Master's thesis

NTNU
Norwegian University of Science and Technology
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Department of Civil and Environmental Engineering

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Classroom acoustics and absorber distribution

Master's thesis in Civil and Environmental Engineering
Supervisor: Tore Kvande, NTNU & Anders Homb, SINTEF
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Abstract

Classrooms are critical educational spaces where the acoustic environment plays a pivotal role in facilitating effective teaching and learning. Modern Norwegian classrooms are designed to have a maximum reverberation time of 0.5 seconds. A lower reverberation time is closely associated with reduced noise levels, thereby ideally enhancing speech perception by increasing the signal-to-noise ratio. However, excessive sound absorption hampers sound transmission within the room, necessitating increased vocal effort to reach all positions effectively. Therefore, improving the passive acoustic environments holds the potential to alleviate the vocal strain caused by the classroom soundscape on teachers and provide increased audibility for listeners.

The present study examines the impact of different ceiling configurations on early reflection in two classrooms located at Salemhuset, Trondheim. These classrooms share a similar construction but vary in terms of size and shape. Three ceiling setups were evaluated: one utilizing the existing ceiling fully covered with absorbents and two where the ceiling was partially replaced with 9 mm plywood. The study followed the guidelines of NS-EN ISO 3382-2, using impulse response measurements by a pink-weighted sine sweep signal. Classroom A featured 3 sound sources and 12 receivers, while Classroom B utilized 2 sources and 10 receivers. T_{20}, EDT, and C_{50} were chosen as parameters to evaluate early reflections. The research focused on three specific questions to guide the investigation and narrow the scope. Post-processing was conducted using Excel. Moreover, the analysis aimed to provide insights for addressing the research questions.

The results of the study indicate that the presence of reflective ceiling tiles had a greater impact on speech clarity than on reverberation. On average, there was a slight increase in T_{20} and EDT of 0.01 seconds, accompanied by a reduction in C_{50} of just under 1 dB within the frequency range of 125 to 4 000 Hz. Additionally, the EDT was measured to be, on average, 0.1 seconds lower than T_{20}. The reflective ceilings also contributed to a reduction in deviation across all combinations of sound sources and receivers. The position of the sound source was found to significantly impact C_{50}. Placing the source centrally close to the long wall was found to be unfavorable for several receiver positions. Additionally, receivers situated near reflecting wall surfaces were generally favorable for early reflection.

Furthermore, the study explores how these findings can contribute to the enhancement of classroom acoustical design. It is suggested that a revision of the current national acoustical requirements for classrooms is advisable to improve speech conditions for teachers and ensure optimal listening conditions for students. Additionally, it is proposed that the existing geometrical shape of classrooms should be reconsidered, encompassing both the floor plan and internal design aspects. However, it is acknowledged that implementing some of these proposals may pose practical challenges and feasibility constraints.

Sammendrag

Det akustiske klasseromsmiljøet er viktig for å oppnå effektiv undervisning og læring. Norske klasserom må etter dagens standard ha en lavere etterklangstid enn 0,5 sekunder. En lavere etterklangstid bidrar til reduserte støynivå, ideelt sett bidrar dette kun til å øke signal-til-støyforholdet. Imidlertid bidrar lydabsorpsjon til å redusere lydoverføringen i rommet, dermed kan det bli nødvendig å snakke høyere for å høres godt i hele rommet. Akustiske tiltak i klasserom har potensiale til å redusere belastningen på stemmen til lærere, samt gjør at lytteren hører formidler bedre.

Denne studien har undersøkt himlingers effekt på tidlig refleksjoner i to forskjellige klasserom. Klasserommene befinner seg i Salemhuset i Trondheim, er konstruert med like materialer, men ulike i størrelse og form. Tre himlings varianter ble evaluert: Den eksisterende systemhimlingen med heldekkende absorbentflate, og to varianter der en større del ble byttet ut med 9 mm kryssfinerplater. Videre ble impulsrespons målinger utført etter retningslinjene gitt i NS-EN ISO 3382-2. Kildesignalet som ble brukt var et rosavektet sinus-sveip. 3 lydkilder og 12 mottager punkt ble brukt i Klasserom A, mens 2 kilder og 10 mottagere i Klasserom B. Parametere T_{20}, EDT og C_{50} ble så brukt for å evaluere rommets tidlige refleksjoner. Tre formulerte forskningsspørsmål veiledet og avgrenset videre undersøkelser. Etterbehandling av måledataen ble utført i Excel. Påfølgende analyse hadde som hovedmål å besvare gitte forskningsspørsmål.

Resultatene av undersøkelsene indikerer at kryssfinerhimlingen hadde større innvirkning på taleklarheten (C_{50}) enn på etterklangstiden. Målingene viste en liten økning i T_{20} og EDT på 0,01 sekunder, samtidig som det var en reduksjon i C_{50} på litt under 1 dB innenfor frekvensområdet 125 til 4 000 Hz. I tillegg ble EDT målt til å være i gjennomsnitt 0,1 sekunder lavere enn T_{20}. De tilførte reflekterende flatene bidro også til å redusere de målte forskjellene mellom både kilde og mottagerposisjonene. Plasseringen av lydkilden ble funnet å ha betydelig innvirkning på C_{50}. Kildeplasseringer sentral plassert nært langvegg ble funnet å være ugunstig for et større antall mottakerposisjoner. Det ble også funnet at mottakere som var plassert nær reflekterende veggflater fikk et gunstig tilskudd av tidlige refleksjoner.

Videre utforskes det hvordan funnene kan bidra til forbedring av akustisk utforming av klasserom. Det blir foreslått en revisjon av dagens nasjonale akustiske krav for klasserom, ettersom dagens krav ikke anses å gi tilstrekkelig gode taleforholdene for lærere, samt gode lytteforhold for elevene. Videre blir det foreslått at den eksisterende geometriske utformingen av klasserom, det diskuteres blant annet potensialet i nye planløsninger, samt innovative løsninger for intern utforming. Imidlertid erkjennes det at flere av forslagene kan være vanskelig å løse og utføre i praksis.

Preface

The present thesis concludes five years of "Bygg og Miljøteknikk" at Institut for Bygg og Miljøteknikk, NTNU. There have been countless hours of hard work, procrastination, engagement in student organizations, days where no motivation is not to be found, and some days filled with loads of interesting ideas and fun. Throughout these years I have gathered valuable expertise from both studies and other engagements. It has been a journey, where I have got to know a lot of curious, knowledgeable, engaged, and overall incredible people. They have helped me stay motivated and thus helped me finish this thesis. For now, I hope this thesis shows some reflections of the knowledge I have gathered through the year.

I would like to share some of my gratitude towards all who have contributed to my success in writing this thesis. First and foremost, my family for always supporting me. Especially my parents Aina and Roald, for sharing their knowledge and passions throughout my childhood. I would also like to gratitude to my supervisors Anders Homb, Tore Kvande, and Vegard Skageseth. Who all have shared their precious time to supervise me throughout this work. A big thanks have to be given to my church, Norkirken Trondheim, who let me use their brand-new classrooms for my project. Throughout the last year, I have also been lucky to share an office with a great group of people at "Satsebrakka". You have truly made this work more enjoyable through our fellowship. Furthermore, I would like to give some appreciation to all friends and relationships I've gained during my studies in Trondheim, including my fellow students, volleyball team, church, and small group. One I would like to give some extra appreciation to is Arild Grimstad and Simen Helbæk Kjølberg, you help me get through the most difficult and important subject to attain this achievement.

Looking back on several amazing years as a student, I do feel truly blessed by both the talents and relationships God has given me. May I still uncover more of creation, both at work and in everyday life living by the words in Ephesians 2:8-10. Finally, I hope you find this topic as interesting as I have. God bless your day, and have a great read!

Trondheim, June 2023
Johan-Didrik Theisen

Nomenclature

Table 1: *Explanation of abbreviations and used symbols*

A	Equivalent absorption area.
α	Acoustic absorption factor.
BGN	Background Noise Level.
C_{50}	Clarity index.
U_{50}	Useful-to-detrimental sound ratio.
EDT	Early Decay Time. Reverberation measurement.
IEQ	Indoor Environmental Quality.
IR & FR	Impulse Response & Frequency Response.
L_p, SPL	Sound Pressure Level.
MLS	Maximum Length Signal.
$p(t)$	Measured pressure level difference at an instant t.
RMS	Root-Mean-Square.
SNR	Signal-to-Noise Ratio.
SS	Sweep-frequency Signal.
STD	Standard deviation.
STI	Speech Transmission Index.
T_{60}, T_{20}	Reverberation time. The duration of time for a reduction of 60 dB.
TEK17	Byggteknisk forskrift. Norwegian building code of 2017.

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1 Introduction

1.1 Background

In recent decades, there has been a progressive increase in awareness towards Indoor environmental quality (IEQ) (Mujan et al., 2019). Already in 2001, people were spending more than 87% of their time indoors (Klepeis et al., 2001). The rise of technology and rapid urbanization have likely increased time spent indoors since then. Thus the importance of IEQ, including acoustic comfort, has become increasingly evident.

A number of studies have shown that poor acoustic conditions in indoor spaces can induce stress, discomfort, and difficulties in perceiving and focusing on voices (Klatte et al., 2013; Connolly et al., 2015; Puglisi et al., 2018). For instance, a study by Mujan et al. (2019) found a correlation between speech clarity (C_{50}) in classrooms and the reading speeds of Italian secondary school students, suggesting that improving the acoustic environment can enhance learning effectiveness. A literature review by Mealings (2022) found a majority of studies concluding that there were some negative or no effects by higher levels of noise, reverberation, and speech clarity. These findings highlight the possible insufficiency in the current design requirements.

Figure 1: *A typical classroom situation (Image by pch.vector on Freepik.com)*

While traditional learning spaces such as classrooms and small auditoriums remain vital, the attempts to revolutionize education through technological aids have had limited success. A depiction of the typical setting is found in Figure 1. Consequently, alternative approaches, including flexible classroom designs and the use of the flipped classroom[1], have gained attention. These modern learning spaces accommodate a combination of digital presentations, interactive software, plenary exercises, and individual concentration work. Each preferring different acoustic environments. Therefore it is crucial to strike a balance that optimizes the room's performance for the activities taking place.

Communication is a fundamental aspect of education, and the surrounding soundscape significantly influences its effectiveness. Noise is a prominent issue in communication models (Dahl, 2013) and a leading cause of frustration, discomfort, and distraction in the learning environment. Reducing noise levels has been emphasized in several studies (Connolly et al., 2015; Bolstad, 2019). Noise levels are also addressed in the Norwegian building code (TEK17), setting a maximum limit of acceptable noise in classrooms (DIBK, 2023, §13-6(1)).

A study by Homb (2022) investigated the conditions of Norwegian primary and secondary schools in 2022. He compared the design requirements across several countries, some of which use a target range instead of a limit as used in Norway. Excessive reduction of reverberation can diminish the perceived strength of a signal, negatively impacting the signal-to-noise ratio (SNR) and effective communication. Therefore, a concern is raised around the maximum limit implying lower reverberation is always better.

Protecting the vocal cords of teachers is another crucial consideration, as vocal disorders, known as phonasthenia[2], are alarmingly prevalent among educators (Borge and Senneset, 2022; Lervik, 2018). Indoor acoustics and dry air contribute to these issues. Therefore, there is a need to revise current classroom design principles and criteria to address these concerns.

1.2 State of speech intangibility parameters

In 2022 Minelli et al. (2022) conducted a literature review on speech intangibility parameters. It found a majority of studies focused on SNR and noise level. Other parameters like the Speech transmission index (STI) and C_{50} were included in 8% and 5% of the included studies. As noise levels and SNR are widely considered the most crucial parameters, this should come as no surprise (Flexer, 2004). However, this approach does not provide a complete understanding of speech perception in a given room. There is a lack of research on other parameters, necessitating further exploration to

[1] The flipped classroom is a way of organizing lectures. Students read the curriculum in advance, before discussion around the topic takes place in the classroom (Harvard, 2023).

[2] A condition mainly caused by extensive use of one's vocal chords, damaging them resulting in voice production difficulties (Dictionary.com, 2023; Winther, 2019)

enhance the quality of speech transmission and perception in classrooms.

Existing acoustical criteria often consist of single-number limits that apply equal restrictions across the entire frequency spectrum. However, in sound engineering, it is widely understood that frequency modification through equalization can significantly impact speech intelligibility. The room itself acts as an equalizer[3], shaping the transmitted sound signal and affecting its perception. When equalizing live music, for instance, certain parts of the frequency spectrum is modified to decrease muddiness and provide clarity. Therefore, it is essential to consider the frequency response of a room to facilitate clear speech transmission.

The speech clarity index (C_{50}) is one of the less used parameters when regarding classroom design, more commonly used when designing rooms for musical applications[4]. Musical rooms do desire an even reflection of all frequencies for all instruments to be favored equally. Considering speech transmission this approach should arguably be altered towards a frequency response favoring speech clarity to the listener. STI aims to fix this by considering the room's frequency response effect on speech, using the Dutch male voice as reference (IEC, 2021). It is often regarded as complicated and dependent on who is conducting the measurement. There is a concern raised around STI favoring male voice spectrum and languages which is similar to Dutch. Thus C_{50} may be more desirable to use. Furthermore, it may make it easier to understand how the reverb behaves throughout the room on a frequency basis and if it remains consistent throughout the room.

1.3 Motivation

Schools and classrooms play a pivotal role in our society as spaces where knowledge is acquired and shared. Consequently, there is a continuous need for building and refurbishing classrooms to provide optimal learning environments. However, tight budgets and pre-accepted solutions often lead to the implementation of similar acoustic systems, such as acoustic system ceilings commonly used in office spaces and corridors. Despite their widespread use, there is a lack of understanding regarding how these ceilings impact speech intelligibility specifically in classrooms. Most studies in this field primarily focus on improving the signal-to-noise ratio and reducing background noise to create a better acoustic environment. However, it is crucial to consider the impact of these design choices on speech intelligibility and the long-term effects on teachers' vocal health and well-being.

The Norwegian standard NS8195:2019 (Norge, 2019) sets an upper limit of 0.5 seconds for reverberation time in classrooms. While this requirement helps reduce overall background noise generated by students, it also has implications for speech intelligibility across the room. Teachers, in particular, are affected by this limitation as they are forced to raise their voice to overcome the reduced

[3] A equalizer (EQ) is used to amplify or reduce specific parts of the frequency spectrum.
[4] In a classroom the border between the early and late reflection of the clarity is set to be 50 ms for speech.

speech intelligibility caused by the shorter reverberation time. This increase in vocal effort can cause fatigue to their voice, potentially leading to work-related injuries throughout their teaching careers.

Despite the importance of speech intelligibility in classrooms and the potential impact on teachers' well-being, there is a lack of comprehensive research on the specific effects of acoustic system ceilings on speech intelligibility. Existing studies predominantly focus on general acoustic conditions and noise reduction, without considering the effects of specific design elements like ceilings. Therefore, there is a need for further investigation on how these ceilings influence speech intelligibility in classrooms, exploring whether alternative design solutions provide a better balance of noise reduction with optimal speech transmission.

1.4 Objective and scope

The present study aims to gain deeper understanding of the effects placement of absorbing surfaces, particularly high-frequency absorbent ceilings, may impact a teacher's ability to communicate efficiently with their class. Additionally, the study wants to start a discussion on whether there is a need for a paradigm shift in the choice of absorbent placement in a classroom. Exploring the potential of increased absorption placed on walls surfaces and whether new options for ceiling materials should be applied, which in turn could improve speech transmission in classrooms.

This study focuses specifically on speech clarity in classrooms as the chosen subject, with a qualitative examination of two similar classrooms. The goal is to comprehend the significance of soundscape design and find ways to improve the perceived clarity of speech throughout a classroom. The parameters of C_{50}, T_{20}, and EDT have been selected as the basis for comparisons between different ceiling configurations. The following research questions were defined to delimit the scope of the study:

1. How does the presence of reflective ceiling tiling affect speech clarity and reverberation in a classroom?
2. What is the impact of the source position on C_{50}?
3. What recommendations can be derived from the findings to enhance the future acoustical design of classrooms?

To conduct the study, two suitable classrooms at Salemhuset were identified. These were selected based on their similar construction and design, differing primarily in size and shape. The availability of these classrooms and the feasibility of conducting interrupted measurements over several days were crucial factors in the selection process. Ideally, the objects would have been in a local public school. Moreover, personal connections made it easy attaining the permissions and access for a temporary ceiling change, making these a viable option for the study within this project time frame of 20 weeks.

The chosen material for comparison with the acoustical ceiling absorbent was plywood, as it met the criteria of being cost-effective, easily cut into tiles, and more significantly more reflective than the original material. Other materials like gypsum were excluded due to their higher dust production and weight.

It is important to note that the focus of this study is not to maintain the same average reverberation level across all configurations, but rather to observe the effect of changing the ceiling material. This approach was chosen to manage the workload and keep a low number of parameters changing between measurements. As a qualitative study, precision in the conducted measurements was emphasized. However, choice of equipment has been limited to what SINTEF had available, who provided all the measurement equipment for this study. This restricted the number of measurements that could be conducted simultaneously. Additionally, the study's budget influenced the choice of materials for the reflective surface.

Furthermore, a Norwegian article have been written for the magazine Byggindustrien, summarizing key aspects and find from this thesis. The article can be found in Appendix E, published in Byggeindustrien nr 11/2023.

2 Theory

2.1 Sound and vibration

Acoustics concerns all types of vibrations and how they interact with the physical world, including what is perceived as sound. Vibration, as defined by the international standard ISO 2041:2018: *"Oscillatory motion about an equilibrium (ISO, 2018)"*. Sound is vibrations propagating as waves in a medium. The three main attributes of oscillatory wave motion are amplitude, frequency, and phase. Amplitude is the range of the oscillating motion. In terms of sound, it indicates the strength of sound, which is the range of sound pressure levels a wave carries. Frequency is the speed of oscillatory motion, the number of oscillations in a given time interval. Sound waves can be simple homogeneous oscillating waves or complex superpositions of a range of waves with different frequencies and amplitudes. Phase is the relative difference between waveforms. Oscillations which is out of phase are oscillating with a time delay, which may cause destructive or constructive interference between the signals. Variation of amplitude, frequency, and phase encodes information into a comprehensible sound signal.

2.2 Measurement of sound

2.2.1 Sound Pressure Level and Sound Intensity

There are two main categories for the measurement of sound, sound pressure measurements and sound intensity measurements. Sound pressure measurements measure the variation of the air pressure at a surface. An intensity measurement measures the variation of an acoustical changing pressure density over time. Vibration measurements consist of samples, which is the pressure at an instant of the duration of signal in time. To precisely measure the sound of a particular frequency, the sampling rate needs to be at least twice as high, which is known as the Nyquist frequency (Vigran, 2008, p.14). For measurements of the audible spectrum of humans, the typical lowest sampling rate is at least 44 100 Hz.

A sound measurement consists of a series of sampling value changes over time, a single sampled value often lite to no valuable information in itself. Sound is pressure variations around an equilibrium over time, finding the average strength will therefore yield little information, as the average is close to the equilibrium. A normal way to address this is through the use of root-mean-square values (RMS), which give the average amplitude of a measurement over a given time interval (Vigran, 2008, p.6). Calculations of RMS are shown in Equation 1.

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 dt} \tag{1}$$

RMS values are close to the exact mean value of the real average amplitude.

Furthermore, a type of sound measurement is the Sound pressure level (SPL), where RMS values are used for its calculation. It is the relative decibel level of a reference sound pressure (Garrett, 2020, p.468). Calculation of SPL can be achieved by Equation 2.

$$L_p = 20 \log \frac{p_{rms}}{p_{ref}} \tag{2}$$

The reference value $p_{ref} = 2 \cdot 10^{-5}$, both values are RMS values.

2.2.2 Soundscape and sound fields

The soundscape references the overall acoustics throughout an environment, to its behaviors and properties. If a soundscape has an equal energy density distribution it is described as a diffuse field (Garrett, 2020, p.633-635). In-room acoustics, it is normal to assume the soundscape is a diffuse field environment for most of the frequency spectrum. Lower frequencies have such low modal density that local variations begin to be noticeable, which they are not in the diffuse field. The acoustic field close to an acoustic source is referred to as the near field. In the near field, there are found larger irregularities, and the source has a larger impact on the transmission of sound. Moving out of the near field, there is the far field which is assumed to be diffuse and yielding little in-regular impact on the signal transmitted, depending on the strength of the source the distinction between changes.

2.2.3 Source signals in measurement

In the measurement of the acoustic properties of an object, the most common approach is to measure the effect on a known acoustic signal. The source signal which is used is determined by several factors, some being attached to a location such as BGN and others could be due to the parameters which are to be measured. For instance, measurements may want to simulate the spectrum of the human voice or look at the effect of a signal with the same amount of each frequency present. Common types are noise signals, Maximum length signals (MLS), and sweep-frequency signals (SS). The most common noise signals are white and pink noise. White noise is a signal consisting of Gaussian noise, which means that all frequencies have the same strength. A Fourier transform of white noise will have all frequencies at approximately the same level. Pink noise is a white noise signal which is modulated such that each frequency band has an equal amount of energy. A spectrum analysis of pink noise will show a descending sloped curve. SS signals to use a continuous signal which may sweep through all desired frequencies. The Sine-sweep is a commonly used signal, which goes through all frequencies from low to high gradually, sweeping through the whole frequency spectrum. SS signals can also be weighted as a with or pink noise spectrum (Vigran, 2008, p.25-26, 29).

2.3 Human auditory system

2.3.1 Perception

Audible sound for humans has frequencies ranging from 20 to 20 000 Hz. The sensitivity of the human auditory system degrades throughout life, depending on age and physical damage to the system. The human auditory system's sensitivity changes depending on both the frequency and the loudness of sound. Figure 2 show equal loudness curves, the loudness of which frequencies are perceived to be equally loud.

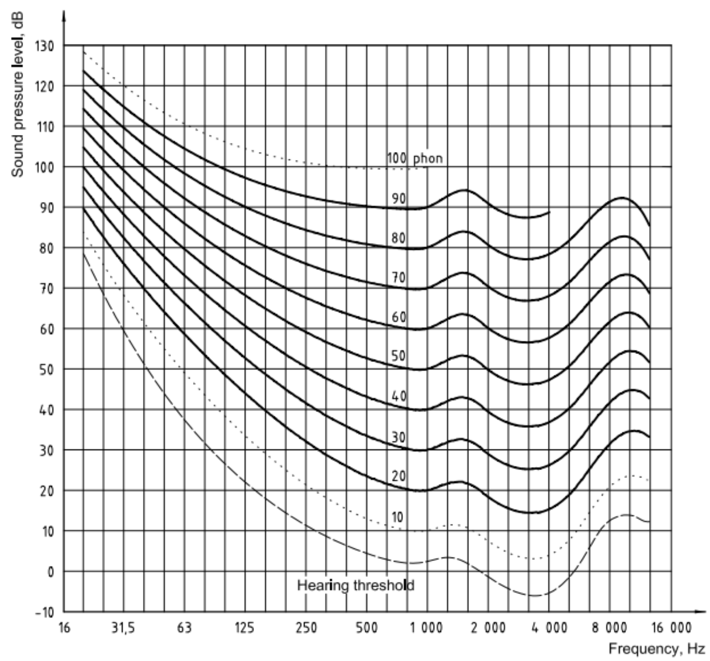


Figure 2: *Equal loudness curves display the SPL of which frequencies are perceived to be equally loud. (ISO, 2003)*

The unit phon is a measure of sound intensity subjectively perceived to be equal. The lowest perceivable sound of a frequency is defined to be 0 phon (Garrett, 2020, p.467).

The human auditory system's ability to distinguish certain frequencies appearing simultaneously is altered by both which frequencies are appearing and how loud they are. A louder mid-frequency will reduce the ear's ability to hear higher frequencies. This effect of lower frequencies reducing the ability to hear higher frequencies is called masking. Masking, therefore, plays an integral role in how we perceive the surrounding soundscape (Nave, n.d.).

When perceiving speech there are several parameters to consider affecting efficiency. Generally, the signal-to-noise ratio (SNR) is considered the most important parameter to attain good perception. Achieving high levels of SNR is correlated with increased perception. To achieve this either increase the source sound level or reduce the background noise, BGN. SNR is measured as the difference between a signal and noise, measured in SPL. The calculation is given in Equation 3.

$$SNR = S - N \tag{3}$$

The signal is denoted by S and the noise by N.

2.3.2 Reproduction

Humans typically communicate with frequencies mostly ranging between 200 and 6 000 Hz (Quam et al., 2012). The frequency spectrum of a human voice is considered unique between individuals. The male voice approximately being an octave lower than a female voice on average. Most languages are constructed by two main types of sounds, vowels, and consonants. The encoded information transmitted through different sounds in speech is not equally important. Vowels contribute less towards the integrability of speech compared to consonants, vowels being much easier to pronounce loudly. Consonants are predominantly found in the above 500 Hz. The 1 000 to 4 000 Hz range is often being regarded as the most important to preserve a high level of intangibility (DPA, 2021). The sound between languages does differ a considerable amount. Comparing Chinese to some African languages with click sounds and English, they utilize quite different sounds to communicate.

2.4 Room acoustics

2.4.1 Reverberation

Reverberation can be described as the attenuation of sound reflection in a given space. This attribute is denoted as T_{60}, measured as the time it takes for a sound signal attenuate by 60 dB. It is often hard to attain an SNR above 60 dB needed for this. Therefore the most common way to measure reverberation is conducting extrapolation of the time needed for a 20 or 30 dB reduction, values denoted as T_{20} or T_{30}. Another used reverberation parameter measures the Early Decay Time (EDT), which often uses a 10 dB reduction. This parameter provides more information on the characteristics of early reflection in a room (Vigran, 2008, p.107-108). There are two approaches to measure reverberation given by NS-EN 3383 - 2 (Standard, 2008), the noise cut method or by an MLS or SS measuring the impulse response. The first method measures reverberation directly as the time of decay of a noise floor significant above BGN. SS method measures reverberation from the impulse response (IR). SS is considered a more precise method.

There are several approaches to calculating the theoretical reverb of a room. One of these is the famous Sabine's formula (Vigran, 2008, p.121), which is given in Equation 4. More precise formulas like Eyring's formula are possible options for estimating reverberation time.

$$T_{60} = \log(10^6)\frac{4V}{c_0 A} \tag{4}$$

c_0 denotes the speed of sound, V the volume of the room, and A the equivalent absorption area of the room given by Equation 5.

$$A = \sum_i \alpha_i S_i \tag{5}$$

S_i is the materials absorption surface area and α_i its absorption factor.

2.4.2 Speech Transmission Index - STI

The speech transmission Index (STI), is a standardized objective measurable parameter of how speech is perceived throughout a room. It is a single number rating, calculated by EN IEC 60267-17 (IEC, 2021). STI rates speech integrability on a scale from zero to one, one being perfect transmission of speech. The typical Dutch male voice was the vocal reference for the development of the index.

2.4.3 Clarity Index

Several parameters are proposed for the measurement of actual speech clarity in classrooms. One of them is the Clarity Index (C_{t_e}). When assessing speech clarity the values of t_e are set to 50 ms. C_{50} measures the ratio between the early and late reflection of sound in a room. This parameter can be calculated by frequency bands but does not have any standardized way of analyzing the results of how speech is perceived (Vigran, 2008, p.109). Calculation of C_{50} can be conducted by Equation 6.

$$C_{t_e} = 10 \cdot \log \frac{\int_0^{t_e} p^2(t)dt}{\int_{t_e}^{\infty} p^2(t)dt} \tag{6}$$

t_e denotes the time frame defined to be included as early reflections.

2.4.4 Useful-to-detrimental sound ratio

Similar to the Clarity Index, the Useful-to-detrimental (U_{50}) uses the early-to-late ratio but includes the noise present and the energy of speech (Cho, 2017). Calculation of U_{50} is achieved following Equation 7.

$$U_{50} = 10 \log \frac{C_{50}}{1 + (C_{50} + 1)N/S} \tag{7}$$

N ambient noise level, and S speech energy.

2.5 Decibel and mathematical operations

Decibel is the relative logarithmic ratio, a tenth of a Bel. The unit is commonly used in sound pressure measurements, due to sound loudness increasing logarithmically. The logarithmic nature of the decibel makes regular arithmetic operations feasible. Therefore it is necessary to make the operation on the original pressure measurement, which yields in several formulas for arithmetic operations on decibels.

2.5.1 Addition and subtraction

Adding two or more decibel values can be achieved by Equation 8.

$$L_p = 10 \cdot \log_{10}\left(\sum_{j=1}^{n} 10^{\frac{L_{p,j}}{10}}\right) \tag{8}$$

L_j denotes measurement j of n values.

2.5.2 Mean values

Equation 9 is used to find the mean of several dB values.

$$\overline{L_p} = 10 \cdot \log_{10}\left(\frac{1}{n}\sum_{j=1}^{n} 10^{\frac{L_{p,j}}{10}}\right) \tag{9}$$

L_j denotes measurement j of n values.

2.6 Literature review

There are released research on the topic of speech and speech perception regularly. A quite recent research conducted by Prodi et al. (2022) researched the effects of different types of reflection on speech perception. They found that diffused reflection had no significant effect on the measured STI values, but showed to affect several other parameters T_{20}, C_{50}, U_{50} to an extent. Distances measured in this study were between 1 and 4 meters, thus diffuses seem to have little impact on speech at small distances. Arvidsson et al. (2021) conducted a study on the effect of diffuses on the soundscape. Results showed a soundscape with less deviation when introducing diffusers. It did not show conclusive evidence for which surfaces provided the best results.

Measurements of C_{50}, T_{20}, and EDT can be conducted in several ways. The IR method is often the preferred method, yielding a high degree of precision (Standard, 2008). Extraction of parameters from IR shows some tendencies to have some correlation. Cho (2017) investigated the relation between U_{50} and STI. Results showed a change of +0.6 STI corresponded to +0.5 dB U_{50}.

In literature, some studies reference C_{50} values greater than 2 dB are universally considered for volumes less than $< 250\ m^3$ (Astolfi, Parati, D'Orazio and Garai, 2019). Vigran (2008) suggest values greater than 0 dB. Bradley et al. (1999) claims the lowest noticeable difference of C_{50} are around 1.1 dB.

A Canadian study Yang and Bradley (2009) on the effects of reverberation on speech perception. It found that changes in reverberation affect speech to some extent. The conclusion of this study state that improved SNR is a more important metric addressing to increase the transmission of speech. Only the average reverberation across the frequency spectrum was used in this study. Nilsson (2010) have assessed the suitability of reverberation time as a design parameter for classrooms. Parameters such as C_{50} and strength (G) were deemed more suitable parameters, as they provide more useful information on the soundscapes effect on speech compared with reverberation time.

Norwegian studies on their classroom environment have questioned the design standard. Homb (2022) asks for a revision of the current requirements for a classroom. Comparing the national standards of several countries, some of which use a target range for reverberation in classrooms. Arguing that short reverberation can reduce reflection to a degree where it gets unnecessarily hard to communicate across a room. Concern around this is also raised by Bolstad (2019), which also asks for requirements adjusted for ceiling height. The study quantified noise generated by different activities, and noise levels that could be used toward a more precise simulation of U_{50}.

Age is another factor that studies have shown to be important, younger pupils are the most prone to noise (Astolfi, Puglisi, Murgia, Minelli, Pellerey, Prato and Sacco, 2019). Prodi et al. (2013) found that babble and activity noise affected performance more extensively than traffic noises for instance. Moreover, Prodi et al. (2019) found that both the sound environment and listeners' gender and age impacted both sentence comprehension and speech intelligibility.

In there are two important main groups of users to consider, teachers and students, of which teachers speak and stay the most. There are several studies that have documented teachers' exposure to vocal stress (Russell et al., 1998; Astolfi et al., 2012; Lervik, 2018). A study has shown talkers raise their vocal intensity by 1.3 to 2.2 dB per the double distance to the listener (Pelegrín-García et al., 2011). The same study found that speakers in rooms with poor and uncomfortable acoustical environments compensated with an increase in vocal intensity, following low speech intelligibility. They also found that speakers tended to increase their fundamental frequency as distance increased, thus increasing the pitch of their voice.

3 Method

3.1 Literature research

The presented theory has a basis in both established curricula for acoustic university courses and peer-reviewed papers. For the literature research, the three primary online sources used were Google Scholar, NTNU Oria, and Scopus. Regular Google searches were used in certain cases, where high-quality literature was not necessary. Only sources that were deemed trustworthy have been used. Furthermore, some of the considered attributes of the literature reviewed have been age, the number of citations, and relevance to the topics discussed. To further discuss the results, similar and related findings from other studies are presented as a part of the theory.

International and national acoustical design standards made the basis for conducting measurements. TEK17 has also been used regularly, which holds the current requirements given for buildings in Norway. Other noticeable sources have been Sintef community publications, these have provided guidelines and helpful comments on how to achieve the set requirements.

Research has also included finding suitable choices for reflector materials. The classroom's MOM documentation gave valuable information on capacities and material attributes. Several stores were investigated to find suitable materials for measurement. Amount the information gathered was price, availability, and documentation of physical attributes such as acoustical properties, dimensions, and density.

3.2 Field measurements

3.2.1 Description of location

The two classrooms measured are located in Salemhuset, located in Prinsens gate 22b in the city center of Trondheim. They were built in 2022 as a part of a larger rehabilitating and extension project of an older church building from 1925. Both classrooms are constructed with similar materials, differing in size, shape, and areal distribution. Pictures of both classrooms are found in Figure 3 and attributes of both classrooms are given in Table 2.

(a) *Classroom A*

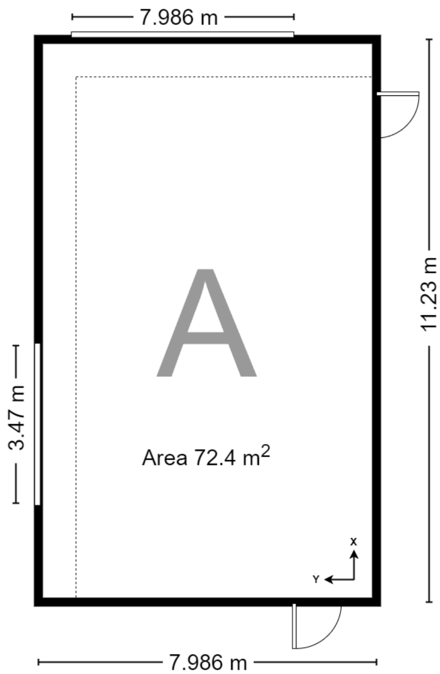
(b) *Classroom B*

Figure 3: *Pictures of Classroom A & B. Room 203 and 204 at Salem Huset.*

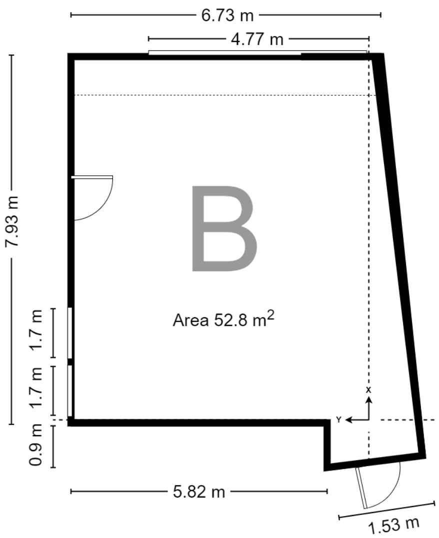
Table 2: *Attributes of Classrooms A and B.*

Attribute	Classroom A	Classroom B
Dimensions	11.23 m x 6.55 m	7.75 m x 7.03 m
Area	72.4 m^2	52.8 m^2
Volume	214 m^3	155 m^3
Glass area	27.10 m^2	23.81 m^2
Other surfaces	Gypsum & Linolium	Gypsum & Linolium
Acoustic ceiling 60 x 60 cm tiles 20 mm	162 pcs	24 pcs
Acoustic ceiling 60 x 60 cm tiles 40 mm	0	93 pcs
Acoustic wall elements	35 pcs	30 pcs
Plywood tiles - Center reflector	55 pcs	32 pcs
Plywood tiles - Chess reflector	63 pcs	48 pcs
Chairs - Plastic	25	18
Desks	13	9
Monitor - TV 60"	2	1
Cabinet	1	1

The most common activities in the room are lectures and group discussions. Normal lecturer positions in the rooms are typically central along the room's length. Students are typically seated in a standard grid desk setup, Figure 3 show the configuration used during measurements. Figure 4 display Classroom A and B as a horizontal cross section, vertical cross sections are given in Figures 5 and 6.

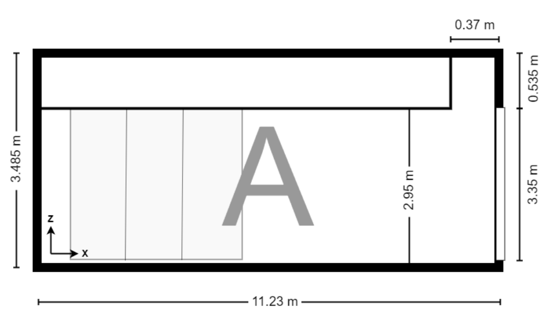


(a) *Classroom A*

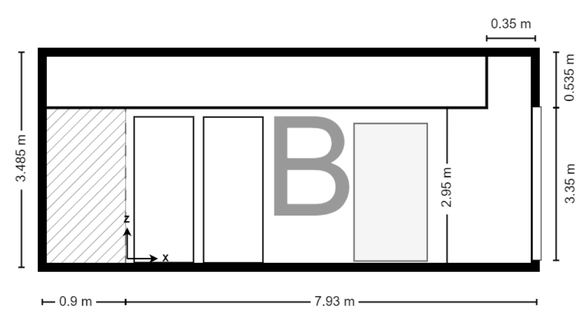


(b) *Classroom B*

Figure 4: *Horizontal dimensions of classroom A and B*

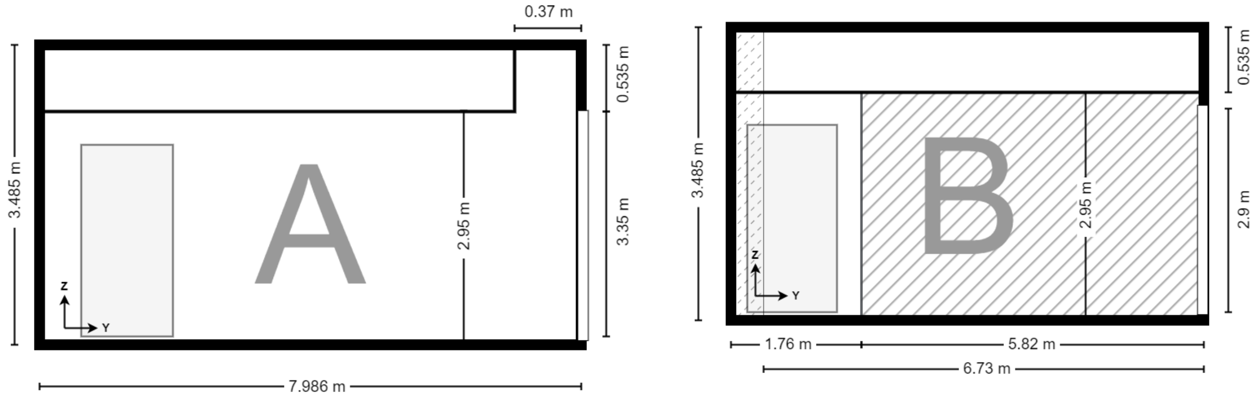


(a) *Classroom A*



(b) *Classroom B*

Figure 5: *Vertical section in the X - Z plane. As seen from from speaker. Hatch markings indicated wall in front.*



(a) *Classroom A* **(b)** *Classroom B*

Figure 6: *Vertical section in the Y - Z plane. Seen towards entrance. Hatch markings full line indicates a closer wall, dotted the changing width over the whole room.*

These classrooms were chosen due to them being accessible, having both the desired acoustic ceiling and clearance to make the temporary changes to it. During measurements, there was road construction work just outside. This made it necessary to conduct measurements after working hours, which reduced the background noise considerably. The structure of the ceiling and floor is given in Tables 3 and 4. All the wall surfaces are constructed with plasterboards, and placed on Rockwool isolated wooden stud structures. The acoustical attributes of the used ceiling tiles and wall absorbents are found in Table 5.

Table 3: *Ceiling structure for both classrooms, seen from inside outwards.*

Ecophone Master A - 60 x 60 cm	20 - 40 mm
Air space	535 mm
Concrete element	320 mm
Parrock insulation element	410 mm

Table 4: *Floor structure for both classrooms, seen from inside outwards.*

GranitSafe. T.Vinylgulv	2 mm
Leveling compound	15 mm
Hollow concrete element	265 mm

Table 5: *Absorption factors (α) of present materials. Plywood absorption based on 10 mm plywood wall data JCW general data (JCW, n.d.) and Echo-phone MOM data sheet.*

Material	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Eco-phone Master A (Ceiling - 20 mm)	0.5	0.85	0.95	0.90	0.95	0.95
Eco-phone Master A (Ceiling - 40 mm)	0.6	0.90	0.95	1	1	0.9
Eco-phone Master B (Walls - 40 mm)	0.25	0.80	0.95	0.95	1	1
Plywood	0.04	0.28	0.17	0.09	0.1	0.1
Glass	0.18	0.06	0.05	0.05	0.04	0.04
Plaster on wood	0.01	0.02	0.03	0.03	0.04	0.05
Vinyl	0.02	0.03	0.03	0.03	0.03	0.02

3.2.2 Measurement setup

In researching a suitable source transducer, several standards for measurements were considered. One of these, the STI standard (IEC, 2021), states that the source signal should be sent from a loudspeaker that matches the directionality of a human voice. The reasoning behind this recommendation is a more realistic simulation of the human voice's impact on the environment. One of the main parameters of this study, the C_{50}, does not have an international standard. STI there was considered a comparable standard for these measurements. A half-spherical transducer was therefore considered a good alternative. It has the advantage of making a better assessment of the actual reverberation of the room, this fulfills the requirements to achieve a precision measurement given in NS-EN ISO 3382-2 (ISO, 2018). For receiver transducers, a pair of precise measurement microphones with a flat frequency response were used. A schematic of the equipment used to carry out measurements is found in Figure 7. A full list of equipment is given in Appendix A.

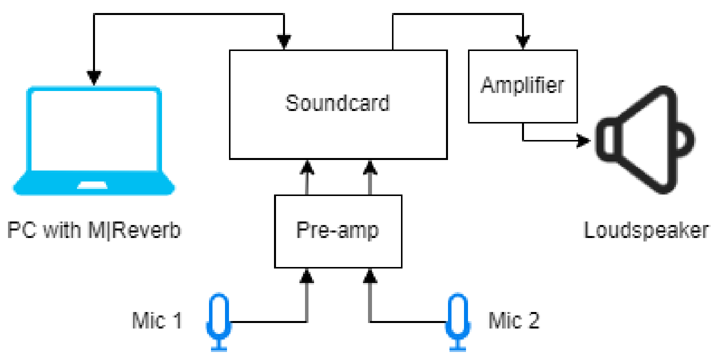


Figure 7: *Measurements setup diagram which was used. The setup uses a total of three transducers, one sender, and two receivers.*

Microphone positions were chosen to fulfill criteria given by NS-EN ISO 3382-2, making sure each position was spread asymmetrically throughout the classroom, with different orientations as well as being in a combination of representative of a student and lectures typical positions. Each position was assigned a height in a range of 1.2 to 1.6 meters, representing the typical height of the ears of a student in the room. Both measures reduce the influence of potential room modes. Source height was constant across all positions at 1.6 meters. A constant height was used both to save time on height adjustments as well as having one less factor being manipulated.

3.2.3 On site preparations

The setup process for both rooms was identical. Both started with removing any potential sources of error, mainly making the room only contain the bare minimum of obstruction outside of chairs, desks, and any permanent installations. Each transducer position was then chosen and marked with tape, to ensure that the placement stayed consistent between measurements. Positions were labeled with both a number and a letter. The letter stating whether the placement was a source (S) or receiver (R). A spreadsheet and diagram were used to log each transducer's position and orientation. Keeping a log of height for each position was deemed especially important to ensure that all measurements were conducted with the same position. Tables 6 and 7 provide position and height for each position in Classroom A and B, the transducer placements are displayed in Figures 8 and 9.

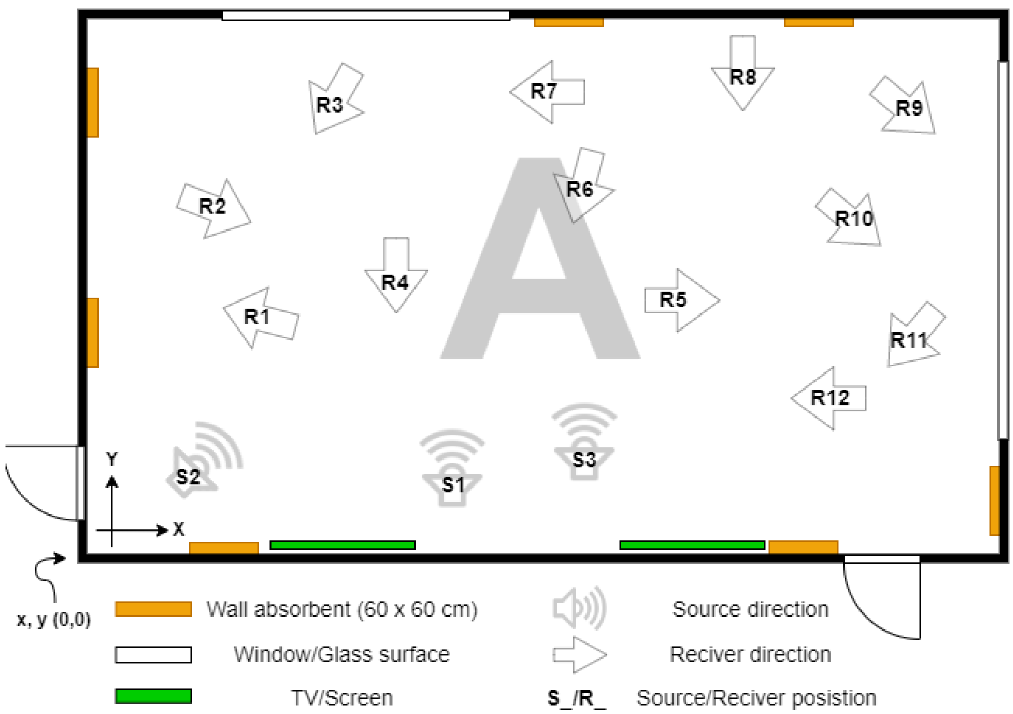


Figure 8: *Classroom A - Transducer placements. The precise positions is given in Table 6*

Table 6: *Positional coordinates of transducers in Classroom A.*

	S1	S2	S3	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
X	4.18	0.84	6.26	1.51	0.85	2.97	3.50	6.01	5.73	4.87	8.21	10.10	9.00	9.61	8.70
Y	0.31	0.75	1.18	2.46	4.31	5.50	2.88	3.24	4.86	5.76	5.44	5.10	3.75	2.45	1.31
Z	1.61	1.61	1.61	1.20	1.10	1.40	1.43	1.50	1.23	1.12	1.25	1.32	1.15	1.55	1.10

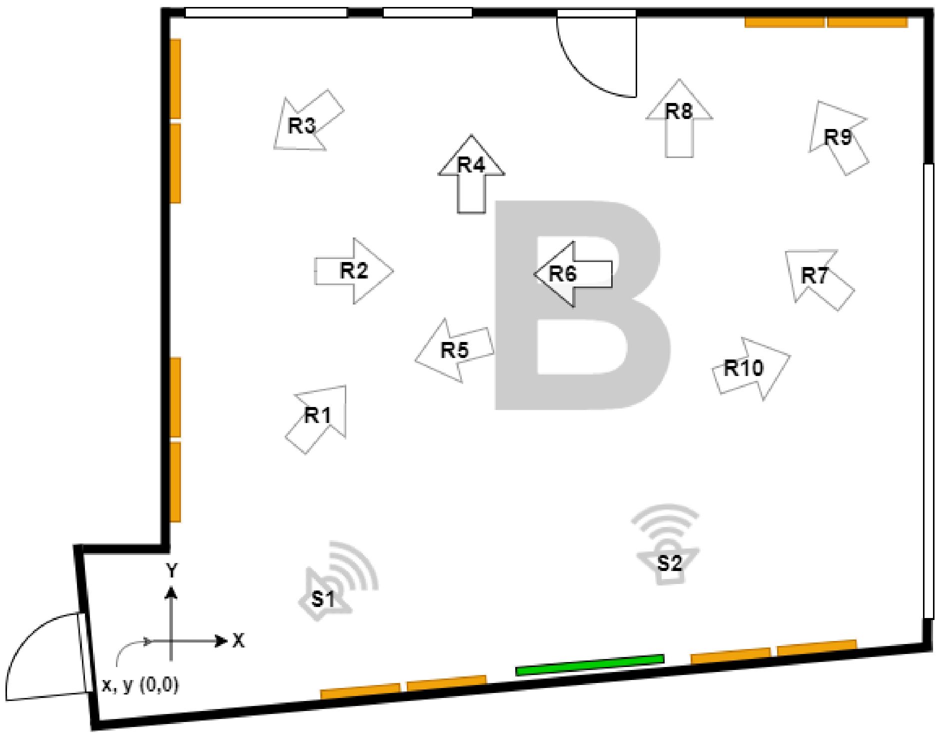


Figure 9: *Classroom B transducer placements. The precise positions are given in Table 7. Axis placement was chosen due to difficulties with glass surfaces with measurement devices.*

Table 7: *Positional coordinates of transducers in Classroom B.*

	S1	**S2**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**
X	1.50	5.90	1.35	2.08	1.34	2.92	2.61	3.75	6.34	4.94	6.55	5.66
Y	0.90	0.50	2.86	4.18	6.19	5.54	2.26	4.44	3.18	5.06	5.45	1.92
Z	1.61	1.61	1.36	1.10	1.59	1.15	1.40	1.15	1.50	1.22	1.30	1.25

All measurements had microphone 1 in an odd number receiver position and mic 2 in an even one. Two measurements were then conducted for each of the three source positions. Thereafter repeating this process until all receiver point was measured. A calibration of the microphones was conducted both before and after measurements to find a potential source of error. Levels of background noise were conducted at different stages during the measurement at two to three positions.

The local temperature, moisture, and air pressure were measured during measurements. Ensuring that any sudden changes in these parameters did not affect the results.

3.2.4 Background Noise and SNR Measurements

To ensure precise measurements BGN measurements were conducted before, during breaks, and after IR measurements. A Nor150 analyzer was used. It was calibrated before and after with a 1 000 Hz, 114 dB calibrator. BGN at 2 to 3 of the receiver position extremities. One at each end of the room, at receiver positions farthest from the sources, which would receive the lowest sound levels from the direct sound. Some BGN measurements were conducted in the center of the room and at other locations throughout the measurement period to ensure all receivers attained great SNR. To reassure a good SNR in the room, the Nor150 was used to measure the signals SPL during some test measurements. The same locations were used for both BGN and SNR.

3.2.5 Measurement procedure in M|reverb

Measurements in M|reverb start off with setting up the program with the equipment. The next step is the calibration of microphones, which was conducted with a 1000 Hz 114 dB calibrator. The calibration values before and after are found in Table 8. These measurements did not use a calibrated source. A source signal was chosen by a measurement test to see which signal yielded the least amount of measurement error. Table 9 shows the settings for the chosen pink-weighted sine-sweep signal. Both lengths of signal and silence were set long enough for good precision and a reasonable time to make all measurements possible in the set time frame. Furthermore, the measurement conditions, sources, and corresponding receivers are configured. Two conditions were used to make two measurements in each receiver position.

Table 8: *Calibration sensitivity of microphones in M/reverb. B denotes before and A After.*

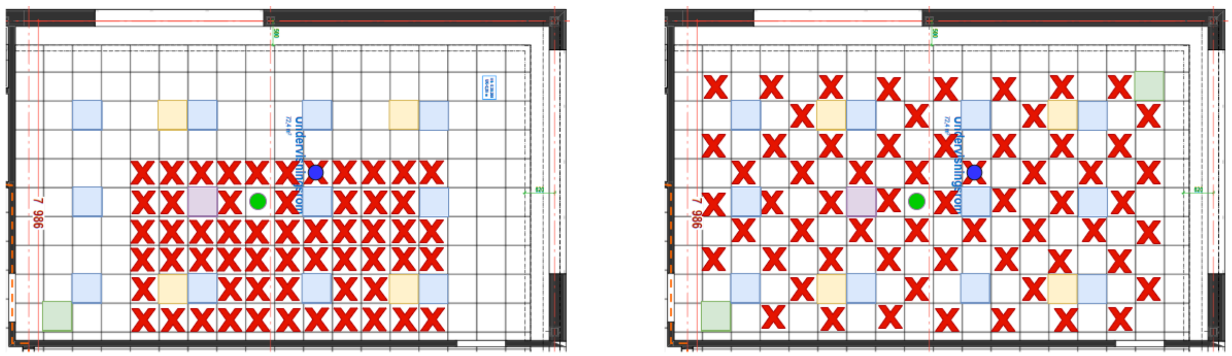
	Mic 1	**Mic 2**
Classroom A - B	1,09 dB	1.47 dB
Classroom A - A	1.10 dB	1.47 dB
Difference	0.01 dB	0 dB
Classroom B - B	1.09 dB	1.43 dB
Classroom B - A	1.08 dB	1.42 dB
Difference	0.01 dB	0.01 dB

Table 9: *Excitation signal used in Mreverb, with a high pass filter set to 31.5 Hz*

Type	**Spectral density**	**Excitation**	**Silence**	**Pulse response**
Sweep	Pink	12 s	8 s	4 s

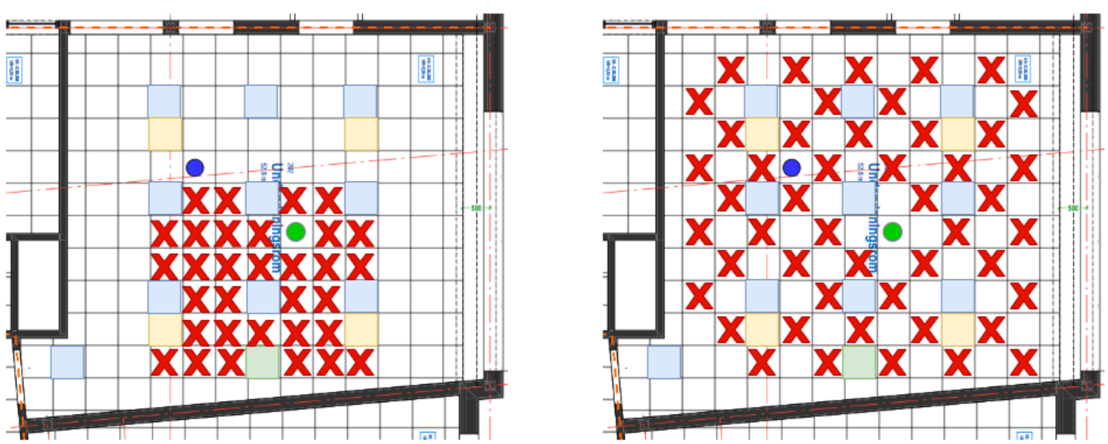
3.2.6 Changing the ceiling

In each classroom, three different ceiling configurations were measured. The first one is the room's regular normal configuration. After measurement of the normal condition, a larger part of the ceiling's acoustic tiling was replaced with 9 mm plywood tiles in the same dimensions, 60 x 60 cm. Two types of tiling structures were chosen, a center and a chess configuration. These a displayed in Figure 11.



(a) *Center reflector* **(b)** *Scattered reflectors*

Figure 10: *Diagram of plywood placement in Classroom A. Tiling's marked by red crosses. Other symbols are explained in the Appendix D.1.*



(a) *Center reflector* **(b)** *Scattered reflectors*

Figure 11: *Diagram of plywood placement in Classroom B. Tiling's marked by red crosses. Other symbols are explained in the Appendix D.1.*

Plywood was chosen for several reasons. Firstly the properties desired for this experiment were a hard smooth surface, and a higher density and weight compared to acoustic tiling. It being a relatively cheap material, it fitted with the given budget. The thickness of 9 mm was chosen as a result of it being within the capacity of the ceiling grid.

3.3 Analysis of data

3.3.1 Data selection

All measurement data were subjected to some criteria to remain in the data set, in an attempt to attain higher precision data for analysis. Data points that were deemed to be imprecise, showed little correlation between the two identical measurements. Moreover, certain receiver and source combination was also excluded from the set, having too small a distance between each other. Having two data points for each position, all the averages of these have been used for further analysis.

After the conducted measurements there were made a decision to use only octave band information for C_{50}, these yielded more consistent results when considering the internal error measurement of M|reverb. Reverberation was the third-octave band chosen for a more precise picture of the room soundscape. EDT values with a Mreverb error of 10% were deemed acceptable due to the total amount of data provided by 36 sender and source combinations. The limit of inclusion for T_{20} error was 5%, following the Norwegian standard of precise reverb measurements. A decision was also made to only look at the frequency range 250 to 4 000 Hz for C_{50}, having the lower part of the range in mind when analysis when deemed relevant. The reverberation range was chosen to be 100 to 5 000 Hz, which is the suggested analysis range given by the standard.

3.3.2 Post-processing

Selected data for each classroom were further processed in Excel and divided into T_{20}, EDT, and C_{50} exported from M|reverb. The program M|Reverb offered limited functionality, therefore Excel was deemed more flexible and easier to execute the desired post-processing.

The same process was applied to both T_{20} and EDT. Step one was excluding data points based on the criteria given in the previous section. Further, the third-octave band reverberation average of the remaining data was calculated for each ceiling configuration and source location. A single number average for reverberation between 125 and 4 000 Hz was calculated, the range is according to the one used by the Norwegian standard NS-EN 3382-2 (Standard, 2008).

A similar process was applied to C_{50}. As a dB value, averages have to be calculated by Equation 9. Each position was averaged first on an octave band level. Furthermore, there was taken an average of positions per octave band. There was also made a single number C_{50} for each position as an average of octave bands between 250 and 4 000 Hz.

Distances were calculated by a simple vector math for measured X and Y coordinates in the room, between the sources and receivers to attain the distances to the plot.

Furthermore, there was two approaches for calculation of STD for reverberation. The first used the method provided by NS-EN 3382-2 for precision measurements, and the second used the inbuilt Excel function "STDEV.P". STD calculation from Excel was mainly used to examine deviation between positions, a similar approached was used with C_{50}.

When presenting data, some key decisions were made to provide the data with additional easily readable information. In all plots between the rooms, the axis has been perceived to make comparison easier. For reverberation and C_{50} the range of values chosen for the Y-axis tried to not exaggerate the measured values. For instance, it could be desirable to narrow down the range of reverb, but this could make close values appear as if they are farther apart than they are in reality.

The spatial plots created for C_{50} were created by first making a template for each classroom using Draw.io. This assured both source and receiver positions remained constant between figures, before filling out with the measured values.

4 Results

4.1 Classroom A

Measurements of Classroom A started on the 22nd of February 2023, concluding on the 23rd of February. Classroom A is located in room 203 at Salemhuset. It has a floor area of 72.4 m^2 and height of 3.485 m^2, of which 2.95 m are underneath the acoustic absorbing ceiling. There was construction works outside the building. To retain a high SNR and thus high precision, all measurements were conducted during pauses. The average a-weighed BGN was measured to be 31.8 dB with an SNR of above 60 dB at frequencies below 8 kHz. Two measurements were made at each combination of source/receiver position and ceiling configuration. Three ceiling configurations were measured, the room's normal configuration and two configurations of plywood reflective ceilings. Each configuration consists of 36 unique measured data points, yielding a combined total of 216 measurements.

4.1.1 Reverberation

The measured impulse response of the normal ceiling configuration yielded an average T_{20} of 0.77 s and an EDT of 0.69 s at frequencies ranging from 125 to 4 000 Hz. Both exceed the lowest acceptable limit 0.5 s by a significant amount. For the plywood center reflector a T_{20} of 0.78 s and EDT of 0.70 s. The scattered reflector yielded a T_{20} of 0.77 s and EDT of 0.70. Thus a rather small increase of 0.01 s average reverberation was introduced by the reflective ceilings, which is close to the average calculated standard deviation. Figures 12 and 13 display the measured third-octave-band spectrum of T_{20} and EDT. The credibility of results were affirmed by an external analysis conducted with a Nor150 Analyzer, a comparison plot is found in Appendix B. Furthermore, the STD of measurement precision was calculated by NS 3382 and is given in Appendix C.

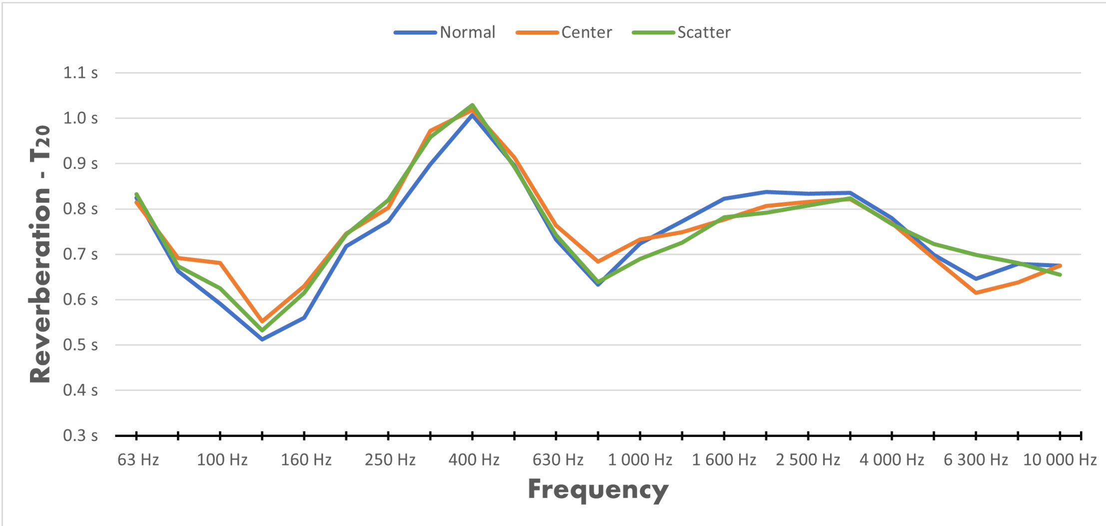


Figure 12: *Classroom A - T_{20} frequency spectrum. Mean values of T_{20} for each configuration were measured in third-octave bands.*

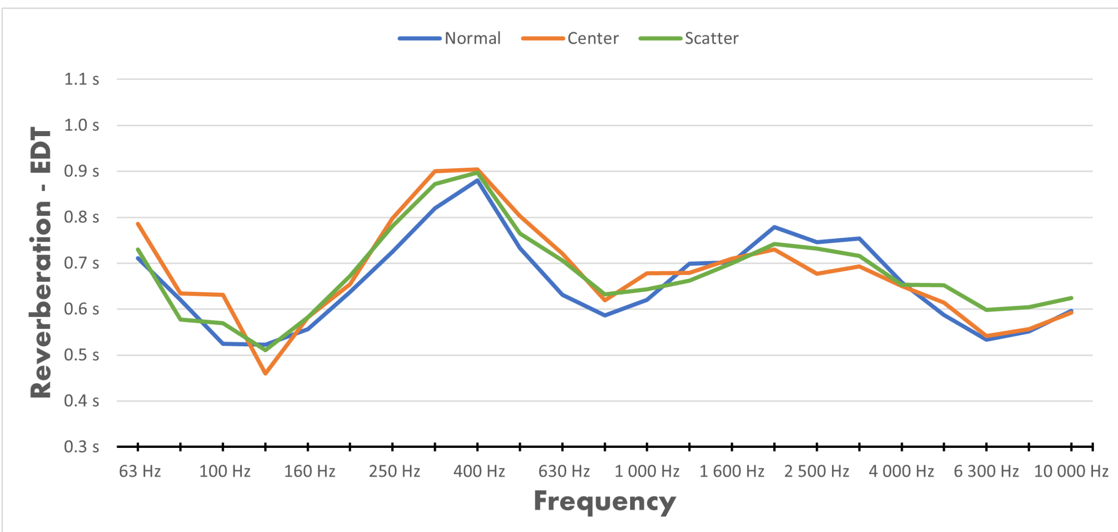


Figure 13: *Classroom A - EDT frequency spectrum. Mean values of EDT for each configuration were measured in third-octave bands.*

The frequency spectrum of T_{20} and EDT both show quite similar distributions. As for the averages, only small variations between each of the ceiling configurations are found. Introducing the plywood ceiling seems to shift the frequency distribution toward the lower part of the spectrum, which was to be expected somewhat due to plywood being a harder and heavier material. A decrease in reverberation is observed between 1.6 kHz and 4 kHz. Furthermore, a general increase of reverberation below 1 kHz is also observed. The scattered configuration shows an increase in reverberation above 4 kHz compared to the two others. The peak of reverberation is found at 400 Hz at around 1.0 seconds T_{20} and 0.9 seconds EDT. All configurations measured the lowest values at 125 Hz quite close to 0.5 seconds at the lowest, yielding a variation of reverberation time across the spectrum of 0.5 s. Another observation is that there seems to be a higher variation in the spectrum of the normal ceiling compared to especially the scattered ceiling.

4.1.2 Clarity index

Measurements of C_{50} were conducted together with reverberation by the measured IR of the room. C_{50} were measured in octave bands, due to several attempts at attaining precise results at all desirable third-octave bands unsuccessfully. The normal, center and scattered ceiling configurations showed logarithmic average C_{50} of 4.2, 3.7, and 3.5 dB for frequencies ranging from 250 to 4 000 Hz. The scattered ceiling with the largest average difference of 0.7 dB compared to the normal configuration. Figure 14 presents the average values at each individual octave band to further see the changes across the frequency spectrum.

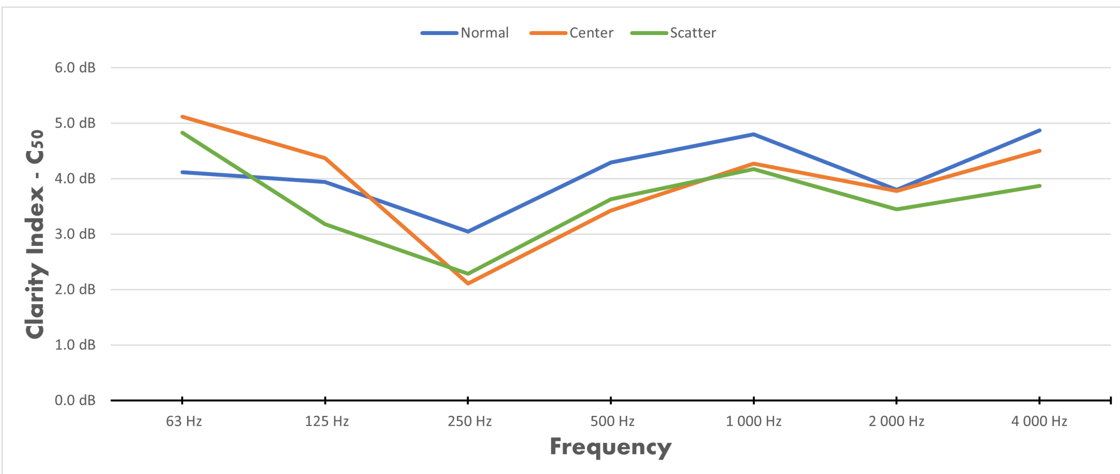


Figure 14: *Classroom A - The combined logarithmic average of C_{50} across every source-receiver combination.*

The results show that both plywood ceilings yield a decrease of C_{50} in frequencies between 250 and 2 000 Hz. Maximum C_{50} in the range of human speech is found at 4 kHz for the normal and center ceiling configurations, with values of 4.9 and 4.5 dB. The scattered ceiling achieves the highest value of 4.2 dB at 1 kHz. The lowest values are observed at 250 Hz for all configurations, measured to be 3.1, 2.1, and 2.3 dB. Significant variation was found in the results for frequencies above 4 kHz, deemed of lesser importance to the discussion these were excluded.

Distance, geometry, materials, source, and receiver position all contribute to local variations of C_{50}. To further investigate the impact of source position, C_{50} values were plotted at the corresponding receiver position, which is found in Figures 15, 16, and 17. All positions in the figures are approximate and there only to provide additional information on the relative differences throughout the soundscape of the room.

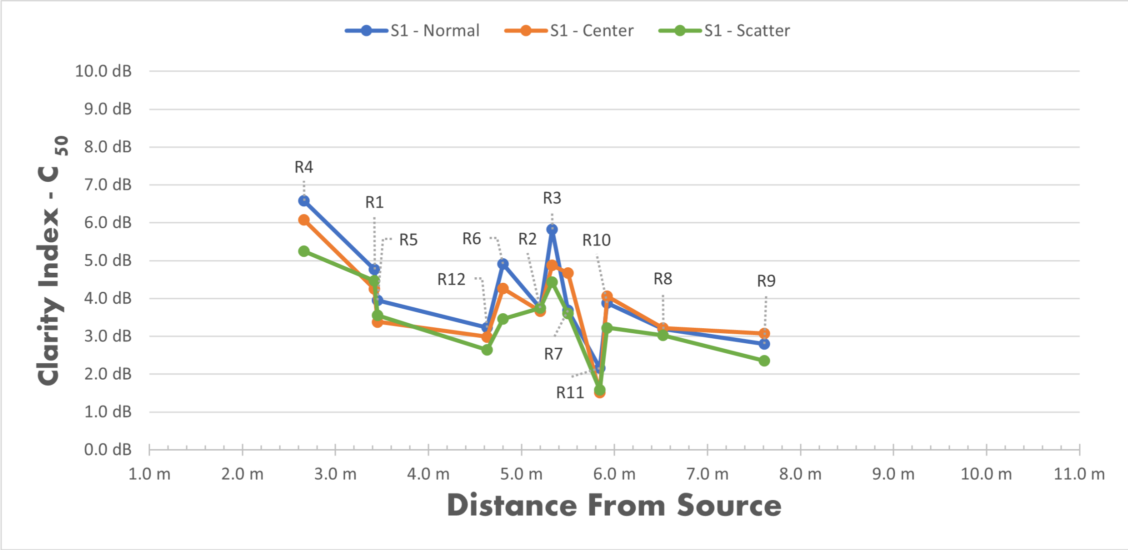


Figure 15: *Classroom A - C_{50} measured using source 1. Plotted by distance to the source..*

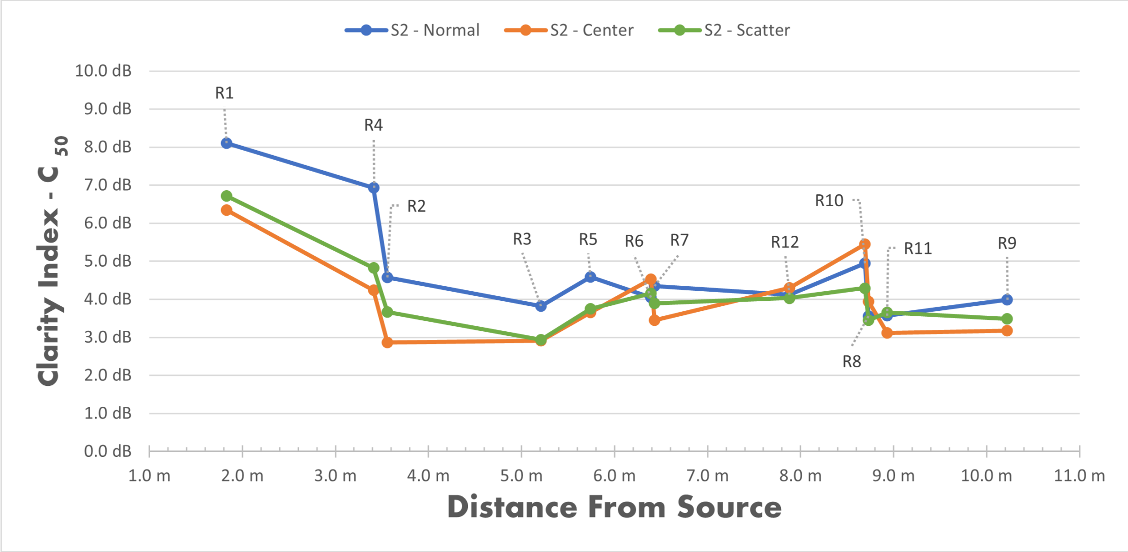


Figure 16: *Classroom A - C_{50} measured using source 2. Plotted by distance to the source.*

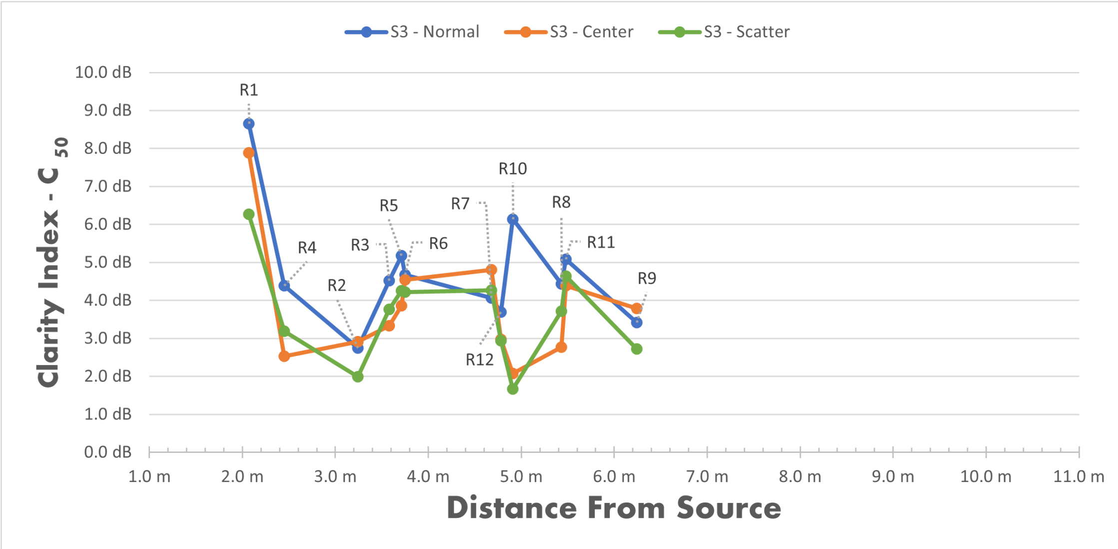
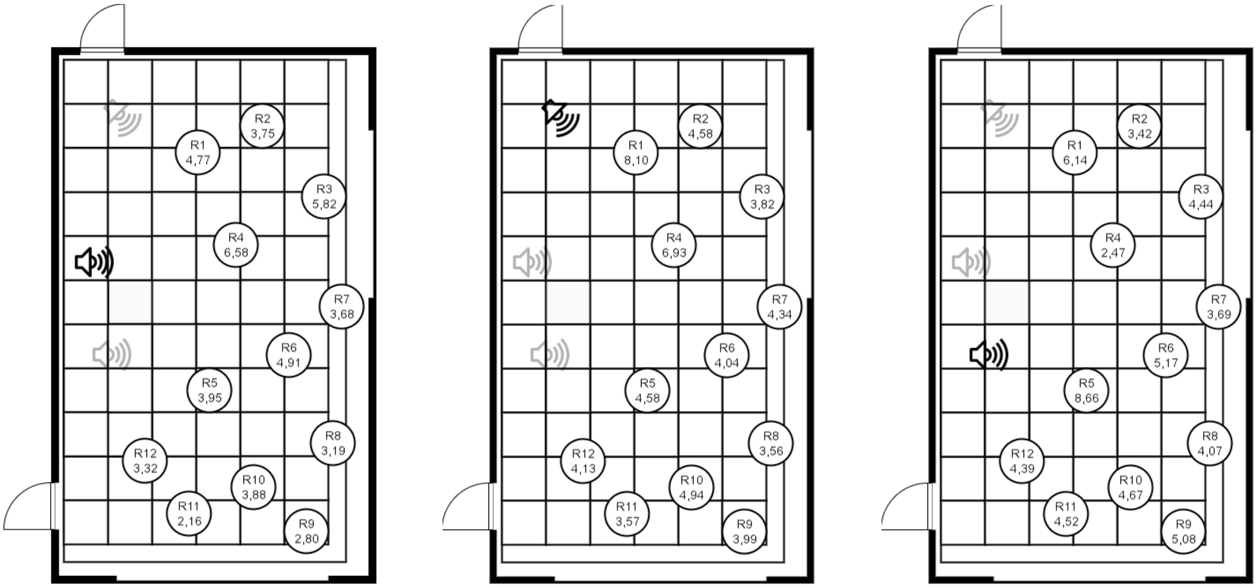


Figure 17: *Classroom A - C_{50} measured using source 3. Plotted by distance to the source.*

When increasing distance there is a trend in the reduction of C_{50}. Source positions 1 and 3, which simulate quite similar situations, yield quite similar C_{50} development when further increasing distance. Some key differences between these positions are found at a distance of 5 meters from source 3, where the normal ceiling performs 4 dB higher at receiver 10. In general, the center and scattered ceilings yield lower values of C_{50}. The center configuration measures slightly higher values overall for sources 1 and 3, which are located underneath the center reflector.

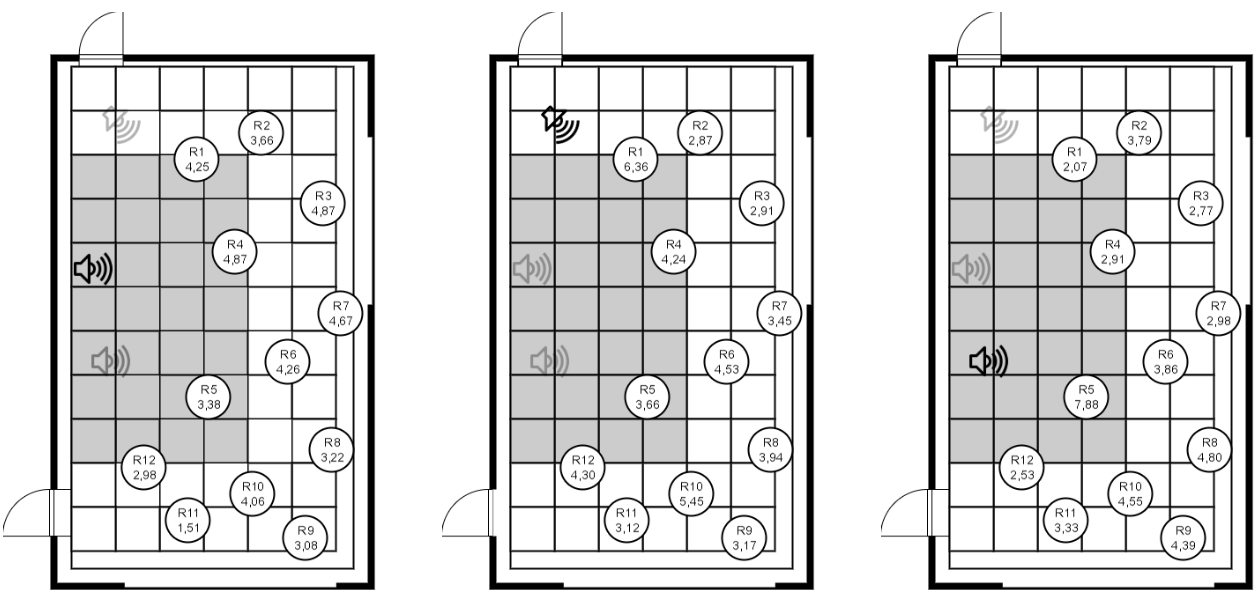
In both Figures 15 and 17 some receivers such as R3 and R5 perform quite similarly regardless of their distance to the source, while others show larger deviations between which source are used like R2 and R11. Source 2 seems to yield a more consistent C_{50} across the room. Differing only by around 1 dB maximum at distances above 3.6 meters in classroom A, ranging values between 3 to 5 dB. Sources 1 and 3 mostly show differences of a maximum of 0.5 dB at most positions, an clear exception to this is R10. Throughout the room, C_{50} takes values between 2 and 6 dB for these sources at distances above 2 meters from the source.

Classroom A geometry, surfaces, and material do contribute to local deviations. Figures 18, 19 and 20 present the measured values of C_{50} at the approximate position plotted in the diagram of Classroom A. The highlighted speaker is the one used for the values in the figure. Figures are sorted by ceiling configuration.



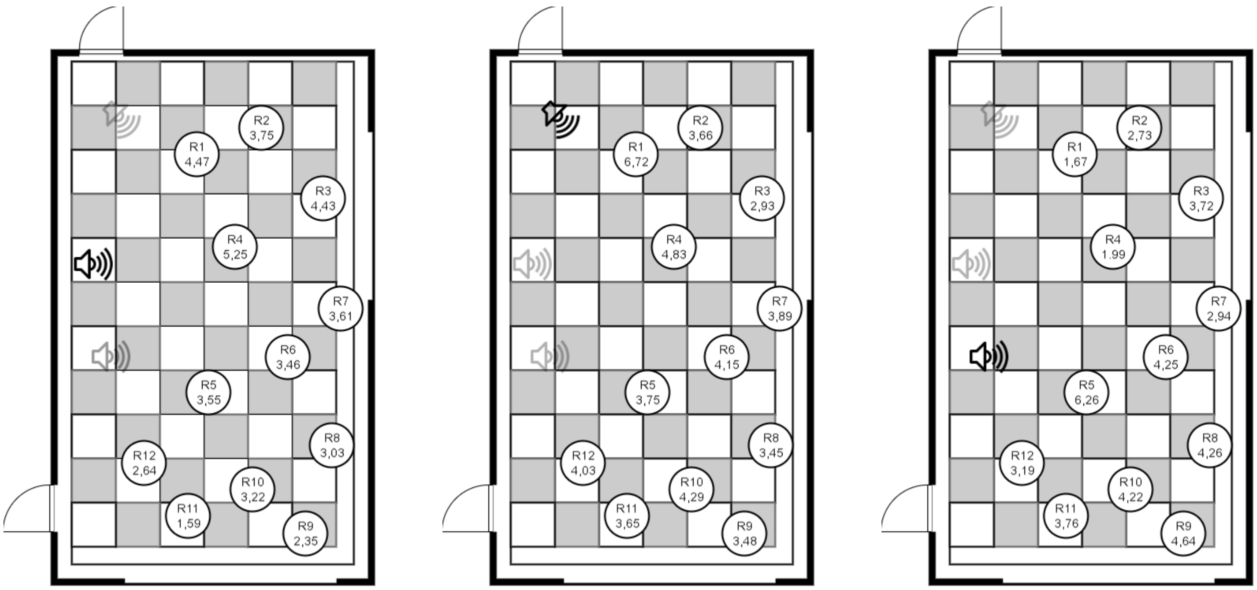
(a) *Source 1* **(b)** *Source 2* **(c)** *Source 3*

Figure 18: *Classroom A - Normal ceiling C_{50} results, plotted at corresponding receiver position.*



(a) *Source 1* **(b)** *Source 2* **(c)** *Source 3*

Figure 19: *Classroom A - Center reflector C_{50} results, plotted at corresponding receiver position.*



(a) *Source 1* **(b)** *Source 2* **(c)** *Source 3*

Figure 20: *Classroom A - Scattered reflector C_{50} results, plotted at corresponding receiver position.*

All ceiling configurations show variations between positions throughout the room. Receiver R4 and R5 in Figure 18 for instance, shows deviations larger than 4 dB between source S1, S2, and S3. The center configuration in Figure 19 shows a less overall difference with the general deviation across the room at around 2 dB. Larger deviations for the center reflector mostly correspond to source S2, an exception is also found between source S1 and S2 at R5. Figure 18 which show the normal ceiling, show to have deviations between source positions and are in general found to be larger when the relative distance increase. The center reflector in Figure 19 shows a similar pattern, with a slightly lower variation of 3 dB for some of the closer receivers and 1 to 1.5 dB across the room. The scattered configuration in Figure 20 shows smaller deviations between receivers except on the closes receivers. Across the room, there are found certain locations where the source seems to have a higher impact on the measured C_{50}.

4.2 Classroom B

Classroom B had measurements conducted on the 24th and 25th of February 2023 in room 204 at Salemhuset. Classroom B has a floor area of 52.8 m^2, and a height of 3.485 m^2, of which 2.95 m are underneath the acoustic absorbing ceiling. No construction works were present outside the classroom during measurements. The average a-weighed BGN was measured to be 24.8 dB with an SNR of above 60 dB at frequencies below 10 kHz. Due to delays caused by construction works, there were taken some measures to reduce time. Since the size of Classroom B is smaller than A, a decision where made to reduce the receiver-source count to 10 and 2, keeping quite similar distribution measurement density across the room. Each configuration consists of 20 unique measured data points, yielding a combined total of 120 measurements.

4.2.1 Reverberation

The impulse response of the normal ceiling yielded an average measured T_{20} of 0.73 s and an EDT of 0.60 s at frequencies ranging from 125 to 4 000 Hz. Hence reverberation in Classroom B also exceeds the limit 0.5 s. For the center reflector a T_{20} of 0.73 s and EDT of 0.61 s were measured. With the scattered reflector a T_{20} of 0.73 s and EDT of 0.63 s were measured. A small increase is found in EDT of 0.03 s when introducing the reflective ceilings. T_{20} shows close to no difference, with only a change of 0.01 s in the averaged part of the frequency spectrum. Figures 21 and 22 display the measured third-octave-band spectrum of T_{20} and EDT.

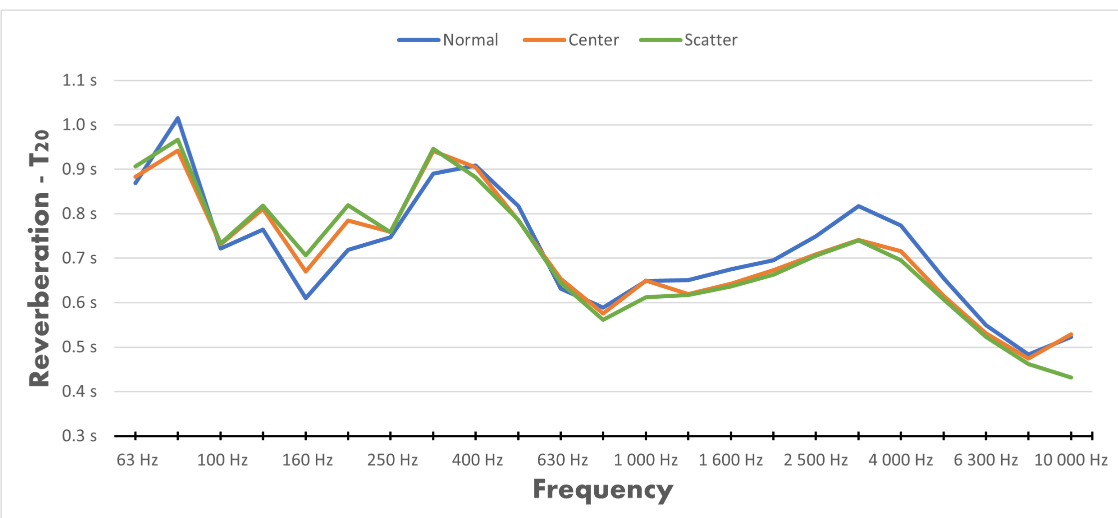


Figure 21: *Classroom B - T_{20} frequency spectrum. Mean values of T_{20} for each configuration were measured in third-octave bands.*

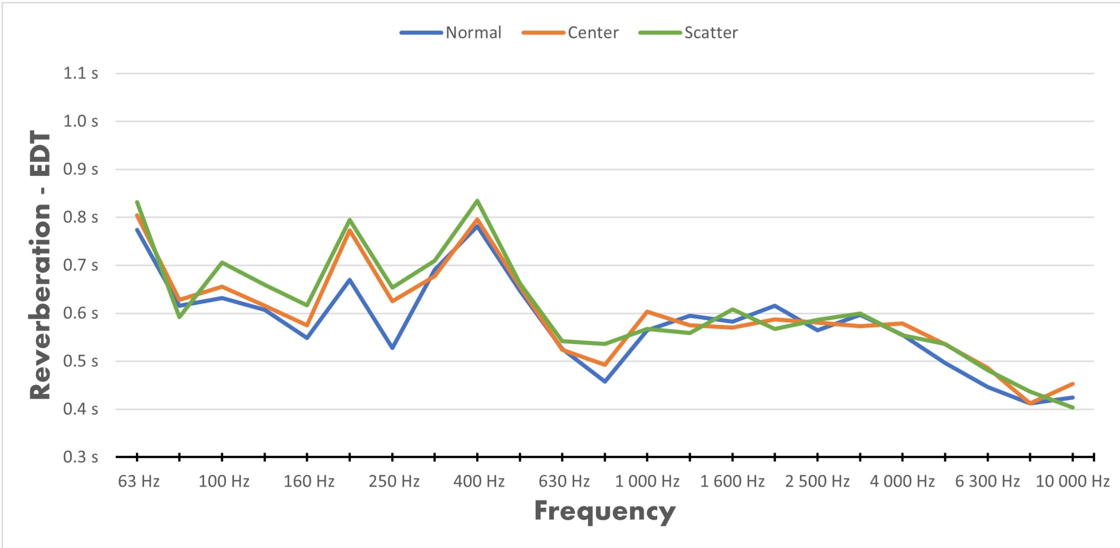


Figure 22: *Classroom B - EDT frequency spectrum. Mean values of EDT for each configuration were measured in third-octave bands.*

T_{20} and EDT both show quite similar distributions for Classroom B. Variations between each configuration are found to be small, which also was true for Classroom A. The introduction of plywood ceilings shifts the frequency distribution toward the lower part of the spectrum similar to Classroom A and T_{20} decreases between 800 and 8 000 Hz. The plywood ceiling configurations do increase reverberation between 100 and 400 Hz. The peak of reverberation in the human vocal range is found at 400 Hz with a measured T_{20} around 0.9 s, and 0.8 s EDT. Both plywood ceilings have an additional peak at 200 Hz very close to 0.8 s as well. A second significant peak for T_{20} is found at 3 150 Hz, measuring 0.8 s of reverberation. The lowest values of T_{20} are found at 8 000 Hz, with a T_{20} of 0.50 s and EDT of 0.42 s. Another is found at 800 Hz, where T_{20} is found to be around 0.58 s and EDT around 0.50 s. The variation in reverberation time across the spectrum is around 0.4 s.

4.2.2 Clarity index

C_{50} were measured by IR in octave bands. The measured mean values of C_{50} for the normal, center, and scattered ceiling configurations were 5.5, 5.0, and 4.7 dB for frequencies ranging from 250 Hz to 4 000 Hz. Hence there is a 0.8 dB difference between the Normal and Scattered configuration. The average values for each octave band are given in Figure 23.

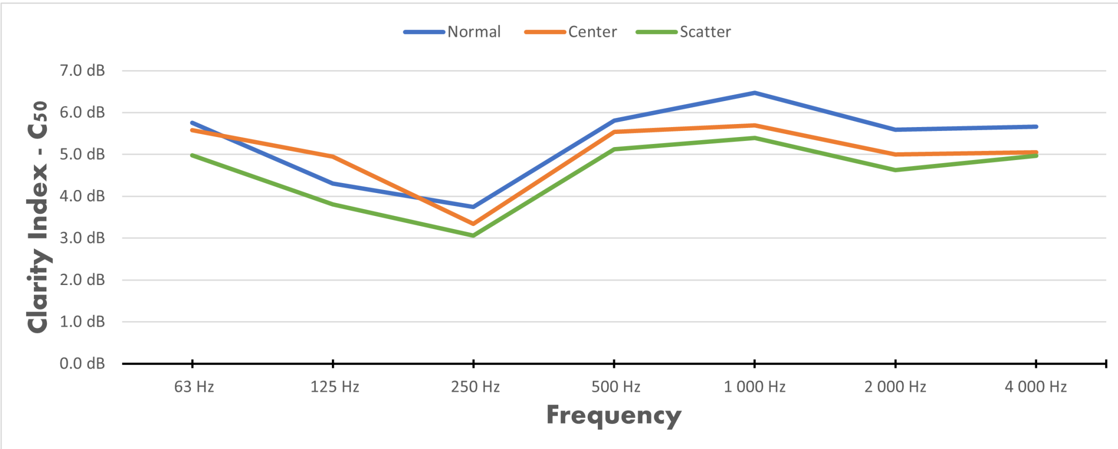


Figure 23: *Classroom B - The combined logarithmic average of C_{50} at frequencies ranging from 63 Hz to 4 000 Hz across every source-receiver combination.*

All ceilings develop similarly across most of the frequency spectrum, the scattered ceiling always yielding the lowest C_{50}. Only at the 125 Hz frequency band does the normal ceiling measure lower than the center ceiling. The Maximum C_{50} of all ceiling configurations is found at 1 000 Hz and found to be 6.5 dB normal, 5.7 dB Center, and 5.4 dB Scattered ceiling. All ceilings show small variations under 0.9 dB for C_{50} values between 500 and 1 000 Hz. The lowest values are observed at 250 Hz for all configurations, measured to be 3.7, 3.3, and 3.1 dB.

Several parameters affect C_{50}, distance and room geometry some of them. C_{50} values in Figures 24 and 25 are plotted at their corresponding receiver positions relative distance to the active source position. The x-axis scale is chosen to remain equal to the Classroom A measurement, to make it easier to visually compare the two. In Classroom B the values of C_{50} show differences of up to 3.7 dB at the Normal ceiling. The center reflector yields a maximum difference of 2.6 dB, and the scattered ceiling had a change of 3.8 dB.

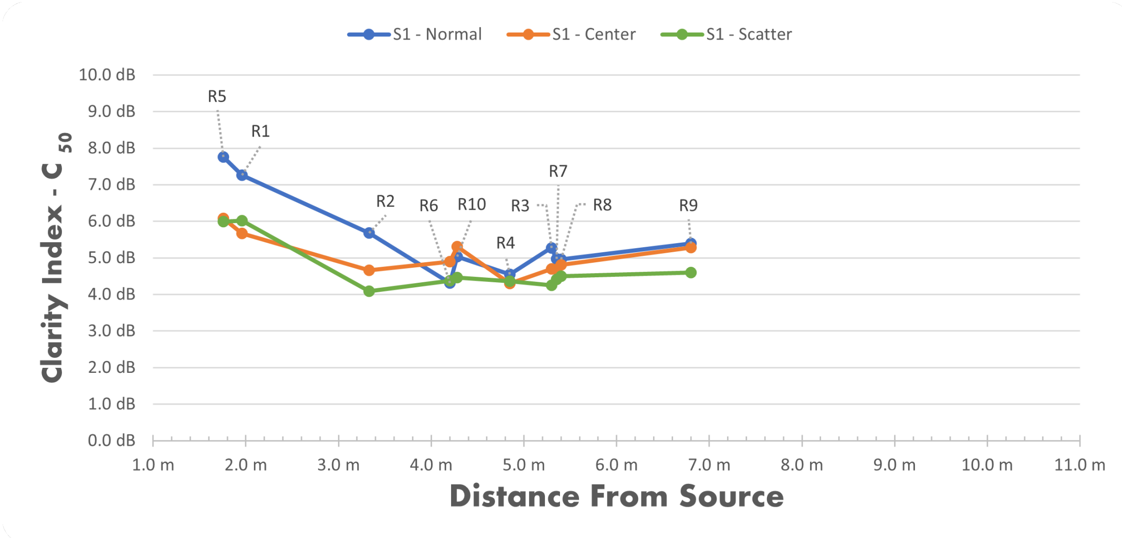


Figure 24: *Classroom B - C_{50} measured using source 1. Plotted by distance to the source.*

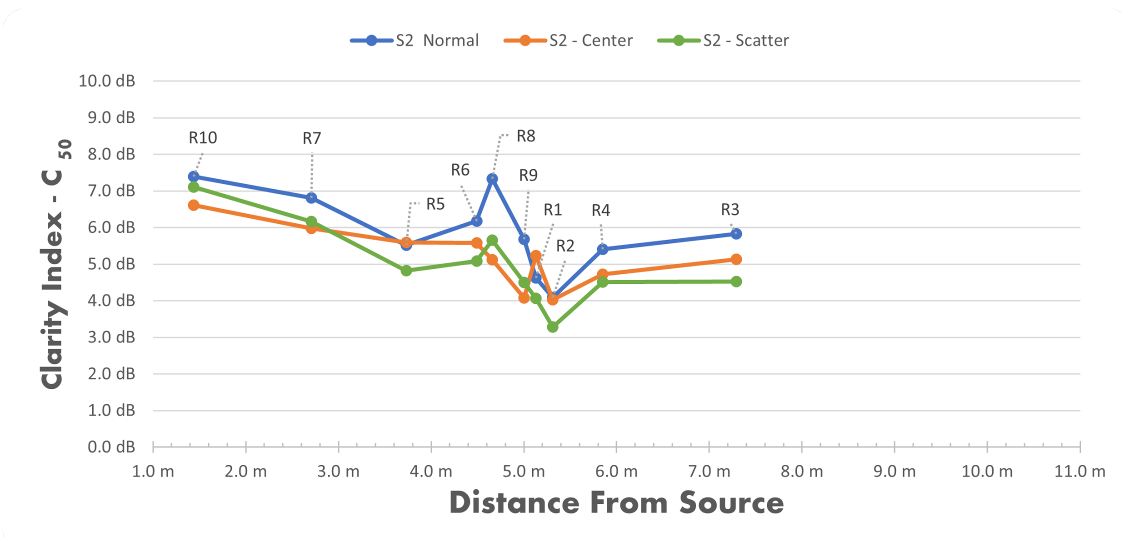
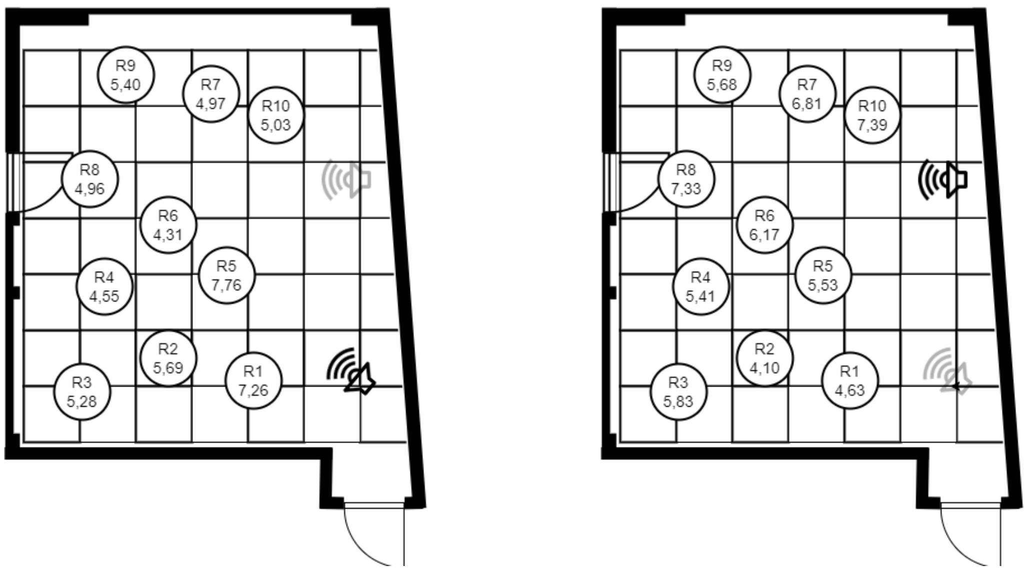


Figure 25: *Classroom B - C_{50} measured using source 2. Plotted by distance to the source.*

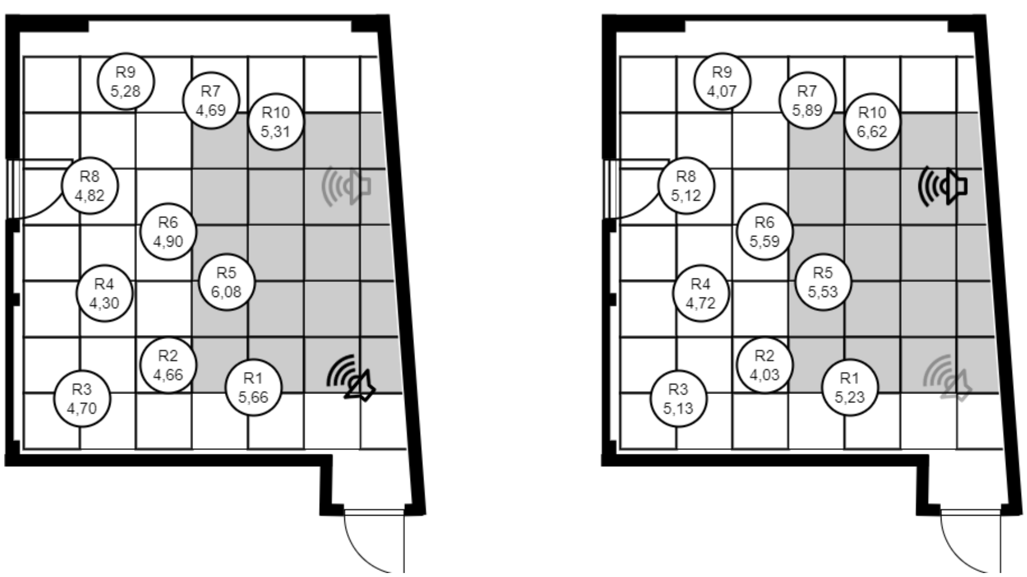
As for Classroom A, there is an observed reduction of C_{50} as distance increases. The reduction found in Classroom B is not as significant, showing only smaller variations across a multitude of distances. Source 2 does make C_{50} causing some positions to deviate more. For instance, position R8 with the normal ceiling measures approximately the same as the closest receiver R10. Slightly further away at R2 show a reduction of 2 dB. C_{50} for the plywood ceiling measures lower at most positions. They show less variation compared to the normal ceiling, with the center reflector showing the lowest variation across all measured positions. Variations are found to be smaller by source 1 C_{50} compared to source 2, with an approximate variation of $0.5\,dB$ and $1\,dB$ at all ceiling types.

To attain further information on the development of C_{50} across the room, the measured C_{50} for each receiver-source combination are presented in Figures 26, 27, and 28. A transparent source denotes it being inactive. The ceiling is just an illustration, not to be used for assumptions on room geometry.



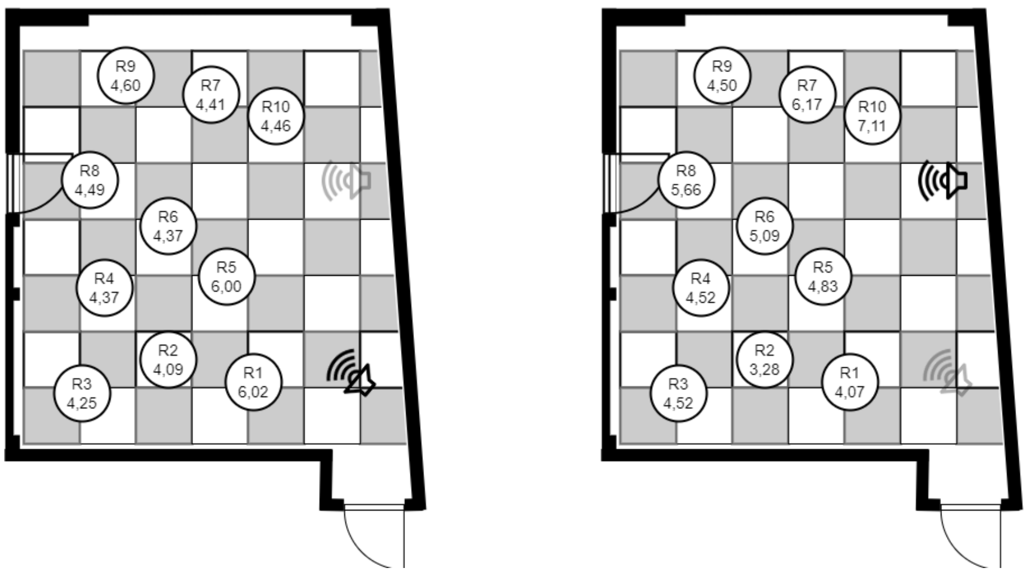
(a) *Source 1* **(b)** *Source 2*

Figure 26: *Classroom B - Normal ceiling C_{50} results, plotted at corresponding receiver position.*



(a) *Source 1* **(b)** *Soruce 2*

Figure 27: *Classroom B - Center reflector C_{50} results, plotted at corresponding receiver position.*



(a) *Source 1* **(b)** *Source 2*

Figure 28: *Classroom B - Scattered reflector C_{50} results, plotted at corresponding receiver position.*

In Figure 26 certain positions stand out. R8 for instance gets significantly impacted by the change of source position, a 2.4 dB change of C_{50} between the two. The impact of geometrical reflection is observed in several positions. For instance, corners in Classroom B show to have a clear advantage regarding wall reflection contributing to a possible higher C_{50}. This effect seems to contribute less if compared to results found in Figures 27 and 28. Position R6 is the only position where one of the plywood ceilings is provided with a higher C_{50} than the one measured with the normal ceiling. The center reflector improves C_{50} by 0.6 dB, which is rather little. Another observation is that most of the closer receivers also experience a reduction of C_{50} when both plywood ceilings are introduced. Similar results are found at certain positions in Classroom A.

4.3 Comparison of parameters

Further research was conducted on measurement data attained from Classrooms A and B. Several approaches were tried to extract potential relations between the measurement data of A and B. In addition, a similar investigation has been made comparing T_{20}, EDT, and C_{50} in different ways. Many were deemed uninteresting and not yelling useful information, thus not worth including in this study.

4.3.1 Differences between T_{20} and EDT

There was observed that EDT yielded lower values than T_{20}. The relative difference is shown in Figures 29 and 30. Calculated by subtracting EDT from T_{20}, this was chosen because EDT showed generally higher values.

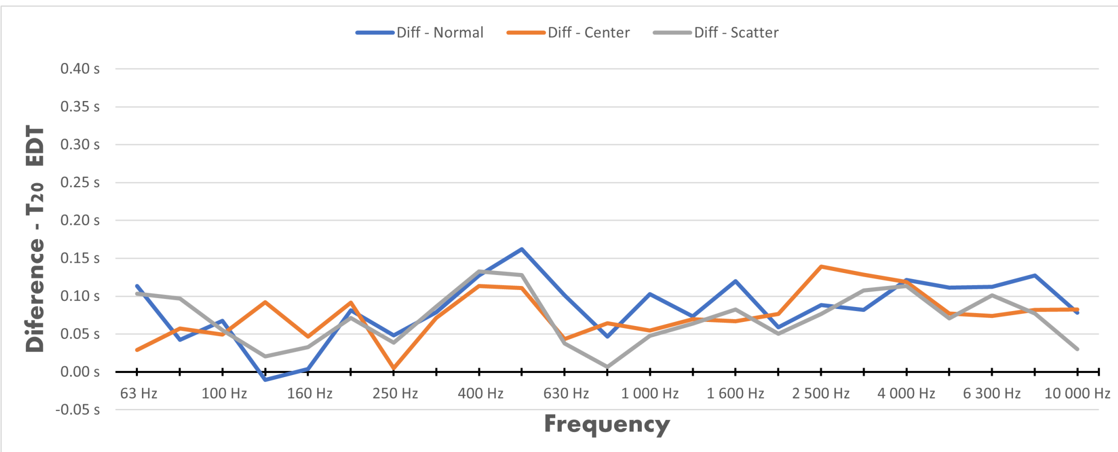


Figure 29: *Differences between T_{20} and EDT - Classroom A*

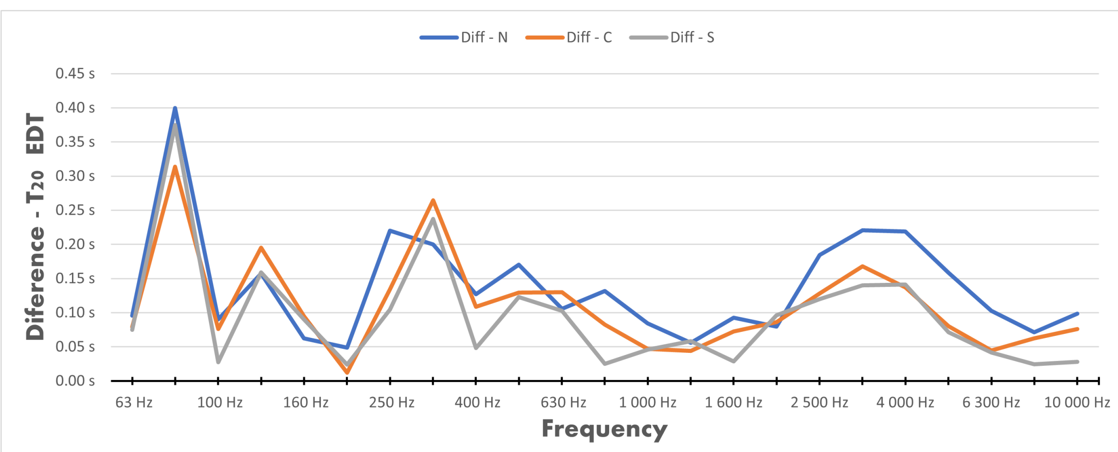


Figure 30: *Differences between T_{20} and EDT - Classroom B*

There is observed that room size seems to affect the difference between EDT and T_{20}, with the smaller Classroom B showing larger differences compared to A. In Classroom A the largest difference of just over 0.16 s is found at 500 Hz for the Normal ceiling. The largest deviation for the center ceiling is found at 2 500 Hz, just underneath 0.14 s. The scattered ceiling shows less deviation at most frequency bands, only exceeding both other configurations at 80 Hz with a difference of 0.10 s. However, Classroom B showed larger differences at several frequencies. All configurations peak at 80 Hz, with the normal configuration yielding a difference of 0.40 s. Moreover, the normal ceiling's largest differences are found at 250, 3 150, and 4 000 Hz with differences of around 0.22 s at all these frequencies. The center and scatter reflector configurations both showed a peak at 315 Hz of 0.26 s and 0.24 s. There is also observed that these ceilings showed around 0.07 s lower at the differences between 2 500 and 6 300 Hz, compared to the normal ceiling.

Furthermore, variations were assessed by calculations of standard deviations (STD). In Figure 31 the calculated STD of combined measurements is shown. An STD tries to look at the variation of STD across the room, thus this is not the same as an STD for the precision of measurements that are given in Appendix C.

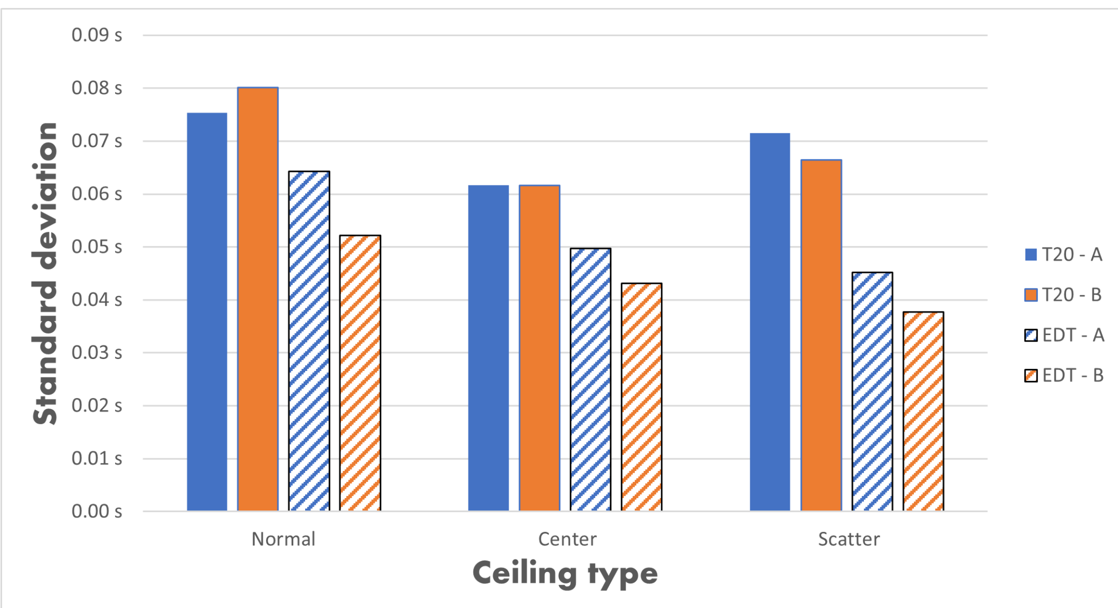


Figure 31: *STD comparison of measurements at all positions for each configuration, measured in seconds. Frequencies between 500 to 4 000 Hz was used in calculation, as this was deemed most interesting regarding speech.*

When considering this as a measurement of variation across the spectrum, the normal ceiling showed the largest deviations for both T_{20} and EDT. There is observed that the center ceiling yields the lowest variation of T_{20} at 0.06 seconds, which is a reduction of 0.015 and 0.01 seconds for Classrooms A and B. Moreover, the largest reduction in STD of EDT is found between the normal and center ceiling, with the scatter ceiling having an STD which are approximately 0.017 seconds lower in Classroom A and 0.011 seconds in B. Another observation of the difference between the STD of EDT and T_{20} in Classroom B is larger than in A, as seen in the differences between Figures 29 and 30.

4.3.2 Variation of C_{50}

In a similar fashion to an assessment of the variation of T_{20} and EDT, STD has been used to give some insight into how large the deviation is across all positions in the classrooms. The same approach has been used to investigate the deviation created by the change of source position in C_{50}. Results are shown in Figures 32 and 33. There should be noted that these figures are used to investigate tendencies rather than to measure the STD of one measurement.

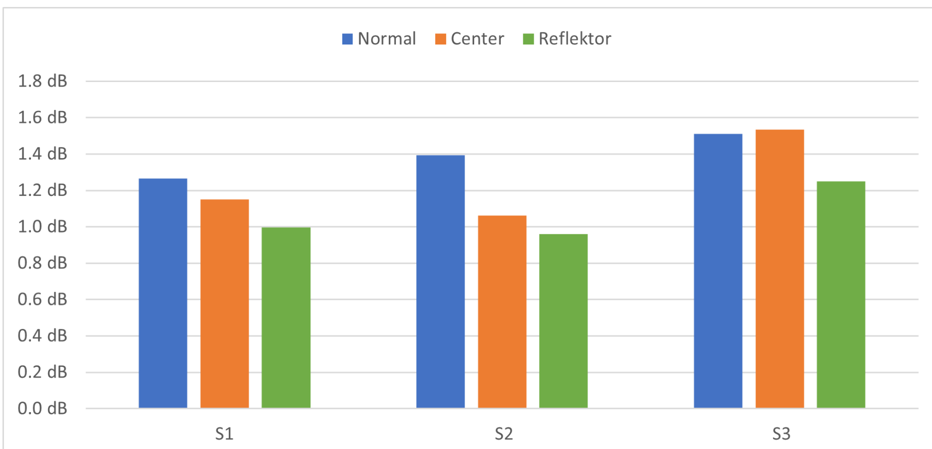


Figure 32: *Source effect on the variation of C_{50} averaged between 250 and 4 000 Hz, calculated as STD - Classroom A*

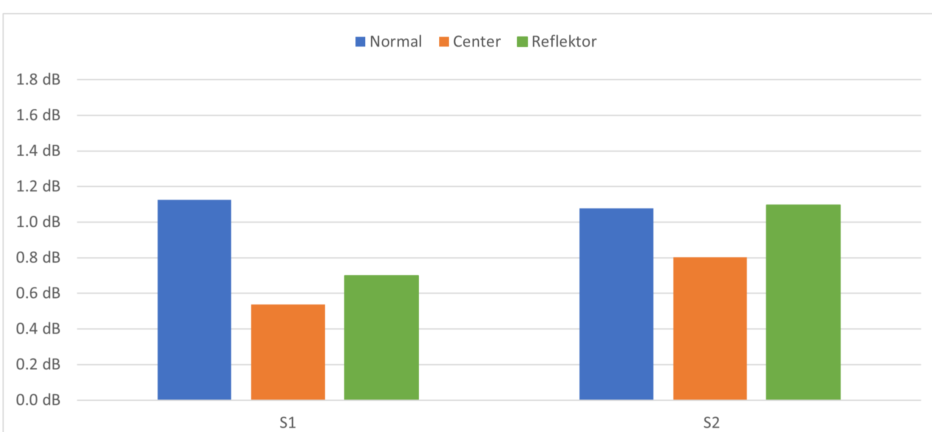


Figure 33: *Source effect on the variation of C_{50} averaged between 250 and 4 000 Hz, calculated as STD - Classroom B*

There observed that both Classrooms showed low STD for the corner positions S2 in Classroom A and S2 and S1 in Classroom B. The center ceiling showed to provide lower variation in most positions, except for S3 which is slightly higher than the normal ceiling. The scattered ceiling showed lower or even values at all sources. Another observation is that there are larger deviations found in Classroom A compared to B, with the center reflector showing larger deviations between the values in A and B.

4.3.3 Comparing T_{20}, EDT, and C_{50}

To further compare all the chosen parameters, a plot including all three parameters was made for each configuration. Figures 34 and 35 show the plots for the normal ceiling configuration in Classroom A and B. The center reflector configuration plots are found in Figures 36 and 37. Moreover, the scatter reflector configuration is found in Figures 38 and 39.

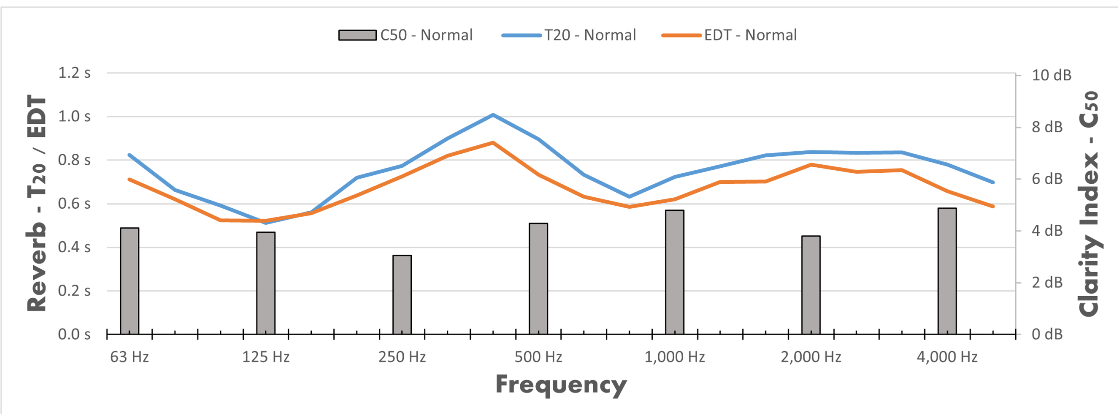


Figure 34: *EDT, T_{20} and C_{50} plot - Normal - Classroom A*

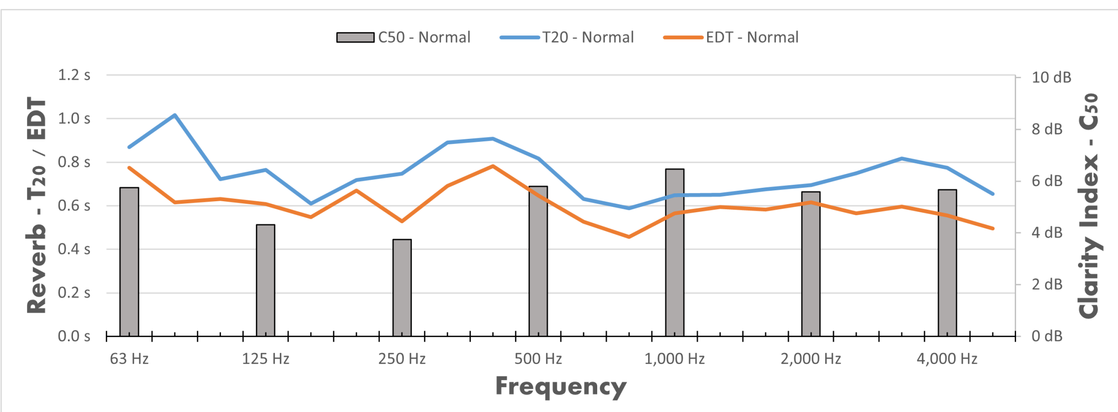


Figure 35: *EDT, T_{20} and C_{50} plot - Normal - Classroom B*

The normal ceiling provided the highest values of C_{50} when T_{20} is around 0.65 seconds in both classrooms. There is also observed that higher C_{50} seems less affected by the higher reverberation levels when in a smaller room, as seen in Classroom B with similar reverberation.

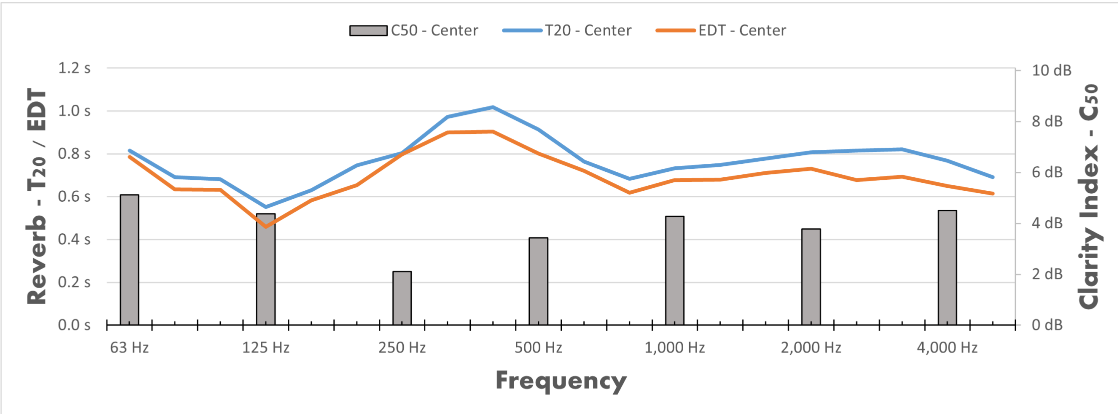


Figure 36: *EDT, T_{20} and C_{50} plot - Center - Classroom A*

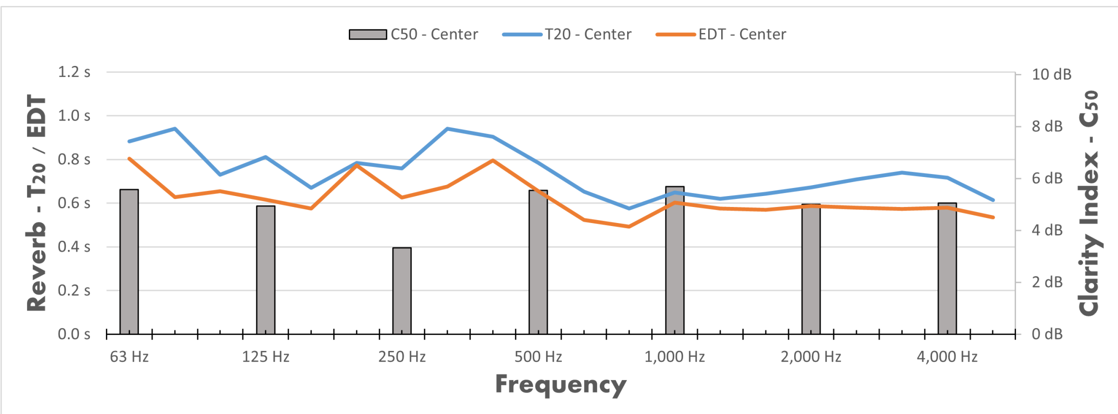


Figure 37: *EDT, T_{20} and C_{50} plot - Center - Classroom B*

The center reflector shows results from Classroom B yielding higher values of C_{50} in comparison to A, as it was for the normal. There are indications of 0.6 seconds of EDT and below are favorable for C_{50} in most of the frequency spectrum. As these plots compare one-third octave and octave bands for reverberation and clarity index, interpreting single values of reverb at one-third octave reverb and C_{50} should is avoided, therefore the comparison should include the close-by band. Moreover, this show that reverberation increase does reduce C_{50}.

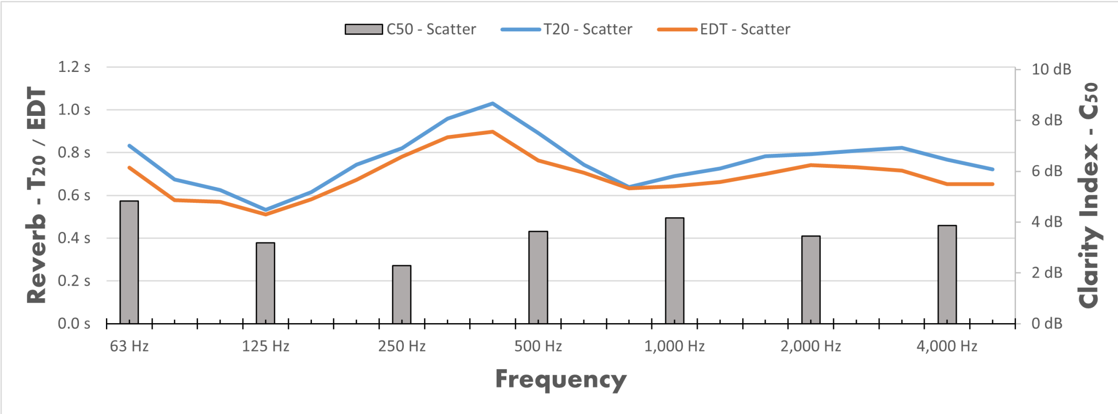


Figure 38: *EDT, T_{20} and C_{50} plot - Scatter - Classroom A*

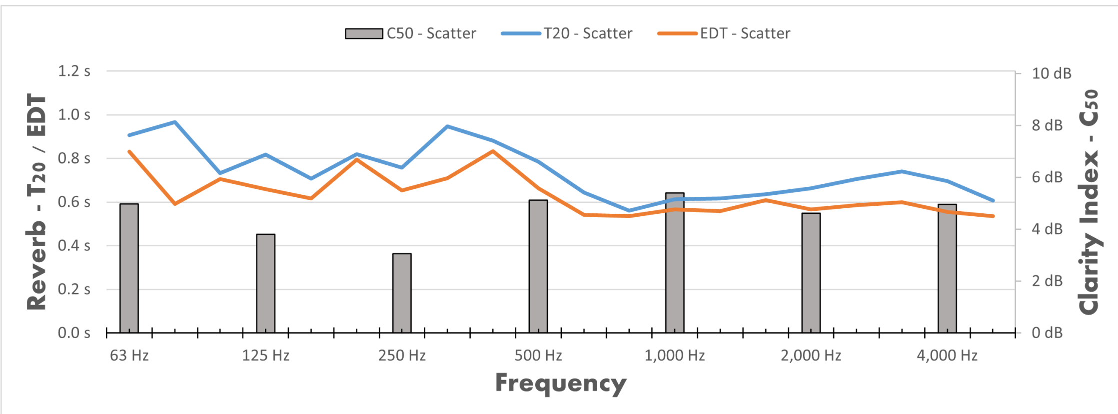


Figure 39: *EDT, T_{20} and C_{50} plot - Scatter - Classroom B*

The difference between T_{20} and EDT seems to have little effect on the average C_{50} regardless of ceiling type. However, these results may suggest that lower EDT is favorable to a degree, with EDT also levels looking to correlate with C_{50} more than T_{20}. Furthermore, the observed reduction of C_{50} at 250 Hz occurring in both classrooms does not seem to be caused by only an increase in reverberation, yielding close to the same levels as in the higher part of the spectrum. In general, there seems to be some correlation between an increase of reverb in a part of the spectrum related to C_{50}, which is according to a theoretical increase in reverb providing more late reflections.

5 Discussion

5.1 How does the presence of reflective ceiling tiling affect speech clarity and reverberation in a classroom?

Introducing a significant number of reflecting surfaces in the ceiling of both rooms resulted in a slight increase of 0.01 s in the average reverberation time for both T_{20} and EDT. This finding suggests that the harder reflecting surface of the plywood had a negligible effect on the room's reverberation. Instead, it appears that the cavity behind the ceiling surface played a more prominent role in influencing the reverberation of the room compared to the acoustic absorbent ceiling tiling. Interestingly, the plywood reduced the reverberation of higher frequencies in contrast to the porous acoustic absorbing materials. This unexpected result could potentially be attributed to the placement of plywood in a suspended grid with a cavity behind it.

Furthermore, the introduction of plywood resulted in a noticeable shift of reverberation towards the lower frequencies in the spectrum. This shift was expected due to the acoustic characteristics of plywood, being a denser and harder material compared to the echo-phone tiles. However, considering the significant increase in reflecting surfaces, a larger increase in reverberation was initially anticipated. Estimating the relative increase using Sabine's formula, Equation 4, reverberation was projected to be around 0.1 s. The discrepancy between the expected and observed increase can likely be attributed to the absorption provided by the volume behind the ceiling, which was not taken into account in the estimation. In a regular grid system, this volume behind the ceiling contributes substantially to the overall absorption. Additionally, these are just estimations, therefore empirical data are expected to differ.

While both classrooms exhibited a shift in the reverberation spectrum, an interesting observation is the reduction of reverberation at higher frequencies with the introduction of plywood. According to theory and the materials' empiric absorption factors, a porous absorbent should be better suited for absorbing these frequencies, thus an increase in this part of the spectrum would have been expected. This observation further highlights the significant influence of the cavity on the room's acoustics. Additionally, it is theorized that the room's skirt cavity structures located at the end of ceilings towards the windows may explain certain aspects of the room's acoustic behavior. Another factor that may contribute to these results is the sound wave's angle of incidence when hitting the ceiling. Moreover, it should be noted that the plywood ceiling did not form a tight seal with the grid due to its imperfect flatness, likely resulting in some airborne leakage. These leakage points, although unintended, may have an effect on the room's acoustics. Specifically, their size and characteristics could potentially favor the absorption of higher frequencies, effectively acting as small Helmholtz resonators. If this hypothesis holds true, it suggests that the frequencies affected by these leakage points would theoretically be outside the range of interest for the current study.

Consequently, this presents a plausible explanation for the observed phenomenon.

Another aspect to consider is the mounting between the plywood and the system grid, which could potentially contribute to additional acoustic dampening. A stiffer mounting directly connected to the studs might increase the reflection, particularly for higher frequencies. Moreover, the seal to the grid system not being tight may have allowed for sound leakage through small air gaps. This factor could have implications for both the reduction of C_{50} and the overall reverberation. As some of the sound is transmitted behind the ceiling, a possible explanation is that the introduction of reflective tiles in the ceiling creates sections where more sound becomes trapped and dissipated behind the ceiling. The acoustical properties of the Eco Phone may be more transparent than expected, which could contribute to this effect where the combination there is transmitted sound mostly through these surfaces and then could be reflected and dissipated behind the plywood ceiling. Thus when there are more reflective areas are introduced, the enclosed volume above the ceiling may trap a greater amount of transmitted sound.

When comparing the effect of plywood on the frequency distribution of T_{20} and EDT, smaller deviations are observed in EDT across the frequency range of 630 Hz to 5 kHz. This effect is also noticeable to some extent in T_{20} for both Classrooms A and B, with Classroom B showing a more pronounced trend. A reduction in the variation of both T_{20} and EDT offers several advantages. Firstly, it facilitates compliance with building code requirements, as all frequency bands need to remain within specified limits. Secondly, it minimizes alterations in the reflective sound, resulting in a more balanced distribution of frequencies in the reflected signal and ensuring equal audibility for all voices.

In the measured classrooms, a spike in reverb at 400 Hz is believed to be influenced by the room dimensions and choice of materials. Additionally, both classrooms feature similar cavities around the ceiling area near the facade windows, which can create a resonance effect, functioning as an amplifier. If this hypothesis holds true, removing them could make this part of the frequency spectrum more even.

Furthermore, introducing the plywood ceiling generally resulted in a clear reduction of C_{50}, indicating a decrease in speech intelligibility. Subjectively, an assessment of the impact of the center reflector on speech revealed an increase in the self-perceived loudness of speech across the room from the typical speaker position at the front center. Experiencing a noticeable amplification of one's voice reduces the perceived need to speak louder, potentially reducing strain on the vocal cords of the speaker. However, it is important to note that subjective assessments by the speaker do not necessarily reflect the listener's perception. In this case, the researcher's own experience cannot provide significant data to support claims regarding the actual effect of the more reflective ceiling.

When considering whether the theoretical impact of increased reverberation on C_{50} should have resulted in a reduction due to the increase in late reflected sound. Therefore, it may have been a deficiency to not maintain a constant level of reverberation. Arguably, the impact of the plywood ceiling should have been mitigated by adding additional absorption. In a practical scenario where such a ceiling is permanently implemented, the surfaces of the walls, windows, and floor would have been designed to provide the necessary additional absorption to meet the requirements. However, a discussion regarding whether the measured C_{50} should be interpreted as higher is warranted. To obtain further affirmation of this, empirical data is needed to determine if this is indeed the case. If it is assumed to be true, the results indicate that increased reflection in the ceiling contributes more to speech clarity compared to the contribution primarily gained from the walls. While this appears to be the case when results are normalized, there is currently no conclusive evidence to support this claim.

The observed alterations provided by the new ceiling configurations could potentially be utilized to achieve a more balanced soundscape. It is possible that the changes in reverberation are localized, resulting in certain areas experiencing an increase in late reflections and a reduction in measured C_{50}. When considering the measured T_{20} in both Classrooms A and B, the increased reverb of frequencies above 1 000 Hz in Classroom B may be viewed in the context of the higher C_{50} observed in this part of the frequency spectrum. Moreover, there is a smaller increase of T_{20} in Classroom A, which coincides with the greater measured C_{50} in Classroom B. Conversely, when examining the frequency spectrum below this value, the opposite trend can be observed. However, there is limited concrete evidence to support these claims, and no explicit correlation can be derived from the results.

In an assessment of the STD deviation of reverberation for all receivers, there is observed a tendency that plywood, especially with the center configuration, yielded less deviation of both T_{20} and C_{50} in the range of 500 - 4 000 Hz. Thus there can be argued sound and early reflection are perceived at a more even level throughout the room. Contrary to interpreting an even distribution as the most favorable condition, there could be possible benefits gained from an equalization approach. For this approach, certain frequencies are desired to be perceived as stronger than others. Some of the attributes which arguably could be favorable are for instance an increase of around 1 000 - 3 150 Hz, making high frequencies easier to hear, which often are considered to increase the clarity of voice in recorded sound. In the present study, ceilings yield quite high reflection in this area. Additionally, the reduction of 500 Hz or so, which often considered to provide mud and boominess to the sound. Further exploration of this approach may be useful for future design considerations.

In the comparison of EDT, T_{20}, and C_{50}, it is observed that C_{50} seems to be less affected by room reverberation in smaller rooms. One possible explanation could be the presence of more direct sound, which boosts the contribution of direct sound and consequently increases C_{50}. Another observation is that EDT appears to be a better indicator of the level of C_{50}, to some extent inversely proportional, when compared as octave band values.

Furthermore, there are some indications a larger percentage change of absorbents in the ceiling could yield better results. In such cases, additional absorbents may be required towards the rear of the room, particularly to counteract the resulting increase in reverberation. Moreover, the changed ceiling of Classroom B removed a significant amount of the 40 mm absorbents, which yield higher levels of absorption compared to the 20 mm. Classroom A did only have 20 mm absorbents while B used both. This discrepancy in absorbent thickness may account for certain differences observed between Classrooms A and B.

5.2 What is the impact of the source position on C_{50}?

In both classrooms, significant variations are evident across the room in terms of C_{50}. It is important to note that a limited number of source positions were used, which means these results do not provide a comprehensive understanding of how changes in source position affect C_{50} throughout the room. Nonetheless, these findings are still valuable in quantifying the impact within these specific classrooms.

When comparing Classrooms A and B, the influence of room size on the effect of source position becomes apparent. Room geometry, for example, appears to have a greater impact on C_{50} in larger rooms. The distance from the source also plays a significant role in determining the contribution to a high C_{50}. Unsurprisingly, the results reflect that the closest receivers generally exhibit higher C_{50} values, as direct sound would be significantly stronger than the later arriving reflection in these positions. However, notable differences in the development of C_{50} are observed as the distance increases. In Classroom A, larger deviations are observed at similar distances, suggesting that the room itself plays a more substantial role in determining C_{50} than the direct signal perceived at that specific location. This observation supports the argument that the importance of the source increases with room size.

In both classrooms, noticeable differences are observed between receivers at similar distances when the sources are placed against a single wall. Receivers located within the range of 4.5 to 6.0 meters, which exhibit these variations, are predominantly positioned in close proximity to vertical surfaces. This suggests that the surrounding geometry has influenced early reflections in these particular locations. To further explain why some receivers increase and decrease, a plausible explanation could be that some receiver positions only gain an increase in early reflection and some increase in late reflections. Another reason why some positions exhibit a reduction of C_{50} may be explained by the formation of standing waves between parallel surfaces. These findings provide evidence for alternate geometrical configurations which could yield a more even distribution of C_{50} throughout the soundscape.

Another observation is that the sources placed toward the corner of the room did provide a more even distribution of C_{50} when compared to the typical sources located at the center of a long wall. A plausible explanation of this is the more concentrated amplification effect for the back wall, which is known to make signals stronger due to the geometry providing more early reflections. A known effect of corners, which is often used to amplify and make the bass distribution more even from a sound system. Standing in the corner of the room may only be a feasible option for smaller rooms and certainly are not a preferred placement accommodating normal classroom floor plan design. This effect does suggest the short side of the room could be preferred.

The classrooms exhibit notable differences in terms of size and shape. Classroom A is rectangular and larger, while Classroom B is smaller and closer to a square shape. The proximity to walls has shown a significant impact on the strength of early reflections, resulting in higher values of C_{50}. This can be attributed, in part, to the shorter reflection paths. The angle between the source position and these surfaces also plays a significant role, as reflections with higher angles of incidence seem to yield a reduction in C_{50}. The nature of vocal speech, which produces approximately spherical waves, helps to explain the observed behavior. Additionally, the angle of incidence between the receiver and the source exhibits higher variation across the room depending on the height of the ceiling. Increasing the horizontal ceiling height, for example, will lengthen the travel path for ceiling reflections and decrease the angle of incidence between the source and receiver. This extension in the travel path relocates the earliest possible reflection farther away from the source. By altering both the height and angle of a ceiling, there is possible to create ceilings that offer favorable geometric reflections, which in turn can lead to a more consistent distribution of C_{50} values.

An analysis of the STD of T_{20} across all positions in classroom A revealed a reduction of STD across the frequency spectrum when the center reflector was introduced. The scattered ceiling also showed a reduction in deviation compared to the normal ceiling, particularly in the range of 125 to 4 000 Hz, which is considered important for human speech. The lower STD indicates less variation in reverberation among different receiver positions. Moreover, there was found that the center reflector did make for even distribution for all three source positions which were used for measurements in Classroom A, there was a similar observation in the results of Classroom B. In addition, the reflection provided by the plywood ceiling also seems to reduce the deviation of EDT. This finding supports the theory that the increase in ceiling reflection contributes to a more even distribution of sound throughout the room.

Further investigation of the results revealed that the plywood center reflector reduced the variation in C_{50} values between source positions by approximately 1 dB. Assuming that the relative difference in C_{50} between the two ceiling configurations is insignificant, it should have been taken into account when designing the experiment to consider the observed increase in total reverberation. The inclusion of the center reflector resulted in a more evenly distributed pattern of early reflections throughout the room. As a result, it reduced the sensitivity of teacher positions compared to the normal ceiling configuration. However, based on the current assumption, it is not sufficient to conclude whether this will create a better soundscape for both students and teachers.

The impact of source positions on C_{50} appears to be influenced by the type of ceiling. An increase in ceiling reflection seems to contribute to a more uniform soundscape across a wider range of source positions. In most classrooms, it is not necessary for the teacher to lecture from every position in the room. However, it is important to have a reasonable range of positions that function equally well since teachers often like to move dynamically during a lecture. Designing newer classrooms to minimize the impact of source position could be beneficial. However, implementing passive permanent solutions may limit the flexibility in room usage. Considering that ceiling grid systems are commonly used, exploring a wider range of ceiling tile designs could be a potential approach to address this issue. Such a solution would make the room flexible, tiles could easily be changed when transforming it from a classroom to a group study space. Although solutions already exist, there may be little incentive to utilize them unless the environment is perceived as severely inadequate.

5.3 What recommendations can be derived from the findings to enhance the future acoustical design of classrooms?

The consideration of reverberation in the design of new classrooms is often approached with a predominantly negative perspective, as evident in the design criteria outlined in TEK17. However, there is a compelling argument to be made for a reverberation requirement of around 0.5 seconds. The current limit of 0.4 seconds does help reduce the overall BGN noise in a given room, simultaneously a lower reverberation makes it harder for a speaker's voice to reach across the room. In addition, such low levels of reverberation can also increase awareness toward impulse sounds[5], which is more distracting with a high SNR compared to a higher level of constant noise. For instance, the modern open office landscapes designed for individual concentration work, a really low BGN can make the noise generated by colleagues more distracting. Therefore some modern office spaces, for instance, use an active sound masking system[6] to combat this. Classrooms, on the other hand, do need to be designed for multiple activities, such as regular lectures, plenary activities, etc. All favoring certain acoustical conditions. Therefore, it is not necessarily advantageous to have excessively low reverberation. The increased vocal effort required to speak, which has been repeatedly emphasized by teachers experiencing vocal problems, should be taken into account.

There is observed an increase of late reflections in the results, indicated by a lower C_{50}, which could stem from the interaction between waves bouncing off the ceiling and floor. If the ceiling is responsible for the heightened reflection, it becomes crucial to introduce additional absorption in the floor area to mitigate this effect. While the use of carpeted floors is a known solution to reduce reverberation, it may enhance the effectiveness of the higher reflections originating from the plywood ceiling. However, the ease of cleaning and durability concerns often undermine the feasibility of this option. Therefore, exploring alternative possibilities related to the placement of furniture in the room is worth considering. For instance, incorporating absorbent materials beneath desks and chairs could attenuate higher-order reflections. However, such a solution would not be applicable within the current design requirements, which must be satisfied prior to introducing furniture. Some may argue that occupant presence alone provides similar absorption, rendering this solution obsolete. While this argument may hold true for rooms with a certain level of occupancy, incorporating absorption beneath desks and chairs could enhance room performance regardless of the occupancy level, offering additional absorption at all times.

One attribute of both Classrooms A and B was the skirts found along the facade windows. could offer new insights for designing future classrooms. The use of enclosed skirts around the acoustic ceiling appears to result in poor acoustic conditions in the room, particularly underneath. This observation is supported by the measured values of C_{50} closest to the wall, where an additional

[5] An sound which appears very briefly. Some examples are hand claps, door knocking, or an exploding balloon.

[6] *"Sound masking is the process of adding background sound to reduce noise distractions, protect speech privacy and increase office comfort"* (Page, 2020)

cavity exists between the wall and the ceiling skirt. Discussions have highlighted that leaving this cavity open can increase the overall reverberation of the room. Several factors likely influenced the choice of this design approach in these classrooms, such as noise generated by ventilation. However, without a response from the design team involved in the project, it can only be speculated whether this is indeed the case.

Furthermore, reverberation alone does not serve as a comprehensive indicator of sound transmission throughout a room. Research findings have demonstrated that, for instance, C_{50} does not exhibit a significant correlation with reverberation. The counterargument against this is the potential increase in noise that could result from an extended reverberation time. Several studies have assessed the noise generated by specific activities (Sala and Rantala, 2016; Prodi et al., 2019; Bolstad, 2019), and these results can be utilized to determine target values such as U_{50} or STI based on the primary activities conducted in the rooms.

In the modern classroom, there is a lack of creativity regarding the geometric shape of classrooms. The standard rectangular box shape, although cheaper and easier to construct, is susceptible to standing waves and yields an uneven distribution of early reflections across the room. Due to familiarity, deviating from this shape may seem unusual to many. However, it is well-established that geometry plays a crucial role in acoustics, which is evident in high-end concert halls and auditoriums filled with reflectors and diffusers of various shapes. The implementation of angled reflectors and diffusing elements may require more use of the space within a room, and thus, it is necessary to have sufficient evidence that these modifications will significantly improve the acoustic environment for its users. Furthermore, incorporating a higher ceiling to meet the minimum height requirement often leads to increased building height or reduced usable space for ventilation, posing additional challenges.

Continuing the discussion on alternative geometric designs, wall design can also contribute significantly to improving acoustics. Findings from the present study indicate that all sources were located at distances around 5 meters, showcasing both favorable and unfavorable geometric contributions. However, implementing geometrical solutions, particularly when it comes to walls, is challenging due to concerns about perceived space inefficiency. It becomes a delicate balance in envisioning room shapes that optimize floor space utilization in a building and have shapes that are practical to use and build. In newer schools, this issue can be addressed from a floor plan perspective by incorporating angled or curved walls between rooms, ensuring efficient space utilization without compromising too much. Designing several classrooms together can help reduce costs and enhance the efficiency of floor space utilization. In existing classrooms, implementing such surfaces can be achieved through the strategic placement of in-classroom lockers and cabinets designed to maximize space utilization. There is undoubtedly potential in exploring such solutions and the possibility of creating more efficient use of space combined with acoustical improvements.

One of the main motivations behind this study has been to improve a classroom's acoustical performance for its users, with a particular focus on teacher's performance. Unfortunately, teachers have often been neglected in terms of acoustical design considerations. It is alarming to note that a high percentage of teachers, potentially as many as 50% (Borge and Senneset, 2022; Russell et al., 1998), struggle with their voices. This can be attributed to various factors. In certain situations, teachers find themselves competing with children's loudness in order to capture their attention. Such circumstances put teachers at a higher risk of vocal cord damage, similar to the strain experienced by singers or football supporters. Passive acoustic amplification of voices, which can be implemented in classrooms, has the potential to reduce the need for teachers to raise their voices. However, it is important to address concerns regarding the design of such amplification, as it may lead to increased levels of noise, thereby lowering SNR. Additionally, the strain caused by heightened noise levels should be carefully considered. To determine whether these concerns outweigh the potential health benefits for teachers, further research is necessary.

Another important factor to consider when evaluating the impact of poor acoustics is age. It is widely recognized that younger pupils are more susceptible to noise and other disruptive factors (Klatte et al., 2013). However, within the education system, there is only a single set of requirements that are generalized to accommodate various aspects of the learning environment. Unfortunately, age does not appear to significantly influence the design choices that are made, which can detrimentally affect the acoustic quality in classrooms for younger children. This is concerning, as learning disabilities often manifest from an early age and can persist throughout a person's life (Flexer, 2004). Moreover, this could yield additional costs for society in terms of the need for social services, which in turn could hamper an individual's potential contributions to the economy. It is undeniable that society greatly benefits from students who thrive at a young age, as it facilitates them toward greater educational achievements. Therefore, enhancing the acoustical design requirements for primary schools would yield significant societal advantages, despite the additional construction costs involved.

Moreover, it is crucial for the authorities to acknowledge and address the concerns pertaining to health issues. A compelling argument can be made to revise the existing building codes in order to enhance the acoustic conditions for speech transmission in classrooms. One potential solution could involve the implementation of a targeted reverberation interval, similar to the proposal presented by (Homb, 2022). Additionally, the ceiling height could be taken into account by introducing a height factor. Another aspect worth considering is the choice of ceiling material. Although there is no conclusive evidence that plywood serves as an optimal ceiling reflector for speech clarity, it is possible to establish reverberation targets based on the selected ceiling material. One advantage of the current reverberation target is its simplicity for contractors. However, it is important to recognize that implementing such requirements may entail significant additional costs, particularly if it limits the range of available materials. Nevertheless, if the identified health issues can be attributed significantly to classroom design, then it becomes justifiable to view these costs as negotiable for the sake of prioritizing student well-being.

5.4 Precision of measurements

When conducting measurements, several potential sources of error were identified. In the following section, some of these will be discussed. Some of these are deemed quite insignificant but are included as they could make an impact.

The precision of sender and transducer placement was considered to be less important. As the available number of sources and receivers was low, they were all moved in between measurements. To reduce the amount of the overall movement, the source position was moved to all locations for each receiver placement. The movement of the source mainly could affect the precision of the measurement from a given source, if these were to be compared to each other. Most of the results considered the average of all 3 positions, thus source placement should be of less importance than the receiver. A remark is not identical between ceiling configurations. An estimated error of $\pm$ 5 cm from the original position, is thought to be acceptable and insignificant to the results.

Background noise at a certain time is a concern worth discussing. While a general SNR of 60 dB was achieved with a background level of approx 29 dB, which should make BGN less of a concern. Some noise from the street potentially impacted some measurements without it getting noticed. Wielding hearing protection and having to stay in the room for all measurements, such noise could be hard to detect. Conducting two measurements at each point, the effects of BGN on some measurements are quite unlikely to make a big difference. The amplifier fan also made some noise, the level of which was not measured but deemed insignificant as well.

A concern regarding reflecting surface sizes. The number of tiles used for each configuration between classrooms was not equally relative to each other. For instance, the size of the center reflector and the degree of furniture in the room had some variation. This makes it less likely to find any correlation between the room sizes for instance. Since the main goal of this experiment was to investigate the effects of reflective ceilings on C_{50}, this seems to be less significant. For a larger study, looking at a wider range of classroom sizes of similar structures, it may be worth discussing whether to set a goal of X % coverage of the total ceiling surface area for more comparable results.

One quite likely source of error is personal mistakes. Several measures were taken to reduce this issue. Some of the restrictions given by software help, as well as the structured logging and documentation conducted throughout the measurements. The area which is most prone to mistakes is post-processing and analysis of the data. Large spreadsheets and lack of concentration could make for easy mistakes. Some errors have been found and fixed, and it is possible that there still are some errors left unidentified. Throughout post-processing and analysis, there have been made control check of whether the code and numbers are correct. Any larger mistakes in results probably were a result of personal mistakes in this segment, given the scope of the task and lack of professional experience in the field.

5.5 Future research

The field of classroom acoustics still holds many unanswered questions and areas for further exploration. This study focused solely on investigating the use of plywood as a replacement material for ceilings, but there is a need for broader research to gain a more comprehensive understanding. It is important to acknowledge the scope and limitations of any research, as they can provide valuable insights but also limit the depth of knowledge obtained. In this section, we will discuss some suggestions for future research to continue advancing speech clarity in classrooms.

Exploring other types of wood and non-wood-based materials may offer valuable insights into the effect of ceiling choices on both C_{50} and reverberation, especially when there is a cavity behind the ceiling. Material science advancements provide an opportunity for further enhancement of classroom acoustics and room acoustics in general. Additionally, investigating the impact of ceiling height on factors such as C_{50} and T_{20} could shed light on the influence of vertical dimensions. Another area of research worth exploring is the use of diffusing surfaces in ceilings, considering their combined effects on background noise (BGN) and signal-to-noise ratio (SNR). Examining how these surfaces affect speech clarity would contribute to a deeper understanding.

The sample size of this study was limited, and further research could compare a larger number of classrooms with similar and different dimensions and shapes. This comparison would provide more comprehensive guidelines on the desirable dimensions and shapes for achieving optimal speech clarity. It might also uncover a point of diminishing returns, indicating different reverberation requirements for rooms of varying sizes. While larger rooms are theoretically expected to benefit more, determining where the threshold lies remains to be determined.

One early idea explored in this project was the creation of C_{50} design curves, similar to the approach used for determining the airborne acoustic reduction number (R_w). This approach is driven by two factors. Firstly, recognizing the limitations of single number ratings for assessing a complex signal like speech. Secondly, acknowledging the importance of certain frequency ranges that contain crucial information for the receiver to accurately decode the signal. This concept aligns partially with the Speech Transmission Index (STI), which does not provide a straightforward indication of specific issues during rehabilitation, for example. Therefore, further research towards developing more user-friendly and effective standard requirements could prove valuable for both end-users and acoustic design consultants, facilitating easier interpretation and improved room design effectiveness.

6 Conclusion

Classroom acoustics remain an area that requires continuous improvement to ensure effective communication within educational settings. The present study focuses on investigating speech transmission in classrooms through a qualitative examination of two comparable classrooms situated in Salemhuset, Trondheim. Specifically, the study explores the impact of absorbent placement on speech clarity. To address this, precise impulse response measurements were conducted using the M|reverb software, comparing three different ceiling configurations. The configurations included the standard setup with eco-phon ceiling tiles and two variations where a section of the ceiling was substituted with 9mm plywood tiles. The analysis primarily centers on three essential parameters: reverberation times measured by T_{20} and EDT, as well as the Clarity Index C_{50}. To provide focused insights and facilitate manageable data analysis, specific research questions were formulated to guide the study.

The measured reverberation levels in Classroom A were found to be a T_{20} of 0.77 seconds and an EDT of 0.69 seconds, while Classroom B exhibited a T_{20} of 0.73 seconds and an EDT of 0.60 seconds. Introducing plywood into the ceiling resulted in a small average increase of 0.01 seconds in T_{20} for both classrooms. Classroom B showed a larger increase of 0.03 seconds in EDT, compared to a 0.01 second increase in Classroom A. Additionally, a shift in the frequency spectrum was observed, showing a decrease in reverberation at higher frequencies. However, these increases were not significantly higher than the standard deviation at lower frequencies. Although the reflective plywood tiles reduced the Clarity Index C_{50} at most receiver positions, the use of a center reflector yielded more consistent C_{50} values across the room. Thus, a reflective ceiling appears to create a more even soundscape.

While the ceiling configuration did not have a significant impact on C_{50}, the position of the sound source was found to have a considerable influence on the measured values. In Classroom A, some receivers exhibited a change of up to 4 dB between different source positions, while Classroom B showed a deviation of 2.4 dB in the normal ceiling configuration. The introduction of reflectors on the ceiling resulted in reduced overall deviation. Moreover, large local variations were observed at similar distances from the source, depending on the source location. The corner position consistently provided a more uniform soundscape across both Classroom A and B, although it generally yielded lower C_{50} values. On the other hand, other source positions displayed higher deviations, particularly between distances of 4.5 to 6 meters. This variability can be attributed to the proximity of receivers to walls, which predominantly contributes to increased early reflections. Contrary, the proximity to corners does suggest these positions also provide unfavorable reflections toward high C_{50}.

To enhance the acoustical quality of future classrooms, several measures are proposed based on the study's findings. Optimizing the speaker position alongside the short wall can improve the contribution of early reflections from walls throughout the entire classroom. Furthermore, drawing inspiration from traditional auditorium design, greater emphasis on the geometrical shape of the classroom is recommended. This includes incorporating increased ceiling reflectors and improving wall surface absorption in areas where the teacher is not lecturing. Introducing angled or parametric reflectors and utilizing diffusers to reduce standing waves are additional strategies to consider.

In conclusion, this research underscores the need for further investigation to advance our understanding of classroom acoustics. The opportunities for improving both current and future classroom designs are significant, benefiting teachers, students, and society at large. Specifically, prioritizing acoustic improvements in primary schools, where the impact would be most profound, is highly recommended.

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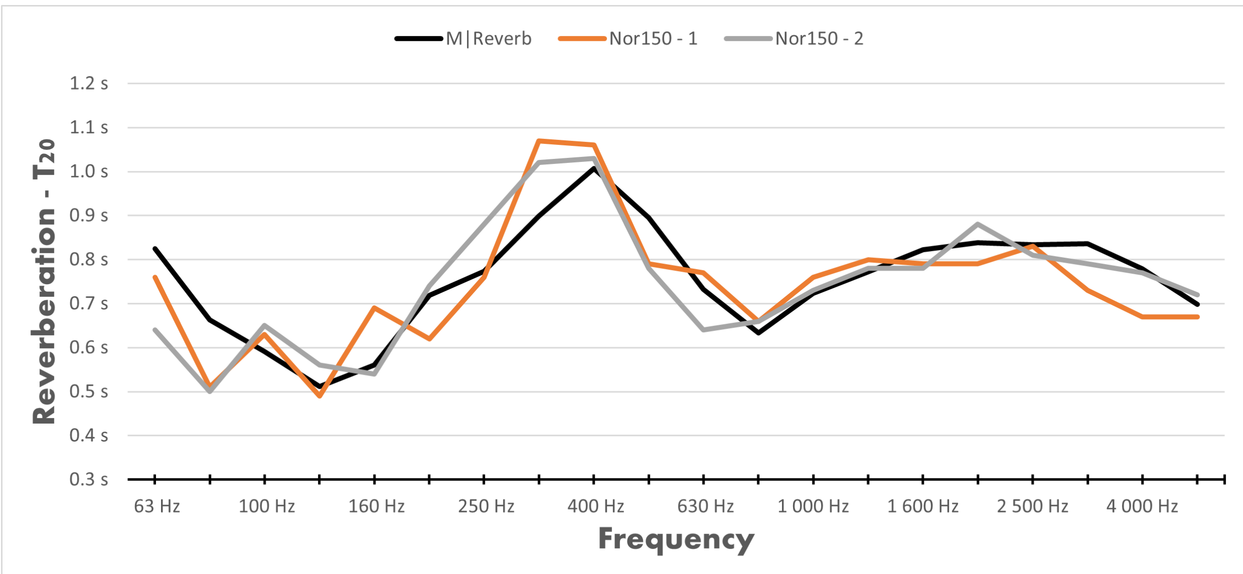
A Equipment list

- Bosch - Laser distance measurement device
- Computer with Mreverb
- Cables - Power cables, Coax, Speak-on, and Fire-wire.
- Ear protection
- Marking tape
- Microphone (1) - Büerl & Kjær - Type 1209
- Microphone (2) - Büerl & Kjær - Type 2105
- Norsonic Analyzer - Nor150
- Norsonic Calibrator (114 dB, 1 kHz)
- Norsonic Half-spherical loudspeaker
- Norsonic Power amplifier - Type 260
- Norsonic Pre amplifier - Type 336
- Stands for microphones (height up to 1.5 to 2 meters)
- Stand for speaker (height up to 1.8 meters)
- RME Soundcard - Fireface UCX II

B T20 measured by Nor150 - Classroom A



C Calculated STD of T20 - Classroom A

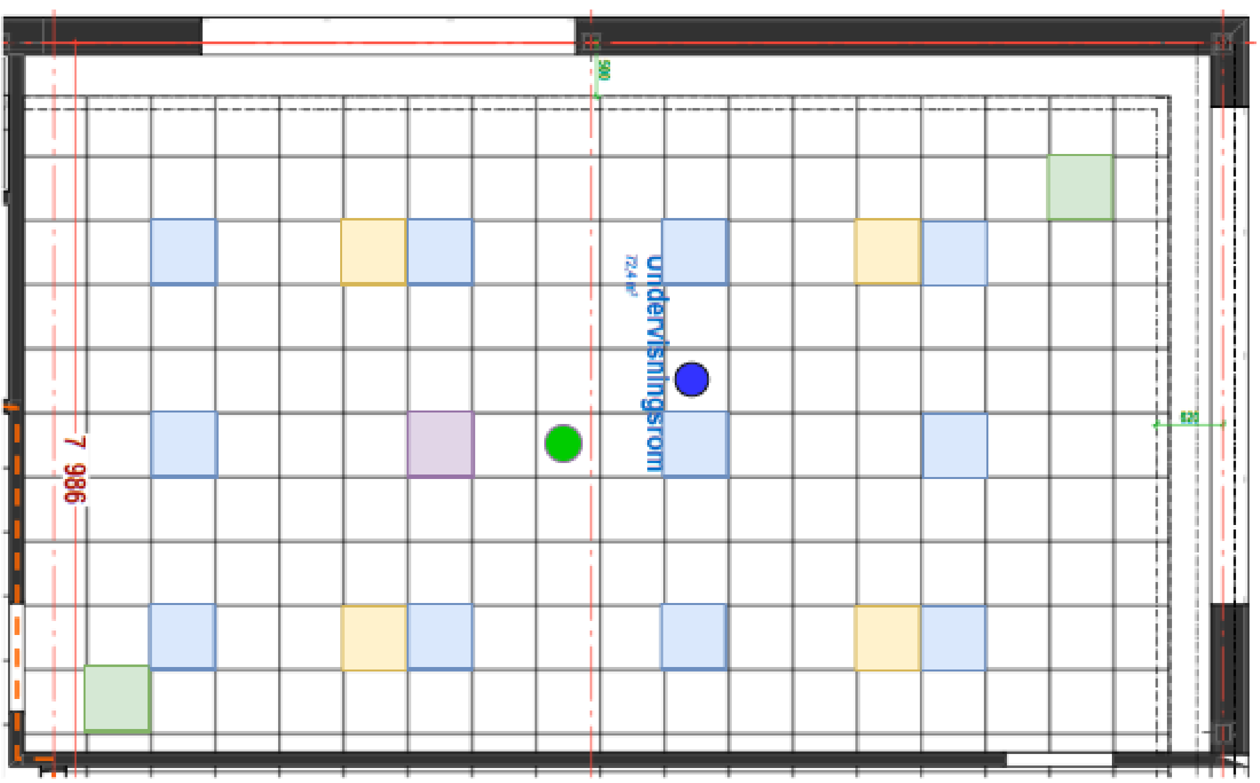
Freq	Normal	STD
50 Hz	1.35 s	0.053 s
63 Hz	0.84 s	0.037 s
80 Hz	0.68 s	0.03 s
100 Hz	0.63 s	0.025 s
125 Hz	0.55 s	0.021 s
160 Hz	0.61 s	0.02 s
200 Hz	0.71 s	0.019 s
250 Hz	0.77 s	0.018 s
315 Hz	0.90 s	0.017 s
400 Hz	1.0 s	0.016 s
500 Hz	0.89 s	0.014 s
630 Hz	0.73 s	0.011 s
800 Hz	0.63 s	0.009 s
1,000 Hz	0.72 s	0.009 s
1,250 Hz	0.77 s	0.008 s
1,600 Hz	0.82 s	0.007 s
2,000 Hz	0.84 s	0.007 s
2,500 Hz	0.83 s	0.006 s
3,150 Hz	0.83 s	0.005 s
4,000 Hz	0.78 s	0.004 s
5,000 Hz	0.70 s	0.004 s
6,300 Hz	0.64 s	0.003 s
8,000 Hz	0.68 s	0.003 s
10,000 Hz	0.67 s	0.003 s
12,500 Hz	0.25 s	0.001 s

D Ceiling plans

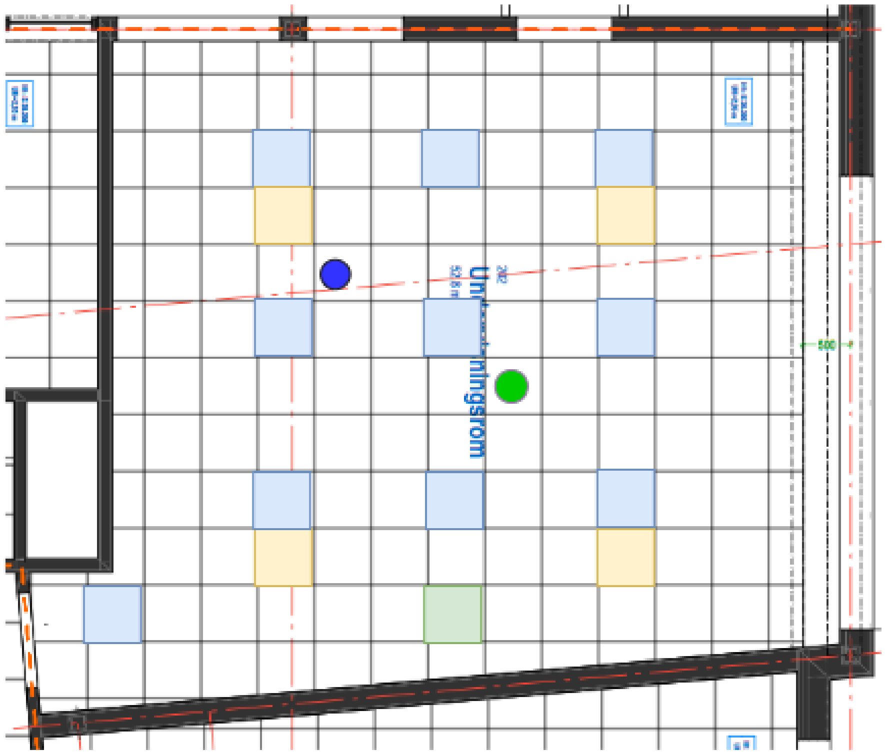
D.1 Symbol Explanation

Ventilation - In (60 x 60 cm)	Plywood tile (60 x 60 cm)
Ventilation - Out (60 x 60 cm)	Fire alarm (d = 10 cm)
Light fixture (60 x 60 cm)	Wifi Ruter (d = 20 cm)

D.2 Normal Ceiling - Classroom A



D.3 Normal Ceiling - Classroom B



E Byggindustrien article

Taletydelighet i undervisningsrom

Akustikkmåling i undervisningsrom. Her måles effekten av å bytte ut himlingsplater med mer lydreflekterende kryssfinerplater lagt i sjakkbrettmønster.

Å sikre gode lyd- og lytteforhold i undervisningsrom er en krevende oppgave. Dette er rom som gjerne blir brukt på mange ulike måter og hvor godt undervisningsutbytte er avhengig av at både lærer og elev hører hverandre. I dag er det etterklangstid som setter hovedkravet til utformingen av undervisningsrom, men en ny masteroppgave ved NTNU har avdekket at dagens krav alene ikke sikrer gode lydforhold i slike rom.

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Taletydelighet i undervisningsrom kan være avgjørende for effektiv læring og godt undervisningsutbytte. Erfaring er at dårlige akustikkforhold lett fører til stress, ubehag og vanskeligheter med å oppfatte og fokusere på stemmer. Tradisjonelle læringsrom som klasserom og små auditorier, er fortsatt viktige, men ny og mer variert bruk av rommene gjør at dagens krav ikke gir optimale akustikkforhold for læring. Moderne undervisningsaktiviteter omfatter i tillegg til tradisjonell lærer-til-elev formidling, kombinasjoner av digitale presentasjoner, interaktiv programvare, plenumsøvelser og individuelt konsentrasjonsarbeid. Hver av disse aktivitetene foretrekker forskjellige akustiske miljøer. Derfor er det avgjørende å finne en balanse som optimerer rommets ytelse for aktivitetene som foregår.

Hvordan sette krav til taletydelighet

Etterklangstid setter i dag hovedkravet til utformingen av undervisningsrom, og er definert som tiden det tar før et lydsignal er redusert til 60 dB. Bakgrunnsstøy kan gjøre det utfordrende å måle etterklangstiden med en full 60 dB reduksjon. Parameteren påvirker tale, men litteraturen virker samstemt på at denne parameteren alene ikke er tilstrekkelig. Andre parametere som brukes i dag for å måle taletydelighet, er taletydelighetsindeksen STI gitt i EN IEC 60267-16:2020 og C_{50} som gir forholdet mellom tidlig og sen refleksjon. STI brukes alt som alternativ til etterklangstiden i Norsk Standard. Det diskuteres hvorvidt C_{50} kan være en mer egnet parameter, ettersom den ikke beskriver hele frekvensspekteret med ett tall.

Masteroppgave

En ny masteroppgave ved NTNU har studert effekten av plassering av lydabsorberende overflater i undervisningsrom med tanke på lærerens muligheter for effektiv kommunikasjon med klassen. Her har spesielt utforming av akustikkhimling vært interessant.

Feltmålinger

Akustikkmålinger er gjennomført i to klasserom ved Salemhuset i Trondheim. Rommene hadde ulik størrelse og form, men hadde ellers like materialoverflater, konstruksjon og design. Tilgjengeligheten til klasserommene og muligheten for å gjennomføre uavbrutte målinger over flere dager var avgjørende faktorer i utvelgelsesprosessen. Akustikkmålinger ble utført med høyeste presisjonsgrad etter NS-EN ISO 3382-2 *Akustikk — Måling av romakustiske parametere — Del 2: Etterklangstid i vanlige rom.* Programmet M|reverb ble brukt til å gjøre målingene av rommenes impulsrespons. Denne gir grunnlag for beregning av etterklangstid og C_{50}.

Hvert klasserom ble målt med tre ulike utforminger av akustikkhimlingen; tradisjonell heldekkende akustikkhimling og to varianter der store deler av himlingsplatene var byttet ut med 9 mm kryssfinérplater. Kryssfinér ble valgt fordi de i sammenligning med akustikkplater har en hard og slett overflate og høy densitet/vekt.

Hovedfunn

Feltmålingeene indikerer at en stor del av lydabsorpsjonen til systemhimlinger skjer i hulrommet over himlingen. Det gjør at den lyden som kommer gjennom himlingsflåten i større grad forblir i hulrommet over når kryssfinerplater er brukt istedenfor akustikkplater. Dette fordi den harde og glatte baksiden av kryssfineren reflekter lyden bedre enn akustikkplatene. Delvis erstatning av akustikkplater i himlingen med kryssfinerplater gav dessuten en jevnere fordeling av C_{50} over rommet.

Lav etterklangstid er gunstig for å dempe oppbygging av støy i rommet, noe som også påvirker hvor lett det er å oppfatte tale tydelig. På et punkt vil imidlertid kortere etterklangstid føre til at det blir vanskeligere å formidle til hele klasserommet. Feltmålinger viser at lengere etterklangstider enn den gitt i norsk standard, gir gode taleforhold.

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