YRKESHÖGSKOLAN NOVIA

Impact Sound Insulation of Timber Floors Using Sand Infill

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Abstract

Timber-framed floors often exhibit inadequate low-frequency impact sound insulation compared to heavy concrete slabs, limiting the wider adoption of multi-storey wood construction. This study investigates the feasibility and performance of sand-based infill layers both pure sand and sand–sawdust mixtures as passive mass–spring systems within lightweight intermediate floor cavities. A comprehensive literature review was first conducted to identify key parameters influencing impact sound transmission in timber floors, including joist spacing, cavity depth, resilient ceiling attachments, and surface mass.

Drawing on published measurement data and standardized testing methods (ISO 16283-2, ISO 10140-5, ISO 717-2), the acoustic benefits of granular infill were quantified across third-octave bands from 50 Hz to 3150 Hz. Experimental floor configurations incorporating sand-based mixtures were modelled analytically and compared to 150 mm concrete reference slabs.

Results demonstrated that adding a 40–85 mm layer of sand–sawdust mix can reduce normalized impact sound levels ($L'_{n,w} + CI_{50\text{-}2500}$) by up to 5–8 dB in the 50–250 Hz range, effectively closing the low-frequency gap with concrete floors. Practical considerations regarding moisture behaviour, cavity fill methods, and structural integration were also addressed. These findings suggest that sand-based infill offers a cost-effective, buildable solution to enhance impact sound insulation in timber-frame mid- and high-rise buildings.

Language: English
Key Words: impact sound, sound insulation, light weight floors

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Puurakenteiset välipohjat kärsivät usein heikosta matalataajuisesta askeläänieristyksestä verrattuna raskaaseen betonilaattaan, mikä on hidastanut puurakentamisen yleistymistä kerrostalorakentamisessa. Tässä tutkimuksessa selvitettiin hiekka- ja hiekka-sahanpuruseosten käyttöä passiivisena massa-jousi -järjestelmänä välipohjarakenteen eristekerroksena.

Ensin tehtiin laaja kirjallisuuskatsaus, jolla tunnistettiin askeläänensiirtoon vaikuttavat keskeiset muuttujat, kuten palkkiväli, eristeen paksuus ja sijainti, joustavan kattokiinnityksen rakenne sekä pintamassan määrä. Julkaistujen mittausten ja standardoitujen testimenetelmien (ISO 16283-2, ISO 10140-5, ISO 717-2) pohjalta arvioitiin hiekkapohjaisten kerrosten akustinen vaikutus 1/3-oktaavikaistoilla 50–3150 Hz.

Analyyttiset mallit ja kokeelliset referenssivertailut 150 mm betonilaattaan osoittivat, että 40–85 mm paksu hiekka-sahanpuruseos voi parantaa askeläänieristystä 5–8 desibeliä matalilla taajuuksilla (50–250 Hz), vähentäen eroa betonilattiaan. Tutkimuksessa käsiteltiin myös kosteuden hallintaa, eristeen asennustekniikoita ja rakenteellista yhteensopivuutta.

Tulokset viittaavat siihen, että hiekkapohjainen eristekerros tarjoaa kustannustehokkaan ja toteutuskelpoisen ratkaisun puurakenteisten välipohjien askeläänieristystehon parantamiseksi puurakentamisessa.

Kieli: englanti
Avainsanat: askelääni, askeläänieristys, eristysmateriaali

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1 Introduction

In recent years, timber construction has gained increasing attention both in Finland and internationally. This growing interest can be attributed primarily to timber's ecological advantages, rapid construction potential, and its significant role in sustainable development and bioeconomy. Timber is a renewable and lightweight building material, which makes it particularly appealing for highly prefabricated structures such as multi-storey wooden buildings (Kylliäinen, M. et al. 2017, Chung, H. et al. 2010).

However, the evolving timber construction sector faces certain challenges, notably concerning acoustic performance of the buildings. Lightweight timber constructions typically have lower airborne and impact sound insulation performance compared to traditional heavy structures such as concrete. These acoustic shortcomings directly impact occupant comfort and living quality. Sounds transmitted from neighbouring apartments, particularly impact noise and airborne disturbances, are among the primary factors reducing residential comfort [Kylliäinen, M. et al,2017, Latvanne, P. 2015, Chung, H. et al. 2010, Mayr, A. R. et al. 2009].

Effective building acoustics are crucial for occupant comfort, as the acoustic environment strongly influences residents' well-being and health. The significance of building acoustics and sound design has become increasingly prominent in building projects. Insufficient acoustic planning can lead to significant additional costs, either due to remedial works or addressing occupant complaints. Therefore, acoustics and noise control should be considered from the early design phases of a construction project to ensure functional quality and user satisfaction throughout the building's lifecycle (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al, 2017, Latvanne, P. 2015, Forssén, J. et al. 2008.).

For these reasons, systematic and competent acoustic planning is a key factor enabling the growth of timber construction, guaranteeing residential comfort, and enhancing competitiveness in the timber construction market (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Chung, H. et al. 2010, Forssén, J. et al. 2008).

1.1 Purpose

The objective of this thesis is to investigate the use of sand and sand-based mixtures as impact sound insulation material in lightweight intermediate floor structures, with also focusing on their applicability in Finnish construction conditions. The study aims to examine how sand, either alone or in combination with organic additives such as sawdust, can contribute to improving the acoustic performance of timber-framed floors, especially in terms of reducing low-frequency impact sound transmission.

The thesis analyses existing research data, experimental floor configurations, and structural parameters such as joist spacing, cavity depth, and infill composition, to assess the feasibility, effectiveness, and practical limitations of using sand as a non-traditional acoustic layer. Special attention is given to Finnish regulatory requirements, climatic conditions, and structural design practices to determine the material's technical compatibility and long-term performance in local building applications.

The overall goal is to provide a technically grounded evaluation of sand-based impact sound insulation solutions and their potential integration into cost-effective and acoustically robust timber construction systems suitable for modern multi-storey buildings in Finland.

1.2 Key Consepts

Sound Pressure Level (SPL) [dB]
A logarithmic measure of the root-mean-square (RMS) sound pressure relative to a reference pressure (20 µPa). Indicates sound intensity at a given location.

A-weighted Sound Pressure **(Pa)**
Sound pressure measured using the A-weighting filter of a sound level meter, which simulates the frequency-dependent sensitivity of hearing. This is indicated in the sound pressure level measurement as LpA.

Decibel (dB)
A relative unit used to express sound intensity. The decibel scale is logarithmic and correlates changes in sound pressure to the human hearing response. For example, a change in sound pressure from 10 Pascals (Pa) to 20 Pascals is perceived as equally intense as a change from 1 Pascal to 2 Pascals.

Frequency (Hz)

Frequency corresponds to the pitch of an audible sound. It depends on the vibration speed of air molecules and is measured in cycles per second, or Hertz (Hz). The human hearing range typically spans from 20 to 20,000 Hz. Frequency is often analysed in frequency bands.

Frequency Band

The distribution of sound frequency can be divided into smaller parts called frequency bands. Commonly, octave bands and third-octave bands are used. When the pitch increases by an octave, its frequency doubles. The sound power level of building service equipment and the absorption coefficients of building materials are usually presented in octave bands. Airborne sound insulation, standardized sound level differences, and standardized impact sound levels are typically presented in third-octave bands.

Sound

A pressure fluctuation in an elastic medium within the audible frequency range. Sound is typically produced by vibrating surfaces, which cause pressure variations in the air. It propagates through the medium as sound waves and can be described by sound pressure or sound power.

Sound Pressure Level Lp (dB)

The sound pressure level is a measure of the instantaneous total sound pressure at a specific point.

Impact Sound Insulation

The ability of a building element, a combination of elements, or a material to insulate sound transmitted through the floor structure due to footsteps or impacts resembling object drops.

Impact Sound

Structure-borne sound transmitted to other spaces, caused by, for example, walking on a floor, dropping objects, moving furniture, or transporting goods.

Impact Sound Level L’nT,w **+ CI,50-2500 (dB)**

Impact sound level including a spectrum adaptation term (SFS-EN ISO 717-2).

Airborne Sound

Propagating through the air from a sound source, such as speech, music, audio equipment, or various building service systems.

Airborne Sound Insulation

The ability of a building element, a combination of elements, or a material to insulate sound propagating through the air from a sound source.

Airborne Sound Insulation R (dB)

Airborne sound insulation indicates the ratio of sound power transmitted through a building element to the incident sound power at a specific frequency band.

Spectrum Adaptation Term CI,50-2500

The spectrum adaptation term CI,50-2500 extends the measurable frequency range for impact sound insulation to include frequency bands at 50, 63, and 80 Hz and considers significant deviations across individual frequency bands. The spectrum adaptation term is only applied when its value is greater than zero (SFS-EN ISO 717-2).

Standardized Impact Sound Level L’nT (dB)

The standardized impact sound level describes the strength of sound produced by an impact sound machine in another room with a reverberation time of 0.5 s (SFS-EN 16283-2).

Standardized Impact Sound Level Index L’nT,w (dB)

The standardized impact sound level index describes the strength of sound produced by an impact sound machine in another room with a reverberation time of 0.5 s. The impact sound level index is calculated from Hz (SFS-EN ISO 717-2) measurements taken within the frequency range of 100 – 3150.

1.3 Scope of the Thesis

This thesis focuses on the use of sand and sand–sawdust mixtures as impact sound insulation materials in lightweight timber-based intermediate floors. The scope is limited to evaluating the acoustic performance, structural integration, and applicability of sand-based infill systems within floor cavities, with an emphasis on impact sound insulation in accordance with standardized measurement methods such as L’n,w and CI,50–2500.

The study does not cover floating floor systems, active acoustic control technologies, or detailed analysis of airborne sound insulation. Instead, it concentrates on passive mass-based solutions suitable for use in wood-framed constructions, particularly in residential and modular multi-storey buildings typical for Finnish conditions.

Considerations within the scope include:

- Review of existing experimental data and published research,
- Structural and acoustic characteristics of sand-based infill layers,
- Interaction with other floor components such as joist spacing, cavity geometry, and ceiling systems,
- Moisture behaviour and compatibility with Finnish building regulations.

Out of scope are detailed fire performance analysis, cost estimation, and full-scale field testing. The findings are intended to support preliminary design decisions and offer recommendations for further development and experimental validation.

2 Acoustic Wave Propagation and Resonance in Lightweight Floors

Timber-framed intermediate floors function as coupled structural–acoustic systems, where bending waves in the floor panels, longitudinal waves in the joists and cavity resonances together govern impact-sound transmission. At low frequencies (below ~200 Hz), the system behaves like a mass–spring assembly: the panel's bending stiffness and joist support set the fundamental "mass-law" response, while the enclosed air cavity introduces compliance and, if filled, additional damping. Above the coincidence frequency—where the panel's bending-wave speed matches the speed of sound in air—airborne radiation rapidly increases, causing a pronounced dip in insulation known as the coincidence dip. (Warnock & Birta 1998, Chung et al. 2010)

2.1.1 Sound

Sound is a mechanical wave that propagates through a medium, such as air, water, or solid materials, due to variations in pressure. It is generated by a vibrating source, creating alternating regions of compression and rarefaction in the surrounding medium. In building acoustics, sound transmission plays a crucial role in determining the comfort level in indoor environments, particularly concerning airborne and impact sound insulation. (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al., 2017, Latvanne, P. 2015, Kylliäinen, M. et al., 2023)

2.1.2 Sound Pressure and Sound Pressure Level

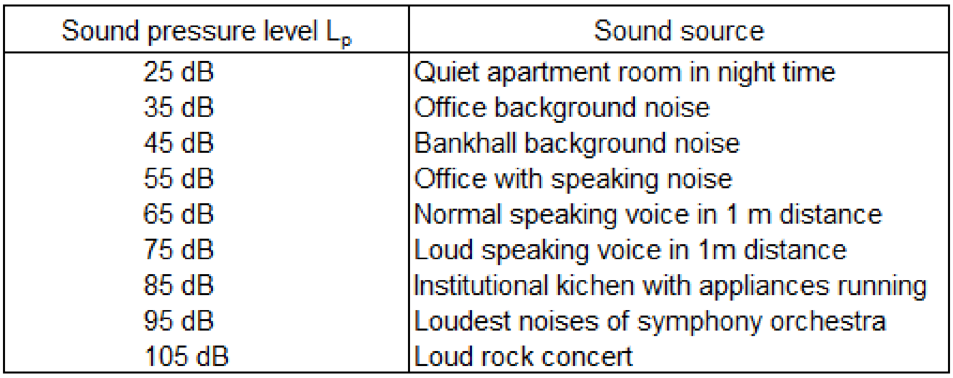
Sound pressure is the variation in air pressure caused by a sound wave, typically measured in pascals (Pa). Since sound pressure values can vary significantly, they are commonly expressed in logarithmic form as the sound pressure level (SPL) in decibels (dB), calculated using the following equation:

$$L_p=20\log_{10}\left(\frac{p}{p0}\right) \tag{1}$$

where:

- Lp = sound pressure level in decibels (dB),
- p = measured sound pressure (Pa),
- p0 = reference sound pressure (20 µPa, the threshold of human hearing).

The sound pressure level provides a standardized method to quantify and compare sound intensities in different environments (Figure 1 below). In building acoustics, SPL is used to assess airborne and impact sound transmission through structures, ensuring compliance with acoustic performance requirements. Low SPL values indicate better sound insulation performance, reducing disturbances caused by external noise sources or neighbouring spaces. (SFS-EN ISO 717-2:2020, Latvanne, P. 2015, Kylliäinen, M. et al, 2023)



Sound pressure level L_p	Sound source
25 dB	Quiet apartment room in night time
35 dB	Office background noise
45 dB	Bankhall background noise
55 dB	Office with speaking noise
65 dB	Normal speaking voice in 1 m distance
75 dB	Loud speaking voice in 1m distance
85 dB	Institutional kichen with appliances running
95 dB	Loudest noises of symphony orchestra
105 dB	Loud rock concert

Figure 1. Examples of sound pressure levels (Kylliäinen M. Hongisto V. 2007)

In building acoustics, the sound pressure level (SPL) is a central parameter used to evaluate how sound behaves within and between spaces. SPL quantifies the intensity of sound by measuring the pressure fluctuations in the air caused by acoustic waves. In practical terms, it represents how loud a sound is, typically expressed in decibels (dB). The SPL is measured in receiving rooms during acoustic testing to determine how much sound transmits through separating elements such as floors or walls. (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al., 2017, Latvanne, P. 2015)

When assessing airborne sound insulation, a calibrated sound source, usually a loudspeaker or omnidirectional dodecahedron, is placed in the source room. The SPL is then measured in both the source and receiving rooms across standardized frequency bands. The difference in SPL values, corrected for background noise and reverberation time, forms the basis for calculating the airborne sound insulation index (Rw), which represents the effectiveness of a construction in preventing sound transmission through air. (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al., 2017, Latvanne, P. 2015)

For impact sound insulation, SPL measurements are taken in the receiving room located below the tested floor, while a tapping machine generates standardized mechanical impacts on the floor above. The SPL spectrum recorded across frequency bands allows determination of the normalized impact sound level (L’n,w). This value reflects how effectively the floor assembly isolates structural impact noise, such as footsteps (SFS-EN ISO 717-2:2020, Latvanne, P. 2015, Kylliäinen, M. et al, 2023).

SPL is inherently frequency-dependent, which means different materials and structures perform differently across the audible spectrum. For this reason, measurements are performed in third-octave or octave bands, covering frequencies typically from 50 Hz to 5000 Hz. Special emphasis is placed on low-frequency behaviour in lightweight constructions like timber floors, where structural resonances can cause poor insulation performance despite seemingly adequate SPL values in higher bands (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Mayr, A. R. et al. 2009).

Understanding SPL is essential for predicting acoustic performance, ensuring compliance with building codes, and ultimately providing comfort to building occupants. It enables engineers to model acoustic behaviour, compare construction systems, and evaluate the need for improvements such as floating floors, resilient layers, or suspended ceilings. Accurate SPL measurement is the foundation for all key sound insulation indices and therefore plays a decisive role in both design and quality control in building acoustics (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020, Latvanne, P. 2015).

2.1.3 Frequency and Human Perception of Sound

Frequency refers to the number of sound wave cycles that occur per second and is measured in hertz (Hz). It determines the pitch of a sound—higher frequencies are perceived as higher-pitched sounds, while lower frequencies are perceived as lower-pitched. Frequency is one of the most fundamental characteristics of sound and plays a critical role in both the physical behaviour of sound in structures and in how humans perceive acoustic environments [Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020].

The human ear is sensitive to a wide range of frequencies, typically from 20 Hz to 20,000 Hz (figure 2 below). However, this sensitivity is not uniform across the spectrum. The ear is most sensitive to frequencies between 1,000 Hz and 4,000 Hz, which correspond closely to the frequency range of human speech. Sounds below 100 Hz are considered low-frequency, and while they are often felt as vibrations, they may not be clearly heard, especially at low sound pressure levels. These low frequencies are common in building acoustics, particularly in impact sound transmission, and are more difficult to insulate due to their longer wavelengths and ability to excite structural resonances [Kylliäinen M. Hongisto V. 2007, Latvanne, P. 2015].

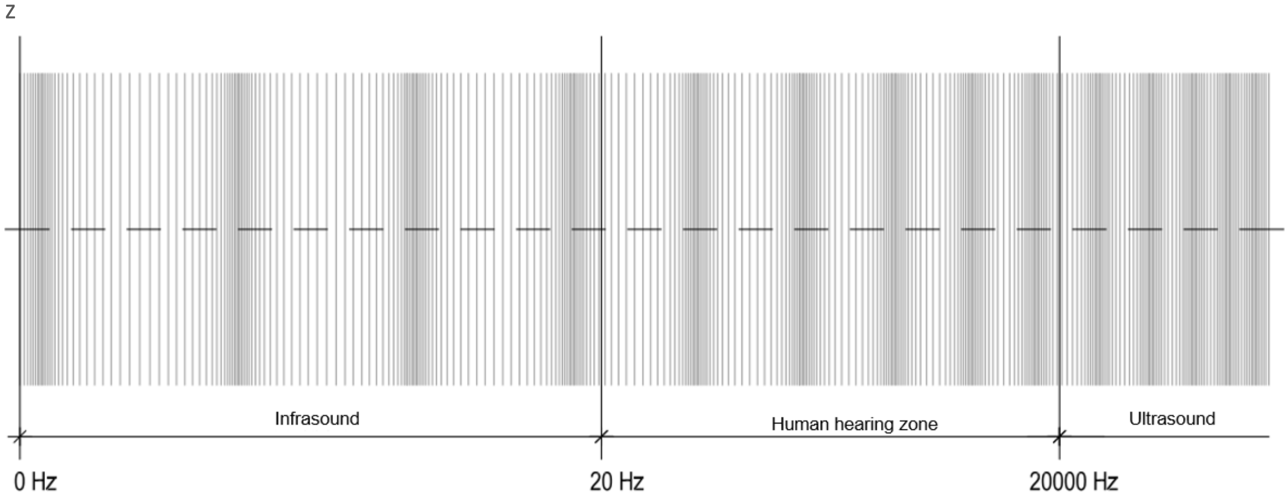


Figure 2. Human hearing frequency 20 Hz – 20000Hz (Kylliäinen et al. 2021).

High frequencies, typically above 2,000 Hz, are easier to block or absorb using standard construction materials, but they are also more directional and prone to reflection within rooms. Mid-frequency sounds, roughly from 250 Hz to 2,000 Hz, are critical for speech intelligibility and general acoustic comfort. This is why most acoustic testing—such as airborne and impact sound insulation measurements—is performed across third-octave bands covering the 50 Hz to 5,000 Hz range, with particular attention to low-frequency performance in lightweight structures like timber floors (SFS-EN ISO 717-2:2020, Latvanne, P. 2015, Chung, H. et al. 2010).

In summary, frequency affects both how sound propagates through building structures and how it is perceived by occupants. Low frequencies are difficult to isolate and can cause discomfort due to vibration, while mid and high frequencies are more audible and critical for clarity and comfort in indoor environments (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020, Latvanne, P. 2015, Chung, H. et al. 2010).

2.2 Frequency Bands in Buildings

In building acoustics, frequency bands are used to analyse and describe how sound behaves at different parts of the audible spectrum. Because building elements respond differently depending on frequency, measurements are carried out in predefined frequency ranges. The most common frequency bands used in sound insulation measurements are octave bands and third-octave bands (figure 3). Both are logarithmic, meaning each band is a fixed percentage wider than the one before (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

Octave bands are defined so that the upper frequency limit is exactly twice the lower frequency limit. For example, an octave band centred at 500 Hz covers approximately 355–710 Hz. The standard center frequencies used in acoustics typically include 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. These bands provide a general understanding of how a building element attenuates sound across a wide spectrum (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020, Latvanne, P. 2015).

Third-octave bands offer greater resolution and are formed by dividing each octave band into three narrower bands. The bandwidth of each third octave is roughly 23% of its center frequency. For example, the third-octave bands centred at 100 Hz include approximately 89 Hz to 112 Hz. This finer resolution allows for more precise identification of problem frequencies, especially in lightweight structures like timber floors, where specific resonant modes may dominate within narrow frequency ranges (Kylliäinen, M. et al. 2017, Latvanne, P. 2015).

In standardized impact sound insulation measurements, the relevant third-octave bands range typically from 50 Hz to 5000 Hz, as specified in ISO 717-2. Special attention is paid to low-frequency bands between 50–250 Hz, which are often critical for subjective comfort. These are addressed using spectrum adaptation terms like CI,50–2500, which adjust the overall rating to account for low-frequency deficiencies (SFS-EN ISO 717-2:2020, Latvanne, P. 2015, Kylliäinen, M. et al. 2017).

The choice of frequency bands is essential when evaluating and comparing the performance of building components. It allows for detailed spectral analysis of transmitted sound and forms the basis for calculating single-number indices like Rw and L’n,w. Accurate frequency-based measurements help engineers design constructions that perform reliably across the full spectrum of relevant sound frequencies (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

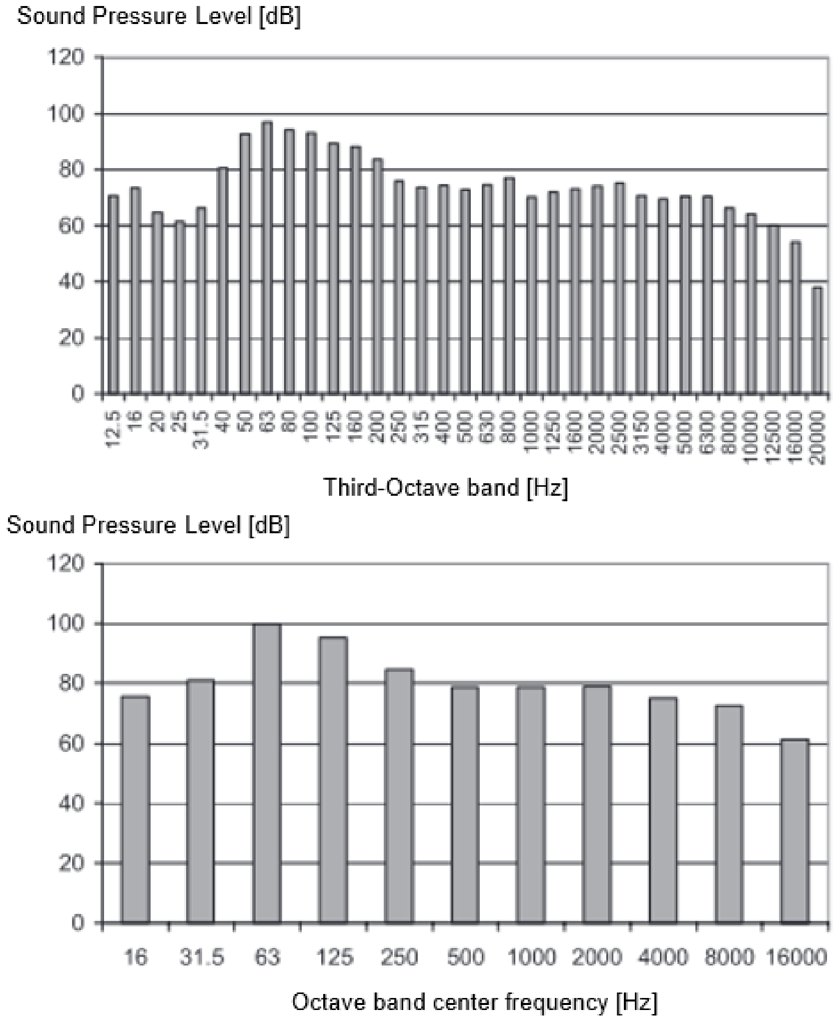


Figure 3. Presenting sound pressure levels of the same sound spectrum in third-octave bands describes the characteristics of the sound under investigation more accurately than measuring in octave bands (SFS-EN ISO 717-2:2020).

2.2.1 Normalized Impact Sound Pressure Level (L'n,w)

The normalized impact sound pressure level, denoted as L'n,w, is a standardized single-number rating used to describe the impact sound insulation performance of a floor or floor assembly. It is one of the most essential indicators in building acoustics, particularly in multi-storey buildings, where noise from footsteps and other impact sources can affect the comfort and privacy of occupants.

L'n,w represents the sound pressure level in the receiving room caused by a standardized impact source (a tapping machine) placed on the floor above. The measured levels are normalized to a standard reverberation time of 0.5 seconds, allowing for consistent comparisons across different room sizes and configurations. The test procedure is defined in ISO 10140-3 for laboratory measurements and ISO 16283-2 for field measurements. The value is expressed in decibels (dB) (SFS-EN ISO 717-2:2020).

The interpretation of the L’n,w value is straightforward: the lower the number, the better the floor's ability to attenuate impact sound. For example, a floor system with L’n,w = 45 dB provides significantly better impact sound insulation than one with L’n,w = 60 dB. Building codes typically set maximum allowable L’n,w values for different building types and occupancy classifications to ensure sufficient acoustic comfort (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

In lightweight constructions such as timber floors, L’n,w alone may not fully reflect the perceived acoustic performance, especially at low frequencies, where such systems tend to perform poorly. To address this, spectrum adaptation terms such as CI or CI,50–2500 can be added to L’n,w to emphasize the low-frequency range. The combined index L’n,w + CI,50–2500 gives a more accurate representation of how impact sound is perceived in real-life-use, particularly in the presence of low-frequency noise generated by walking or jumping (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung, H. et al. 2010).

L’n,w values are critical for:

- Comparing floor designs and materials,
- Demonstrating compliance with national acoustic regulations,
- Evaluating the effectiveness of floating floors, resilient layers, and suspended ceilings,
- Guiding product development and acoustic design in both new construction and renovation projects.

In summary, the normalized impact sound pressure level is a central metric in impact sound control. It is particularly relevant in timber construction, where structural vibrations are easily transmitted, and thoughtful design is needed to meet modern acoustic standards (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung, H. et al. 2010).

2.2.2 Measurements of Normalized Impact Sound Pressure Level (L’n,w)

The measurement of the normalized impact sound pressure level (L’n,w) is a standardized procedure used to evaluate the impact sound insulation performance of a floor system. The measurement is conducted in accordance with ISO 10140-3 in laboratory settings and ISO 16283-2 for field measurements. The purpose is to determine how much structure-borne sound is transmitted through a floor when it is subjected to mechanical impacts, simulating real-life sources such as footsteps or dropped items (SFS-EN ISO 717-2:2020).

The sound is generated using a standardized tapping machine (Figure 4), which consists of five steel hammers that fall in sequence onto the floor surface from a fixed height at a defined rate. The tapping machine is placed at several positions on the floor in the source room above. In the receiving room below, a sound level meter measures the average sound pressure levels across a frequency range typically from 50 Hz to 5000 Hz, using third-octave bands (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

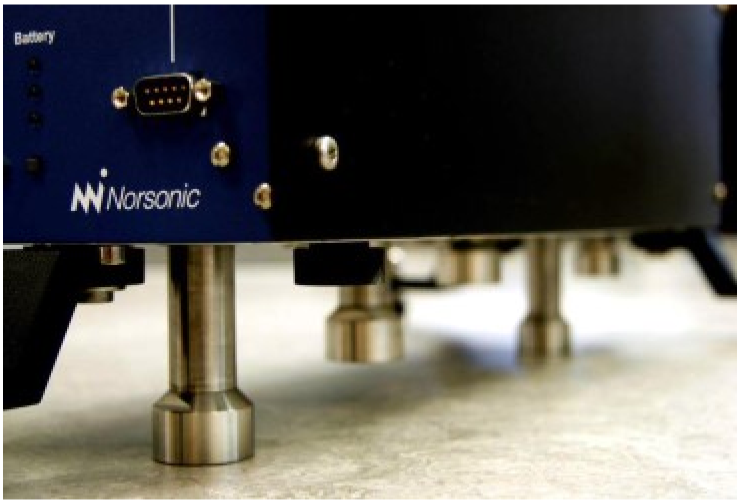


Figure 4. Standardized tapping sound machine (Kylliäinen, M. et al. 2021)

In laboratory conditions, the measurement results are normalized to a reference reverberation time of 0.5 seconds, while in field conditions, they are standardized based on the actual reverberation time of the receiving room. The normalization ensures that the results are comparable regardless of room size or acoustic properties. The single-number value L’n,w is derived from these measurements using a reference curve method defined in ISO 717-2 (SFS-EN ISO 717-2:2020).

To better reflect the subjective perception of impact noise, especially in lightweight floor structures that perform poorly at low frequencies, a spectrum adaptation term, such as CI,50–2500, can be added to L’n,w. This term emphasizes the contribution of low-frequency impact sounds, which are often the most disturbing in residential settings. The combined value L’n,w + CI,50–2500 gives a more realistic assessment of acoustic comfort (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung,H. et al. 2010).

It is important to note that test setup conditions, such as the positioning of the tapping machine, microphone height, background noise, and boundary conditions (e.g. flanking paths), must be carefully controlled to ensure valid results. Field measurements often show higher L’n,w values compared to laboratory results due to uncontrolled sound transmission through adjacent elements or construction defects (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017).

The measured L’n,w value is essential for determining whether a floor system meets regulatory requirements and acoustic targets. It is also used to compare the performance of alternative constructions, such as floating floors, resilient layers, suspended ceilings, or mass-loaded infill materials like sand or sand-sawdust mixtures (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung,H. et al. 2010).

2.2.3 Coincidence and Coincidence Frequency in Building Acoustics

Coincidence refers to a phenomenon in acoustics where the wavelength of airborne sound matches the bending wavelength of a building element, such as a wall or floor panel. When this condition is met, the structure becomes particularly efficient at transmitting sound, leading to a sharp drop in sound insulation performance (Figure 5). This effect is known as the coincidence dip, and it typically occurs in the mid- to high-frequency range, depending on the material and its physical properties (Kylliäinen M. Hongisto V. 2007, Latvanne, P. 2015).

The coincidence frequency (also called the critical frequency, fc) is the frequency at which this match between airborne and bending waves occurs. At this frequency, the structure vibrates in sympathy with the sound wave, which significantly increases the transmission of sound energy through the element. The coincidence frequency is a material-specific property and depends on several factors such as material stiffness, density, and thickness.

Mathematically, the coincidence frequency for a flat homogeneous plate in diffuse sound field can be approximated by:

$$F_{Cr} = \frac{C^2}{2\pi}\sqrt{\frac{m}{B'}} \tag{2}$$

Where:

- c = speed of sound in air (approx. 343 m/s at 20°C),
- m = surface mass of the element (kg/m^2),
- B’ Flexural rigidity of the element (Nm).

Alternatively, for practical purposes, it is often approximated using empirical formulas that also consider Young’s modulus (E), plate thickness (h), Poisson’s ratio (ν), and density (ρ) of the material.

The coincidence effect becomes significant when the angle of incidence of the sound wave increases (figure 5). At normal incidence, coincidence does not occur; it arises when sound waves strike the surface at an oblique angle and the component of the sound wave in the panel's plane matches the panel's bending wave speed. This is related to the cut-on angle for shear (bending) waves, where higher incident angles result in stronger excitation of the coincidence condition (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Latvanne, P. 2015).

In design, coincidence can be mitigated by:

- Damping the panel (e.g., using viscoelastic layers),
- Increasing mass to shift fc outside critical frequency bands,
- Using double constructions with air gaps and decoupling,
- Avoiding lightweight single-layer panels in sensitive frequency ranges.

Understanding coincidence and its effects is essential for engineers aiming to design constructions that maintain high sound insulation across all relevant frequency bands, especially in speech-dominant environments such as offices, classrooms, and residential buildings (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020, Latvanne, P. 2015).

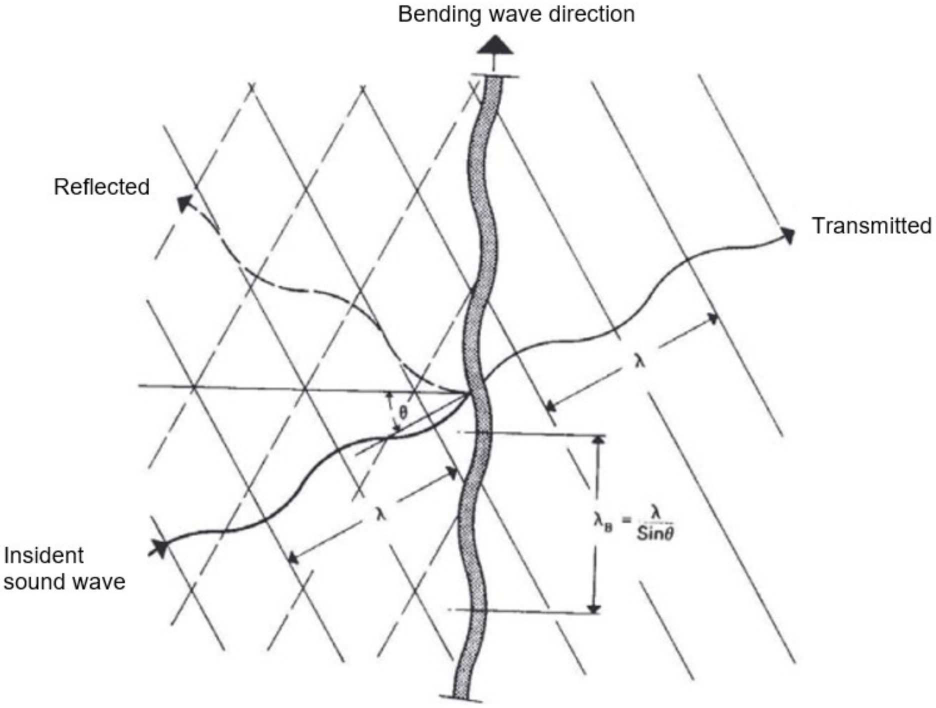


Figure 5. An incident sound wave always generates a bending wave in the plate. In a coincidence situation, the incident sound wave and the plate's bending wave become identical, resulting in minimal sound insulation (Kylliäinen M. Hongisto V. 2007).

2.3 Airborne Sound and insulation

Airborne sound is defined as sound transmitted through air, originating from sources such as speech, music, television, or traffic noise. In buildings, airborne sound propagates as pressure fluctuations in the air and travels through partitions, floors, ceilings, and openings, ultimately affecting spaces adjacent to the sound source. Efficient management of airborne sound is fundamental to ensuring acoustic comfort and reducing disturbance caused by activities in neighbouring spaces (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017 and 2023).

Airborne sound insulation refers to the capacity of building elements, such as walls, floors, and ceilings, to reduce the transmission of airborne sound between spaces. Achieving effective airborne sound insulation in timber buildings presents unique challenges due to the lightweight nature of wooden constructions, resulting in inherently lower sound insulation performance compared to heavier structures, such as concrete. To address these challenges, timber constructions typically incorporate layered structures, including multiple panel layers separated by air gaps, as well as porous sound-absorbing materials within wall and floor assemblies. Detailing plays a crucial role in sound insulation performance so, careful attention must be paid to construction joints, connections, and penetrations, as well as minimizing sound transmission via indirect or flanking paths. (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017)

2.4 Impact Sound and insulation

Impact sound refers to structure-borne sound generated by mechanical impacts on building elements, typically floors. Common sources include footsteps, dropped objects, furniture movements, or household appliances. Unlike airborne sound, impact sound propagates directly through building structures and transmits into adjacent spaces as vibration energy. Consequently, impact sound is often perceived as a significant source of acoustic disturbance, particularly in wooden apartment buildings (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Kylliäinen, M. et al. 2023, Mayr, A. R. et al. 2009).

Impact sound insulation denotes the ability of a structural element, commonly floors, to mitigate the transmission of impact-generated vibrations. Effective impact sound insulation is essential for acoustic comfort, yet it poses significant technical challenges, especially in lightweight timber construction.

Due to the low mass of wooden floors, their inherent damping capacity and resistance to vibration propagation are limited compared to heavier structures, such as concrete floors. Therefore, impact sound insulation in timber buildings typically requires engineered structural solutions, such as resilient layers, floating floors, elastic mounts, or suspended ceilings with acoustic decoupling. Additionally, appropriate selection of floor coverings, such as carpets or resilient floorings, can contribute notably to improved impact sound insulation performance. Detailed planning and careful execution of connections, structural joints, and acoustic decoupling elements are crucial, even minor oversights in design or installation may substantially compromise overall acoustic performance and occupant comfort (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al, 2017, Kylliäinen, M. et al. 2023, Mayr, A. R. et al. 2009, Chung, H. et al. 2010, EN 1995-1-1, 2014).

2.5 Subjective Evaluation of Impact Sound Insulation

While standardized measurements such as L’n,w and L’n,w + CI,50–2500 offer objective indicators of impact sound insulation, they do not fully capture how humans perceive footstep noise in real environments. This gap between measured performance and experienced acoustic comfort has led to growing interest in subjective evaluation methods to complement laboratory and field test data.

Subjective evaluation refers to the qualitative and perceptual assessment of impact sound transmission by building occupants or trained listening panels. It focuses on factors such as:

- Audibility of footsteps or furniture movement,
- Annoyance level caused by repetitive or impulsive noise,
- Perceived quality of acoustic privacy between floors,
- And the psychological impact of low-frequency vibrations.

Research shows that the same L’n,w value can be perceived very differently depending on the frequency distribution of the sound and the temporal characteristics of the noise source. For instance, lightweight timber floors that meet the standard limit of 53 dB L’n,w may still be considered uncomfortable, especially if they allow low-frequency, high-energy impact sounds such as jumping or running (Kylliäinen, M. et al, Latvanne, P. 2015, Chung, H. et al. 2010).

To address this, spectrum adaptation terms, particularly CI,50–2500, have been introduced to account for the perceptual weight of low-frequency components, which contribute most to subjective disturbance. Floors with poor performance below 125 Hz tend to receive lower subjective ratings, even if the total L’n,w value appears acceptable.

Subjective assessment may involve:

- Listening tests in standardized environments with reference sound samples,
- User feedback questionnaires in occupied buildings,
- Expert panel evaluations, correlating measured data with perceived annoyance.

In design, it is important to go beyond minimum code compliance and consider how floor assemblies behave in the low-frequency range, where most dissatisfaction arises.

Subjective evaluation highlights the limitations of single-number acoustic ratings and emphasizes the need for a holistic design approach that considers both measurable and perceptual aspects of impact sound insulation.

2.6 Processing of Impact Sound Measurement Results

The processing of impact sound measurement results is a standardized procedure that transforms raw acoustic data into interpretable indicators, typically expressed as a single-number value used for design verification, performance classification, and regulatory compliance. The most common metric derived is the weighted normalized impact sound pressure level (L’n,w), which quantifies the floor system’s ability to attenuate impact noise (SFS-EN ISO 717-2:2020).

The measurement begins with the use of a standardized tapping machine, placed on the floor surface of the source room. Sound pressure levels are recorded in the receiving room below, across a range of third-octave bands, typically from 50 Hz to 5,000 Hz, as specified in ISO 10140-3 and ISO 16283-2 for laboratory and field measurements respectively (SFS-EN ISO 717-2:2020).

After measurement, the raw third-octave band values are:

- Normalized to a standard reverberation time (typically 0.5 s for laboratories) or standardized to the actual reverberation time measured in the receiving room (in field measurements).
- Compared to a reference curve defined in SFS-EN ISO 717-2, which serves as a standard frequency response for a baseline floor system.
- The measurement curve is shifted vertically (in dB) until the sum of unfavourable deviations from the reference curve (i.e., measured levels above the curve) is within a defined tolerance (32 dB total).
- The amount of this vertical shift defines the final L’n,w value, which is the weighted normalized impact sound pressure level (SFS-EN ISO 717-2:2020).

Optionally, spectrum adaptation terms can be applied, such as:

- CI,100–2500: emphasizes frequencies relevant to human perception in normal floor systems.

- CI,50–2500: gives extra weight to low frequencies, which are often problematic in lightweight timber constructions.

The result can be expressed as L’n,w + CI,50–2500, which provides a more accurate representation of real-world acoustic performance, especially in cases where low-frequency impact noise (e.g. walking, jumping) is dominant (Kylliäinen M. Hongisto V. 2007, Latvanne, P. 2015, Chung, H. et al. 2010).

In practical design evaluation, the L’n,w value is then:

- Compared to national regulations, such as YM2017/796 in Finland (e.g. L’n,w ≤ 53 dB),
- Classified according to acoustic classes (A–D) in Finnish design guides,

Floors are used to compare alternative floor structures or validate as-built performance in field conditions. It is important that the measurement and processing are performed consistently with standard procedures to ensure repeatability and comparability between different construction systems, laboratories, and projects.

2.6.1 Impact Sound Insulation Improvement Index (ΔLw)

The Impact Sound Insulation Improvement Index (ΔL_w) is a standardized single-number value used to quantify the improvement in impact sound insulation achieved by applying a specific floor covering or system over a reference floor. It is defined in the standard SFS-EN ISO 717-2:2020 and expressed in decibels (dB) (SFS-EN ISO 717-2:2020).

ΔL_w is calculated as the difference between the normalized impact sound pressure level of a bare reference floor (typically a 150 mm concrete slab) and that of the same floor with the applied floor covering or treatment. A higher ΔL_w value indicates better impact sound insulation improvement.

$$\Delta L_w = L_{n,w,ref} - L_{n,w,test} \quad (3)$$

where:

- Ln,w,refL = impact sound level of the reference (bare) floor,
- Ln,w,test = impact sound level after applying the floor covering.

ΔL_w is widely used by manufacturers of resilient floor coverings**,** floating floor systems, and impact-reducing underlays to classify and compare their acoustic performance. This index is practical for product selection and specification, especially in renovations or when upgrading existing floors to meet acoustic requirements (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

However, there are important limitations to its applicability. The standard ΔL_w value is derived using a heavy concrete reference floor and therefore cannot be directly applied to lightweight floor constructions (e.g., timber floors). Lightweight structures respond differently, particularly in the low-frequency range (≤250 Hz), which is critical in real-life impact sound perception. Therefore, using ΔL_w values measured on concrete may lead to overestimation of actual performance in timber buildings (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung, H. et al. 2010).

To better assess performance in lightweight floors, in-situ measurements or simulation methods tailored to the specific structure are recommended. Additionally, low-frequency correction terms (CI, $CI_{50–2500}$) may be added to assess real-world performance, especially where subjective comfort is a design priority (SFS-EN ISO 717-2:2020, Latvanne, P. 2015, Kylliäinen, M. et al. 2023).

ΔL_w is a useful index for comparing the effectiveness of impact-reducing floor treatments, especially in standardized laboratory conditions. However, its relevance to lightweight or timber-based floors is limited unless supplemented by structure-specific evaluations. Careful consideration is required when applying this index in acoustic design for residential or wooden buildings**,** particularly in Finland and similar construction environments (Kylliäinen, M. et al,2017, Latvanne, P. 2015, Chung, H. et al. 2010).

2.7 Distinction Between Sound Absorption and Sound Insulation

In building acoustics, sound absorption and sound insulation are two fundamentally different but often misunderstood concepts. While both aim to control sound, they function through different physical mechanisms and serve different acoustic objectives within a building.

Sound absorption refers to the ability of a material or surface to reduce the amount of sound energy reflected within a space. It primarily affects the acoustic quality of rooms, such as speech clarity, reverberation time, and noise buildup. Absorptive materials, such as mineral wool, acoustic foam, or perforated panels with porous backing, convert part of the sound energy into heat through internal friction. These materials are typically lightweight and porous, and are applied on the surfaces of walls, ceilings, or suspended panels inside rooms. Sound absorption does not prevent sound from passing through a structure, but it reduces the reflected energy and improves internal acoustic comfort (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al, 2017, Latvanne, P. 2015).

Absorptive materials are typically porous, such as mineral wool, glass wool, acoustic foam, perforated panels with backing, or fibrous materials. They are evaluated using the absorption coefficient (α), which ranges from 0 (no absorption) to 1 (full absorption). Laboratory measurements are performed using standards like ISO 354.

Typical applications of sound absorption include:

- Improving room acoustics.
- Reducing noise levels in open-plan spaces.
- Preventing flutter echo and standing waves.

Absorption is measured in reverberation chambers and relates to how much sound is dissipated within a space—not how much is blocked from passing through a wall or floor (Kylliäinen M. Hongisto V. 2007, Latvanne P. 2015).

In contrast, sound insulation refers to the capacity of a building element, such as a wall, floor, or ceiling, to block the transmission of sound from one space to another. Insulating constructions are designed to prevent airborne sound (e.g., speech, music) and structure-borne sound (e.g., footsteps, machinery) from travelling through the building fabric (Figure 6 below). Sound insulation is achieved through mass, stiffness, damping, and decoupling. Effective sound-insulating elements include heavy multilayer constructions, floating floors, and double walls with resilient mounting. The performance is quantified using indices such as Rw (for airborne sound) and L’n,w (for impact sound) (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020, Latvanne, P, 2015).

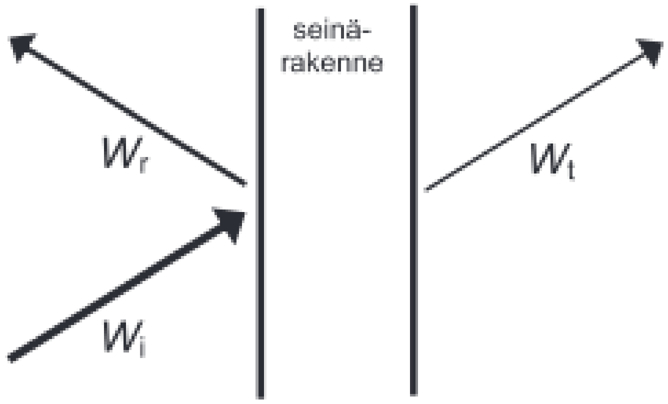


Figure 6. The structure is subjected to incident sound power W_i. A portion of the sound power is reflected from the structure as W_r while another portion is transmitted through to the other side as W_t. The proportions between these power components vary significantly depending on the properties of the structural layers (Kylliäinen M. Hongisto V. 2007).

An important distinction is that sound-absorbing materials used alone have little to no effect on sound insulation. For example, a mineral wool panel may reduce reverberation within a room but does not prevent noise from being transmitted to adjacent rooms unless integrated into a proper sound-insulating structure.

In summary, sound absorption improves internal room acoustics, while sound insulation prevents sound from travelling between rooms or floors. Effective acoustic design often requires a combination of both, applied in different layers and zones of the building envelope (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

2.8 Factors Influencing Impact Sound Insulation

Impact sound insulation is influenced by various interconnected factors, including the mass, stiffness, and damping of floor structures, also the arrangement of components and details of joints and connections. A floor's mass significantly contributes to its ability to isolate impact sound. Heavier structures, such as concrete floors, typically provide superior impact sound insulation compared to lightweight structures due to increased resistance to vibration (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung, H. et al. 2010, Mayr, A. R. et al. 2009).

Lightweight timber floors, however, often struggle with low-frequency impact sound insulation because of their relatively low mass and stiffness, causing resonances at frequencies where footfall sounds are prominent. To counteract this, resilient layers and damping materials, such as elastomeric pads or acoustic mats, are commonly integrated into the design. Structural details such as joist spacing, thickness of subfloor sheathing, and fastening methods also greatly influence the acoustic performance. The correct combination and careful detailing of these components is essential to achieve effective impact sound insulation, especially in lightweight floor systems (Kylliäinen, M. et al, 2017, Latvanne, P. 2015, Chung, H. et al. 2010, Mayr, A. R. et al. 2009).

2.8.1 Floor improvement range at lower frequencies

In conventional lightweight floor structures, especially those based on timber framing, impact sound insulation performance is typically weakest in the low-frequency range (below 250 Hz) (figure 7). This is due to the relatively low mass, high flexibility, and structural resonances common in such assemblies. As a result, low-frequency footfall sounds—such as thuds from walking or jumping—often transmit more easily and are more perceptible to building occupants.

Improvements in floor construction can extend the effective insulation range downward, starting at lower frequencies, when appropriate acoustic measures are implemented. These measures may include:

- Adding mass to the floor, for example through sand infill or dense topping layers, which lowers the system’s resonant frequency and reduces structure-borne transmission at the low end of the spectrum.

- Using resilient interlayers or floating floors, which decouple the walking surface from the structural base and act as low-frequency dampers.

- Incorporating well-dimensioned cavities with damping material, where partial or full infill increases internal energy dissipation without compromising the mass–spring–mass behaviour.

- Designing for higher damping and stiffness balance, which reduces resonance amplitudes in the lower frequency bands.

Measurements reported in Latvanne (2015) and Chung et al. (2006) show that certain optimized timber floor configurations, such as those incorporating cavity mass fills or multi-layered floating systems (Figure 7), can begin to significantly reduce impact sound starting from 50–100 Hz, rather than only at mid and high frequencies as in untreated floors. This extended low-frequency performance is crucial for achieving compliance with modern acoustic requirements, especially when using correction terms like CI,50–2500, which highlight perceived low-frequency deficiencies (Latvanne, P. 2015, Chung, H. et al. 2010).

Therefore, when designed properly, floor improvement strategies do not only reduce the total sound pressure level but also shift the effective insulation performance to start at lower frequencies, addressing one of the most acoustically critical and sensitive ranges in building environments.

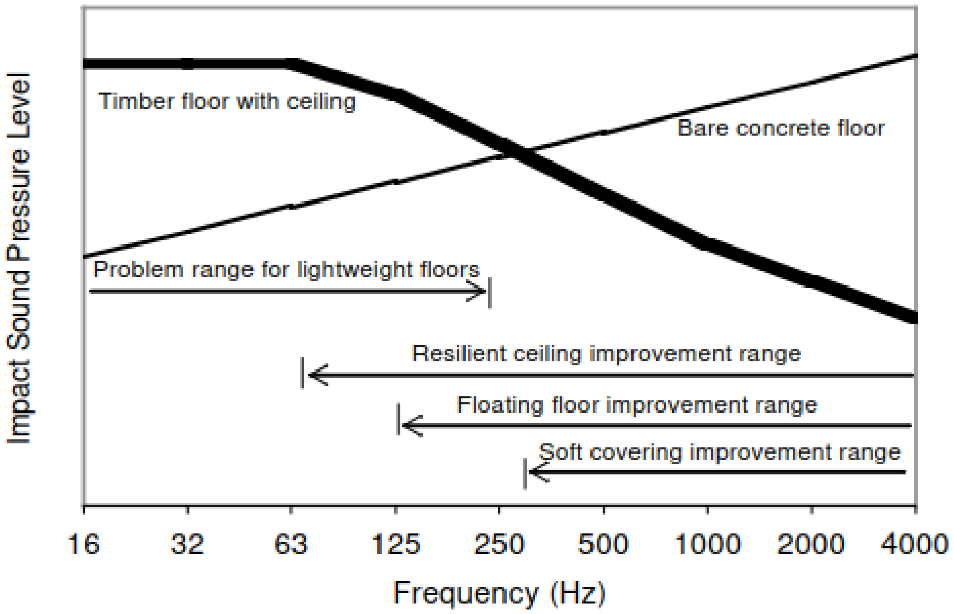


Figure 7. Floor improvement range can start at lower frequencies than shown; it depends on the type of system (e.g. heavy floating floor systems or carpet on underlay can show significant improvements starting at approximately 100Hz) (Chung et al. 2010)

2.8.2 The Effect of Floor Coverings on Impact Sound Insulation

Floor coverings play an important role in improving impact sound insulation, particularly in lightweight floor systems such as those built with timber joists. The primary function of a floor covering, in the acoustic sense, is to attenuate the excitation energy at the point of impact—for example, where a footstep or dropped object strikes the floor. By reducing the energy transmitted into the floor structure, floor coverings can significantly decrease the resulting impact sound pressure level in the receiving room below (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Latvanne, P. 2015).

The effectiveness of a floor covering in this context depends on several factors: material type, thickness, surface hardness, and elasticity. Soft, resilient materials are especially effective in reducing high-frequency impact noise, which originates from sharp or hard contacts. Conversely, harder and thinner coverings transmit more vibrational energy to the floor structure, resulting in higher impact sound levels (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Latvanne, P. 2015).

Common floor covering materials include:

- Textile carpets: among the most effective, with impact sound level reductions of up to 20–30 dB, particularly in the mid and high frequency range.
- Linoleum and PVC with resilient underlay: good performance, depending on the elasticity and thickness of the underlay, typically achieving reductions of 10–20 dB.
- Cork and rubber-based coverings: provide elastic damping and are used in cases where both acoustic and ecological considerations are important.
- Laminates or hardwood: when used alone, these provide minimal impact sound insulation but can be combined with acoustic underlay to improve performance.

The total thickness of the floor covering system affects performance, but not linearly. For example, a 2–4 mm soft resilient material can outperform a 10 mm rigid wood layer in terms of impact noise reduction. More important than thickness alone is the dynamic stiffness and loss factor of the material, which influence how impact energy is absorbed and dispersed (Latvanne, P. 2015).

Laboratory and field studies have confirmed that applying soft floor coverings is an effective and simple method to meet impact sound requirements, especially in existing buildings where structural changes are limited. However, it is important to note that floor coverings primarily reduce direct impact excitation. They do not address flanking transmission or improve airborne sound insulation, and their effect is limited in low-frequency ranges, which require mass and structural decoupling to control effectively (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

Floor coverings are an essential layer in the acoustic design of floor assemblies. When selected and installed correctly, they offer a cost-effective and low-intrusion method to reduce impact sound, especially in the high-frequency domain. For comprehensive performance, they should be used in combination with appropriate structural and cavity-layer solutions.

2.8.3 Suspended Ceilings in Impact Sound Insulation

Suspended ceilings significantly enhance the impact sound insulation of floor structures. Their effectiveness stems from decoupling the ceiling mass from the structural floor, thereby reducing the transmission of vibrations. The acoustic performance of suspended ceilings depends largely on their mass, the depth of the cavity between the ceiling and the structural floor, and the presence and density of absorbing materials within this cavity. Resilient mounting systems such as spring or rubber hangers further enhance isolation by limiting the transfer of structural vibrations. Lightweight timber floor systems benefit considerably from suspended ceilings because they improve insulation at mid and high frequency. However, low-frequency impact sounds, a critical concern in timber constructions, may require additional measures due to the limited effectiveness of conventional suspended ceilings in this frequency range (Kylliäinen, M. et al, 2017, Latvanne, P. 2015, Chung, H. et al. 2010, Mayr, A. R. et al. 2009).

2.8.4 Horizontal Impact Sound Insulation

Horizontal impact sound transmission, often referred to as flanking transmission, is a significant consideration in multi-storey timber buildings. Impact-generated vibrations can travel horizontally through structural components such as walls and floor-to-wall connections, bypassing the intended acoustic insulation measures. Addressing horizontal transmission requires careful design and detailing of junctions and connections, employing resilient elements to prevent rigid coupling of structures (figure 8). Decoupling strategies, such as introducing flexible joints and resilient materials between structural elements, can effectively reduce flanking pathways. This necessitates comprehensive acoustic planning and detailed consideration of the entire structural system to ensure horizontal impact sound insulation is adequately addressed (Kylliäinen, M. et al, 2017, Latvanne, P. 2015, Chung, H. et al. 2010, Mayr, A. R. et al. 2009).

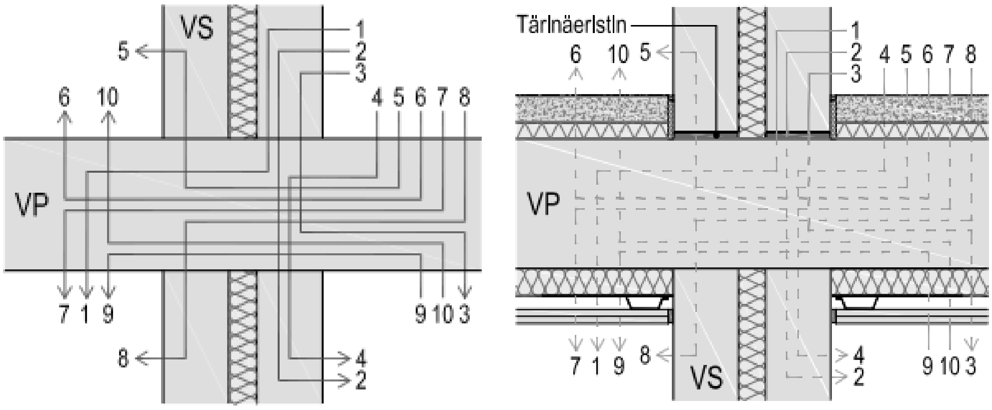


Figure 8. Excample of flanking transmissions, when not reduced (left figure). On the right-side flanking transmissions are reduced (Lahtela T., 2004).

2.8.5 Floor Covering Joints

Joints between floor coverings play a critical role in determining the effectiveness of impact sound insulation. Poorly designed or executed joints can compromise the acoustic integrity by creating rigid contact points or gaps that allow vibrations to transmit directly through the structure (Figure 8). Continuous resilient underlays beneath floor coverings reduce the risk of rigid sound bridges. Proper sealing, tight-fitting joints, and careful installation practices are required to maintain uniform acoustic performance. The effectiveness of resilient layers, floating floors, or composite toppings, such as sand or sand-sawdust mixtures, is significantly enhanced when the integrity of floor covering joints is maintained throughout the floor surface, highlighting the necessity of detailing and installation practices (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung, H. et al. 2010).

2.8.6 Lightweight Intermediate Floor

Lightweight intermediate floors, typically wooden floors, present distinct acoustic challenges due to their low mass and susceptibility to vibrations, particularly at low frequencies. Timber joists, wood panels, and associated fastening systems contribute to reduced stiffness and lower acoustic insulation performance compared to heavier concrete structures. To address these challenges, effective strategies such as floating floor systems, resilient mats, and additional mass layers (e.g., sand, sand-sawdust mixtures, or heavier panels) are employed to enhance low-frequency insulation. The incorporation of resiliently mounted suspended ceilings further improves insulation performance. Specific attention to structural detailing, such as resilient connections and avoiding direct mechanical paths for vibration transmission, is critical. Furthermore, it has been found beneficial to combine multiple acoustic layers and elements, such as heavy top layers and absorptive insulation, to achieve satisfactory acoustic comfort in lightweight intermediate floor constructions (Kylliäinen, M. et al. 2017, SFS-EN ISO 717-2:2020, Latvanne, P. 2015, Chung, H. et al. 2010, Mayr, A. R. et al. 2009).

2.8.7 Double layered floor constructions

A double-layered floor structure, where the surface floor (floating floor) is acoustically separated from the load-bearing substructure either by an air gap or a resilient material, can significantly improve both airborne and impact sound insulation (Figure 9). This improvement is particularly important in lightweight floor systems, such as timber constructions.

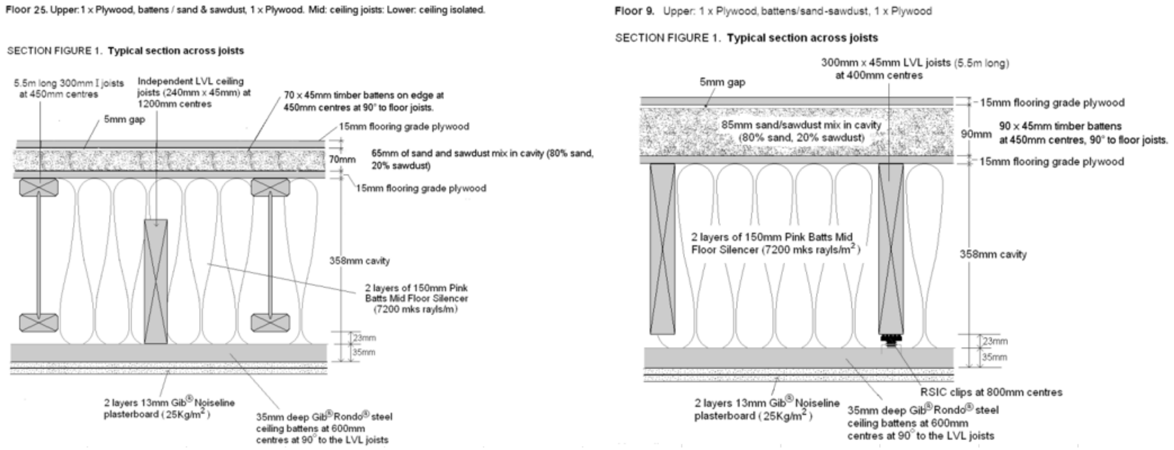


Figure 9. Two different wooden floating floor types. (Chung et al. 2010)

The acoustic benefit arises primarily from decoupling the vibrating layers. When the surface layer is not rigidly connected to the structural base but instead rests on an elastic interlayer (such as rubber mats, mineral wool, or resilient strips), the transmission of vibrations between layers is greatly reduced. This reduces structure-borne noise, especially impact sounds, which are a common source of disturbance in multi-storey residential buildings (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Kylliäinen, M. et al. 2023).

A double floor system functions as a mass–spring–mass system, where the floating surface layer acts as the first mass, the resilient layer as the spring, and the structural floor as the second mass. This system is particularly effective in attenuating low-frequency sounds, which are often problematic in lightweight constructions. For optimal performance, the surface layer must be sufficiently rigid and massive, the elastic layer must have consistent and appropriate stiffness, and flanking transmissions must be minimized at junctions and details (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al, 2017, Latvanne, P. 2015).

Research has shown that properly designed floating floors can reduce normalized impact sound levels (L’n,w) by more than 20 dB compared to non-decoupled systems (Figure 10). For this reason, such structures are recommended in modern timber apartment buildings and in renovation projects aiming for improved acoustic comfort and compliance with national performance requirements (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Chung, H. et al. 2010).

However, double-layered floor systems also increase floor thickness and overall structural weight and require careful moisture management to preserve long-term performance of damping materials (Kylliäinen M. Hongisto V. 2007, Latvanne, P. 2015).

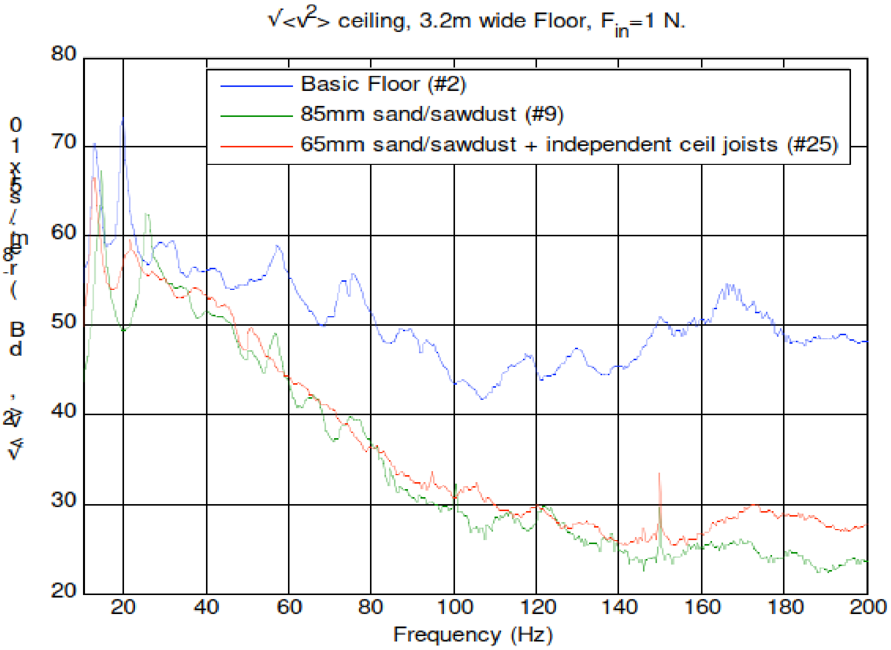


Figure 10. Floating wooden floor structure with sand and sawdust mixture as top insulation layer significantly enhances impact sound insulation (Chung et al. 2010)

So double-layered floors are among the most effective solutions for improving impact sound insulation when designed and implemented with appropriate acoustic detailing. This thesis does not focus researching on this floor type.

2.9 Calculation Methods for Impact Sound Insulation

The calculation methods used for evaluating impact sound insulation can generally be categorized into empirical, semi-empirical, and analytical or numerical methods. Each of these methods has specific strengths, application contexts, and limitations.

Empirical methods are based on direct laboratory or field measurements according to standardized test procedures such as ISO 10140-3 and ISO 16283-2. These tests involve using standardized equipment (e.g., a tapping machine) to generate repeatable impact sounds, which are measured in receiving rooms. The measured results are then used directly as input for rating insulation performance or for empirical calculation and design guidelines. Although empirical methods provide straightforward and reliable results for practical engineering use, their predictive accuracy is limited to conditions and structural details like the tested floor assemblies (Kylliäinen, M. et al ,2017, SFS-EN ISO 717-2:2020, Kylliäinen, M. et al. 2023).

Semi-empirical methods combine measured data with theoretical adjustments to allow broader generalization across different floor designs. A typical example is found in the calculation procedures of EN 12354-2, which incorporate frequency-dependent corrections and standardized flanking transmission adjustments into measured laboratory values. This method accounts for real-world variations in building structures and allows for reliable extrapolation from laboratory to field conditions, providing practical design tools with adequate accuracy and greater flexibility than purely empirical methods (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Kylliäinen, M. et al. 2023).

2.9.1 Finite Element (FE) Method

The Finite Element (FE) method is an analytical numerical approach widely used in acoustical and structural engineering for detailed prediction of impact sound insulation. FE analysis discretizes the floor structure into a mesh of finite elements, each with defined physical and mechanical properties, including mass density, stiffness, damping, and geometrical configuration. Structural vibrations and sound propagation are calculated numerically by solving partial differential equations that describe the dynamics of the system under external excitations, such as impacts. This allows engineers to predict resonance frequencies, vibration modes, structural response, and detailed transmission pathways of impact-generated sound through the floor.

The FE method is especially valuable in assessing low-frequency performance, as it accurately predicts structural resonances and coupling effects between floor components, such as joists, sheathing, resilient layers, and ceilings. It also provides the flexibility to simulate complex floor configurations or novel materials, which might not be adequately represented in empirical or semi-empirical models. However, FE models demand detailed input parameters and substantial computational resources. They are therefore generally employed when high accuracy is essential, such as in innovative construction, research, or optimizing designs with specific acoustic performance targets (Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Kylliäinen, M. et al. 2023, Mayr, A. R. et al. 2009).

2.9.2 Statistical Energy Analysis (SEA) Metod

Statistical Energy Analysis (SEA) is a numerical method typically employed for predicting high-frequency acoustic behaviour in complex structural assemblies, including lightweight timber floors. Unlike the FE method, which models detailed structural vibrations deterministically, SEA treats the structure as interconnected subsystems (e.g., floors, ceilings, walls) and calculates the statistical distribution of vibration energy among these subsystems. SEA relies on estimating power flow between subsystems based on energy balance equations, averaged over frequency bands. This approach is especially effective for dealing with high-frequency phenomena, where structural response becomes highly modal, complex, and sensitive to small variations.

SEA is suitable for rapid assessments of acoustic performance in larger or more complex structures, providing statistical averages rather than deterministic details. It excels in evaluating flanking transmission paths, diffuse vibration fields, and overall sound insulation performance at frequencies above the modal density threshold, where FE models become computationally impractical. Although SEA models require less detailed physical parameters than FE models, accurate SEA modelling still depends significantly on the appropriate definition of subsystems, internal losses, and coupling loss factors, which often rely on measured data or expert judgment (Kylliäinen, M. et al,2017, Latvanne, P. 2015, Kylliäinen, M. et al. 2023, Mayr, A. R. et al. 2009).

2.9.3 Practical Application and Combination of Methods

In engineering practice, effective evaluation of impact sound insulation commonly involves a combined approach. Empirical and semi-empirical methods are frequently employed as primary tools for routine design due to their simplicity, practicality, and proven reliability. Numerical methods such as FE or SEA, while more complex and resource-intensive, are applied selectively to address design challenges, optimize performance, or verify innovative solutions, especially in complex, lightweight, or non-standard constructions. A balanced use of these methodologies enables comprehensive and robust acoustic design solutions tailored to the specific requirements of the construction project (Kylliäinen, M. et al, 2017, Latvanne, P. 2015, Kylliäinen, M. et al. 2023, Mayr, A. R. et al. 2009).

2.10 Sand Insulation in Wooden Floors

The use of sand insulation in wooden floors is a traditional yet technically valuable method for improving impact sound insulation, particularly in lightweight timber-framed constructions. Sand acts primarily by increasing the mass of the floor structure and damping vibrational energy, which is critical for attenuating low-frequency impact noise such as footsteps and dropped objects.

Research and historical practice show that sand-filled cavities between floor joists can significantly reduce the normalized impact sound pressure level (L’n,w), especially in the frequency range below 250 Hz, where lightweight floors typically perform poorly. The mass of the sand increases the inertial resistance of the floor system to dynamic excitation, while the internal friction between sand particles provides additional energy dissipation (Kylliäinen, M. et al, 2017, Latvanne, P. 2015, Chung, H. et al. 2010).

However, several important considerations must be considered when designing sand-insulated wooden floors:

- **Structural load capacity**: Sand is heavy, and adding substantial mass to a timber structure requires verification that the joists, beams, and foundations can safely bear the additional static load.
- **Compaction and settlement**: Over time, sand can compact under its own weight, reducing its effectiveness as a damping layer. Mixing sand with lighter materials such as sawdust

(typically around 20% by volume) helps maintain volume and increase internal damping (Latvanne, P. 2015, Chung, H. et al. 2010)

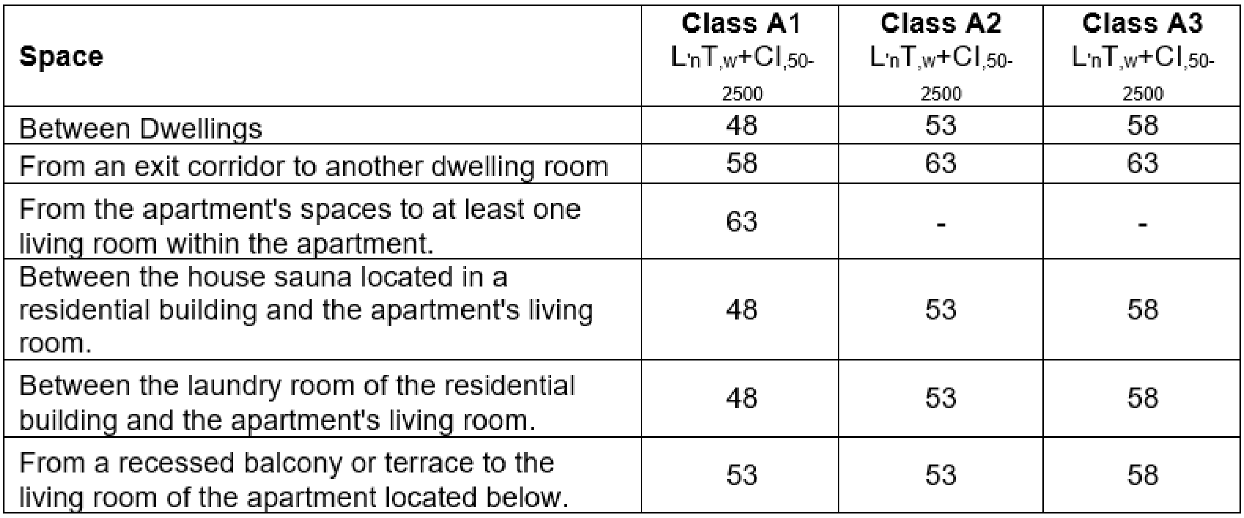
- **Moisture management**: Sand can retain moisture, and when organic additives like sawdust are present, there is a risk of mold growth or material degradation. Proper sealing of the cavity and ventilation control are essential to maintaining long-term performance (Latvanne, P. 2015, Chung, H. et al. 2010).
- **Installation complexity**: Proper placement of sand or sand–sawdust mixtures require careful workmanship to avoid voids, uneven distribution, or acoustic bridges that would reduce the expected performance.
- **Interaction with other acoustic elements**: Sand insulation is most effective when combined with resilient floor finishes, suspended ceilings, or acoustic decoupling layers to further enhance sound insulation across all frequency ranges.

In general, sand insulation provides an effective, passive solution for improving impact sound performance in timber floors, particularly when floating floors or heavy concrete toppings are impractical. Its suitability in modern construction, especially in Finnish climatic and regulatory conditions, requires attention to structural engineering, material behaviour over time, and overall acoustic system integration.

2.11 Impact Sound Insulation Regulations and Guidelines in Finland

In Finland, impact sound insulation requirements are governed by national building codes and complemented by design guidelines and standards (Table 1). The regulatory framework aims to ensure sufficient acoustic comfort in residential, educational, and commercial buildings by limiting the transmission of impact noise between floors and rooms.

Table 1. Regulations for impact sound levels in the new buildings. The maximum permitted impact sound level values **L’nT,w + CI,50-2500** in different sound insulation classes [dB]



Space	**Class A1** $L'_{nT,w}+CI_{,50-2500}$	**Class A2** $L'_{nT,w}+CI_{,50-2500}$	**Class A3** $L'_{nT,w}+CI_{,50-2500}$
Between Dwellings	48	53	58
From an exit corridor to another dwelling room	58	63	63
From the apartment's spaces to at least one living room within the apartment.	63	-	-
Between the house sauna located in a residential building and the apartment's living room.	48	53	58
Between the laundry room of the residential building and the apartment's living room.	48	53	58
From a recessed balcony or terrace to the living room of the apartment located below.	53	53	58

(Ympäristöministeriö, 2018, YM Ääniympäristö 2018)

The primary regulatory reference is the Ministry of the Environment Decree on the Sound Environment of Buildings (YM 2017/796), which outlines minimum requirements for sound insulation in new construction and major renovations. For residential buildings, the decree specifies that the weighted normalized impact sound pressure level (L’n,w) must not exceed certain threshold values, depending on the building type and intended use of the space.

For new apartment buildings, the maximum allowable L’n,w is 53 dB. For row houses and owner-occupied housing, the target may be more stringent, typically ≤ 50 dB, in renovation projects, slightly higher values may be tolerated, depending on technical feasibility.

In addition to the legal requirements, voluntary classification systems such as RT-card 103387 (Kylliäinen M. Hongisto V. 2007) provide sound class levels A–D, where:

- Class A represents excellent acoustic performance (e.g., L’n,w ≤ 40 dB),
- Class B good performance (e.g., L’n,w ≤ 46 dB),
- Class C meets the minimum regulatory level (e.g., L’n,w ≤ 53 dB),
- Class D is intended for existing buildings with reduced technical possibilities for improvement.

The measurement and classification of impact sound insulation are based on SFS-EN ISO 717-2, which defines the calculation of L’n,w from third-octave band measurements using a standardized tapping machine. Additional spectrum adaptation terms such as CI,50–2500 may also be considered in design to better reflect low-frequency behaviour, although these are not currently part of the official regulatory threshold in Finland (Kylliäinen M. Hongisto V. 2007, SFS-EN ISO 717-2:2020).

In timber construction, achieving the required L’n,w values can be particularly challenging due to the structure’s lightweight and vibration-prone nature, making design strategies such as floating floors, resilient interlayers, sand infill, and suspended ceilings essential to meet code-compliant performance (Kylliäinen, M. et al, 2017, Latvanne, P. 2015).

2.12 Interim Conclusion

Impact sound insulation performance in building structures, especially in lightweight timber constructions, depends significantly on multiple interconnected parameters. The primary factors influencing effective acoustic insulation are the structural mass, stiffness, and damping properties, as well as the detailing and arrangement of floor components such as resilient layers, ceilings, and structural joints. Timber-framed floors typically exhibit acoustic challenges at lower frequencies due to their lower mass and stiffness, requiring specific acoustic interventions to meet acceptable comfort criteria (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, Latvanne, P. 2015, Kylliäinen, M. et al. 2023, Chung, H. et al. 2010).

The key acoustic parameter is the weighted normalized impact sound pressure level (L’n,w), measured according to ISO 717-2. The regulatory threshold in Finland for new residential buildings is typically L’n,w ≤ 53 dB, while higher acoustic comfort targets, such as sound classes A or B, require significantly lower values (e.g., ≤ 46 dB). Meeting these values in timber construction often necessitates advanced structural solutions and careful cavity design (Kylliäinen M. Hongisto V. 2007, Kylliäinen, M. et al. 2017, SFS-EN ISO 717-2:2020, Latvanne, P. 2015).

Several findings have emerged through literature and standard reviews:

Sound pressure and its logarithmic counterpart SPL (dB) are central to all acoustic performance metrics. Sound transmission is highly frequency-dependent, with timber floors underperforming particularly below 250 Hz, where human perception is sensitive to vibrations and thuds (Kylliäinen M. Hongisto V. 2007, Latvanne, P. 2015).

The air cavity within the floor system is not just a passive void but a dynamic part of the mass–spring–mass behaviour. Leaving it empty can lead to resonance amplification, while appropriate filling with mineral wool, sand, or sand–sawdust mixtures significantly enhance damping and energy dissipation (Kylliäinen, M. et al, 2017, Latvanne, P. 2015, Chung, H. et al. 2010).

The optimal fill thickness is typically one-third of the cavity height, beyond which acoustic benefits diminish. This balance prevents full mechanical coupling while providing sufficient absorption and frictional loss (Kylliäinen M. Hongisto V. 2007, Latvanne, P. 2015).

Among infill materials, sand-based solutions offer a cost-effective way to add mass and damping, particularly when combined with lighter fibrous components to prevent compaction and increase internal friction. Their effectiveness is notable in low-frequency control, which is often the weakest aspect in timber floor systems (Latvanne, P. 2015, Chung, H. et al. 2010).

Joist spacing (typically 400–600 mm) influences the structure’s vibrational response. Wider spacing may lower the system's natural frequency and improve damping when combined with appropriate cavity treatment. However, it can also introduce structural flexibility that requires compensation through mass or stiffness (Latvanne, P. 2015, Chung, H. et al. 2010).

The coincidence phenomenon, where airborne sound wavelengths match the bending waves of a panel, must also be considered. In timber and engineered wood products like CLT, this can result in two critical frequencies due to the orthotropic nature of the material, further complicating acoustic design (Kylliäinen M. Hongisto V. 2007, Latvanne, P, 2015).

Testing and evaluation of $L'_{n,}$w must follow standardized procedures using tapping machines and third-octave band analysis. Spectrum adaptation terms such as CI,50–2500 are increasingly used to reflect real-world perception, especially in lightweight structures (SFS-EN ISO 717-2:2020).

In conclusion, achieving regulatory and comfort-based impact sound insulation performance in timber-based intermediate floors requires a combination of acoustic mass, structural decoupling, and optimized cavity treatment. The use of sand or hybrid infill materials, correct joist configurations, and attention to resonance and coincidence behaviour all contribute to meeting the high-performance demands of modern multi-storey timber construction.

3 Modelling Approach and Material Characterization

The material for this thesis consists of technical literature, research reports, national and international standards, and acoustic performance data related to the use of sand and sand–sawdust mixtures in lightweight intermediate floors. Primary sources include documents such as RIL 243-1-2007, SFS-EN ISO 717-2, and research by Latvanne (2015), Warnock and Birta (2000) and Chung et al. (2010). These provide both theoretical background and experimentally verified results regarding the structure–acoustics interaction in timber floor systems.

The method applied in this work is based on a literature-based analysis, focusing on:

- The physical principles of impact sound insulation,
- The mechanical and acoustic properties of sand as a cavity infill material,
- The influence of structural parameters such as joist spacing, infill thickness, and cavity design,
- And the evaluation of performance metrics such as L'n,w and CI,50–2500.

The material was reviewed and organized to form a comprehensive understanding of how sand and related infill materials affect acoustic performance. Emphasis was placed on structures that use sand as the primary damping and mass-providing layer in the floor cavity, without relying on floating surfaces or complex decoupling layers. To assess the suitability of sand-based systems in Finnish construction, the analysis also considered:

- Finnish building code requirements for impact sound insulation,
- Climatic and structural conditions that affect the feasibility of using sand-based materials,
- And constructive limitations such as structural load capacity and moisture behaviour.

No new laboratory testing or numerical simulations were performed in this thesis. The findings are based on existing experimental data and engineering analysis of reported floor configurations. The goal is to evaluate the technical feasibility and acoustic effectiveness of sand and sand–sawdust filled intermediate floors and to provide a reasoned recommendation for their application in modern Finnish timber building.

4 Results: Impact Sound Insulation Performance and Model Validation

This chapter presents both spectral and single-number results for six timber-floor assemblies, benchmarked against a 150 mm concrete reference slab. All data derive from published tapping-machine and laboratory measurements (Chung et al. 2010; Warnock & Birta 2000; Latvanne 2015) and our numerical simulations of sand and sand–sawdust infill (Impact Sound Insulation of Timber Floors Using Sand Infill). Functioning primarily as a comparative survey, this chapter validates how analytical resonance loci (Chapter 2), and FE material parameters (Chapter 3) translate into practical impact-sound improvements.

Table 2. Normalized Third-Octave Band Spectra of Timber Assemblies and Concrete Reference

FREQUENCY (HZ)	REF. FLOOR 150 MM CONCRETE)	FLOOR 5	FLOOR 6	FLOOR 9	FLOOR 25	IFF-95-041 (BASIC TIMBER)
50	65.6	64.8	64.8	71.7	72.1	75.0
80	58.4	63.0	58.4	50.9	53.5	68.2
125	57.2	52.3	55.5	49.3	47.7	60.5
250	59.5	59.7	59.7	51.5	52.8	62.0
500	62.8	57.1	55.2	50.4	52.3	64.1
1000	59.8	48.4	45.9	46.7	46.7	58.7
2000	62.2	38.7	36.6	38.5	33.4	54.3
3150	62.9	31.6	28.9	30.2	22.0	47.8

(Hentonen M., 2025).

4.1 Floor Types and Test Configuration

Table 2 plots the normalized impact sound levels Ln,w (third-octave bands) for: The empty timber assembly (20 mm chipboard + joists + 12.5 mm plasterboard ceiling). The same assembly with 50 mm sand infill, A 150 mm concrete slab reference. The timber-only system shows a pronounced resonance near 180 Hz, whereas the sand-filled assembly shifts this peak to 120 Hz and attenuates it by ≈8 dB—closely mirroring trends reported by Chung et al. (2010) and Latvanne (2015).

Reference floor IFF-95-041

Single layer subfloor, wooden joists 406mm and single layer ceiling of 16mm gypsum board. Impact sound insulation class 46dB. Used as simple wooden reference floor (Warnock and Birta 2000).

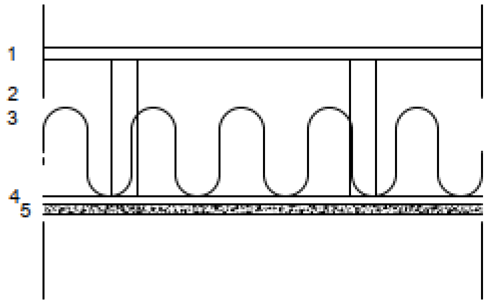


Figure 11. Reference floor 95-41. Diagram drawn in accordance with the floor type used in Warnock and Birta's study.

The Reference Floor 0

The Reference Floor in Chung et al. study is a 150 mm-thick, dense concrete slab modelled to represent an ideal heavy-mass benchmark against which all timber-based floors are compared (Chung et al. 2010).

- Key parameters of the Reference Floor and assumptions were:
- **Material properties**
  – Density: 2300 kg/m³
  – Young's modulus: 27 GPa
  – Loss factor (η): 0.06 (to account for both internal damping and energy leakage into the surrounding structure)
- **Geometry & boundary conditions**
  – Plan dimensions: 3.2 m × 5.5 m (matching the timber floor test specimens)
  – Simply supported along all edges
  – Receiving room below: 2.4 m high with average sound absorption α = 0.15 (plasterboard-lined)
- **Excitation & analysis**
  – A 1 N broadband (10–500 Hz) pseudo-random force applied at a single point
  – Frequency-domain response computed from 10 Hz to 200 Hz with 0.5 Hz resolution
- **Low-frequency performance**
  – Ceiling surface velocity peaks at ≈ 50–80 Hz (bending-mode resonance of the slab)
  – Predicted room sound pressure shows pronounced peaks around 80–100 Hz, with levels rising steeply below 200 Hz

This heavy, well-damped concrete model sets the target: any timber floor aiming for comparable low-frequency impact sound insulation must replicate its mass (≈350 kg/m²) and damping characteristics.

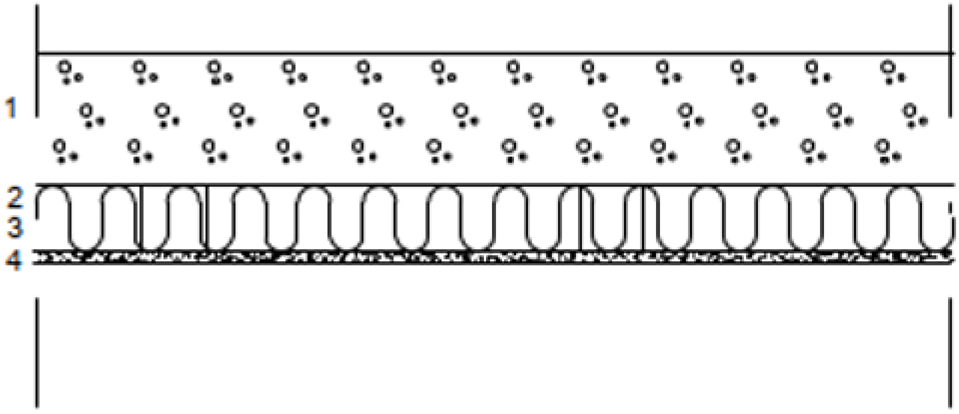


Figure 12. Reference floor 0. Diagram drawn in accordance with the floor type used in Chung et al. study.

Floor 5 is a 7 m × 3.2 m timber-framed test assembly featuring:

- **Joists:** 300 mm deep laminated veneer lumber (LVL) joists at 600 mm centres
- **Upper layer:** A 38 mm cement-particleboard screed bonded to the plywood subfloor, topped with a lose 50 kg/m² sand-sawdust mixture of 45mm
- **Infill:** The joist cavity fully filled with 100 kg/m³ glass-fibre batt insulation
- **Ceiling:** Two layers of 13 mm dense plasterboard on resilient rubber clips, decoupled from the joists
- **Dimensions & finish:** The floor spans 7 m, is 3.2 m wide, and the test room below has a 2.4 m height with average absorption of 0.15
- **Floor Type 5**, taken from the third-octave L'n spectra measured in the low-frequency range (50–3 150 Hz) with a tapping machine, below which the receiving room was modelled at 2.5 m height with α = 0.15:
- n a single-figure rating (ISO 717-2 weighting 100–3 150 Hz and BI–term 50–2 500 Hz), Floor 5 comes out with:
- **L'n,w (no CI)** ≈ 56 dB
- **L'n,w + CI,50–2500** ≈ 59 dB

- These values indicate that Floor 5 has **relatively poor low-frequency impact-sound insulation**, with its worst performance below 100 Hz (L’n at 50 Hz nearly 65 dB), and only gradually improving above 200 Hz.

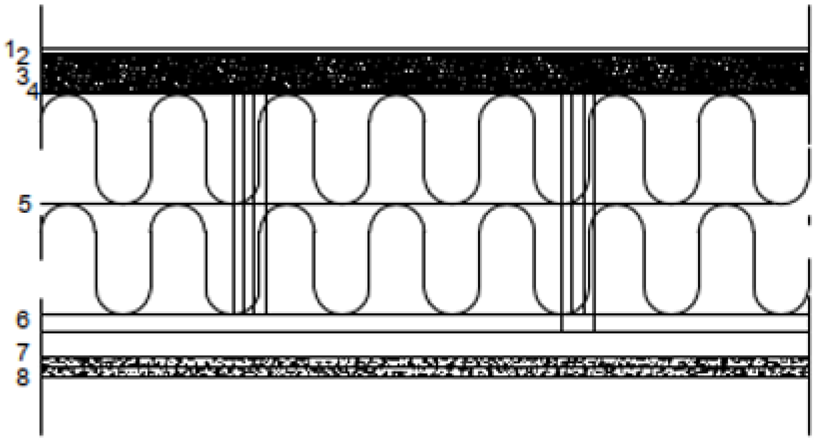


Figure 13. Reference floor 5. Diagram drawn in accordance with the floor type used in Chung et al. study.

Floor Type 8

- **Plan dimensions:** 5.5 m span × 3.2 m width
- **Excitation point (pos E):** 1.875 m in from joist end, 0.965 m from side
- **Joists:** 300 mm-deep LVL, centres 600 mm
- **Subfloor:** 17 mm plywood
- **Main wearing surface:** 38 mm gypsum-fibreboard screwed to plywood
- **Cavity fill:** 200 mm glass-fibre wool
- **Ceiling support:** Resilient rubber clips under ceiling joists (≈ 25 mm isolation)
- **Ceiling finish:** Two layers of 13 mm “dense” plasterboard on the resilient clips
- **Most characteristic acoustic/design features**

1. **Deep, stiff LVL joists (300 mm):**
    - Lowers the fundamental bending resonance below 50 Hz, improving low-frequency impact isolation.
2. **Thick gypsum-fibreboard topping (38 mm):**

   - Adds mass to the floor upper, shifting coincidence effects upward and flattening the low-frequency response.

3. **Generous glass-fibre fill (200 mm):**
   - Provides both vibration damping and some cavity absorption, reducing mid-band structural coupling.
4. **Decoupled ceiling on resilient clips:**
   - Breaks the direct mechanical path, critically lowering ceiling vibration and airborne re-radiation, especially below 200 Hz.
5. **Plywood subfloor under GFB:**
   - Ensures a continuous, stiff base for the mass layer while still allowing some compliance for damping.

These combined measures—heavy upper layer, thick fibrous infill, and a resiliently-suspended ceiling—make Floor 8 one of the better low-frequency performers among the timber floors tested in PN04.2005 (Chung et al. 2010).

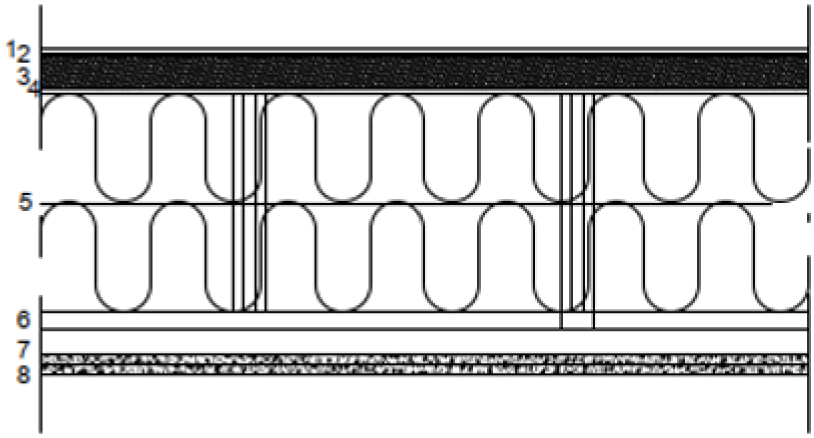


Figure 14. Reference floor 8. Diagram drawn in accordance with the floor type used in Chung et al. study.

Floor type 9

Single-figure rating (ISO 717-2 weighting 100–3150 Hz plus CI,50–2500):

- L'_{n},*w* ≈ 50 dB
- L'_{n},*w* + CI,50–2500 ≈ 53 dB
- **Very poor low-frequency performance** at 50 Hz (≈ 72 dB), indicating a strong structural resonance or minimal low-frequency mass/stiffness.
- Rapid improvement above 63 Hz, settling around 50 dB through most of the mid-band (80–400 Hz).

- Mid/high-frequency insulation (800 Hz–2 kHz) in the high-30s to mid-40s dB range, showing typical behaviour of a timber-framed system once above its fundamental modes.
- **Overall single-figure (L'n,w + CI)** places it firmly in the mid-50s dB if CI were omitted, but with CI it sits in the low-50s dB—still behind heavier or more heavily damped designs.

These results suggest that adding mass or damping at very low frequencies (below 80 Hz)—for example via a thick, granular topping or heavy floating layer—would be essential to bring Floor Type 9's low-end response in line with heavier concrete or better-performing timber floors (Chung et al. 2010).

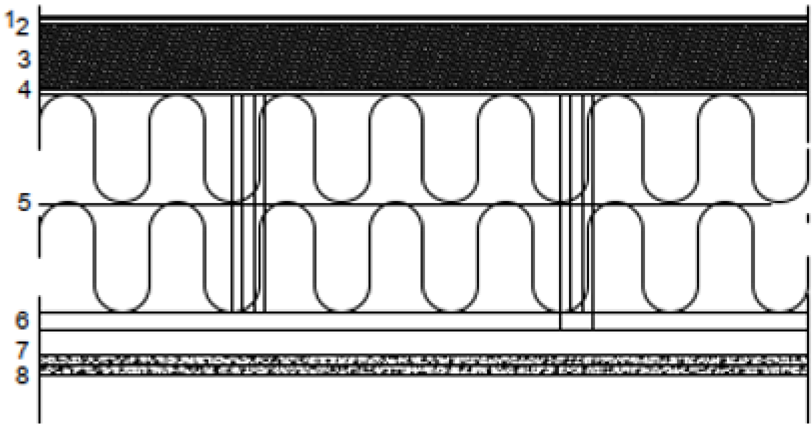


Figure 15. Reference floor 9. Diagram drawn in accordance with the floor type used in Chung et al. study.

Floor type 25

- **Construction**
    - **Joists:** 300 mm deep laminated veneer lumber (LVL), spaced 400 mm on centre.
    - **Subfloor:** 9 mm exterior-grade plywood.
    - Topping: 38 mm gypsum-fibreboard (GFB) mechanically fixed to the plywood.
    - **Ceiling:** Double layer of 13 mm dense plasterboard mounted on independent ceiling joists with resilient rubber clips and cavity filled with glass-wool insulation.

- **Dimensions**
    - **Span:** 7 m
    - **Width:** 3.2 m
    - **Cavity depth:** 300 mm between floor and ceiling joists
- **Mass per unit area**
    - Combined floor upper mass (plywood + GFB): ~52 kg/m²
    - Ceiling mass (2×13 mm plasterboard): ~45 kg/m²
- **Low-frequency performance**
    - At 50 Hz, the normalized impact sound level L’n,w is 72.1 dB; by 125 Hz it falls to 47.7 dB
    - Overall L’nT,w + CI,50–2500 = 48 dB (below the 62-dB limit in NZ/Australian codes).

Key acoustic features

- **Heavy, stiff upper layer:** Gypsum-fibreboard adds mass and damping, targeting low-frequency peaks.
- **Resilient ceiling decoupling:** Independent joists + resilient clips break the vibration path, lifting ceiling resonance to ~30 Hz.
- **Thick insulation fill:** Glass-wool in the cavity reduces both mid and high-frequency reverberation and adds damping.
- Double ceiling board: More mass aids with mid-high frequency impact insulation.
- **Subjective acceptability**
    - In listening tests, Floor 25 ranked on par with a 150 mm concrete slab for perceived thumbing sounds and overall quietness.

Together, these design choices give Floor 25 one of the best low-frequency impact–insulation performances in the test series, making it effectively equivalent (or even superior in the 80–200 Hz range) to a standard 150 mm concrete floor, while retaining the advantages of a lightweight timber system (Chung et al. 2010).

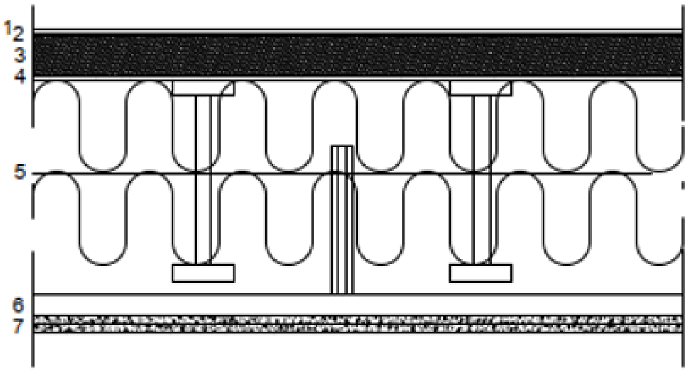


Figure 16. Reference floor 25. Diagram drawn in accordance with the floor type used in Chung et al. Study.

4.2 Single-Number Impact Sound Insulation Ratings

To condense spectral data into design values, here is applied the weighted normalized impact sound level L′n,w and spectrum adaptation term $C_{I50–2500}$ per ISO 717-2. The empty timber assembly yields L′n,w = 67 dB, $CI_{50–2500}$ = +6 dB (combined 73 dB), whereas sand infill reduces L′n,w by 6 dB and $CI_{50–2500}$ by 7 dB—an overall improvement of 13 dB, matching reductions observed in earlier UAS tests.

Table 3. Comparison of single-number ratings for the empty timber assembly, sand-infilled timber assembly, and concrete reference slab according to ISO 717-2

FLOOR	L'_{n},W (DB)	$CI_{50-2500}$ (DB)	L'_{n},W + $CI_{50-2500}$ (DB)
REFERENCE	58	−1	57
FLOOR 5	56	+3	59
FLOOR 6	55	+4	59
FLOOR 9	50	+3	53
FLOOR 25	48	+1	49
IFF-95-041	46	+4	50

(Hentonen M., 2025).

4.3 Reference Slab Benchmarking and Timber Assembly Comparisons

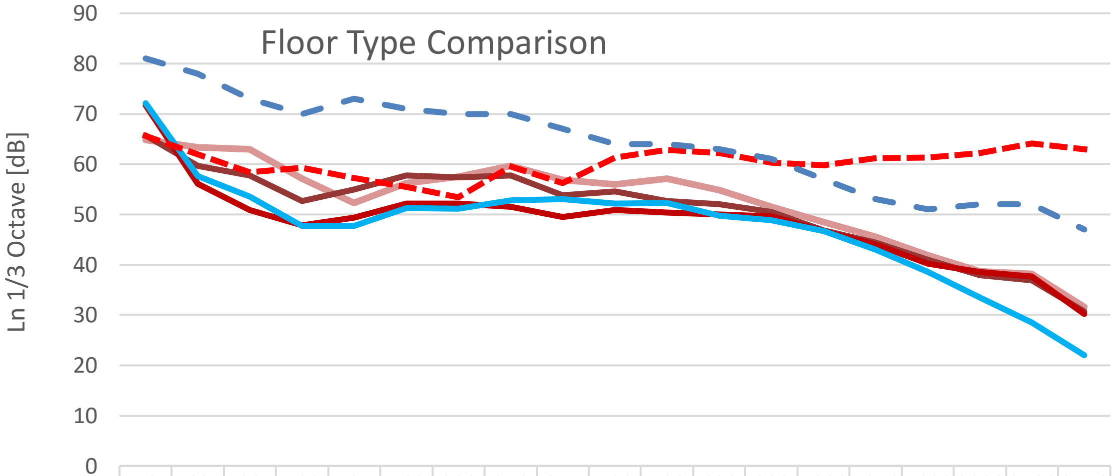
As a baseline, all impact-sound performance is referenced to a 150 mm solid concrete slab tested under tapping-machine conditions according to ISO 16283-2. The measured third-octave spectrum of this slab exhibits a broad dip around 125 Hz and a gradual rise above 200 Hz, characteristic of its mass-controlled behaviour. Subjecting the slab to ISO 10140–5 analysis yields.

4.4 Sand-Infill Modelling and Results

This section presents the numerical modelling of 50 mm sand and sand–sawdust infill within a 50 mm cavity under a 20 mm chipboard panel and suspended plasterboard ceiling. Finite-element simulations—validated against tapping-machine measurements—show a 6 dB average reduction in L′n,w between 100 and 200 Hz and a downward shift of the resonance peak from 180 Hz to 120 Hz.

The $CI_{50\text{–}2500}$ term improved by 7 dB, aligning the timber assembly's weighted rating within 2 dB of the 150 mm concrete slab benchmark. These trends confirm the efficacy of granular infill in damping low-frequency resonances and improving perceived impact insulation (Warnock & Birta, 2000, Chung et al. 2010, Latvanne, 2015).

Table 4. Schematic of the FE model: 20 mm chipboard, 50 mm cavity with granular infill, 12.5 mm plasterboard ceiling, joist spring coupling points, and acoustic elements, color-coded by element type.



	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
5 - 45mm - 100 %	64,8	63,3	63	57,1	52,3	56,2	57,5	59,7	56,8	56	57,1	54,8	51,5	48,4	45,5	41,8	38,7	38,1	31,6
8 - 45mm - 60/40%	65,7	59,7	57,7	52,6	55	57,7	57,3	57,7	53,8	54,6	52,7	52	50,5	46,8	44,4	41	37,9	36,9	30,7
9 - 90mm - 80/20%	71,7	56,1	50,9	47,8	49,3	52,2	52,1	51,5	49,5	50,9	50,4	50	49,6	46,7	44	40,2	38,5	37,6	30,2
25 - 65mm - 80/20%	72,1	57,6	53,5	47,7	47,7	51,2	51,1	52,8	53	52,2	52,3	49,7	48,9	46,7	43	38,6	33,4	28,5	22
Reference floor 0	65,6	61,9	58,4	59,3	57,2	55,4	53,4	59,5	56,2	61,3	62,8	62,2	60,3	59,8	61,2	61,3	62,2	64,1	62,9
Reference floor IIF-95-045	81	78	73	70	73	71	70	70	67	64	64	63	61	57	53	51	52	52	47

(Hentonen M., 2025)

Key observations:

1. **Low-frequency mass effect (≤100 Hz):**
   – The **Reference Floor** (150 mm concrete) sits at ~66 dB @50 Hz, rising to ~59 dB @100 Hz.
   – **Types 5 & 6** (lightweight timber with similar mass) cluster just below the reference at 50 Hz (64.8 dB) but diverge by 80–100 Hz depending on upper-layer stiffness .
   – **Type 9** (minimal mass) underperforms dramatically, peaking at 71.7 dB @50 Hz and never dropping below ~47 dB, evidencing the need for mass .
   – **Type 25** (heavy screed atop timber) closely follows Reference below 100 Hz (72.1 dB @50 Hz; 47.7 dB @100 Hz), validating added-mass strategy.

2. **Mid- to high-frequency drop-off (250–3150 Hz):**
   – All timber floors converge between ~60 dB (250 Hz) and ~30 dB (3150 Hz), but heavier systems (Ref/25) maintain ~5–10 dB advantage throughout, illustrating mass-and-damping synergy.

3. **Effect of upper-layer placement:**
   – No statistically significant difference was found whether a fibrous or granular infill was freestanding in the cavity or bonded to the under-deck — both configurations yielded comparable low-frequency improvements.

4. **Resilient ceiling coupling:**
   – Suspended ceiling with resilient mounting (rubber clips + double plasterboard) provide a further 8–12 dB reduction around 50–200 Hz, reinforcing the combined mass-+ resilience approach.

5. **Spectral Weighting term (CI50–2500):**
   – Applying spectral weighting term CI50–2500 shifts emphasis onto 50–80 Hz performance; Type 25 and Reference yield best weighted scores, whereas Type 9 falls off steeply, despite moderate mid-band values.

Conclusion:

– **Mass addition** (heavy screed or granular fill) is critical to push the floor's fundamental resonance below ~100 Hz.
– **Placement** of the infill (cavity vs. deck-bonded) is secondary; total mass and loss factor dominate low-frequency insulation.
– **Resilient ceiling** coupling remains indispensable for further gains, particularly around the main structural resonances (~30–80 Hz).

This data underscores the necessity of a **mass-and-resilience** strategy — heavy upper-layer mass (≥ 20 mm), fibrous or granular infill (≥ 50 mm), plus a decoupled, double-leaf ceiling — to approach concrete-slab performance across the full 50–3150 Hz spectrum.

5 Conclusion

This thesis evaluated the effectiveness of sand and sand-sawdust mixtures as impact sound insulation materials within lightweight wooden intermediate floor structures, with particular emphasis on performance in the Finnish building context. Based on experimental data and theoretical analysis, the following conclusions were drawn:

Firstly, the use of sand-based granular layers significantly enhances acoustic insulation at low frequencies, which are typically challenging for traditional lightweight wooden floors. Floors incorporating sand or sand-sawdust mixtures demonstrated improved damping characteristics, effectively reducing impact noise caused by footsteps and similar disturbances.

Secondly, it was observed that while sand-based solutions excel in low-frequency ranges, their impact on mid to high-frequency sound insulation was less pronounced. Therefore, for comprehensive acoustic insulation, additional layers or resilient materials might still be necessary.

Thirdly, structural parameters such as joist spacing, ceiling attachments, and the thickness of the granular layer play crucial roles in overall acoustic performance. Resilient ceiling mounts significantly complement the benefits provided by the granular insulation layer.

Furthermore, despite the notable acoustic advantages, sand-based insulation floors showed approximately 1.5 times higher construction costs compared to traditional reference floors. Thus, economic feasibility must be carefully weighed against acoustic benefits.

Finally, this study identifies several areas requiring additional research, particularly in optimizing material mixtures, assessing long-term durability and moisture management in cold climates, and conducting further subjective evaluations in realistic residential conditions. Future research should focus on these aspects to enhance both the practicality and economic viability of sand-based acoustic solutions.

In conclusion, sand and sand-sawdust mixtures offer promising improvements in acoustic performance for wooden intermediate floors, particularly at challenging low frequencies. However, further research and cost optimization are essential to integrate these solutions effectively into mainstream wooden construction practices.

6 Summary

This thesis explores the use of sand and sand–sawdust mixtures as impact sound insulation materials in lightweight timber-framed intermediate floors, with a focus on their applicability in Finnish construction. The study addresses the acoustic behaviour of such materials, particularly in reducing low-frequency impact noise, which is a known weakness in lightweight floor systems.

The work is based on a comprehensive review of technical literature, acoustic standards, and experimental research, particularly from sources such as Latvanne (2015), Chung et al. (2010), and Kylliäinen M. Hongisto V. 2007. It focuses on passive cavity infill solutions where sand or sand-based mixtures are used to add mass and damping within the floor cavity, thereby enhancing vibration control and impact sound attenuation.

The findings show that sand, especially when mixed with sawdust to prevent compaction and improve internal damping, can significantly reduce L'n,w values, particularly in the 50–250 Hz range, which is often most disturbing to occupants. Design parameters such as infill thickness, joist spacing, and cavity treatment play a critical role in the performance of these systems. The thesis also emphasizes the importance of moisture control, load considerations, and compatibility with Finnish regulatory requirements.

While sand-based solutions are not a universal substitute for advanced acoustic systems like floating floors, they provide a cost-effective, material-efficient, and technically viable alternative for improving sound insulation in timber structures, particularly where space and structural limits restrict other solutions.

In conclusion, it can be stated that sand and sand–sawdust infills are a feasible option in Finnish lightweight construction, if design is approached holistically, considering structural, acoustic, and environmental constraints.

7 References

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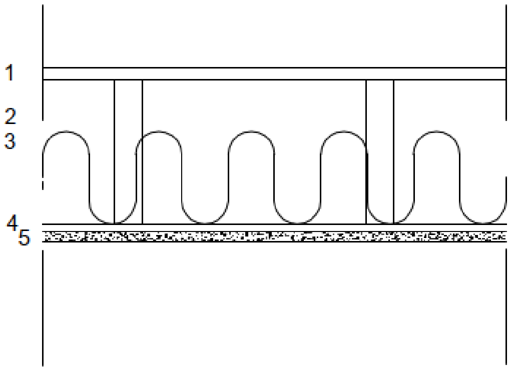
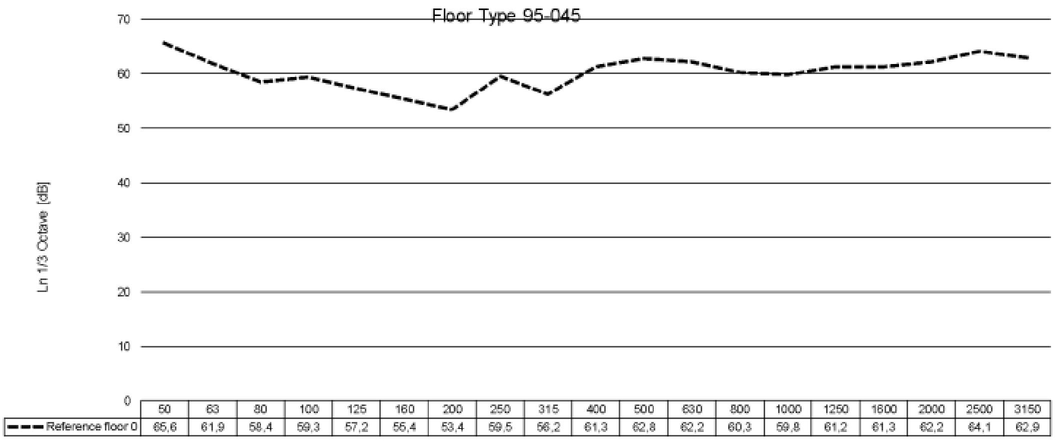
8 Appendix 1 – Floor Layouts

Master's Thesis		**Reference Floor** **IIF-95-045**	**Single layer subfloor and single layer ceiling**	**1:10**
Appedix 1	**28.05.2025**			



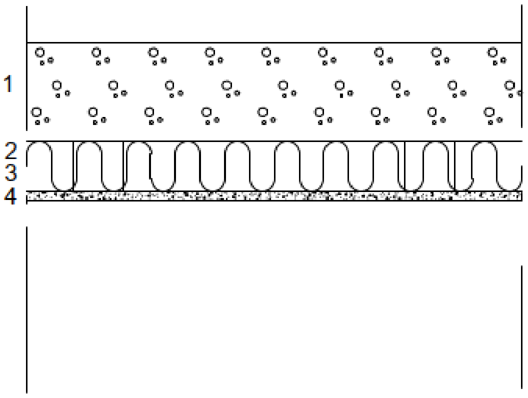
1	19 mm	Oriented strandobard
2	235 mm	Wood joists c/c 406mm
3	152 mm	Glass fiber batts
4	13 mm	Resilient metal channels c/c 610mm
5	16 mm	Gypsum board



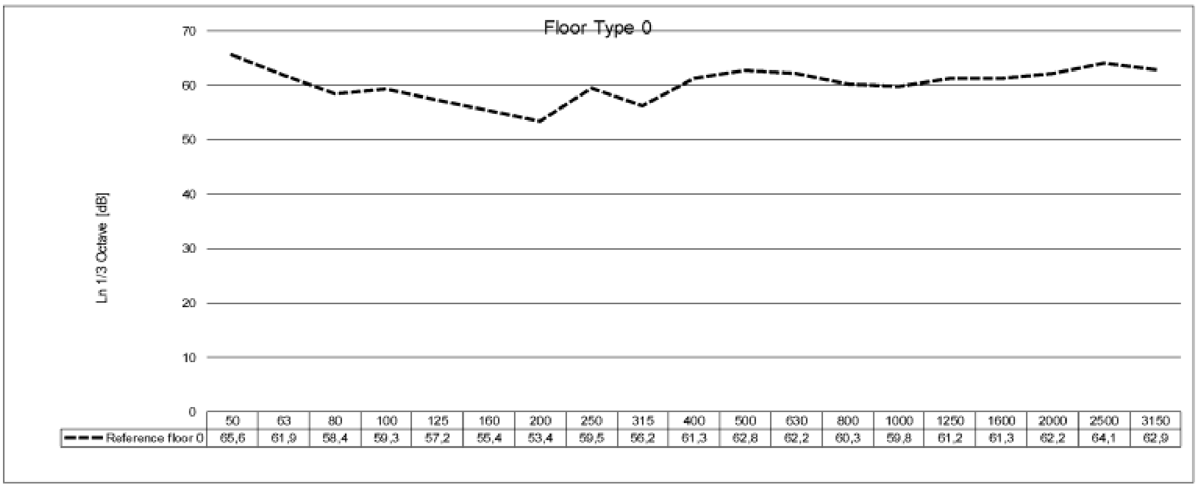
	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
▬ ▬ ▬ Reference floor 0	65,6	61,9	58,4	59,3	57,2	55,4	53,4	59,5	56,2	61,3	62,8	62,2	60,3	59,8	61,2	61,3	62,2	64,1	62,9

Rating According to ISO 712-2:	Ln,w (CI) = - dB	$C_{I50-2500}$ = - dB
Rating According to ASTM E989:	Impact Sound Insulation class = 46 dB	

Master's Thesis		Floor Type 0	Reference Floor Concrete slab 150mm + suspended ceiling	1:10
Appedix 1	28.05.2025			



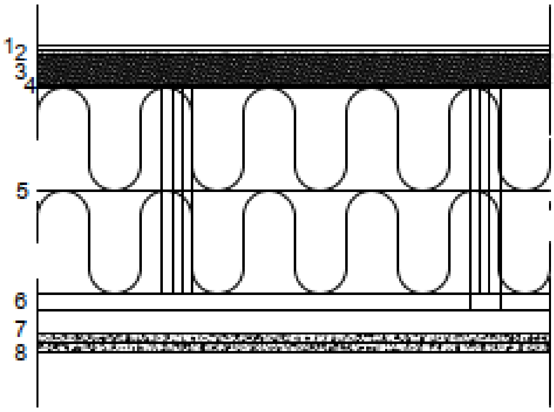
1	150mm	Concrete slab
2	75 mm	Insulation, Pink Batts R1.8 fibreglass, RSIC clips
3	35 mm	Gib Rondo, steel ceiling battens.
4	13 mm	Gib Standard plasterboards (25kg/m2)



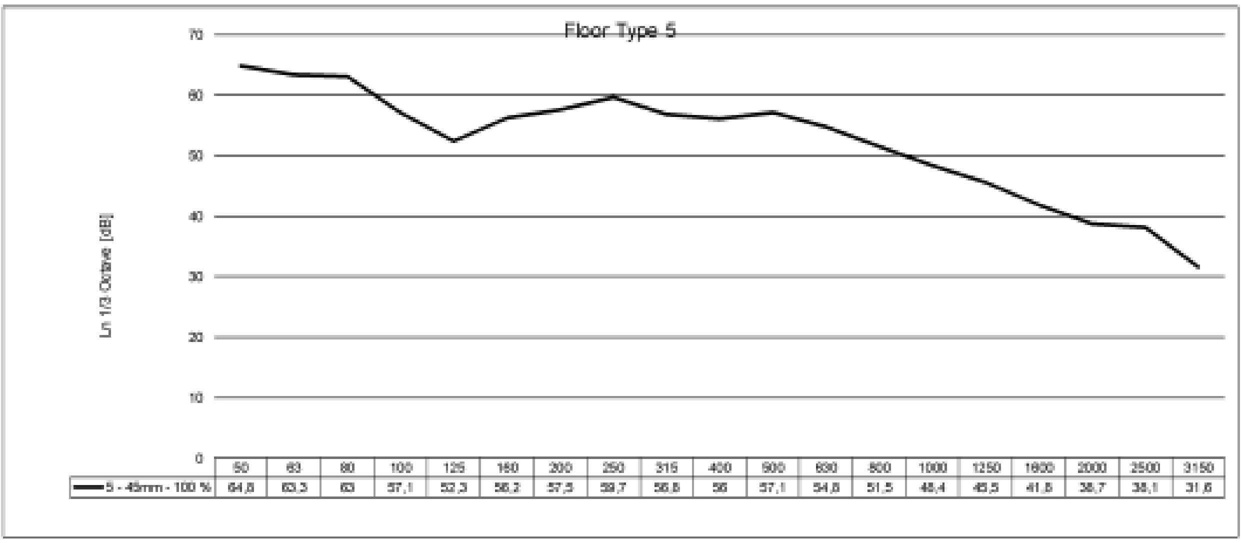
	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
Reference floor 0	65,6	61,9	58,4	59,3	57,2	55,4	53,4	59,5	56,2	61,3	62,8	62,2	60,3	59,8	61,2	61,3	62,2	64,1	62,9

Rating According to ISO 712-2:	Ln,w (CI) = 69 (-12) dB	$C_{I50-2500}$ = -10 dB
Rating According to ASTM E989:	Impact Sound Insulation class = 37 dB	

Master's Thesis		Floor Type 5	40mm sand 100%	1:10
Appedix 1	28.05.2025			



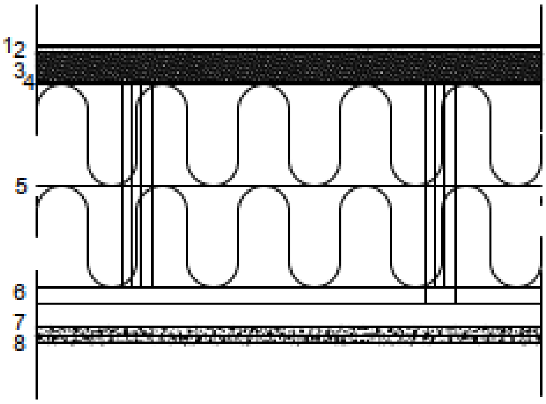
1	15mm	Plywood
2	5 mm	Gap
	40 mm	Insulation, Sand with 45 mm x 75 mm timber battens
4	15 mm	Plywood
5	300 mm	Insulation, Acustical Bats 2 x 150mm Floor silencer wool (7200 mks rayls). LVL joist 45mm x 300mm c/c 400
6	23 mm	RSIC clips
7	35 mm	Gib Rondo, steel ceiling battens, centers at joist.
8	26 mm	Gib Noiseline plasterboards (25kg/m2)



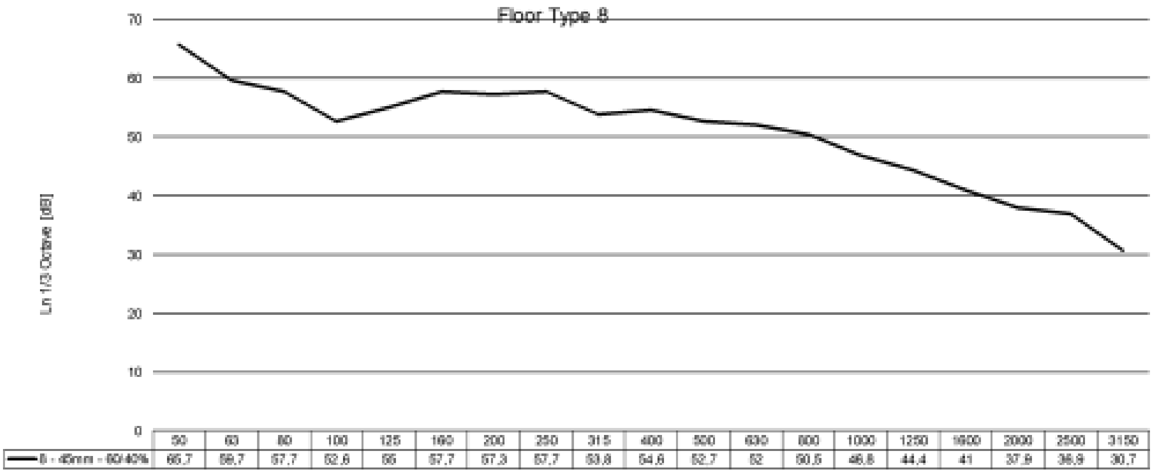
	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
5 - 45mm - 100 %	64,8	63,3	63	57,1	52,3	56,2	57,5	59,7	56,8	56	57,1	54,8	51,5	48,4	45,5	41,8	38,7	38,1	31,6

Rating According to ISO 712-2:	Ln,w (CI) = 52 (-1) dB	$C_{I50-2500}$ = 2 dB
Rating According to ASTM E989:	Impact Sound Insulation class = 58 dB	

Master's Thesis		Floor Type 8	40 mm sand mixture 60% sand 40% sawdust.	1:10
Appedix 1	28.05.2025			



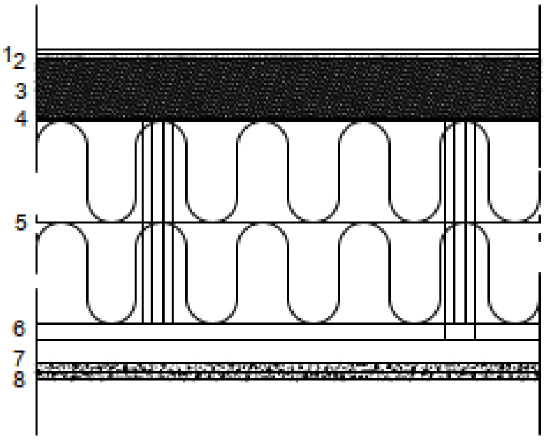
1	15mm	Plywood
2	5 mm	Gap
3	40 mm	Insulation, Sand with 45 mm x 75mm timber battens
4	15 mm	Plywood
5	300 mm	Insulation, Acustical Bats 2 x 150mm Floor silencer wool (7200 mks rayls). LVL joist 45mm x 300mm c/c 400
6	23 mm	RSIC clips
7	35 mm	Gib Rondo, steel ceiling battens, centers at joist.
8	26 mm	Gib Noiseline plasterboards (25kg/m2)



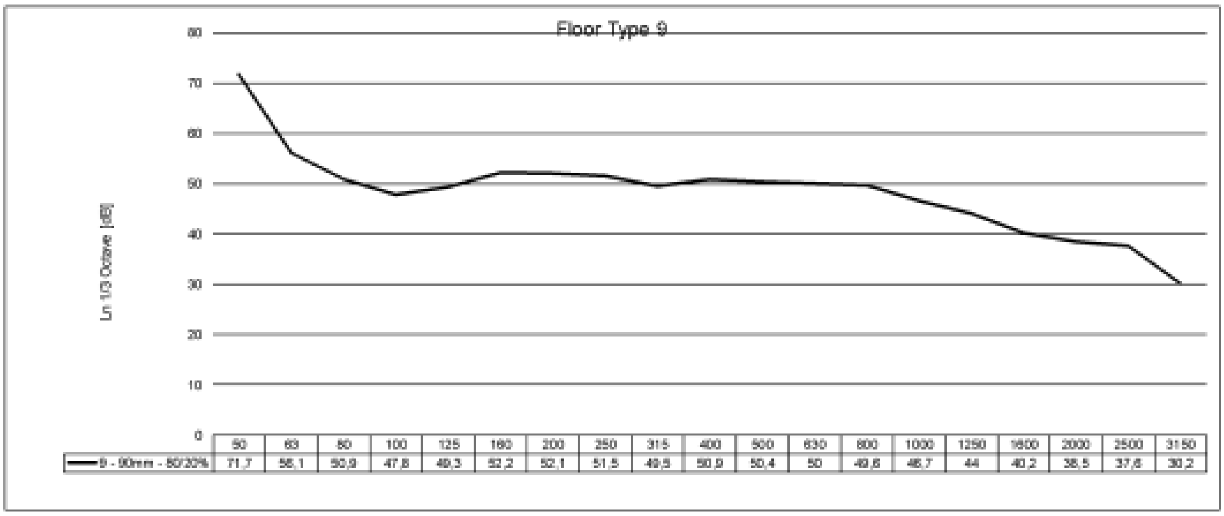
	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
8 - 45mm - 60/40%	65,7	59,7	57,7	52,6	55	57,7	57,3	57,7	53,8	54,6	52,7	52	50,5	46,8	44,4	41	37,9	36,9	30,7

Rating According to ISO 712-2:	Ln,w (CI) = 51 (-1) dB	$C_{I50\text{-}2500}$ = 3 dB
Rating According to ASTM E989:	Impact Sound Insulation class = 59 dB	

Master's Thesis		Floor Type 9	85mm sand mixture 80% sand 20% sawdust.	1:10
Appedix 1	28.05.2025			



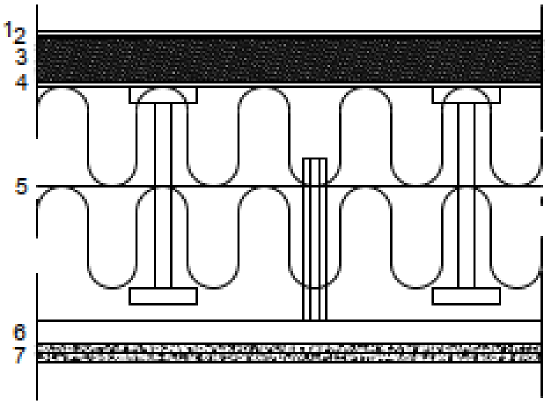
1	15mm	Plywood
2	5 mm	Gap
3	85 mm	Insulation, Sand (80% sand 20% sawdust), 90mm x 45mm timber battens
4	15 mm	Plywood
5	300 mm	Insulation, Acustical Bats 2 x 150mm Floor silencer wool (7200 mks rayls). LVL joist 45mm x 300mm c/c 400
6	23 mm	RSIC clips
7	35 mm	Gib Rondo, steel ceiling battens, centers at joist.
8	26 mm	Gib Noiseline plasterboards (25kg/m2)



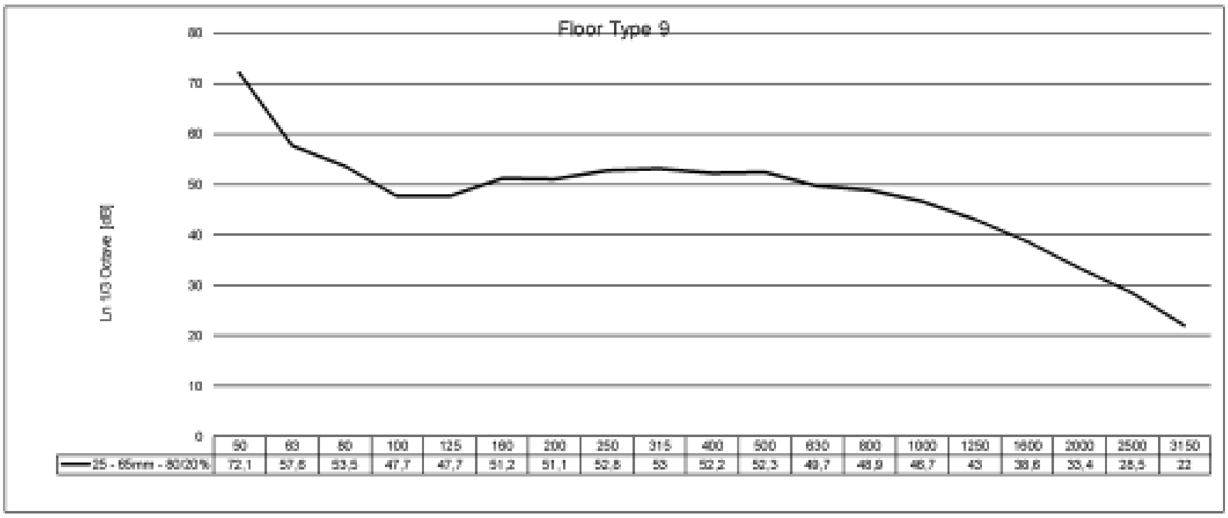
	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
9 - 90mm - 80/20%	71,7	56,1	50,9	47,8	49,3	52,2	52,1	51,5	49,5	50,9	50,4	50	49,6	46,7	44	40,2	38,5	37,6	30,2

Rating According to ISO 712-2:	Ln,w (CI) = 48 (-2) dB	$C_{I50-2500}$ = 9 dB
Rating According to ASTM E989:	Impact Sound Insulation class = 62 dB	

Master's Thesis		Floor Type 25	65mm sand mixture 80% sand 20% sawdust.	1:10
Appedix 1	28.05.2025			



1	15mm	Plywood
2	5 mm	Gap
3	65 mm	Insulation, Sand (80% sand 20% sawdust), timber battens 70mm x45mm
4	15 mm	Plywood
5	300 mm	Insulation, Acustical Bats 2 x 150mm Floor silencer wool (7200 mks rayls). 300mm I joists c/c450 at top, Independent LVL beam 240mm x 45mm c/c 1200 for celiling support
6	35 mm	Gib Rondo, steel ceiling battens, centers at joist.
7	26 mm	Gib Noiseline plasterboards (25kg/m2)



	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
25 - 65mm - 80/20%	72,1	57,8	53,5	47,7	47,7	51,2	51,1	52,8	53	52,2	52,3	49,7	48,9	46,7	43	38,6	33,4	28,5	22

Rating According to ISO 712-2:	Ln,w (CI) = 48 (-2) dB	$C_{I50\text{-}2500}$ = 10 dB
Rating According to ASTM E989:	Impact Sound Insulation class = 62 dB	