulation Index

Articulation Index (AI) is a metric which rates the intelligibility according to the fraction of understood syllables in speech tests. These tests are based on the identification of the structured nonsense syllable that is inserted in a neutral carrier sentence. The AI concept which was first introduced at Bell Laboratories in the late 1920s and early 1930s by Fletcher was then developed by French and Steinberg. Kryter in 1970 set a method for the calculation of the expected speech intelligibility. The signal to noise ratios are calculated by extracting the noise level from 12dB added long term speech signal level in third octave frequency bands. Then, the signal to noise ratio is multiplied by a weighting factor according to the band. Articulation index is the summation of these weighted signal to noise ratios. The range of the articulation index values are defined between 0 and 1. Total word or sentence comprehension is expressed with the number 1. Figure 2.15 is an example of an articulation index calculation from Kryter [9].

According to the suggestion of Beranek, AI values less than 0.3 is not satisfactory, the values between 0.3 to 0.5 are acceptable, the interval 0.5 to 0.7 indicates a good intelligibility and values above 0.7 express an excellent intelligibility [9].



BAND	SPEECH PEAKS MINUS NOISE (dB)	WEIGHT	COLUMN 2 x 3
200	5	0.0004	0.0020
250	12	0.0010	0.0120
315	18	0.0010	0.0180
400	26	0.0014	0.0364
500	23	0.0014	0.0322
630	18	0.0020	0.0360
800	17	0.0020	0.0340
1000	16	0.0024	0.0384
1250	15	0.0030	0.0450
1600	14	0.0037	0.0518
2000	12	0.0037	0.0444
2500	10	0.0034	0.0340
3150	8	0.0034	0.0272
4000	6	0.0024	0.0144
5000	5	0.0020	0.0100
AI = 0.4358			

Figure 2.13 : An Articulation Index Calculation [9]

2.3.4 Articulation Loss of Consonants

Articulation loss of consonants (AL_{cons}) is another metric used to identify the intelligibility. Rather than the AI concept, the comprehensible consonants are used to define the intelligibility level in this method. It is found that the articulation loss was much smaller for the vowels contrasting to the consonants [9].

Peutz carried out speech intelligibility tests under different conditions. The test method was the method used for measuring syllable articulation losses. In his approach, Peutz examined the intelligibility according to the wrongly perceived vowels and consonants. The recognition of the words and sentences mostly depends on the articulation loss of consonants. The results of these experiments were used to

derive a formula which express the articulation loss of consonants in different room conditions. The intelligibility in a room was found to be decreased with the increasing distance between the source and the receiver. The intelligibility remains constant beyond a critical distance independent of the distance between the source and the receiver. The critical distance in a room is found as in Eq. 2.27 [24].

$$r_c = 0,20\sqrt{V/T} \quad (2.27)$$

r_c : Critical distance (m)

V : Volume (m³)

T : Reverberation time (sec.)

The articulation loss of consonants are calculated by the formula in Eq. 2.28 at distances smaller than the critical distance [24].

$$Al_{cons} = \left(\frac{200r^2T^2}{V} \right) \quad (2.28)$$

r : The distance between the speaker and the listener

Beyond the critical distance, the Al_{cons} is derived from the formula in Eq. 2.29 [24].

$$Al_{cons} = 9T \quad (2.29)$$

For an ideal speaker and ideal listener, when Al_{cons} is below 10%, the intelligibility is very good. If Al_{cons} is between 10 and 15%, the intelligibility is good. In the situation where Al_{cons} is above 15%, the intelligibility is only sufficient for good listeners and speakers [24].

3. CLASSROOM ACOUSTICS INVESTIGATION METHODS AND A HISTORY OF PREVIOUS STUDIES

3.1 Classroom Acoustics Investigation Methods

In the assessment of classroom acoustics, especially for speech intelligibility, the methods described below are used.

3.1.1 Speech Intelligibility Tests

Testing intelligibility by speech tests is a widely used method for evaluating the intelligibility in an enclosure. These tests are also done to compare the results with the results of speech intelligibility metrics whether the results of these metrics give accurate predictions about the speech intelligibility in that enclosure or not.

There are many kinds of speech tests. Most commonly used ones are segmental evaluation tests which only a single segment or phoneme intelligibility is tested. The diagnostic rhyme test, or known as Fairbank's Rhyme Test consists of 96 word pairs which differs by a single acoustic feature in the initial consonant. The subject listens one word then at the same time chooses one of the words that he thinks correct on the answering sheet. The evaluation is made by averaging the error rates from answering sheets and the total error percentage is given at last. The other test methods like, modified rhyme test, diagnostic medial consonant test are the modified versions of Fairbank's Rhyme Test. These tests are preferred because test procedure is not time consuming. Naive listeners can participate and reliable results can be obtained with small subject groups that listener numbers are between 10 and 20 in these tests. Some of these segmental evaluation tests are modified according to the language [25].

Another kind of speech intelligibility tests is a sentence level test which participants listen an order of words either the words form a meaningful sentence or not, and expected to make the right choice on the answering sheet. Sentences in these tests are chosen according to the occurrence frequency of words in each particular language. Using fixed sentences is very problematic because learning effect can change the results. Listeners can be participated only once for reliable results [25].

Other type of speech tests like comprehension tests are not used in speech intelligibility assessments.

3.1.2 Field Measurements

Another way to get an idea about the acoustical performance in a classroom is to carry out field measurements. In various classroom acoustics researches [15, 26, 27] , field measurements are carried out. The measured metrics in these researches are reverberation time, background noise levels, speech pressure levels, clarity (C_{35} , C_{50} , C_{80}), definition (D_{50}) , EDT, T_s , STI and RASTI. The measured data sometimes are supported with the speech intelligibility tests.

The conditions during the measurement process have to be defined to qualify the measured data. It is essential to take notes about the occupancy of the room, background noise sources, the description of the room, the materials and their amount used in the classroom.

The signal source may be either a directional or omnidirectional speaker, or a pistol used to create an impulse sound. As the signal sound, a computer that can create sweeps, pseudorandom (MLS) or arbitrary (FFT) sound, a noise generator, or an impulsive source may be used. The location of the source with its height above the floor level should have stated. Also the descriptive information about the microphones and their location within the room must be recorded. The identification of measurement equipment like the type, model must be kept in order to do the same measurement again if it is needed.

Data storage, processing and analysis is done by means of a computer. Besides, there are also traditional methods that include devices such as a noise generator, a sound level meter or a pen plotter.

There are a number of standards drawn for room acoustic measurements. Procedures with regard to field measurements are defined in these standards. International Standards Organization published “ISO 3382:1997 Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters” in 1997 [28]. The standard ISO 3382 describes the measurement procedures, apparatus, required coverage, data evaluation methods and presenting the test report. Its content includes not only reverberation time but also relative sound pressure ratios (G),

acoustical energy ratios (C,D), lateral energy fraction (LEF), interaural cross correlation (IACF, IACC) and background noise levels.

3.1.3 Computer Simulations

Predictions to assess the acoustical conditions in a classroom may be either analytical or numerical. Analytical predictions are based on formulas which are developed by investigating the existing acoustical conditions. Numerical predictions are based on simulations. Mainly these simulations are realized by the computer softwares.

Modelling techniques of room acoustics can be classified under three headings: wave based modelling, ray based modelling and statistical modelling. Figure 3.1 shows the principle computational modelling techniques. There are also hybrid models that connect different modelling techniques [29]. The main objective of computer simulation programs is to calculate an energy time curve (square room impulse response) to compute various room acoustical metrics.

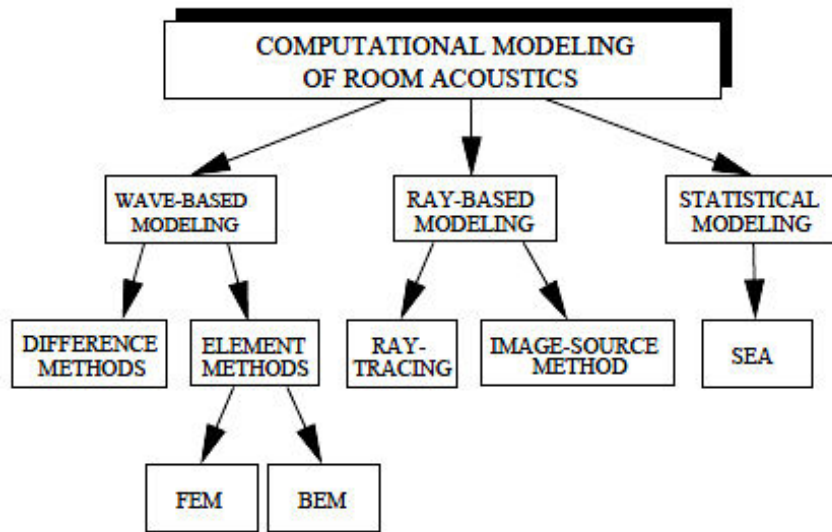


Figure 3.1 : Principle computational models of room acoustics [29].

Sound is described whether as particles or waves. The wave based approach admits that the propagation of sound eventuates with the vibration of air (or the transmission medium) as a whole, three dimensionally acting system. The sound waves which are reflecting between surfaces in an enclosure create a complex modal spectrum. The element methods (FEM, BEM) of finite difference time domain (FDTD) calculations give specific and accurate results at single frequencies. In wave based modelling, modes in a room increase with the third power of frequency and calculations become

difficult for higher frequencies and larger volumes. The whole room is discretized with elements in the FEM technique. On the other hand in the BEM technique, just the boundaries of the room are discretized. The derivatives in the wave equation are replaced by corresponding finite differences in the FDTD method.

The ray-based technique depends on the geometrical acoustics theory and the sound is accepted to act like rays. There are two different ray-based modelling methods: ray tracing method and image source method.

In the ray tracing method, a sound source emits sound rays to the enclosure and the sound rays reflect at the surfaces of that enclosure according to the surface reflection characteristics. Diffusion of sound on surfaces is also considered in some computer simulation programs. Rays penetrate to the receiver if the receiver is on the axis of the reflection path. The simulation runs until the energy of the rays is over or until the predefined time is ended. The program gives the signal response diagram according to the total energy received at the receiver. This diagram is used to calculate several room acoustical metrics.

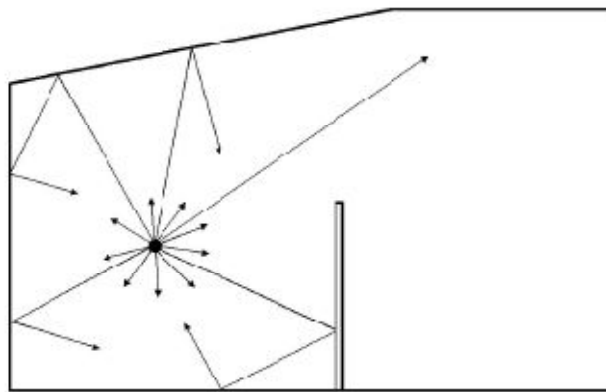


Figure 3.2 : A 2D representation of the ray tracing algorithm [30]

There are two approaches in the ray tracing algorithm. The rays can be emitted as predefined or randomized. In both approaches, a uniform distribution of rays over a receiver is desired [29].

The area defined for the receiver can either be a sphere or a planar. Beam tracing on the receiver's sphere surface is done by defining fragments on it. Fragmentation as cones or pyramids are the ways used in simulation programs. Defining the surface as cones can lead to an overestimation of the energy because of the overlapping cone

surfaces. Pyramids give more accurate results contrasting with cone defined surfaces [31].

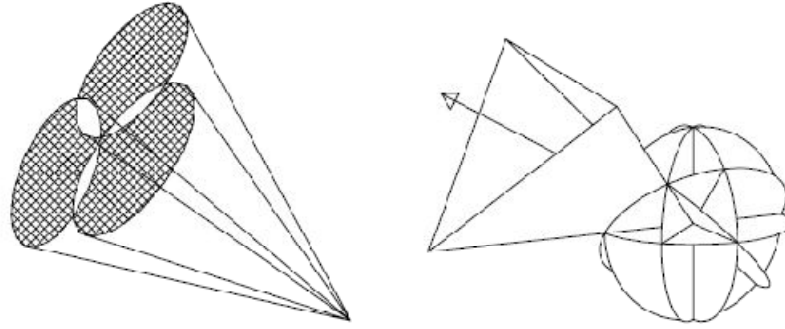


Figure 3.3 : Conic and pyramidal tracing methods [32]

In the image source method, the reflected path from the real source becomes a direct path from the reflected mirror image of the source. Figure 3.4 is a 2D representation of the image source method [30].

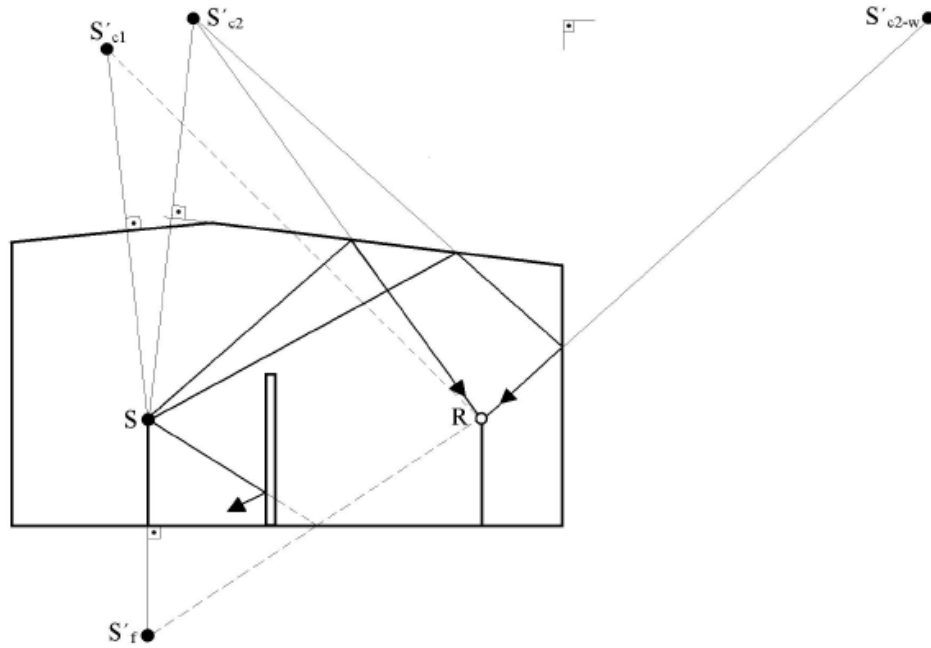


Figure 3.4 : A 2D representation of image source method [30]

As seen in figure 3.4, the mirror source images according to different surfaces (ceiling -c-, wall -w-, floor -f-) represent different sources in the model. The invisible image sources do not contribute to the impulse response. In figure 3.4, the image source S'_{c1} and S'_{f} can not directly see the receiver, R, so are not contributed to the calculations. Besides the first order mirror images, also the reflected images of the mirror source images through surfaces of a room are taken into account [30].

3.2 Previous Researches About Speech Intelligibility in Classrooms

Researches of Houtgast and Steeneken

In Chapter 2, speech transmission index metric which is developed by Houtgast and Steeneken is explained in detail. Houtgast and Steeneken had various researches on the modulation transfer function concept and tried to explain the relations between STI and different metrics [6, 21, 32, 33]. They defined a qualification scale for speech transmission index and show the variation of STI depending on reverberation time and signal to noise ratios [34].

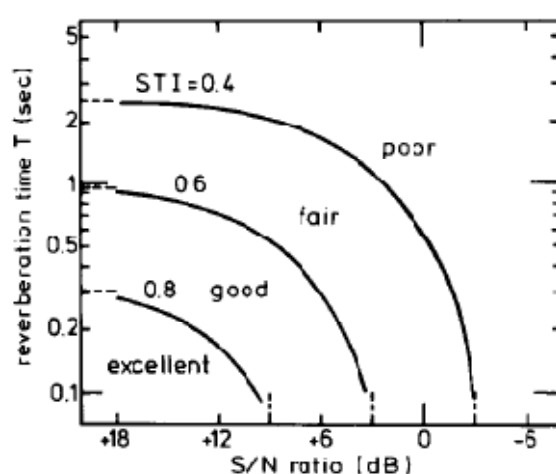


Figure 3.5 : Curves of consonant STI values as a function of Signal to noise ratio and reverberation time [34]

They investigated the effect of distance and absorption of surfaces on the distribution of STI contours over a room area [21, 33].

Houtgast conducted intelligibility tests under a variety of noise conditions and found that the interfering effect of noise in classrooms become audible and disrupt intelligibility when the indoor noise level exceeds 15dB of the teachers long term speech level [34].

Researches of Bradley

Bradley and his colleagues have done various researches on the subject of speech intelligibility. He carried out intelligibility tests in real classrooms with a recorded speech material played back using a loudspeaker. Subjects were tested with a fairbanks rhyme test. He also measured the impulse response and background noise in the occupied classrooms. %100 speech intelligibility is defined where the mean

trend of intelligibility test result did not have a further effect in speech intelligibility scores. He compared AI, STI, SN(A), C_{80} , U_{80} and U_{50} values with intelligibility scores and defined the optimum values for classrooms. In Figure 3.6, the graphics that show various metrics versus speech intelligibility scores are given [35].

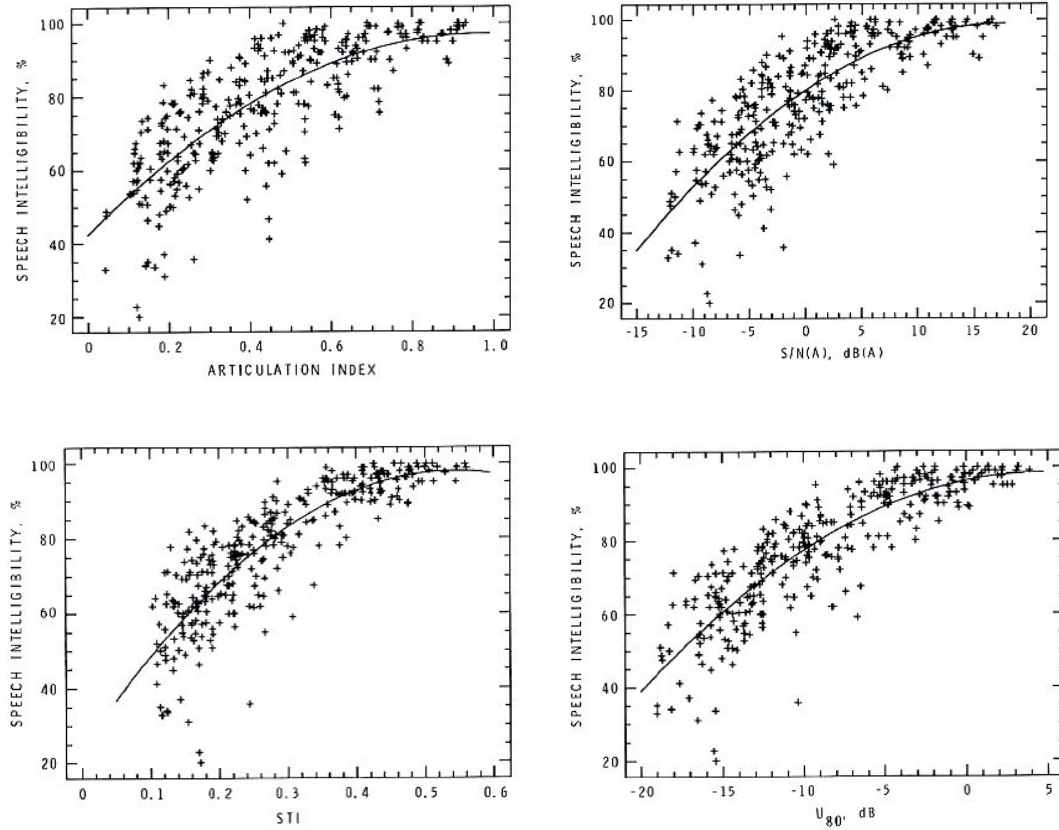


Figure 3.6 : AI, SN(A), STI and U_{80} (1kHz) versus SI scores [35].

The reserach [35] shows that optimum value for AI is derived at 0,9. STI with a value of 0,55 represents a good speech intelligibility. A SN(A) ratio of 15dB(A) provides a good intelligibility. Bradley also examined the optimum conditions for the metric U_{50} and found that 1dB is the value of U_{50} (1kHz) that gives a good intelligibility. For U_{80} , 4dB is required to achieve a good intelligibility. In Figure 3.7, the graphic on the left is to find the optimum reverberation time according to room volume. The other graphic is to determine the optimum A weighted background level in the chosen volume.

In a different research [19] simulated sound fields are used to create the full range combinations of room acoustics and SN effects. It is found in this research that SN ratios have much more influence on intelligibility than room acoustics effects.

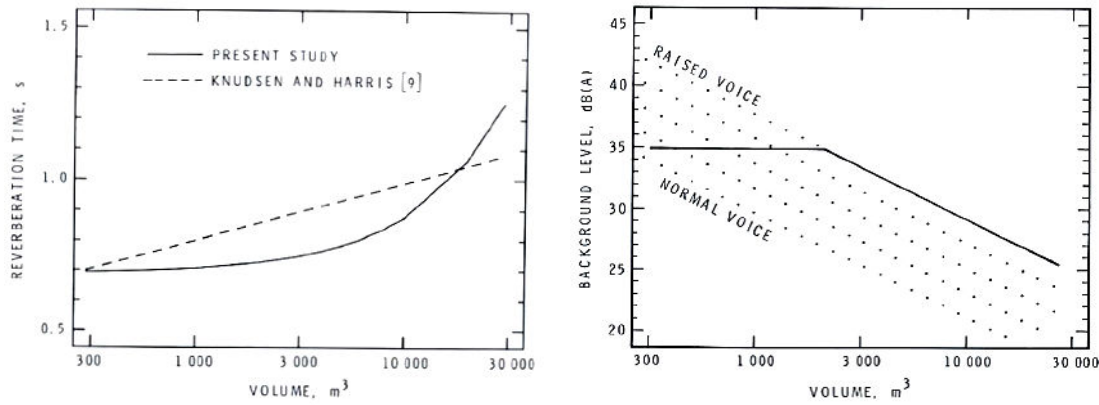


Figure 3.7 : Optimum reverberation tom and background noise level [35]

Reverberation time predictions is also another subject that Bradley interested in which related closely with intelligibility. He compared the experimental results with the analytical and computer simulation predictions of reverberation time by varying the sound absorption treatments in a simulated classroom [36]. Besides sound scattering factor, the distribution of sound absorbing material is also important to achieve a diffuse sound field [36].

Together with Bistafa, Bradley published a comparative study of speech intelligibility metrics [4]. It was observed that the values of speech intelligibility metrics reach to a maxima for the reverberation times between 0,1 and 0,3s. The study also showed that 20 and 25 dB background noise levels below the voice level at 1m in front of the speaker, are ideal and acceptable maximum values respectively. Bradley stated in his another research that 25dB background level is hard to be achieved and may not be necessary [13]. He also searched the teachers' voice levels and the needs of various special group of listeners. In Figure 3.8, teachers seem to talk more loudly according to the increase in noise levels depending on the age of the students.

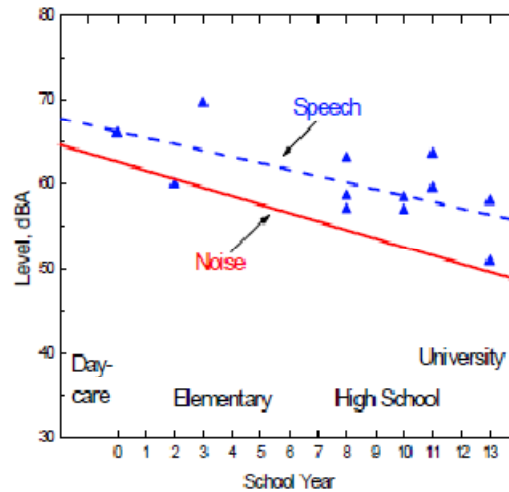


Figure 3.8 : Speech levels of teachers measured in classrooms [13]

The signal to noise effect on intelligibility with the age of the listeners can be seen in Figure 3.9.[13]

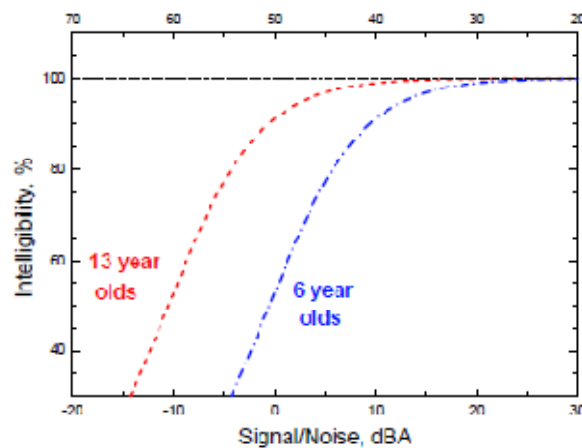


Figure 3.9 : The mean SI versus SN for classroom measurements of 13 year-olds compared with an estimate of the expected relationship for 6 year-olds [13].

Researches of Hodgson

Hodgson conducted a research to identify the typical speech and background noise levels in university classrooms during lectures. Recordings made in the classrooms were analyzed and the various average A weighted data are collected as follows: ventilation noise 40,9 dB, student activity noise 41.9 dB, total background noise 44,4 dB and received speech signal 50,8 dB. Multivariable regression analysis are done to develop empirical models to predict the room average A weighted results [15].

In his latter research, he questioned the effect of noise and occupancy on optimal reverberation times for speech intelligibility in classrooms. He studied to explain the theoretical and experimental prediction differences of optimal reverberation time and built a model which was incorporated into diffuse field theory by considering both speech and noise sources and the effects of reverberation on their steady-state levels. The result drawn by the model was that the optimal reverberation time is zero when the speech source is closer to the listener than the noise source, and nonzero when the noise source is closer than the speech source. The reverberation times of unoccupied classrooms are determined according to the diffuse field theory by using the given optimal values for the occupied classrooms.

As Bradley, Hodgson also used the auralization to search the optimum reverberation times for speech intelligibility for normal and hearing-impaired listeners in classrooms with diffuse sound fields. The tests present similar results both for normal hearing and hearing impaired subject groups. The optimal reverberation time was zero when the speech source was closer to the listener than the noise source. Both zero and nonzero reverberation time values are achieved when the noise source is closer to listener than the speech source. The early time limit in early to detrimental energy ratio (U) is found to be 50-60ms for normal hearing subjects but 70, 80 or 90ms gives more accurate results for hearing impaired subjects.

Other researches done about speech intelligibility

The placement of absorptive material in a classroom is another subject which was investigated through measurements and simulations by a couple of researchers [27,37,38]. The favorable scores for intelligibility metrics such as D_{50} and STI are obtained when the absorptive material is mounted on the rear wall of the classrooms [38, 39]. In another research done to clarify the placement of absorptive material, the highest RASTI values were measured when the absorptive material was placed on to the ceiling [37].

The distribution of the background noise and speech intelligibility scores through classrooms are also examined [40, 41]. Since real classroom environments do not represent the ideal diffuse sound field, distribution of the speech intelligibility scores connected with the background noise levels and the signal levels vary depending on the position of the receiver in classrooms. Unevenly distribution of background noise

levels has a considerable effect on STI values only if the receiver is very close to the noise source. The size of the noise source also affects the distribution of noise levels [40].

3.3 Criterias, Standards and Regulations

In the previous part, several researches about the speech intelligibility issues are summarized. While some of them states specific requirements for optimum intelligibility, the others try to define a range for various conditions. Below in Table 3.1, the optimum values for speech intelligibility is shown. The table is a collection of data from various researches.

Table 3.1: Optimum conditions for speech intelligibility

Researcher	Year of publication	Reverberation time	Background noise level	Signal to noise ratio	STI	U ₅₀	Source
Knudsen and Harris	1965	0,7 s. (300m ³)	36 dBA (NC 30)				[20]
Beranek	1971		NC 30 - 40 (38 - 47 dBA)				[20]
Finitzo, Hieber, Tilmann	1978			+12 dB			[42]
Houtgast	1981		42 dBA	+ 15 dBA =<			[34]
Stumpf and Sharland			NC 30 - 35				[20]
Parkin and Humphreys			NC 25				[20]
Burns			NC 20 - 30				[20]
Bradley	1985	0,35 s.	35 - 42 dBA	+ 15 dBA			[4]
	1986	0,4 - 0,5 s.	30 dBA			+1	[20]
Nijs, van Berlo, van der Voorden	2001	max 0,5 s. (occupied)			0,8		[43]

A number of standards and regulations are set by countries. They define the acceptable acoustic conditions for classrooms. Some of them also set criterias for hearing impaired students. In Table 3.2, standards and regulations according to the countries are given.

Table 3.2: Standards and regulations of countries about the acceptable reverberation time and background noise levels

Country	Publication	Reverberation time	Background noise level	Source
Australia/New Zealand	Standard, AS/NZS 2107:2000	0,4 - 0,5 s.	35-45 (max) dBA	[44]
Belgium	Standard, '87	0,7 - 1 s. (200m ³)	30-45 dBA	[43, 44]
France	Decree, '95	0,4 - 0,8 s.	38 dB	[43, 44]
Germany	Standard, '80 and 83	0,3s./0,45s./0,5s. (Std. '80)	30 dB	[43, 44, 45]
Italy	Std, UNI 8199 '75	max. 1 s. (200m ³)	36 dBA	[43, 44]
Netherlands		max. 1 s. (200m ³)	35dBA	[43]
Portugal	Decree, '02	0,6 - 0,8 s.(200m ³)	35 dBA	[43]
Sweden	Standard, '01	0,5 - 0,6 s.	26-40 dB	[44]
Turkey	Regulation, '08		35 dBA (windows closed), 45dBA(windows open)	[46]
UK	Std, BB93	<0,6/0.8 (elementary/secondary school classrooms)	35 dBA (Leq, 30 min) (elementary/secondary school classrooms)	[10]
		<0,4 s. (classrooms for hearing impaired)	30 dBA (Leq, 30 min, classrooms for hearing impaired)	
USA	ANSI S12.60-2002	0,6 - 0,7 s.	35 - 40 dBA (1 hr.)	[47]

Although in researches and regulations, there is a tendency to define the background noise levels and reverberation times for optimum speech intelligibility, it is still controversial to state a specific value for various conditions. A standard value can not be acceptable because the speech intelligibility changes depending on the students' age, hearing ability, teachers vocal effort, classroom volume and even the placement of absorptive material.

4. A MODEL FOR THE EVALUATION OF SPEECH INTELLIGIBILITY IN CLASSROOMS

The aim of the research is to develop a model to evaluate the speech intelligibility in elementary school classrooms. Two main goals are considered in the research to develop the model:

- Deriving a formula to calculate speech intelligibility in a classroom depending on STI metric
- Developing an easy to use graphic which will be used to predict the acoustical quality of a classroom during the design phase

To achieve these goals, two sub-models are developed and integrated to form a final model. The first sub model is a simulation based model to calculate STI for a specific location in a classroom. The second sub-model is created to develop an easy to use graphic for architects to evaluate the signal level that can occur in a classroom. Then the outcomes of two sub-models are combined to finalize a hybrid model which will be used by architects to qualify the speech intelligibility of a classroom in its design stage.

4.1 The simulation based sub-model

A variety of classrooms similar to the classrooms in Turkey are simulated in an acoustic simulation program, and then the data from the simulations is combined with different background noise conditions. Afterwards the total data is analyzed by a statistic program to determine the relation between acoustic and geometric parameters to obtain a regression formula based on STI metric to qualify the speech intelligibility in classrooms. Below in Figure 4.1, a flow chart explaining the methodology of the model based on simulations is given.

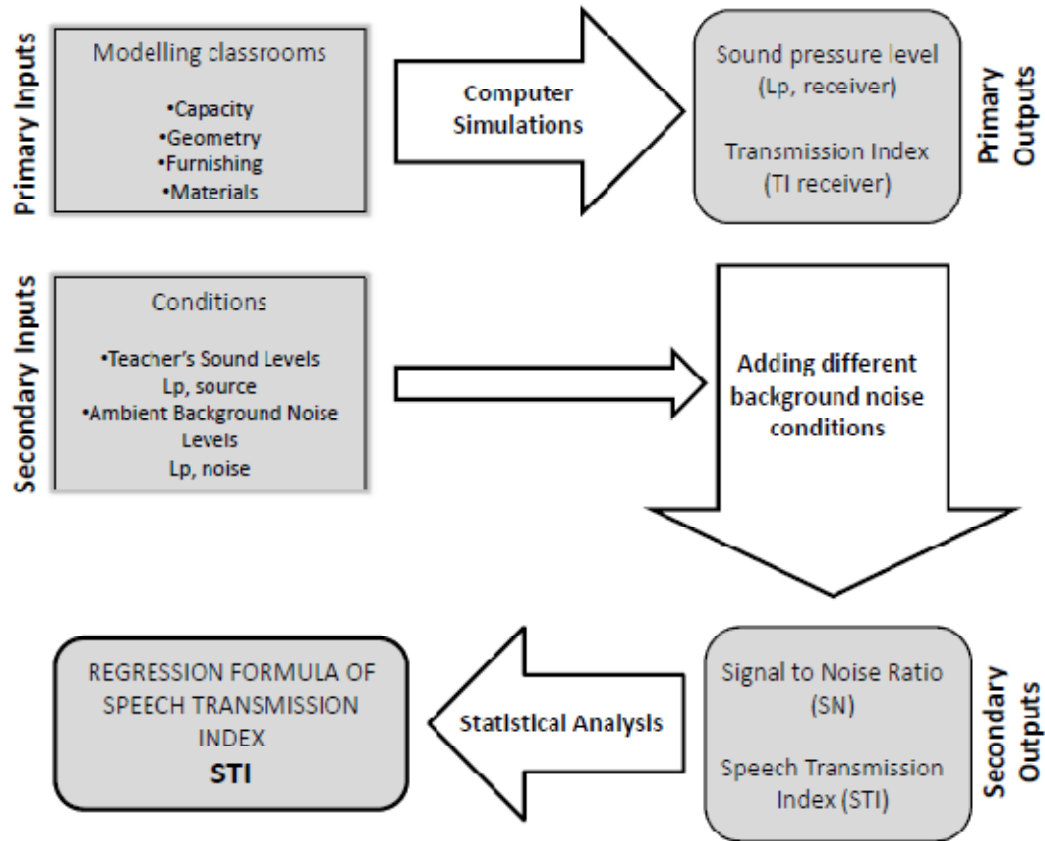


Figure 4.1 : Methodology of the simulation based model

4.1.1 Simulations

The acoustic simulation program used is CATT Acoustics. The Prediction module in the program utilizes the unique Randomized Tail-corrected Cone-tracing (RTC-II), the Image Source Model as well as Ray Tracing [48]. Classrooms are modelled in AutoCAD, and then imported to CATT.

The geometry of modelled classrooms and the properties of the materials used in the simulation:

The geometry and dimensions of the simulated classrooms depends on the previous research done about the acoustics of the elementary schools in Istanbul [ref]. According to the examined classroom types of the elementary schools in Istanbul, dimensionally 30 different classroom types are modelled similar to present classrooms. The student capacity of classrooms are changing from 18 to 56. The dimensions and the student capacity of modelled classrooms are given in Table 4.1.

Table 4.1 : Dimensions and student capacity of classrooms

Type	Width (w)	Length (l)	Height (h)	S_{surface}	S_{ceiling}	Volume (V)	l/w	l/h	w/h	Student Capacity
1	5	5,5	3	146,3	27,5	82,5	1,1	1,83	1,67	18
2	5	5,5	3,5	156,8	27,5	96,25	1,1	1,57	1,43	18
3	5	5,5	4	167,3	27,5	110	1,1	1,38	1,25	18
4	5	6,75	3	173,3	33,75	101,3	1,35	2,25	1,67	24
5	5	6,75	3,5	185,1	33,75	118,1	1,35	1,93	1,43	24
6	5	6,75	4	196,8	33,75	135	1,35	1,69	1,25	24
7	5	7,95	3	199,9	39,75	119,3	1,59	2,65	1,67	30
8	5	7,95	3,5	212,8	39,75	139,1	1,59	2,27	1,43	30
9	5	7,95	4	225,8	39,75	159	1,59	1,99	1,25	30
10	5	9,15	3	226,4	45,75	137,3	1,83	3,05	1,67	36
11	5	9,15	3,5	240,6	45,75	160,1	1,83	2,61	1,43	36
12	5	9,15	4	254,7	45,75	183	1,83	2,29	1,25	36
13	5	10,35	3	253	51,75	155,3	2,07	3,45	1,67	42
14	5	10,35	3,5	268,3	51,75	181,1	2,07	2,96	1,43	42
15	5	10,35	4	283,7	51,75	207	2,07	2,59	1,25	42
16	7	5,5	3	187,3	38,5	115,5	0,79	1,83	2,33	24
17	7	5,5	3,5	199,8	38,5	134,8	0,79	1,57	2	24
18	7	5,5	4	212,3	38,5	154	0,79	1,38	1,75	24
19	7	6,75	3	222,1	47,25	141,8	0,96	2,25	2,33	32
20	7	6,75	3,5	235,9	47,25	165,4	0,96	1,93	2	32
21	7	6,75	4	249,6	47,25	189	0,96	1,69	1,75	32
22	7	7,95	3	255,9	55,65	167	1,14	2,65	2,33	40
23	7	7,95	3,5	270,9	55,65	194,8	1,14	2,27	2	40
24	7	7,95	4	285,8	55,65	222,6	1,14	1,99	1,75	40
25	7	9,15	3	289,7	64,05	192,2	1,31	3,05	2,33	48
26	7	9,15	3,5	305,9	64,05	224,2	1,31	2,61	2	48
27	7	9,15	4	322	64,05	256,2	1,31	2,29	1,75	48
28	7	10,35	3	329,3	72,45	217,4	1,48	3,45	2,33	56
29	7	10,35	3,5	346,6	72,45	253,6	1,48	2,96	2	56
30	7	10,35	4	364	72,45	289,8	1,48	2,59	1,75	56

Furnishing in the classrooms consists of student desks, a teacher table, chairs and a board, a wallboard and bookshelves. The furniture layouts do not show any difference according to different classroom types. Only the student desks and chairs are added to the classroom layout with the increased capacity. Capacities are increased by adding a table row at the back of the classroom. Figure 4.1 is a 3D view of a modelled classroom. Spheres show the receiver points and the rectangular box represents the source.

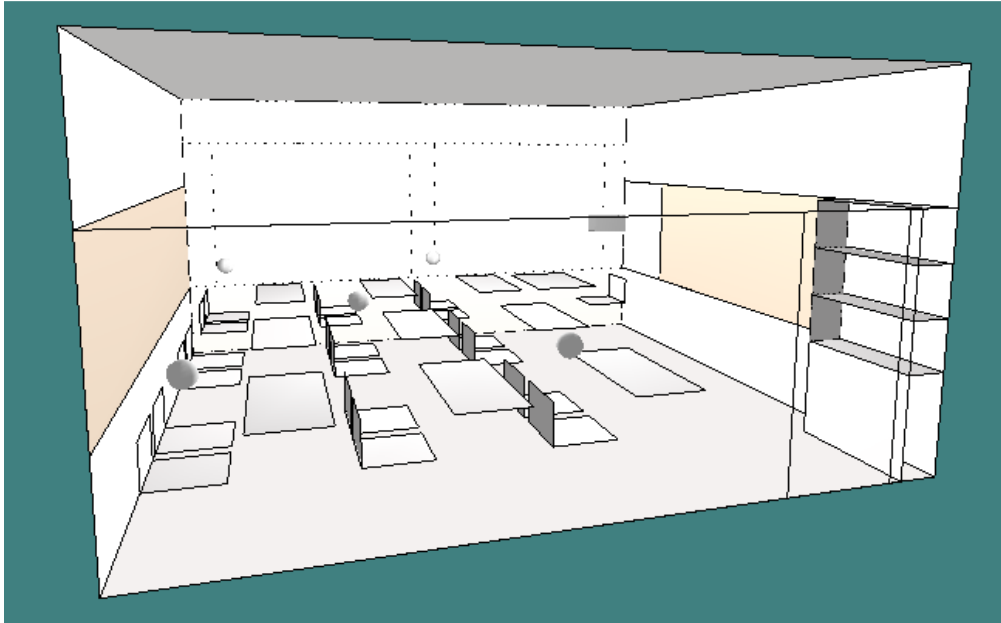


Figure 4.1 : 3D view of a modelled classroom

After setting dimensions the most important part of the model is the material choice for the surfaces of the model. In every classroom, the sitting and furniture layout stays same but the student capacity changes, so that the area of the materials covered also change. According to the variance in dimensions; wall, ceiling, floor, window, tables, board and wall board areas change proportionally.

The materials used for the surfaces of the model are given in Table 4.2. For observing the effect of ceiling absorption, 6 different materials are chosen for the ceiling surface and this create 180 different classroom settings according to the dimensions and the ceiling type.

Scattering coefficients of all materials are set to 0.1 for octave band frequencies since no information on scattering characteristics are available for the materials used in the model.

Mean absorption coefficients and reverberation time changes according to the materials and dimensions. They also show a little difference with the source placement because of the ray tracing method the simulation program used. The number of rays used is set automatically by the simulation program so that the energy decay is different in every prediction. In Appendix B, reverberation times of 180 different classrooms according to the sources used are given.

Table 4.2 : Absorption coefficients of the materials used in simulations

place	material description	Absorption coefficients according to frequencies (Hz)					
		125	250	500	1000	2000	4000
Wall	brick wall, stuccoed with a rough finish [7]	0,03	0,03	0,03	0,04	0,05	0,07
Wallboard, board	hardwood, mahogany[10]	0,19	0,23	0,3	0,3	0,37	0,42
Bookshelf, tables, chairs	50mm wood [49]	0,01	0,05	0,05	0,04	0,04	0,04
Floor	Linoleum or vinyl, stuck to concrete [10]	0,02	0,02	0,03	0,04	0,04	0,05
Door	solid timber door [10]	0,14	0,1	0,06	0,08	0,1	0,1
Window	double glazing, 2-3mm glass, 1 cm air gap [49]	0,1	0,07	0,05	0,03	0,02	0,02
Ceiling material 1	Smooth concrete painted and glazed [10]	0,01	0,01	0,01	0,02	0,02	0,02
Ceiling material 2	Plaster panels, 25mm rock wool backing, 32 mm air space behind [10]	0,2	0,22	0,18	0,15	0,15	0,16
Ceiling material 3	12% perforated plaster tiles absorbent felt glued to back, 200mm ceiling void [10]	0,45	0,7	0,88	0,52	0,42	0,35
Ceiling material 4	under purlin lining profiled steel sheet (%30 perforated) fleece layer and 180mm thick 23kg/m ² rock wool insulation [10]	0,09	0,11	0,17	0,4	0,44	0,4
Ceiling material 5	standard mineral fibre tile(0,6 inch) [9]	0,68	0,76	0,6	0,65	0,82	0,76
Ceiling material 6	standard mineral fibre tile (1inch) [9]	0,76	0,84	0,72	0,89	0,85	0,81

The information about the source and the receivers used in the simulations and the simulation program setup:

Background noise levels are set to 10dB for each octave frequency in every simulated classroom. The effect of background noise to the acoustic parameters is calculated afterwards, by using the outputs of the simulation program.

A female human sound source is chosen as the source in simulations. It is the level of a normal speaking female. The directivity of the source [48] resembles the characteristic of a human source. The source sound pressure levels on axis, 1m away and the directivity indexes are given in Table 4.3.

Table 4.3 : Source sound pressure levels and directivity index (DI) values according to frequencies

	Frequency - Hz					
	125	250	500	1000	2000	4000
Source sound pressure level (dB)	40	65,3	58,1	50,9	44,2	43,3
Directivity index of the source [48]	1,7	2,1	3,1	2,9	5,5	6,2

The source is located at three different positions. The source, called A0, is at the corner of the classroom where a teacher usually locates in a classroom. The other source, A1, is where the teacher usually stands, in front of the board, faced to the students. The last one, A2, is close to the rear wall which represents the situation if a student becomes a speaker. All the sources are placed 1.5 meter above floor level. The Figure 4.2 shows the locations of these sources.

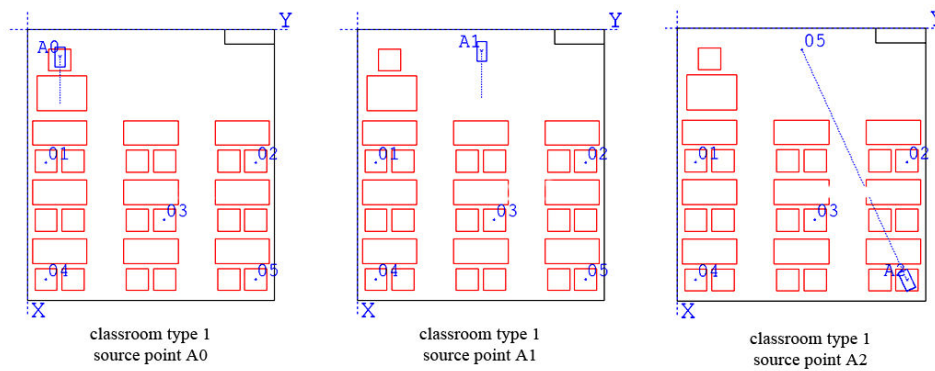


Figure 4.2 : Location of sound sources in classroom type 1

There are five receiver points (01, 02, 03, 04, 05) in every classroom. Two of these are located in the first row of the sitting plan. The third one is in the centre of the classroom. The other ones are placed in the last row, close to rear wall. When source A2 is used, one of the receiver points at the back becomes a source point and the source point that source A0 locates becomes a receiver point. Except the situations where A2 used as a source, the receivers are 1.1 meter above the floor level. In the situations source A2 used, receiver 5 which resembles the teacher is levelled 1.5 meter above floor level.

The distance from the receiver to the source is varying according to the location of the receiver and source in the classrooms. Receiver to source distances are given in Appendix C.

Number of rays per octave and ray truncation time are set automatically by the simulation program.

4.1.2 Introducing background noise

A variety of background noise conditions are entered to model by adding different background noise levels into the simulation program outputs. Sound pressure levels (dB) and transmission index values (%) at the receiver positions from CATT outputs are combined with noise levels to calculate the noise added STI and SN values.

The formula used to calculate SN values is given in Equation 4.1. Besides introducing different background noise levels, an adjustment for the speech level is included to the formula. A different female source [9] is used. The directivity characteristic of the source stays same but the source sound pressure levels are changed.

$$SN_{calculated} = L_{p,womanPBF} - (L_{p,source} - L_{p,receiver}) - L_{noise} \quad (4.1)$$

$L_{p,womanPBF}$: Sound pressure level of a woman (from Pearson, Bennett and Fidell Report) [9]

$L_{p,source}$: The sound pressure level of the source at 1m (from CATT)

$L_{p,receiver}$,: The sound pressure level at the receiver point (from CATT)

The signal level at the receiver point changes according to the room characteristics and distance between source and receiver. Sound pressure level difference between the source point and the receiver point is subtracted from the voice level to obtain the signal level in the equation.

Background noise levels in a classroom normally are not distributed evenly through the classroom. The noise level at a receiver point changes with the distance to noise source. Also, there will be multiple noise sources in a classroom. Since it is not possible to predict exact noise source locations at the design phase of a classroom, it is presumed that the noise levels in the classrooms are evenly distributed. The model is built in according to be applicable to a general design concept.

In most of the regulations (see Table 3.1), frequency distributions of the levels are not given. So that balanced noise criterion curves are used in calculations. The background noise levels introduced to the model in Equation 4.1 are the octave band frequency levels of NCB 30, 35, 40, 45, 50 and 55 curves. They represent different background noise conditions in classrooms. Level distributions and A-weighted sound levels according to these curves are shown in Table 4.4.

Table 4.4 : Level distributions and A-weighted sound levels according to curves

	Background Noise Levels						dBA
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	
NCB 30	47	39	35	32	28	25	38
NCB 35	51	44	40	37	33	30	43
NCB 40	55	49	45	42	38	35	48
NCB 45	59	53	50	47	43	40	53
NCB 50	63	58	55	52	48	45	58
NCB 55	67	62	60	57	53	50	62

Knowing SN ratios, STI index is calculated according to the procedure below. As it is mentioned before, TI (%) values taken from simulation outputs are the ones without noise.

Combining both Equation 2.22 and 2.24, Equation 4.2 gives the modulation reduction factor which is derived from CATT simulations.

$$m_{CATT} = \frac{1}{1 + 10^{\left[\frac{-\left(\frac{30TI}{100} - 15 \right)}{10} \right]}} \quad (4.2)$$

Signal to noise ratios is the ratio of the modulation after the noise to the difference of the modulations occurred before and after the noise. Equation 4.3 gives the modulation reduction factor that occurs after noise is added.

$$m_{NOISE} = \frac{m_{CATT}}{1 + 10^{\frac{-SN}{10}}} \quad (4.3)$$

After estimating the modulation reduction factor in the noise added situation, TI with noise (%) according to frequencies is calculated by Equation 4.4.

$$TI_{NOISE} = 100. \left[\frac{15 + 10 \log_{10} \left(\frac{m_{NOISE}}{1 - m_{NOISE}} \right)}{30} \right] \quad (4.4)$$

Afterwards, clipping is done according to the rule below:

If $TI_{NOISE} < 0$, then $TI_{NOISE} = 0$

As it is known, STI is a single number which is the sum of weighted TI_{NOISE} values. Normally, STI is presented between 0 and 1. The data from CATT is given in %, so that the calculated STI values are expressed in %. Equation 4.5 gives the formula of STI.

$$\begin{aligned} STI(\%) = & 0,15.TI_{125} + 0,16.TI_{250} + 0,13.TI_{500} + 0,14.TI_{1000} \\ & + 0,22.TI_{2000} + 0,2.TI_{4000} \end{aligned} \quad (4.5)$$

4.1.3 Statistical analysis

Noise added data is analyzed to determine the relations between the geometric and acoustic parameters. In analyzes, the statistic program SPSS 15.0 (Statistical Package for the Social Sciences) is used. Geometric and acoustic parameters are set as “variables”. Depending on different frequencies (6), classroom types (30), ceiling materials (6), background noise levels (6), source (3) and receiver (5) combinations, 97200 data is entered to the program. Descriptive statics of some variables are given in Table 4.5. The table shows minumum and maximum values, the mean of the total data and the standard deviation that occurs. Vact is the room volume excluding the furnitures and Sact is the total surface area including the surface area of furnitures.

All data is analyzed to derive a regression formula for the STI metric. In the theory STI relates with modulation transfer function and signal to noise ratios. Room reverberation time affects both modulation transfer function and SN.

Table 4.5 : Descriptive statics of some variable

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Frequency	97.200	125	4.000	1.312,50	1.353,532
Capacity	97.200	18	56	35,00	11,180
m ² /student	97.200	1,2	1,5	1,360	0,0917
Width	97.200	5	7	6,0000	1,00001
Length	97.200	5,5	10,4	7,9500	1,72541
Height	97.200	3	4,00	3,5000	0,40825
V _{room}	97.200	82,50	290,00	166,7267	50,09467
V _{act}	97.200	81,00	271,00	163,2000	47,29675
S _{room}	97.200	118,00	284,00	192,9333	41,46822
S _{act}	97.200	146,30	364,00	242,2633	55,71963
S _{ceiling}	97.200	27,50	72,80	47,7000	13,16637
α_{ceil}	97.200	0,01	0,89	0,4269	0,30882
NRC _{ceiling}	97.200	0,02	0,83	0,4417	0,29740
α_{mean}	97.200	0,03	0,27	0,1332	0,06355
RT	97.200	0,38	4,14	1,0956	0,70685
R(dist. to source)	97.200	2,2	11,03	5,5511	2,21543
L _{p,bkg}	97.200	25	67	46,3056	10,41591
SN	97.200	-40,10	55,70	-2,2842	12,80952
STI	97.200	0	74	32,23	16,377
Valid N	97.200				

Correlations between these acoustic parameters are investigated through SPSS. The result shows that while signal to noise ratios are highly correlated with STI values, the correlation between reverberation times and STI values are weak (Table 4.6).

Table 4.6 : The correlations between SN, RT and STI

		Correlations					
		RT125	RT250	RT500	RT1000	RT2000	RT4000
STI	Pearson Correlation	-,079(**)	-,077(**)	-,083(**)	-,083(**)	-,081(**)	-,081(**)
	Sig. (2-tailed)	0,000	0,000	0,000	0,000	0,000	0,000
	N	16.200	16.200	16.200	16.200	16.200	16.200
		SN125	SN250	SN500	SN1000	SN2000	SN4000
STI	Pearson Correlation	,855(**)	,866(**)	,897(**)	,910(**)	,912(**)	,921(**)
	Sig. (2-tailed)	0,000	0,000	0,000	0,000	0,000	0,000
	N	16.200	16.200	16.200	16.200	16.200	16.200

**. Correlation is significant at the 0.01 level (2-tailed).

The correlation between variables increase while values are getting close to 1 or -1.

Considering these relations, signal to noise ratios of each frequency are used to derive a regression formula that gives STI. The formula derived from the statistical analysis is given in Equation 4.6.

$$STI = -14,213 - 1,926.SN_{125} + 0,657.SN_{250} + 1,162.SN_{500} \\ - 0,011.SN_{1000} - 4,515.SN_{2000} + 6,044.SN_{4000} \quad (4.6)$$

Although not every SN values contribute to STI with a strong coefficient, the effect of SN in every frequency are thought to be included to the equation. R squared is the proportion of variation in the dependent variable explained by the regression model. The values of R squared range from 0 to 1. Small values indicate that the model does not fit the data well. R^2 of Equation 4.6 is **0.903** which shows that this equation explains STI satisfyingly.

The regression formula derived explains the STI metric. On the other hand it is not so usable by architects since signal to noise ratios couldn't be identified without knowing any information about the geometry and acoustical properties of a classroom. The acoustical and geometrical properties of a classroom defined at the design stage will affect the possible signal levels at any location in the designed classroom. That is why a formula based sub-model is developed through this research.

4.2 The formula based graphic sub-model

The second sub-model is created to develop an easy to use graphic for architects to predict the signal levels at any location in a designed classroom. Main design requirements that are used to design a classroom are included to the graphical model as variables. The sound pressure levels according to direct and reverberant field at any location in a classroom can be found by reading the graphics. These pressure levels are summed to obtain the signal level at the receiver point. The methodology of the formula based graphic sub-model is given in Figure 4.3.

Determining the possible classroom design goals of an architect is the starting point for developing the model. Student capacity and area per student in a classroom are the primary design inputs for architects.

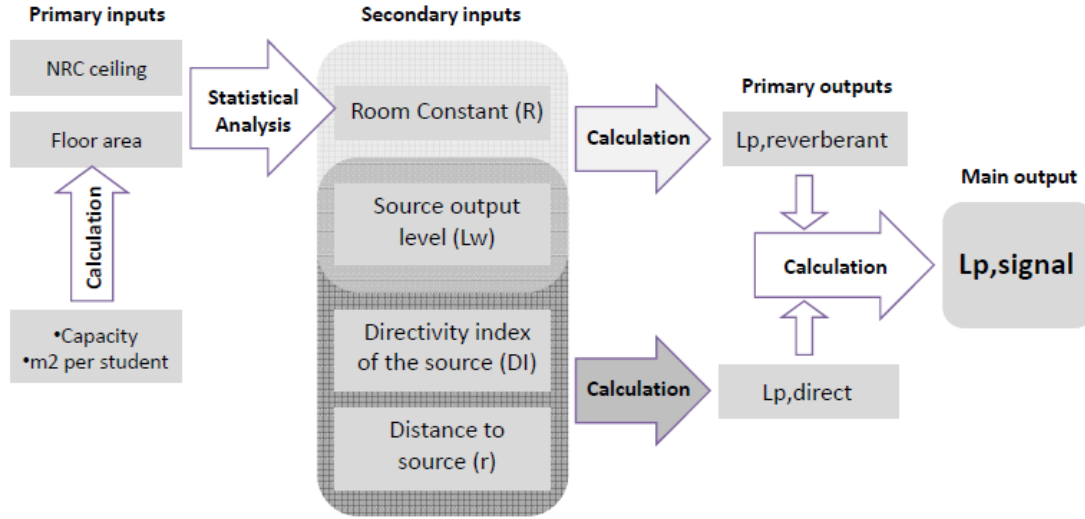


Figure 4.3 : Methodology of the formula based graphic model

The Ministry of National Education published a guide in 1997 about the planning of elementary school buildings. According to this guide, proposed maximum student capacity for an elementary school classroom is 30 students. Although area per student in classrooms is not stated in the guide, area per student is found as 1.7 m² by dividing the suggested total area of a typical classroom to the capacity of that classroom. These proposals are not widely considered in many of the school buildings. Student capacity is more than 30 in many school classrooms and area per student changes mostly between 1.2 to 1.5 m² [1, 2]. Simulations have done considering these present situations, so that the model is formed alike.

Reverberant Sound Pressure Level

The first step of the model is a graphic which gives a way to find the signal level at a certain point in a classroom. The signal level at a point consists of both reverberant sound and direct sound. If the direct sound coming through is neglected, then the reverberant sound at a receiver point is calculated as in Equation 4.7 [7].

$$L_R = L_{w(womanPBF)} + 6 + 10 \log_{10} \left(\frac{1 - \alpha}{A} \right) \quad (4.7)$$

As mentioned before, a different sound source is used while evaluating signal to noise ratios in the first model. This source's sound power levels according to frequencies are given in Table 4.7 [9].

Table 4.7 : Source sound power levels according to frequencies [9]

	Frequency (Hz)					
	125	250	500	1k	2k	4k
L_{w,womanPBF} (dB)	48,4	66,1	67,1	62,9	56	53,2

In Equation 4.7, the last expression $(1-\alpha/A)$ can be written as $1/R$ in which R indicates the room constant. The formula of R is given in Equation 4.8 [7].

$$R = \frac{A}{1 - \alpha} \quad (4.8)$$

R : Room constant

α : Mean sound absorption coefficient (sabin)

A : Total absorption (m^2 sabin)

Regression analysis are done to explain the room constant. As a general approach, the absorptive material which will affect the speech intelligibility is placed to the rear wall or to the ceiling of a classroom [10, 37, 38]. Considering that walls are commonly used to hang information posters or paper works, ceiling is the most suitable surface for absorptive material placement. It is accepted that possible material choices for the surfaces rather than the ceiling surface will not show much difference. So that, the absorption of the ceiling could clarify the room absorption characteristics.

Instead of entering the ceiling area, the floor area is entered to the formula because the floor area of a classroom is designated according to the required student capacity and will be the same as the ceiling area. Absorptive materials are commonly presented to the consumer by their noise reduction coefficients. Noise reduction coefficient, NRC is the average absorption coefficient over speech frequencies, 250 Hz to 2 kHz [9] as shown in Equation 4.9. NRC of the ceiling material is used in this step.

$$NRC = \frac{1}{4}(\alpha_{250} + \alpha_{500} + \alpha_{1k} + \alpha_{2k}) \quad (4.9)$$

NRC : Noise reduction coefficient

The regression formula, in Equation 4.10 is derived from the statistical analysis to calculate the room constant, R at 1 kHz frequency. Mid frequencies are important for speech communication and R will represent the whole room's absorptive characteristics.

$$R_{1kHz} = -24,638 + 61,942.NRC_{ceiling} + 0,761.S_{floor} \quad (4.10)$$

R_{1kHz} : Room constant at 1kHz

$NRC_{ceiling}$: Noise reduction coefficient of the ceiling material

S_{floor} : Surface area of the floor

R^2 of the Equation 4.10 is **0,872**. The floor surface area in Equation 4.10 is calculated by multiplying the student capacity of a classroom with the required floor area per student as shown in Equation 4.11.

$$S_{floor} = n.S_{perstudent} \quad (4.11)$$

Direct Sound Pressure Level

In Equation 4.7, room reverberant character is considered only. Signal level at the receiver point is also affected by the distance between source and receiver. The signal sound pressure level considering only direct sound field is calculated as in Equation 4.12.

$$L_D = L_{w(womanPBF)} + DI - 20\log_{10}(r) - 11 \quad (4.12)$$

DI : Directivity index of the source

r : Distance between sound source and the receiver

In the model, the distance between source and receiver is limited. Length (l) and width (w) combinations of the classrooms define the maximum limit. Hypotenuse of l and w give the maximum source-receiver distance.

Developing the graphic

The graphics developed to obtain the reverberant and direct sound level at a certain point of a designed classroom is given in Figure 4.5. The starting point to design a classroom is the student capacity selection at the upper part of the figure. The floor area is found with the student capacity and the required area per student. The maximum distance from receiver to source ($r_{\max}$) is defined according to the obtained floor area. The area below $r_{\max}$ line represents a range for possible distances between the receiver and the source according to the floor area. The dark blue area represents the possible change of $r_{\max}$ according to different room length and width combinations. The choice according to the width of the designed classroom is limited between **5 and 7 meter**. The direct sound pressure level for octave band frequencies at a certain distance to source is then read from the graphic by intersecting a horizontal line, drawn through the chosen 'distance to source', with the direct sound pressure level frequency lines.

The deviation in the direct sound pressure levels originated from the classroom width choice is shown in Figure 4.4. If the chosen 'distance to source' is in the dark blue area of the graphic, possible deviation in direct sound pressure levels can be between - 0,4dB to -2,2dB depending on the floor area independent from frequency.

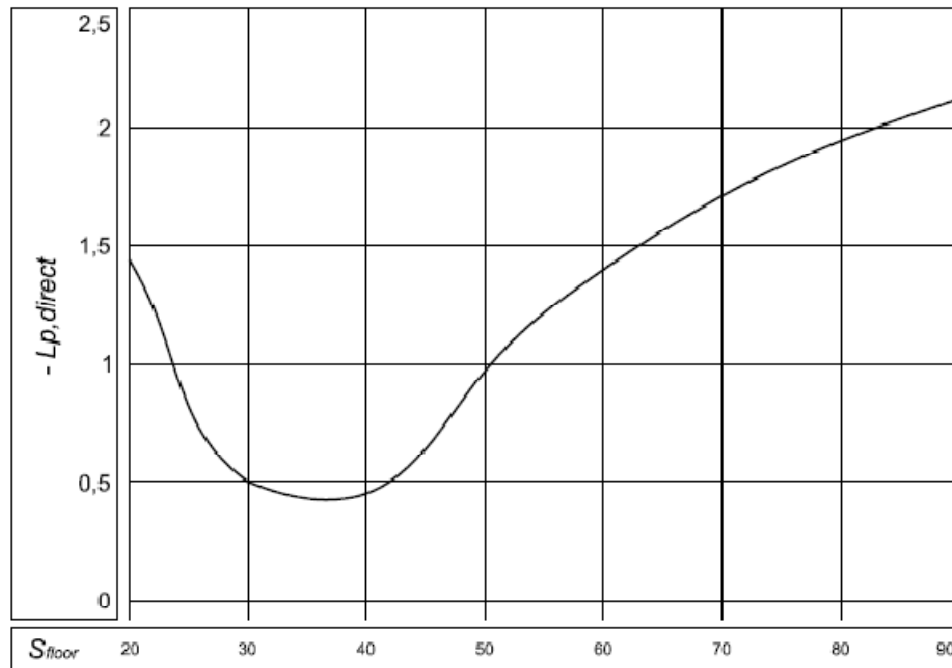


Figure 4.4 : Possible level decrease in $L_{p, \text{direct}}$ (independent from frequency) in accordance to $r_{\max}$ of a classroom of which the width changes between 5 to 7 m.

The lower part of the Figure 4.5 is used to find reverberant sound pressure levels. First of all, the room constant is obtained by the determined floor area and the NRC of the ceiling material that is supposed to be used. Then a horizontal line is drawn through the room constant which intersects with the reverberant sound pressure level frequency lines.

An example of using the graphics will be shown in another section with the hybrid model developed.

Signal Sound Pressure Level

After finding L_R and L_D , signal level is calculated as in the Equation 4.13.

$$L_{signal} = 10 \log_{10} \left(10^{L_D/10} + 10^{L_R/10} \right) \quad (4.13)$$

Signal level at the receiver point is obtained from the second sub-model. The next step is to combine both sub-models to form a hybrid model to predict the speech intelligibility in a designed classroom.

4.3 The hybrid model: Integration of the simulation based model and the formula based graphic model

The final model is a hybrid model which combines the simulation based sub-model and the formula based graphic sub-model. The signal levels obtained by the formula based graphic model are used in the calculation of signal to noise ratios.

An architect has to design the classroom according to the acceptable background noise levels stated in regulations or standards. The acceptable background noise levels may either be given as A-weighted levels or a noise criterion curve. The noise levels according to the NCB curves are included to the integrated model. Frequency distributions of noise levels are given in Table 4.4. The formula that gives SN ratio is shown in Equation 4.14.

$$SN = L_{signal} - L_{noise} \quad (4.14)$$

L_{signal} : Signal sound pressure level derived from formula based graphic model

L_{noise} : Background noise level chosen from Table 4.4

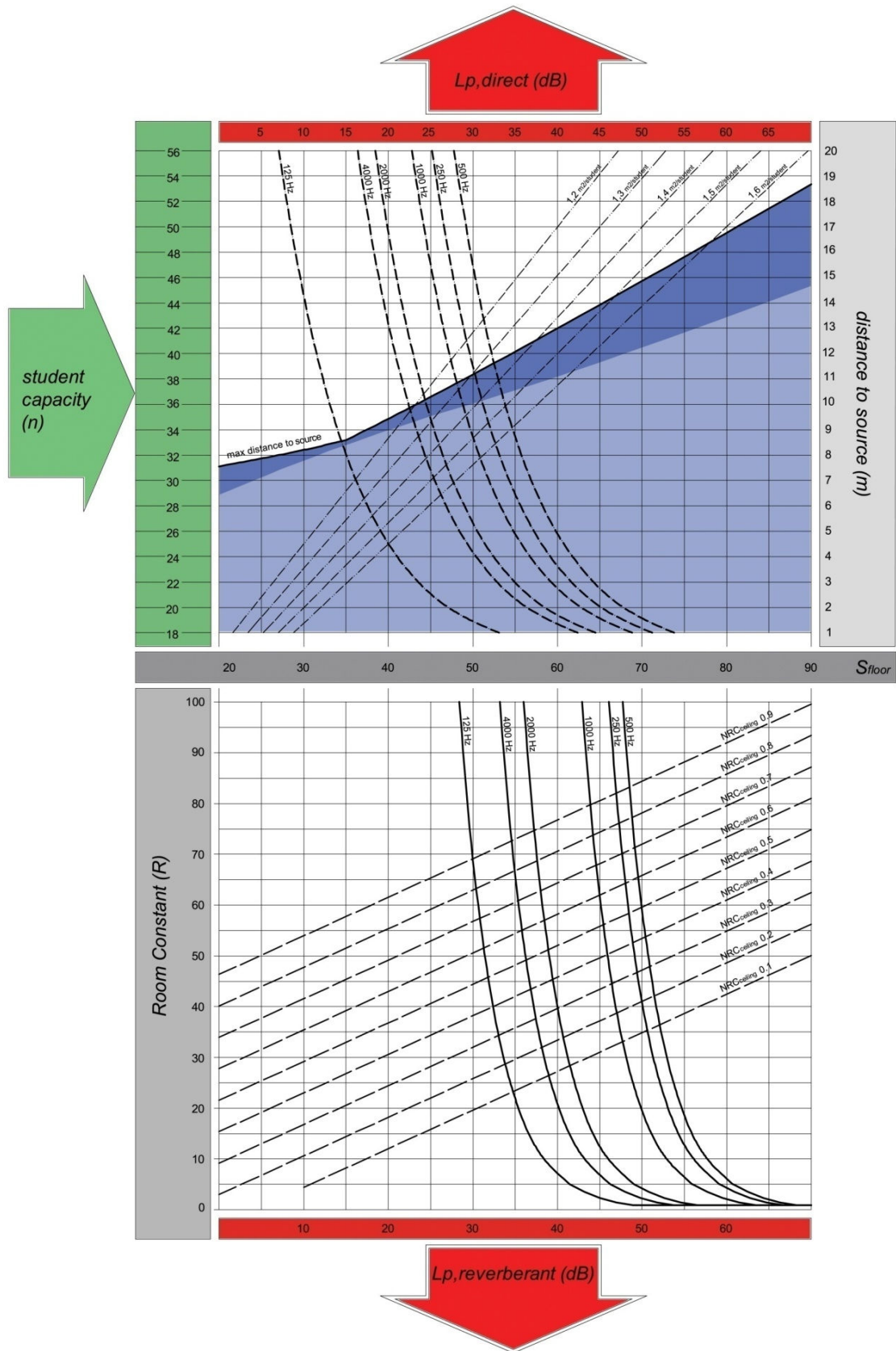


Figure 4.5 : Graphic set to find $L_{reverberant}$ and L_{direct}

After calculating SN values for every octave band frequency, Equation 4.6 is used to estimate STI at a chosen distance to an imaginary source in the classroom. The speech transmission index metric is qualified as seen in Figure 4.6 [23].

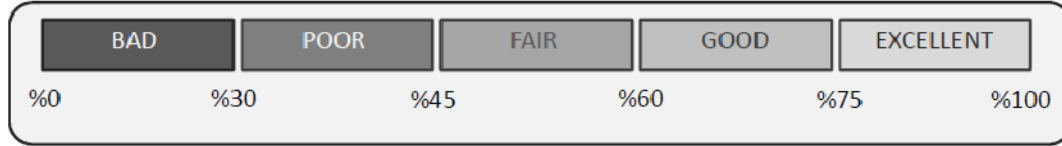


Figure 4.6 : STI (%) qualification scale [14]

STI found by the integrated hybrid model is an approximate result. Another regression analyze is done to determine the relation between STI values derived from the integrated model and STI values calculated from noise added outputs of CATT simulations. Regression line between these two different STI values is found as in Figure 4.7.

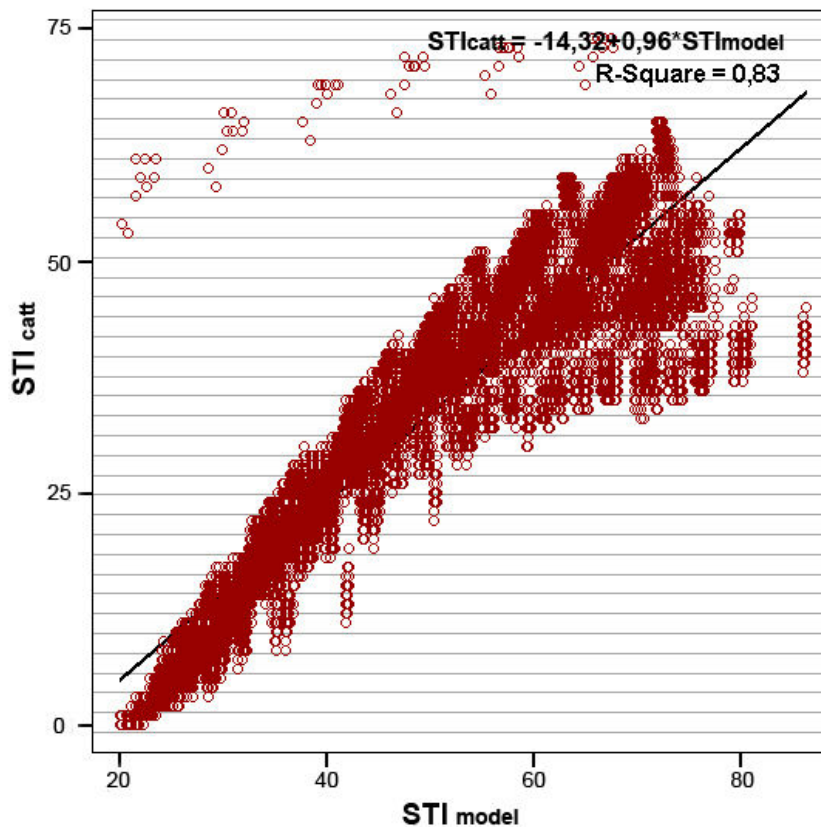


Figure 4.7 : Regression line of STI_{model} versus STI_{catt}

As it is seen from the regression line, the result from the model is close enough to make a prediction about the speech intelligibility in a classroom at the design stage with an approximate way. The flow chart in Figure 4.8 explains the steps in the model.

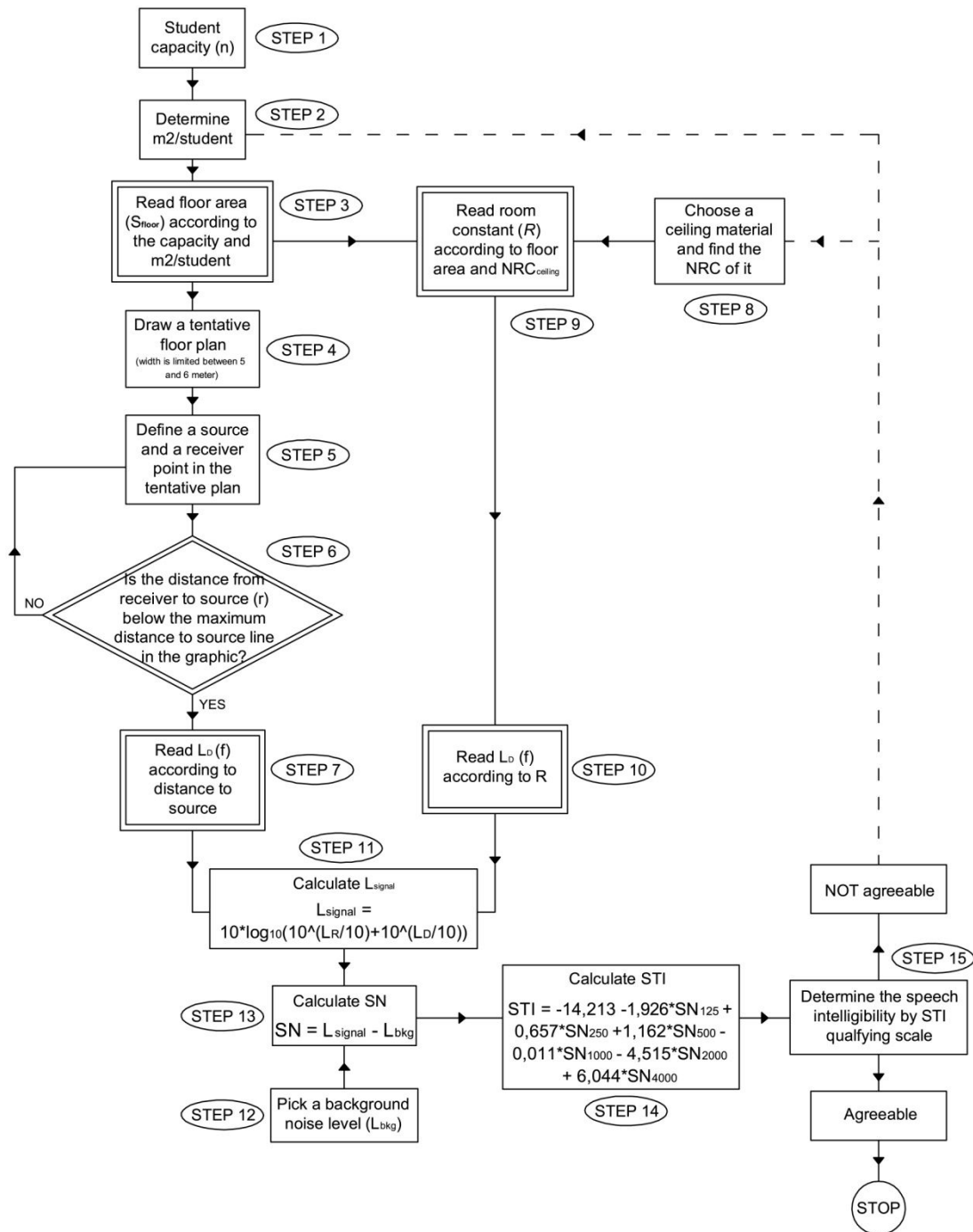


Figure 4.8 : The flow chart of the model to design a classroom (Dashed lines indicates a multi optional return to the previous steps. Box in box is the steps where the graphic is used)

4.4 Using the model – an example

The previous parts of the thesis explain the methodology to derive the sub-models and the final hybrid model. Under this title, using the hybrid model is going to be explained by an example.

- Step 1:

At the beginning of the design process, the user requirements are set. According to the user requirements, the student capacity of the classroom is determined. Architect should start with selecting the capacity in the upper side of the formula based graphic (Figure 4.10). In our example, the student capacity of the classroom is planned to be 36.

- Step 2:

Then the second step is to determine the surface area per student according to economic and ergonomic needs. For the example classroom, the area per student is defined as 1.5 m^2 (Figure 4.10).

- Step 3:

The third step is to read the floor area from the graphic (Figure 4.10) according to the student capacity and the m^2 area per student. The area for the floor is 54m^2 for our example.

- Step 4 and 5:

After finding the floor area, a tentative floor plan is drawn to decide according to which points of the classroom; speech intelligibility is intended to be determined. The tentative plan for the designed classroom and the defined receiver and source points in the classroom are shown in Figure 4.9.

- Step 6 (Control):

The distance to source is 7.5 m. in the example. The maximum distance according to the graphic for the chosen floor area is 11.9 m so that the chosen distance is shorter than the r_{max} .

- Step 7:

L_D is read from the graphic (See Figure 4.10) by crossing a line from the chosen distance to source through the direct sound pressure level frequency lines.

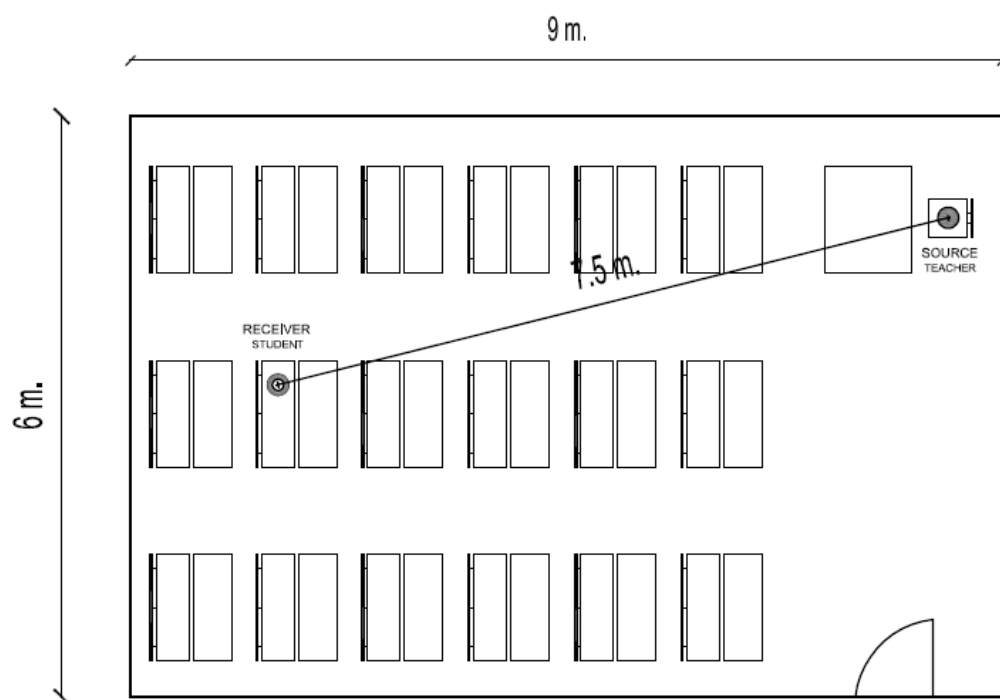


Figure 4.9 : Tentative plan of the example classroom

- Step 8:

After obtaining the direct sound pressure levels, next step is to choose a ceiling material for the classroom. In the example, gypsum tiles (%17 perforated) are preferred. The NRC value for this material is 0,7 [10].

- Step 9:

The R value is found with the floor area and NRC_{ceiling} (Figure 4.10) . In our example it is found as 60.

- Step 10:

The reverberant sound pressure levels are read by drawing a horizontal line through reverberant sound pressure level frequency lines (Figure 4.10).

- Step 11:

The formula based graphic model ends with the calculation of the signal level according to Equation 4.13. The direct and reverberant sound pressure levels and the achieved signal levels for the example classroom at the receiver point are given in Table 4.8.

Table 4.8 : Reverberant, direct sound pressure levels and the signal level obtained for the receiver in the example.

	Frequency (Hz)					
	125	250	500	1k	2k	4k
Ldirect	16	33,5	36,5	32	27	25
Lreverberant	31	48	50	45	38	36,5
L signal	31,1	48,2	50,2	45,2	38,3	36,8

- Step 12

In step 12, acceptable background noise level in the classroom is chosen from Table 4.4. In this example, NCB 35 curve is chosen. The overall A-weighted level of this curve is under the limit 45dBA which is stated in The Regulation 08 of Turkey for a classroom, windows opened.

- Step 13:

The signal to noise values are calculated in this step according to the Equation 4.14. The calculated SN ratios is shown in Table 4.9 with the signal and noise levels.

Table 4.9 : Signal and noise levels and SN ratios at the receiver point in the example

	Frequency (Hz)					
	125	250	500	1k	2k	4k
L signal	31,1	48,2	50,2	45,2	38,3	36,8
L noise (NCB 35)	51	44	40	37	33	30
SN	-19,9	4,2	10,2	8,2	5,3	6,8

- Step 14:

After finding SN ratios, the Equation 4.6 is used to estimate STI at the receiver point of the example designed classroom. In our example STI calculated for the receiver point is found **55,8**.

- Step 15:

In the last step STI value found for the example classroom is qualified according to the qualification scale in Figure 4.6 and speech intelligibility at the receiver point in the example classroom is found as **FAIR**.

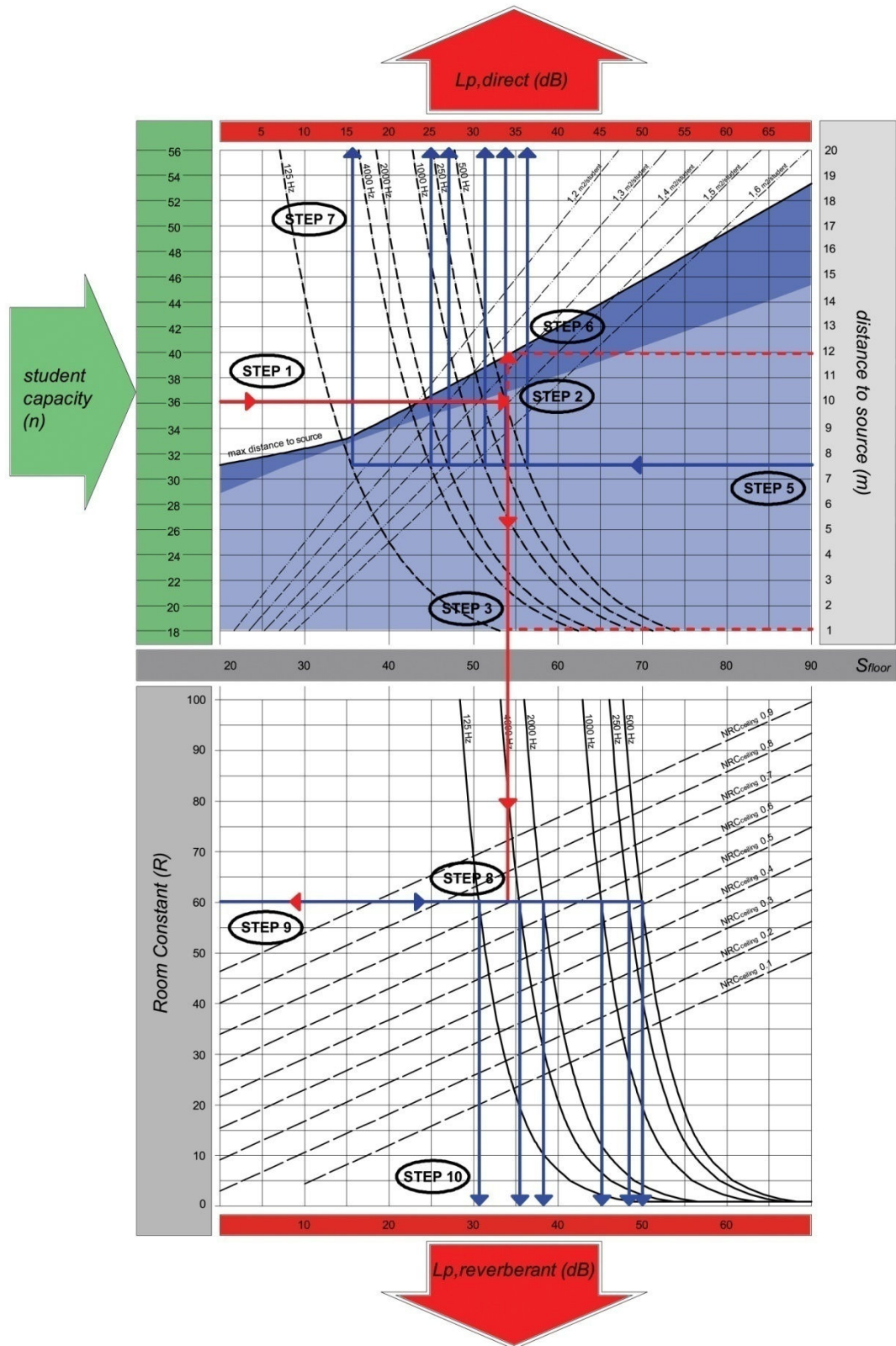


Figure 4.10 : Using the graphic set to find $L_{reverberant}$ and L_{direct}

According to the design criteria, if the speech intelligibility at a fair level is acceptable, the architect is free to design the classroom according to the decisions given at Step 2, and Step 8 of the model.

If the intelligibility level is unacceptable, the architect have to change one or more input he decide. These inputs are:

- Area per student (Step 2)
- NRC ceiling (Step 3)

Another choice is to add more absorptive material to the surfaces of the classroom other than ceiling. It is advisable to locate the absorptive material to the rear wall of the classroom [10, 37, 38].

5. CONCLUSION AND RECOMMENDATIONS

The major purpose of this research was to develop a model for the evaluation of speech intelligibility in a classroom during its design stage. In this way, the architect can realize whether his/her design decisions will result in an acoustically comfortable classroom.

Previous researches show that reverberation times, speech and noise levels are the effective factors in speech intelligibility. Reverberation in a room increases the early sound energy which has a strengthening character on speech, on the other hand too much reverberation can lead to a decrease in signal to noise ratios. The background noise level should not exceed a certain level because it has a masking effect on speech. Moreover, the tendency of teachers during noisy conditions is to increase their voice levels to be audible. This effort causes long term vocal fatigues.

The model developed in the context of this thesis presents some opportunities for architects:

- STI value at any receiver point in a classroom can be obtained by the model, so that the distribution of STI throughout the classroom depending on an exact source location is known.
- It is easy to integrate the model into the design process of a classroom since it consists of multiple design choices.
- The model is designed to be user friendly. By reading graphics and doing a few calculations, an architect can estimate the degree of speech intelligibility in a classroom.
- The model is developed according to the present classroom projects so it associates with the real situations.

Further studies should be done to improve the accuracy of the model. By increasing the variation of the classroom types and material choices, many situations have to be simulated in a simulation program to achieve more reliable statistics between different parameters. Hereby, regression formulas derived in this way will represent the general relations more strongly. Also the graphical method should be broadened to include the other steps where some calculations are done.

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APPENDICES

APPENDIX A: Noise Criterion Curves

APPENDIX B: Reverberation times derived for the simulated classrooms in
various source, ceiling type and receiver combination

APPENDIX C: Distance between source and receiver

APPENDIX A

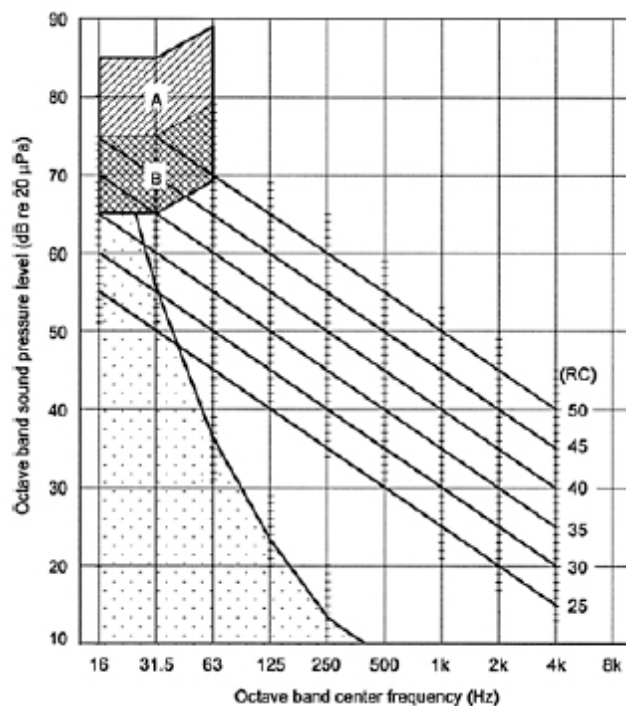


Figure A.1 : Room Criteria Curves

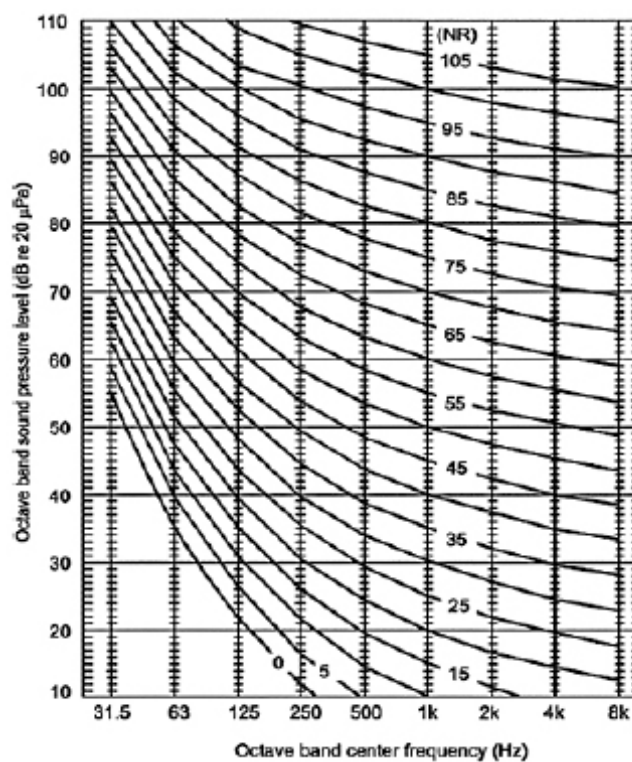


Figure A.2 : Noise Rating Curves

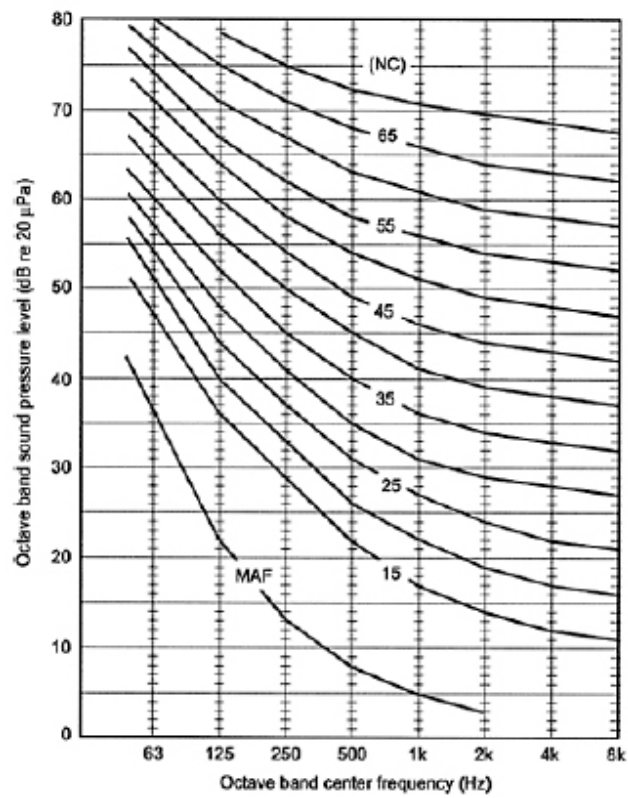


Figure A.3 : Noise Criteria Curves

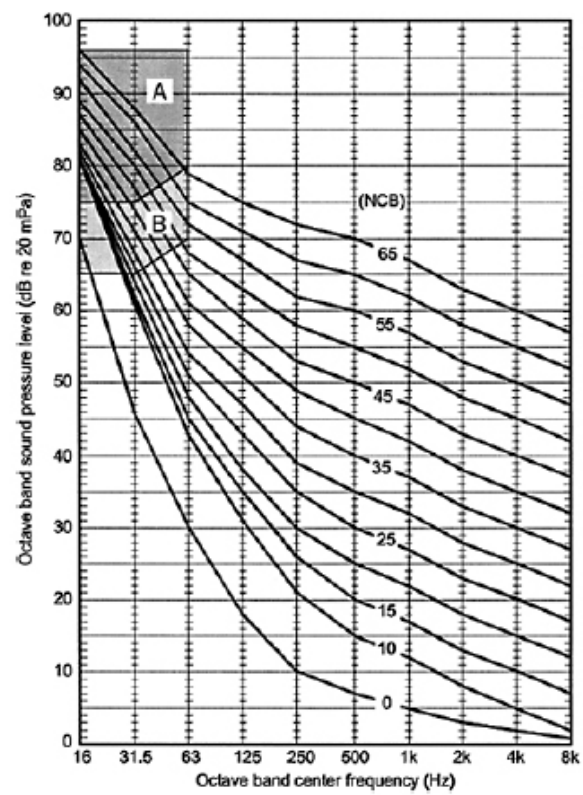


Figure A.4 : Balanced Noise Criteria Curves

APPENDIX B

Table B1: Reverberation time of simulated classrooms

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A0	1	1	2,47	1,97	1,75	1,6	1,36	1,03
A0	1	2	1,24	1,05	1,07	1,11	0,99	0,79
A0	1	3	0,74	0,51	0,41	0,59	0,63	0,6
A0	1	4	1,74	1,39	1,1	0,7	0,61	0,56
A0	1	5	0,55	0,48	0,55	0,51	0,41	0,39
A0	1	6	0,5	0,44	0,48	0,4	0,4	0,38
A0	2	1	2,72	2,19	1,95	1,77	1,49	1,11
A0	2	2	1,4	1,19	1,22	1,25	1,1	0,86
A0	2	3	0,86	0,58	0,48	0,68	0,71	0,66
A0	2	4	1,95	1,57	1,25	0,8	0,7	0,63
A0	2	5	0,63	0,55	0,63	0,58	0,47	0,44
A0	2	6	0,58	0,51	0,56	0,47	0,46	0,43
A0	3	1	2,94	2,39	2,14	1,91	1,6	1,17
A0	3	2	1,56	1,33	1,36	1,37	1,2	0,93
A0	3	3	0,96	0,66	0,54	0,76	0,79	0,73
A0	3	4	2,14	1,73	1,38	0,89	0,77	0,69
A0	3	5	0,71	0,62	0,71	0,66	0,53	0,49
A0	3	6	0,65	0,58	0,63	0,53	0,51	0,47
A0	4	1	2,72	2,14	1,92	1,75	1,5	1,12
A0	4	2	1,3	1,1	1,13	1,18	1,06	0,84
A0	4	3	0,77	0,52	0,42	0,61	0,66	0,63
A0	4	4	1,86	1,47	1,16	0,73	0,64	0,59
A0	4	5	0,56	0,49	0,56	0,52	0,42	0,41
A0	4	6	0,51	0,45	0,49	0,41	0,41	0,39
A0	5	1	2,99	2,38	2,13	1,93	1,63	1,2
A0	5	2	1,47	1,25	1,29	1,33	1,18	0,92
A0	5	3	0,88	0,6	0,49	0,7	0,75	0,7
A0	5	4	2,09	1,66	1,32	0,83	0,73	0,66
A0	5	5	0,65	0,56	0,65	0,6	0,48	0,46
A0	5	6	0,59	0,52	0,57	0,48	0,47	0,44
A0	6	1	3,23	2,6	2,34	2,09	1,76	1,27
A0	6	2	1,64	1,39	1,43	1,46	1,29	0,99
A0	6	3	0,99	0,68	0,55	0,79	0,83	0,76
A0	6	4	2,29	1,84	1,47	0,92	0,81	0,72
A0	6	5	0,73	0,64	0,73	0,68	0,54	0,51
A0	6	6	0,67	0,59	0,64	0,54	0,53	0,49
A0	7	1	2,9	2,26	2,04	1,86	1,59	1,19
A0	7	2	1,34	1,13	1,18	1,23	1,11	0,88
A0	7	3	0,78	0,53	0,43	0,63	0,68	0,65
A0	7	4	1,95	1,53	1,21	0,75	0,66	0,61
A0	7	5	0,57	0,49	0,58	0,54	0,43	0,42

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A0	7	6	0,52	0,45	0,5	0,42	0,42	0,4
A0	8	1	3,2	2,52	2,27	2,05	1,74	1,27
A0	8	2	1,53	1,29	1,34	1,38	1,24	0,96
A0	8	3	0,9	0,61	0,5	0,72	0,77	0,72
A0	8	4	2,19	1,73	1,37	0,85	0,75	0,68
A0	8	5	0,66	0,57	0,66	0,61	0,49	0,47
A0	8	6	0,6	0,53	0,58	0,48	0,48	0,45
A0	9	1	3,46	2,75	2,49	2,22	1,87	1,34
A0	9	2	1,7	1,44	1,49	1,52	1,35	1,03
A0	9	3	1,02	0,69	0,56	0,81	0,86	0,79
A0	9	4	2,41	1,92	1,53	0,95	0,84	0,74
A0	9	5	0,74	0,65	0,75	0,69	0,56	0,52
A0	9	6	0,68	0,6	0,66	0,55	0,54	0,5
A0	10	1	3,08	2,37	2,14	1,95	1,68	1,24
A0	10	2	1,38	1,16	1,21	1,27	1,15	0,91
A0	10	3	0,8	0,53	0,43	0,64	0,7	0,67
A0	10	4	2,03	1,58	1,25	0,76	0,68	0,62
A0	10	5	0,57	0,5	0,58	0,54	0,44	0,42
A0	10	6	0,52	0,46	0,51	0,43	0,43	0,4
A0	11	1	3,38	2,64	2,39	2,15	1,83	1,33
A0	11	2	1,57	1,32	1,38	1,43	1,28	0,99
A0	11	3	0,92	0,62	0,5	0,73	0,79	0,74
A0	11	4	2,27	1,79	1,41	0,87	0,77	0,69
A0	11	5	0,66	0,58	0,67	0,62	0,5	0,48
A0	11	6	0,61	0,53	0,59	0,49	0,49	0,46
A0	12	1	3,66	2,89	2,62	2,33	1,97	1,4
A0	12	2	1,74	1,47	1,54	1,58	1,4	1,07
A0	12	3	1,03	0,7	0,57	0,82	0,88	0,81
A0	12	4	2,5	1,98	1,57	0,97	0,85	0,76
A0	12	5	0,75	0,65	0,76	0,7	0,56	0,53
A0	12	6	0,69	0,6	0,67	0,56	0,55	0,51
A0	13	1	3,21	2,46	2,23	2,03	1,75	1,29
A0	13	2	1,4	1,18	1,24	1,3	1,18	0,93
A0	13	3	0,81	0,54	0,44	0,65	0,71	0,68
A0	13	4	2,08	1,62	1,27	0,77	0,69	0,63
A0	13	5	0,58	0,5	0,59	0,55	0,44	0,43
A0	13	6	0,53	0,46	0,51	0,43	0,43	0,41
A0	14	1	3,53	2,73	2,48	2,24	1,91	1,38
A0	14	2	1,6	1,34	1,41	1,47	1,32	1,02
A0	14	3	0,93	0,62	0,51	0,74	0,8	0,76
A0	14	4	2,34	1,83	1,45	0,88	0,78	0,71

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A0	7	6	0,52	0,45	0,5	0,42	0,42	0,4
A0	8	1	3,2	2,52	2,27	2,05	1,74	1,27
A0	8	2	1,53	1,29	1,34	1,38	1,24	0,96
A0	8	3	0,9	0,61	0,5	0,72	0,77	0,72
A0	8	4	2,19	1,73	1,37	0,85	0,75	0,68
A0	8	5	0,66	0,57	0,66	0,61	0,49	0,47
A0	8	6	0,6	0,53	0,58	0,48	0,48	0,45
A0	9	1	3,46	2,75	2,49	2,22	1,87	1,34
A0	9	2	1,7	1,44	1,49	1,52	1,35	1,03
A0	9	3	1,02	0,69	0,56	0,81	0,86	0,79
A0	9	4	2,41	1,92	1,53	0,95	0,84	0,74
A0	9	5	0,74	0,65	0,75	0,69	0,56	0,52
A0	9	6	0,68	0,6	0,66	0,55	0,54	0,5
A0	10	1	3,08	2,37	2,14	1,95	1,68	1,24
A0	10	2	1,38	1,16	1,21	1,27	1,15	0,91
A0	10	3	0,8	0,53	0,43	0,64	0,7	0,67
A0	10	4	2,03	1,58	1,25	0,76	0,68	0,62
A0	10	5	0,57	0,5	0,58	0,54	0,44	0,42
A0	10	6	0,52	0,46	0,51	0,43	0,43	0,4
A0	11	1	3,38	2,64	2,39	2,15	1,83	1,33
A0	11	2	1,57	1,32	1,38	1,43	1,28	0,99
A0	11	3	0,92	0,62	0,5	0,73	0,79	0,74
A0	11	4	2,27	1,79	1,41	0,87	0,77	0,69
A0	11	5	0,66	0,58	0,67	0,62	0,5	0,48
A0	11	6	0,61	0,53	0,59	0,49	0,49	0,46
A0	12	1	3,66	2,89	2,62	2,33	1,97	1,4
A0	12	2	1,74	1,47	1,54	1,58	1,4	1,07
A0	12	3	1,03	0,7	0,57	0,82	0,88	0,81
A0	12	4	2,5	1,98	1,57	0,97	0,85	0,76
A0	12	5	0,75	0,65	0,76	0,7	0,56	0,53
A0	12	6	0,69	0,6	0,67	0,56	0,55	0,51
A0	13	1	3,21	2,46	2,23	2,03	1,75	1,29
A0	13	2	1,4	1,18	1,24	1,3	1,18	0,93
A0	13	3	0,81	0,54	0,44	0,65	0,71	0,68
A0	13	4	2,08	1,62	1,27	0,77	0,69	0,63
A0	13	5	0,58	0,5	0,59	0,55	0,44	0,43
A0	13	6	0,53	0,46	0,51	0,43	0,43	0,41
A0	14	1	3,53	2,73	2,48	2,24	1,91	1,38
A0	14	2	1,6	1,34	1,41	1,47	1,32	1,02
A0	14	3	0,93	0,62	0,51	0,74	0,8	0,76
A0	14	4	2,34	1,83	1,45	0,88	0,78	0,71

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A0	21	4	2,47	1,96	1,53	0,95	0,83	0,74
A0	21	5	0,75	0,65	0,75	0,69	0,56	0,52
A0	21	6	0,68	0,6	0,66	0,55	0,54	0,5
A0	22	1	3,23	2,47	2,17	1,97	1,68	1,25
A0	22	2	1,41	1,18	1,22	1,28	1,15	0,91
A0	22	3	0,81	0,54	0,44	0,64	0,7	0,67
A0	22	4	2,09	1,62	1,25	0,77	0,68	0,63
A0	22	5	0,58	0,5	0,59	0,55	0,44	0,42
A0	22	6	0,53	0,47	0,51	0,43	0,43	0,41
A0	23	1	3,58	2,76	2,43	2,19	1,85	1,35
A0	23	2	1,61	1,35	1,4	1,45	1,29	1,01
A0	23	3	0,94	0,62	0,51	0,74	0,79	0,75
A0	23	4	2,36	1,84	1,43	0,88	0,77	0,7
A0	23	5	0,67	0,58	0,68	0,63	0,5	0,48
A0	23	6	0,61	0,54	0,59	0,49	0,49	0,46
A0	24	1	3,89	3,03	2,68	2,38	2	1,43
A0	24	2	1,8	1,51	1,56	1,6	1,42	1,09
A0	24	3	1,05	0,71	0,57	0,83	0,88	0,82
A0	24	4	2,61	2,05	1,6	0,98	0,86	0,77
A0	24	5	0,76	0,66	0,77	0,71	0,57	0,54
A0	24	6	0,7	0,61	0,67	0,56	0,55	0,51
A0	25	1	3,44	2,59	2,29	2,07	1,78	1,31
A0	25	2	1,45	1,21	1,26	1,32	1,2	0,95
A0	25	3	0,82	0,55	0,44	0,65	0,71	0,69
A0	25	4	2,18	1,68	1,29	0,78	0,69	0,64
A0	25	5	0,59	0,51	0,6	0,55	0,45	0,43
A0	25	6	0,54	0,47	0,52	0,43	0,43	0,41
A0	26	1	3,81	2,9	2,57	2,3	1,95	1,41
A0	26	2	1,65	1,38	1,44	1,49	1,34	1,04
A0	26	3	0,95	0,63	0,51	0,75	0,81	0,77
A0	26	4	2,46	1,9	1,48	0,89	0,79	0,72
A0	26	5	0,68	0,59	0,69	0,64	0,51	0,49
A0	26	6	0,62	0,54	0,6	0,5	0,5	0,47
A0	27	1	4,14	3,18	2,82	2,5	2,11	1,49
A0	27	2	1,85	1,55	1,61	1,65	1,47	1,12
A0	27	3	1,07	0,71	0,58	0,84	0,91	0,84
A0	27	4	2,72	2,12	1,65	1	0,88	0,79
A0	27	5	0,77	0,67	0,78	0,72	0,58	0,55
A0	27	6	0,7	0,62	0,68	0,57	0,56	0,52
A0	28	1	3,31	2,47	2,2	1,99	1,72	1,28
A0	28	2	1,36	1,13	1,19	1,25	1,14	0,91

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A0	28	3	0,77	0,51	0,41	0,61	0,67	0,65
A0	28	4	2,07	1,59	1,22	0,73	0,65	0,61
A0	28	5	0,55	0,47	0,55	0,51	0,41	0,4
A0	28	6	0,5	0,44	0,48	0,4	0,4	0,39
A0	29	1	3,67	2,77	2,47	2,22	1,89	1,38
A0	29	2	1,56	1,3	1,36	1,42	1,28	1
A0	29	3	0,89	0,59	0,48	0,7	0,77	0,73
A0	29	4	2,34	1,81	1,4	0,84	0,74	0,68
A0	29	5	0,63	0,55	0,64	0,59	0,48	0,46
A0	29	6	0,58	0,51	0,56	0,47	0,47	0,44
A0	30	1	4,02	3,07	2,73	2,43	2,06	1,47
A0	30	2	1,75	1,46	1,53	1,58	1,41	1,09
A0	30	3	1	0,67	0,54	0,79	0,86	0,8
A0	30	4	2,59	2,01	1,57	0,95	0,83	0,75
A0	30	5	0,72	0,63	0,73	0,68	0,54	0,52
A0	30	6	0,58	0,51	0,56	0,47	0,47	0,44
A1	1	1	2,47	1,97	1,75	1,6	1,36	1,03
A1	1	2	1,23	1,05	1,07	1,11	0,99	0,79
A1	1	3	0,75	0,51	0,41	0,59	0,63	0,6
A1	1	4	1,74	1,39	1,1	0,7	0,61	0,56
A1	1	5	0,55	0,48	0,55	0,51	0,41	0,39
A1	1	6	0,5	0,44	0,48	0,4	0,4	0,38
A1	2	1	2,72	2,19	1,95	1,77	1,49	1,11
A1	2	2	1,4	1,19	1,22	1,25	1,1	0,86
A1	2	3	0,86	0,58	0,48	0,68	0,72	0,67
A1	2	4	1,95	1,57	1,25	0,8	0,7	0,63
A1	2	5	0,63	0,55	0,63	0,58	0,47	0,44
A1	2	6	0,58	0,51	0,56	0,47	0,46	0,43
A1	3	1	2,94	2,39	2,14	1,92	1,6	1,17
A1	3	2	1,56	1,33	1,36	1,37	1,2	0,93
A1	3	3	0,96	0,66	0,54	0,76	0,79	0,73
A1	3	4	2,14	1,73	1,38	0,89	0,77	0,69
A1	3	5	0,71	0,62	0,71	0,66	0,53	0,49
A1	3	6	0,65	0,58	0,63	0,53	0,51	0,47
A1	4	1	2,71	2,13	1,91	1,74	1,49	1,12
A1	4	2	1,29	1,09	1,13	1,18	1,06	0,84
A1	4	3	0,77	0,52	0,42	0,61	0,66	0,63
A1	4	4	1,86	1,47	1,16	0,73	0,64	0,59
A1	4	5	0,56	0,49	0,56	0,52	0,42	0,41
A1	4	6	0,51	0,45	0,49	0,41	0,41	0,39
A1	5	1	2,99	2,38	2,13	1,93	1,63	1,2

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A1	5	2	1,47	1,25	1,29	1,33	1,18	0,92
A1	5	3	0,88	0,6	0,49	0,7	0,75	0,7
A1	5	4	2,09	1,66	1,32	0,83	0,73	0,66
A1	5	5	0,65	0,56	0,65	0,6	0,48	0,46
A1	5	6	0,59	0,52	0,57	0,48	0,47	0,44
A1	6	1	3,23	2,6	2,34	2,09	1,75	1,27
A1	6	2	1,64	1,39	1,44	1,46	1,29	0,99
A1	6	3	0,99	0,68	0,55	0,79	0,83	0,76
A1	6	4	2,29	1,84	1,47	0,92	0,81	0,72
A1	6	5	0,73	0,64	0,73	0,68	0,54	0,51
A1	6	6	0,67	0,59	0,64	0,54	0,53	0,49
A1	7	1	2,91	2,26	2,04	1,86	1,6	1,19
A1	7	2	1,34	1,13	1,18	1,23	1,11	0,88
A1	7	3	0,78	0,53	0,43	0,63	0,68	0,65
A1	7	4	1,95	1,53	1,21	0,75	0,66	0,61
A1	7	5	0,57	0,49	0,58	0,54	0,43	0,42
A1	7	6	0,52	0,45	0,5	0,42	0,42	0,4
A1	8	1	3,2	2,52	2,27	2,05	1,74	1,27
A1	8	2	1,52	1,29	1,34	1,38	1,23	0,96
A1	8	3	0,9	0,61	0,5	0,72	0,77	0,72
A1	8	4	2,19	1,73	1,37	0,85	0,75	0,68
A1	8	5	0,66	0,57	0,66	0,61	0,49	0,47
A1	8	6	0,6	0,53	0,58	0,48	0,48	0,45
A1	9	1	3,46	2,75	2,49	2,22	1,87	1,34
A1	9	2	1,7	1,44	1,49	1,53	1,35	1,04
A1	9	3	1,01	0,69	0,56	0,81	0,86	0,79
A1	9	4	2,41	1,92	1,53	0,95	0,84	0,74
A1	9	5	0,74	0,65	0,75	0,69	0,56	0,52
A1	9	6	0,68	0,6	0,66	0,55	0,54	0,5
A1	10	1	3,08	2,37	2,15	1,95	1,68	1,24
A1	10	2	1,38	1,16	1,21	1,27	1,15	0,91
A1	10	3	0,8	0,53	0,43	0,64	0,69	0,67
A1	10	4	2,03	1,58	1,25	0,76	0,68	0,62
A1	10	5	0,57	0,5	0,58	0,54	0,44	0,42
A1	10	6	0,52	0,46	0,51	0,43	0,43	0,4
A1	11	1	3,39	2,64	2,39	2,15	1,83	1,33
A1	11	2	1,57	1,32	1,38	1,43	1,28	0,99
A1	11	3	0,92	0,62	0,5	0,73	0,79	0,74
A1	11	4	2,27	1,79	1,41	0,87	0,77	0,69
A1	11	5	0,66	0,58	0,67	0,62	0,5	0,48
A1	11	6	0,61	0,53	0,59	0,49	0,49	0,46

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A1	12	1	3,67	2,89	2,62	2,33	1,97	1,4
A1	12	2	1,75	1,48	1,54	1,58	1,4	1,07
A1	12	3	1,03	0,7	0,57	0,82	0,88	0,81
A1	12	4	2,5	1,98	1,57	0,97	0,85	0,76
A1	12	5	0,75	0,65	0,76	0,7	0,56	0,53
A1	12	6	0,69	0,6	0,67	0,56	0,55	0,51
A1	13	1	3,21	2,46	2,23	2,03	1,75	1,29
A1	13	2	1,41	1,18	1,24	1,31	1,18	0,93
A1	13	3	0,81	0,54	0,44	0,65	0,71	0,68
A1	13	4	2,08	1,62	1,27	0,77	0,69	0,63
A1	13	5	0,58	0,5	0,59	0,55	0,44	0,43
A1	13	6	0,53	0,46	0,51	0,43	0,43	0,41
A1	14	1	3,53	2,73	2,48	2,24	1,91	1,38
A1	14	2	1,6	1,34	1,41	1,47	1,32	1,02
A1	14	3	0,93	0,62	0,51	0,74	0,8	0,76
A1	14	4	2,34	1,83	1,45	0,88	0,78	0,71
A1	14	5	0,67	0,58	0,68	0,63	0,51	0,49
A1	14	6	0,61	0,54	0,59	0,5	0,49	0,46
A1	15	1	3,83	2,99	2,73	2,43	2,05	1,45
A1	15	2	1,78	1,5	1,57	1,62	1,44	1,1
A1	15	3	1,05	0,7	0,58	0,83	0,89	0,83
A1	15	4	2,58	2,03	1,61	0,99	0,87	0,78
A1	15	5	0,76	0,66	0,77	0,71	0,57	0,54
A1	15	6	0,69	0,61	0,67	0,56	0,56	0,52
A1	16	1	2,7	2,12	1,84	1,68	1,42	1,07
A1	16	2	1,29	1,09	1,11	1,15	1,02	0,81
A1	16	3	0,77	0,52	0,42	0,6	0,64	0,61
A1	16	4	1,85	1,47	1,14	0,71	0,63	0,58
A1	16	5	0,56	0,49	0,56	0,52	0,42	0,4
A1	16	6	0,51	0,45	0,49	0,41	0,41	0,38
A1	17	1	2,98	2,37	2,07	1,86	1,56	1,16
A1	17	2	1,47	1,25	1,26	1,29	1,14	0,9
A1	17	3	0,88	0,6	0,49	0,69	0,73	0,69
A1	17	4	2,08	1,66	1,29	0,82	0,71	0,64
A1	17	5	0,65	0,56	0,64	0,6	0,48	0,45
A1	17	6	0,59	0,52	0,57	0,47	0,47	0,44
A1	18	1	3,24	2,6	2,27	2,03	1,69	1,23
A1	18	2	1,64	1,39	1,41	1,43	1,25	0,97
A1	18	3	1	0,68	0,55	0,78	0,82	0,75
A1	18	4	2,3	1,84	1,44	0,91	0,8	0,71
A1	18	5	0,73	0,64	0,73	0,67	0,54	0,5

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A1	18	6	0,67	0,59	0,64	0,53	0,52	0,48
A1	19	1	3	2,32	2,03	1,85	1,57	1,17
A1	19	2	1,36	1,15	1,18	1,23	1,1	0,87
A1	19	3	0,79	0,53	0,43	0,63	0,68	0,65
A1	19	4	1,99	1,56	1,21	0,74	0,66	0,61
A1	19	5	0,57	0,5	0,58	0,53	0,43	0,41
A1	19	6	0,52	0,46	0,5	0,42	0,42	0,4
A1	20	1	3,32	2,59	2,27	2,05	1,72	1,27
A1	20	2	1,55	1,31	1,34	1,38	1,23	0,96
A1	20	3	0,91	0,61	0,5	0,72	0,77	0,72
A1	20	4	2,24	1,77	1,37	0,85	0,75	0,68
A1	20	5	0,66	0,57	0,66	0,61	0,49	0,47
A1	20	6	0,6	0,53	0,58	0,49	0,48	0,45
A1	21	1	3,6	2,84	2,5	2,23	1,86	1,34
A1	21	2	1,73	1,47	1,5	1,53	1,35	1,04
A1	21	3	1,03	0,69	0,56	0,81	0,86	0,79
A1	21	4	2,47	1,96	1,53	0,95	0,83	0,74
A1	21	5	0,75	0,65	0,75	0,69	0,56	0,52
A1	21	6	0,68	0,6	0,66	0,55	0,54	0,5
A1	22	1	3,23	2,47	2,17	1,97	1,68	1,25
A1	22	2	1,41	1,18	1,22	1,28	1,15	0,91
A1	22	3	0,81	0,54	0,44	0,64	0,7	0,67
A1	22	4	2,09	1,62	1,25	0,77	0,68	0,63
A1	22	5	0,58	0,5	0,59	0,55	0,44	0,42
A1	22	6	0,53	0,47	0,51	0,43	0,43	0,41
A1	23	1	3,58	2,76	2,43	2,19	1,85	1,35
A1	23	2	1,61	1,35	1,39	1,45	1,29	1
A1	23	3	0,93	0,62	0,51	0,74	0,79	0,75
A1	23	4	2,36	1,84	1,43	0,88	0,77	0,7
A1	23	5	0,67	0,58	0,68	0,63	0,5	0,48
A1	23	6	0,61	0,54	0,59	0,49	0,49	0,46
A1	24	1	3,89	3,03	2,67	2,38	2	1,43
A1	24	2	1,79	1,51	1,56	1,6	1,41	1,08
A1	24	3	1,05	0,71	0,57	0,83	0,88	0,82
A1	24	4	2,61	2,05	1,6	0,98	0,86	0,77
A1	24	5	0,76	0,66	0,77	0,71	0,57	0,54
A1	24	6	0,7	0,61	0,67	0,56	0,55	0,51
A1	25	1	3,45	2,59	2,29	2,08	1,78	1,31
A1	25	2	1,45	1,21	1,26	1,32	1,2	0,95
A1	25	3	0,82	0,55	0,44	0,65	0,71	0,69
A1	25	4	2,18	1,68	1,29	0,78	0,69	0,64

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A1	25	5	0,59	0,51	0,6	0,55	0,45	0,43
A1	25	6	0,54	0,47	0,52	0,43	0,43	0,41
A1	26	1	3,81	2,9	2,57	2,3	1,95	1,41
A1	26	2	1,66	1,39	1,44	1,5	1,34	1,04
A1	26	3	0,95	0,63	0,51	0,75	0,81	0,77
A1	26	4	2,46	1,9	1,48	0,89	0,79	0,72
A1	26	5	0,68	0,59	0,69	0,64	0,51	0,49
A1	26	6	0,62	0,54	0,6	0,5	0,5	0,47
A1	27	1	4,14	3,18	2,82	2,51	2,11	1,49
A1	27	2	1,85	1,55	1,61	1,66	1,47	1,13
A1	27	3	1,07	0,71	0,58	0,84	0,91	0,84
A1	27	4	2,72	2,12	1,65	1	0,88	0,79
A1	27	5	0,77	0,67	0,78	0,72	0,58	0,55
A1	27	6	0,7	0,62	0,68	0,57	0,56	0,52
A1	28	1	3,33	2,48	2,21	2	1,73	1,28
A1	28	2	1,36	1,13	1,18	1,25	1,14	0,9
A1	28	3	0,77	0,51	0,41	0,61	0,67	0,65
A1	28	4	2,07	1,59	1,22	0,73	0,65	0,61
A1	28	5	0,55	0,47	0,55	0,51	0,41	0,4
A1	28	6	0,5	0,44	0,48	0,4	0,4	0,39
A1	29	1	3,69	2,79	2,48	2,23	1,9	1,38
A1	29	2	1,56	1,3	1,36	1,42	1,28	1
A1	29	3	0,88	0,59	0,48	0,7	0,76	0,73
A1	29	4	2,34	1,81	1,4	0,84	0,74	0,68
A1	29	5	0,63	0,55	0,64	0,59	0,48	0,46
A1	29	6	0,58	0,51	0,56	0,47	0,47	0,44
A1	30	1	4,01	3,06	2,73	2,43	2,05	1,46
A1	30	2	1,75	1,47	1,53	1,58	1,42	1,09
A1	30	3	1,01	0,67	0,54	0,8	0,86	0,81
A1	30	4	2,59	2,01	1,57	0,95	0,83	0,75
A1	30	5	0,72	0,63	0,73	0,68	0,54	0,52
A1	30	6	0,58	0,51	0,56	0,47	0,47	0,44
A2	1	1	2,47	1,97	1,75	1,6	1,36	1,03
A2	1	2	1,24	1,05	1,07	1,11	0,99	0,79
A2	1	3	0,75	0,51	0,41	0,59	0,63	0,6
A2	1	4	1,74	1,39	1,1	0,7	0,61	0,56
A2	1	5	0,55	0,48	0,55	0,51	0,41	0,39
A2	1	6	0,5	0,44	0,48	0,4	0,4	0,38
A2	2	1	2,72	2,19	1,95	1,76	1,49	1,11
A2	2	2	1,4	1,19	1,22	1,24	1,1	0,86
A2	2	3	0,86	0,58	0,48	0,68	0,71	0,67

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A2	2	4	1,95	1,57	1,25	0,8	0,7	0,63
A2	2	5	0,63	0,55	0,63	0,58	0,47	0,44
A2	2	6	0,58	0,51	0,56	0,47	0,46	0,43
A2	3	1	2,94	2,39	2,14	1,91	1,6	1,17
A2	3	2	1,56	1,33	1,36	1,37	1,2	0,93
A2	3	3	0,96	0,66	0,54	0,76	0,79	0,73
A2	3	4	2,14	1,73	1,38	0,89	0,77	0,69
A2	3	5	0,71	0,62	0,71	0,66	0,53	0,49
A2	3	6	0,65	0,58	0,63	0,53	0,51	0,47
A2	4	1	2,71	2,14	1,91	1,75	1,49	1,12
A2	4	2	1,3	1,09	1,13	1,18	1,06	0,84
A2	4	3	0,77	0,52	0,42	0,61	0,66	0,63
A2	4	4	1,86	1,47	1,16	0,73	0,64	0,59
A2	4	5	0,56	0,49	0,56	0,52	0,42	0,41
A2	4	6	0,51	0,45	0,49	0,41	0,41	0,39
A2	5	1	2,99	2,38	2,14	1,93	1,63	1,2
A2	5	2	1,47	1,25	1,29	1,33	1,18	0,92
A2	5	3	0,88	0,6	0,49	0,7	0,75	0,7
A2	5	4	2,09	1,66	1,32	0,83	0,73	0,66
A2	5	5	0,65	0,56	0,65	0,6	0,48	0,46
A2	5	6	0,59	0,52	0,57	0,48	0,47	0,44
A2	6	1	3,23	2,6	2,34	2,09	1,75	1,27
A2	6	2	1,64	1,39	1,43	1,46	1,29	0,99
A2	6	3	0,99	0,68	0,55	0,79	0,83	0,76
A2	6	4	2,29	1,84	1,47	0,92	0,81	0,72
A2	6	5	0,73	0,64	0,73	0,68	0,54	0,51
A2	6	6	0,67	0,59	0,64	0,54	0,53	0,49
A2	7	1	2,91	2,26	2,04	1,86	1,6	1,19
A2	7	2	1,34	1,13	1,17	1,23	1,11	0,88
A2	7	3	0,78	0,53	0,43	0,63	0,68	0,65
A2	7	4	1,95	1,53	1,21	0,75	0,66	0,61
A2	7	5	0,57	0,49	0,58	0,54	0,43	0,42
A2	7	6	0,52	0,45	0,5	0,42	0,42	0,4
A2	8	1	3,2	2,52	2,27	2,05	1,74	1,27
A2	8	2	1,52	1,29	1,34	1,38	1,24	0,96
A2	8	3	0,9	0,61	0,5	0,72	0,77	0,72
A2	8	4	2,19	1,73	1,37	0,85	0,75	0,68
A2	8	5	0,66	0,57	0,66	0,61	0,49	0,47
A2	8	6	0,6	0,53	0,58	0,48	0,48	0,45
A2	9	1	3,46	2,76	2,49	2,22	1,87	1,34
A2	9	2	1,7	1,44	1,49	1,53	1,35	1,04
A2	9	3	1,02	0,69	0,56	0,81	0,86	0,79

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A2	9	4	2,41	1,92	1,53	0,95	0,84	0,74
A2	9	5	0,74	0,65	0,75	0,69	0,56	0,52
A2	9	6	0,68	0,6	0,66	0,55	0,54	0,5
A2	10	1	3,08	2,37	2,14	1,95	1,68	1,24
A2	10	2	1,38	1,16	1,21	1,27	1,15	0,91
A2	10	3	0,8	0,53	0,43	0,64	0,69	0,67
A2	10	4	2,03	1,58	1,25	0,76	0,68	0,62
A2	10	5	0,57	0,5	0,58	0,54	0,44	0,42
A2	10	6	0,52	0,46	0,51	0,43	0,43	0,4
A2	11	1	3,39	2,64	2,39	2,15	1,83	1,33
A2	11	2	1,57	1,32	1,38	1,43	1,28	1
A2	11	3	0,92	0,62	0,5	0,73	0,79	0,74
A2	11	4	2,27	1,79	1,41	0,87	0,77	0,69
A2	11	5	0,66	0,58	0,67	0,62	0,5	0,48
A2	11	6	0,61	0,53	0,59	0,49	0,49	0,46
A2	12	1	3,66	2,89	2,62	2,33	1,97	1,4
A2	12	2	1,75	1,47	1,54	1,58	1,4	1,07
A2	12	3	1,03	0,7	0,57	0,82	0,88	0,81
A2	12	4	2,5	1,98	1,57	0,97	0,85	0,76
A2	12	5	0,75	0,65	0,76	0,7	0,56	0,53
A2	12	6	0,69	0,6	0,67	0,56	0,55	0,51
A2	13	1	3,2	2,45	2,23	2,03	1,75	1,29
A2	13	2	1,41	1,18	1,24	1,31	1,18	0,93
A2	13	3	0,81	0,54	0,44	0,65	0,71	0,68
A2	13	4	2,08	1,62	1,27	0,77	0,69	0,63
A2	13	5	0,58	0,5	0,59	0,55	0,44	0,43
A2	13	6	0,53	0,46	0,51	0,43	0,43	0,41
A2	14	1	3,53	2,74	2,49	2,24	1,91	1,38
A2	14	2	1,6	1,34	1,41	1,47	1,32	1,02
A2	14	3	0,93	0,62	0,51	0,74	0,8	0,76
A2	14	4	2,34	1,83	1,45	0,88	0,78	0,71
A2	14	5	0,67	0,58	0,68	0,63	0,51	0,49
A2	14	6	0,61	0,54	0,59	0,5	0,49	0,46
A2	15	1	3,82	2,99	2,72	2,42	2,05	1,45
A2	15	2	1,78	1,5	1,57	1,62	1,44	1,1
A2	15	3	1,05	0,7	0,58	0,83	0,89	0,83
A2	15	4	2,58	2,03	1,61	0,99	0,87	0,78
A2	15	5	0,76	0,66	0,77	0,71	0,57	0,54
A2	15	6	0,69	0,61	0,67	0,56	0,56	0,52
A2	16	1	2,7	2,12	1,84	1,68	1,42	1,07
A2	16	2	1,3	1,09	1,11	1,15	1,02	0,82

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A2	16	3	0,77	0,52	0,42	0,61	0,65	0,61
A2	16	4	1,85	1,47	1,14	0,71	0,63	0,58
A2	16	5	0,56	0,49	0,56	0,52	0,42	0,4
A2	16	6	0,51	0,45	0,49	0,41	0,41	0,38
A2	17	1	2,99	2,37	2,07	1,86	1,56	1,16
A2	17	2	1,47	1,25	1,26	1,29	1,14	0,9
A2	17	3	0,88	0,6	0,49	0,69	0,73	0,69
A2	17	4	2,08	1,66	1,29	0,82	0,71	0,64
A2	17	5	0,65	0,56	0,64	0,6	0,48	0,45
A2	17	6	0,59	0,52	0,57	0,47	0,47	0,44
A2	18	1	3,25	2,6	2,27	2,03	1,69	1,23
A2	18	2	1,64	1,39	1,41	1,43	1,25	0,97
A2	18	3	1	0,68	0,55	0,78	0,82	0,75
A2	18	4	2,3	1,84	1,44	0,91	0,8	0,71
A2	18	5	0,73	0,64	0,73	0,67	0,54	0,5
A2	18	6	0,67	0,59	0,64	0,53	0,52	0,48
A2	19	1	3	2,32	2,03	1,84	1,57	1,17
A2	19	2	1,36	1,15	1,18	1,23	1,1	0,87
A2	19	3	0,79	0,53	0,43	0,63	0,67	0,65
A2	19	4	1,99	1,56	1,21	0,74	0,66	0,61
A2	19	5	0,57	0,5	0,58	0,53	0,43	0,41
A2	19	6	0,52	0,46	0,5	0,42	0,42	0,4
A2	20	1	3,31	2,59	2,27	2,04	1,72	1,26
A2	20	2	1,55	1,31	1,34	1,38	1,23	0,96
A2	20	3	0,91	0,61	0,5	0,72	0,77	0,72
A2	20	4	2,24	1,77	1,37	0,85	0,75	0,68
A2	20	5	0,66	0,57	0,66	0,61	0,49	0,47
A2	20	6	0,6	0,53	0,58	0,49	0,48	0,45
A2	21	1	3,6	2,84	2,5	2,23	1,86	1,34
A2	21	2	1,73	1,46	1,5	1,53	1,35	1,04
A2	21	3	1,03	0,69	0,56	0,81	0,86	0,79
A2	21	4	2,47	1,96	1,53	0,95	0,83	0,74
A2	21	5	0,75	0,65	0,75	0,69	0,56	0,52
A2	21	6	0,68	0,6	0,66	0,55	0,54	0,5
A2	22	1	3,24	2,47	2,17	1,97	1,68	1,25
A2	22	2	1,41	1,18	1,22	1,28	1,15	0,91
A2	22	3	0,81	0,54	0,44	0,64	0,7	0,67
A2	22	4	2,09	1,62	1,25	0,77	0,68	0,63
A2	22	5	0,58	0,5	0,59	0,55	0,44	0,42
A2	22	6	0,53	0,47	0,51	0,43	0,43	0,41
A2	23	1	3,57	2,76	2,43	2,18	1,85	1,34
A2	23	2	1,61	1,35	1,4	1,45	1,29	1,01

Table B1: Reverberation time of simulated classrooms(contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A2	23	3	0,93	0,62	0,5	0,73	0,79	0,75
A2	23	4	2,36	1,84	1,43	0,88	0,77	0,7
A2	23	5	0,67	0,58	0,68	0,63	0,5	0,48
A2	23	6	0,61	0,54	0,59	0,49	0,49	0,46
A2	24	1	3,88	3,02	2,67	2,38	1,99	1,43
A2	24	2	1,8	1,51	1,56	1,6	1,42	1,08
A2	24	3	1,05	0,71	0,57	0,83	0,88	0,82
A2	24	4	2,61	2,05	1,6	0,98	0,86	0,77
A2	24	5	0,76	0,66	0,77	0,71	0,57	0,54
A2	24	6	0,7	0,61	0,67	0,56	0,55	0,51
A2	25	1	3,44	2,59	2,29	2,07	1,78	1,31
A2	25	2	1,45	1,21	1,26	1,33	1,2	0,95
A2	25	3	0,82	0,55	0,44	0,65	0,71	0,69
A2	25	4	2,18	1,68	1,29	0,78	0,69	0,64
A2	25	5	0,59	0,51	0,6	0,55	0,45	0,43
A2	25	6	0,54	0,47	0,52	0,43	0,43	0,41
A2	26	1	3,81	2,9	2,56	2,3	1,95	1,41
A2	26	2	1,66	1,39	1,44	1,5	1,34	1,04
A2	26	3	0,95	0,63	0,51	0,75	0,81	0,77
A2	26	4	2,46	1,9	1,48	0,89	0,79	0,72
A2	26	5	0,68	0,59	0,69	0,64	0,51	0,49
A2	26	6	0,62	0,54	0,6	0,5	0,5	0,47
A2	27	1	4,14	3,18	2,82	2,51	2,11	1,49
A2	27	2	1,85	1,55	1,61	1,65	1,47	1,12
A2	27	3	1,07	0,71	0,58	0,84	0,91	0,84
A2	27	4	2,72	2,12	1,65	1	0,88	0,79
A2	27	5	0,77	0,67	0,78	0,72	0,58	0,55
A2	27	6	0,7	0,62	0,68	0,57	0,56	0,52
A2	28	1	3,32	2,48	2,2	2	1,72	1,28
A2	28	2	1,36	1,13	1,19	1,25	1,14	0,91
A2	28	3	0,76	0,5	0,41	0,61	0,67	0,65
A2	28	4	2,07	1,59	1,22	0,73	0,65	0,61
A2	28	5	0,55	0,47	0,55	0,51	0,41	0,4
A2	28	6	0,5	0,44	0,48	0,4	0,4	0,39
A2	29	1	3,68	2,78	2,48	2,22	1,9	1,38
A2	29	2	1,56	1,3	1,36	1,42	1,28	1
A2	29	3	0,89	0,59	0,48	0,7	0,77	0,73
A2	29	4	2,34	1,81	1,4	0,84	0,74	0,68
A2	29	5	0,63	0,55	0,64	0,59	0,48	0,46
A2	29	6	0,58	0,51	0,56	0,47	0,47	0,44
A2	30	1	4,04	3,08	2,75	2,44	2,07	1,47
A2	30	2	1,75	1,47	1,53	1,58	1,42	1,09

Table B1: Reverberation time of simulated classrooms (contd.)

Source	Classroom type	Ceiling material	Frequency					
			125	250	500	1000	2000	4000
A2	30	3	1,01	0,67	0,54	0,8	0,86	0,81
A2	30	4	2,59	2,01	1,57	0,95	0,83	0,75
A2	30	5	0,72	0,63	0,73	0,68	0,54	0,52
A2	30	6	0,58	0,51	0,56	0,47	0,47	0,44

APPENDIX C

Table C1: Distance between source and receivers

Source	classroom type	receiver	receiver to source distance	Source	classroom type	receiver	receiver to source distance
A0	1, 2, 3	01	2,2	A0	25, 26, 27	02	6,23
A0	1, 2, 3	02	4,52	A0	25, 26, 27	03	5,69
A0	1, 2, 3	03	3,95	A0	25, 26, 27	04	8,19
A0	1, 2, 3	04	4,55	A0	25, 26, 27	05	10,06
A0	1, 2, 3	05	6,02	A0	28, 29, 30	01	2,2
A0	4, 5, 6	01	2,2	A0	28, 29, 30	02	6,23
A0	4, 5, 6	02	4,52	A0	28, 29, 30	03	5,69
A0	4, 5, 6	03	5,07	A0	28, 29, 30	04	9,36
A0	4, 5, 6	04	5,79	A0	28, 29, 30	05	11,03
A0	4, 5, 6	05	7,01	A1	1, 2, 3	01	3,14
A0	7, 8, 9	01	2,2	A1	1, 2, 3	02	3,11
A0	7, 8, 9	02	4,52	A1	1, 2, 3	03	3,46
A0	7, 8, 9	03	5,07	A1	1, 2, 3	04	5,13
A0	7, 8, 9	04	7,16	A1	1, 2, 3	05	5,1
A0	7, 8, 9	05	8,17	A1	4, 5, 6	01	3,14
A0	10, 11, 12	01	2,2	A1	4, 5, 6	02	3,11
A0	10, 11, 12	02	4,52	A1	4, 5, 6	03	4,73
A0	10, 11, 12	03	5,07	A1	4, 5, 6	04	6,28
A0	10, 11, 12	04	8,19	A1	4, 5, 6	05	6,27
A0	10, 11, 12	05	9,1	A1	7, 8, 9	01	3,14
A0	13, 14, 15	01	2,2	A1	7, 8, 9	02	3,11
A0	13, 14, 15	02	4,52	A1	7, 8, 9	03	4,73
A0	13, 14, 15	03	5,07	A1	7, 8, 9	04	7,58
A0	13, 14, 15	04	9,36	A1	7, 8, 9	05	7,55
A0	13, 14, 15	05	10,16	A1	10, 11, 12	01	3,14
A0	16, 17, 18	01	2,2	A1	10, 11, 12	02	3,11
A0	16, 17, 18	02	6,23	A1	10, 11, 12	03	4,73
A0	16, 17, 18	03	4,79	A1	10, 11, 12	04	8,58
A0	16, 17, 18	04	4,55	A1	10, 11, 12	05	8,57
A0	16, 17, 18	05	7,4	A1	13, 14, 15	01	3,14
A0	19, 20, 21	01	2,2	A1	13, 14, 15	02	3,11
A0	19, 20, 21	02	6,23	A1	13, 14, 15	03	4,73
A0	19, 20, 21	03	4,79	A1	13, 14, 15	04	9,72
A0	19, 20, 21	04	5,79	A1	13, 14, 15	05	9,71
A0	19, 20, 21	05	8,22	A1	16, 17, 18	01	3,78
A0	22, 23, 24	01	2,2	A1	16, 17, 18	02	3,89
A0	22, 23, 24	02	6,23	A1	16, 17, 18	03	3,58
A0	22, 23, 24	03	5,69	A1	16, 17, 18	04	5,54
A0	22, 23, 24	04	7,16	A1	16, 17, 18	05	5,61
A0	22, 23, 24	05	9,23	A1	19, 20, 21	01	3,78
A0	25, 26, 27	01	2,2	A1	19, 20, 21	02	3,89

Table C1: Distance between source and receivers (contd.)

Source	classroom type	receiver	receiver to source distance	Source	classroom type	receiver	receiver to source distance
A1	19, 20, 21	03	3,58	A2	13, 14, 15	03	5,11
A1	19, 20, 21	04	6,62	A2	13, 14, 15	04	4,25
A1	19, 20, 21	05	6,68	A2	13, 14, 15	05	9,71
A1	22, 23, 24	01	3,78	A2	16, 17, 18	01	6,58
A1	22, 23, 24	02	3,89	A2	16, 17, 18	02	2,39
A1	22, 23, 24	03	4,75	A2	16, 17, 18	03	2,73
A1	22, 23, 24	04	7,87	A2	16, 17, 18	04	6,13
A1	22, 23, 24	05	7,92	A2	16, 17, 18	05	5,6
A1	25, 26, 27	01	3,78	A2	19, 20, 21	01	7,13
A1	25, 26, 27	02	3,89	A2	19, 20, 21	02	3,64
A1	25, 26, 27	03	4,75	A2	19, 20, 21	03	3,44
A1	25, 26, 27	04	8,83	A2	19, 20, 21	04	6,13
A1	25, 26, 27	05	8,88	A2	19, 20, 21	05	6,67
A1	28, 29, 30	01	3,78	A2	22, 23, 24	01	7,91
A1	28, 29, 30	02	3,89	A2	22, 23, 24	02	5
A1	28, 29, 30	03	4,75	A2	22, 23, 24	03	3,57
A1	28, 29, 30	04	9,94	A2	22, 23, 24	04	6,13
A1	28, 29, 30	05	9,98	A2	22, 23, 24	05	7,91
A2	1, 2, 3	01	4,86	A2	25, 26, 27	01	8,61
A2	1, 2, 3	02	2,39	A2	25, 26, 27	02	6,04
A2	1, 2, 3	03	2,22	A2	25, 26, 27	03	4,38
A2	1, 2, 3	04	4,25	A2	25, 26, 27	04	6,13
A2	1, 2, 3	05	5,1	A2	25, 26, 27	05	8,87
A2	4, 5, 6	01	5,59	A2	28, 29, 30	01	9,47
A2	4, 5, 6	02	3,64	A2	28, 29, 30	02	7,21
A2	4, 5, 6	03	2,22	A2	28, 29, 30	03	5,38
A2	4, 5, 6	04	4,25	A2	28, 29, 30	04	6,13
A2	4, 5, 6	05	6,26	A2	28, 29, 30	05	9,98
A2	7, 8, 9	01	6,57				
A2	7, 8, 9	02	5				
A2	7, 8, 9	03	3,16				
A2	7, 8, 9	04	4,25				
A2	7, 8, 9	05	7,56				
A2	10, 11, 12	01	7,39				
A2	10, 11, 12	02	6,04				
A2	10, 11, 12	03	4,04				
A2	10, 11, 12	04	4,25				
A2	10, 11, 12	05	8,57				
A2	13, 14, 15	01	8,37				
A2	13, 14, 15	02	7,21				

CURRICULUM VITA



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