LUND UNIVERSITY

MANAGEMENT OF ACOUSTICS IN LIGHTWEIGHT STRUCTURES

KLAS HAGBERG

Engineering Acoustics

Doctoral Thesis

DEPARTMENT OF CONSTRUCTION SCIENCES

DIVISION OF ENGINEERING ACOUSTICS

ISRN LUTVDG/TVBA--18/1015--SE (1-151) | ISSN 0281-8477

ISBN 978-91-7753-600-0 (print) | ISBN 978-91-7753-601-7 (pdf)

DOCTORAL THESIS

MANAGEMENT OF ACOUSTICS IN LIGHTWEIGHT STRUCTURES

KLAS HAGBERG

Printed by V-husets tryckeri LTH, Lund, Sweden, April 2018 *(Pl).*

For information, address:

Div. of Engineering Acoustics, Faculty of Engineering LTH,
Lund University, Box 118, SE-221 00 Lund, Sweden.

Homepage: http://www.akustik.lth.se

PREFACE

Management of acoustics in lightweight structures has become increasingly important over the 25 years I have spent as a person in authority, researcher, consultant and manager within this highly interesting topic. I had the opportunity to start my career as an acoustician by adapting the Swedish building regulations to a completely new way to build multi storey buildings, i.e. by using wood in structural bearing components. Over these 25 years, I have had the pleasure to work within standardisation[1], research organisations[2] and development of new building systems for the wood industry, always with the same curiosity. All together, the topic and the challenges still left to overcome have inspired me to summarise my perspectives in this thesis.

This thesis comes up with an overview of the building process and its impact on acoustic quality after completion of a building made of wood. Additionally, it comprises an extensive background regarding regulations and their impact on wood building sector, then the challenges to overcome on a global basis for further development of wood buildings in terms of acoustics. Finally, the importance of using current knowledge and transfer this back into the building process continuously is described, in order to accomplish a fast and progressive development of the wood building industry.

[1] The author is member of several standardisation committees within SIS and ISO: https://sis.se/standardutveckling/tksidor/tk100199/sistk197/ and https://www.iso.org/committee/48558.html .

[2] The author has participated in COST actions TU 0901 (http://www.costtu0901.eu/) and FP 0702 (http://www.cost.eu/COST_Actions/fps/FP0702) and managed three research projects (one Swedish and two European) as a representative for RISE (Research Institute of Sweden, www.ri.se) over the last ten years.

ACKNOWLEDGEMENTS

The work ending up in this PhD thesis has been supported by several organisations. I have done the work during commissions and research projects and I am very grateful for all support over the years. Hence, there are a number of people and organisations to thank and I start at the department of Construction Sciences of Lund University (Division of Engineering Acoustics), with Prof. Göran Sandberg and later Erik Serrano as main supervisors, both encouraging me to finish. However, there is one more person specifically who deserves extra attention and it is Birgit Östman, who promoted research actively in the field of acoustics over the last ten years, a field which is normally not her own. She understands the needs for the future wood building industry and she took the initiative to start two very important research projects, the Swedish project *AkuLite* and the Wood Wisdom-Net project *AcuWood*, both managed by the author, thanks for the trust! The financial support from all funding organisations (especially VINNOVA and Formas) and industrial representatives for these two projects is highly appreciated and they were necessary in order to complete this work. I would also like to pay attention to Wood Wisdom Net team for promoting two acoustic projects *AcuWood* and *Silent Timber Build* and CEI–Bois for their support for the latter. Thanks also for all support from Swedish wood and all their representatives, organising seminars and promoting the research in many ways.

Additionally, I would like to thank the National Board of Housing, Building and Planning (Boverket) and their representatives, who early understood the requisites for a strong future wood industry in Sweden. Thanks for backing up the change in the regulations but also for supporting research in the beginning of the work with this thesis. Already in 1999 Sweden was the first country in the world to change the minimum regulations in order to adapt to the "new industry" and still 18 years later Sweden is the only country that has made these changes! I would also like to thank the team in the Nordic Committee on Building regulations active during the 1990´ies. Last, but not least thank all researchers involved in the COST actions TU 0901 and FP 0702. Thanks to RISE for supporting me as a coordinator for three research projects (I still hope there will be more), and to my employer WSP and all clients providing interesting projects over the years. Thanks also to Rikard Öqvist at Tyréns for nice scientific discussions at the end of my work.

Finally, I would also certainly like to thank my wife, my love and my best friend, and all my fantastic children, who have supported and followed my research over the years.

All support hereby gratefully acknowledged.

Klas Hagberg

ABSTRACT

Lightweight buildings and in particular wood buildings have a lot of potential to grow in numbers. Wood is a renewable material useful in a number of different manners. It is a human friendly material and additionally it can reduce the environmental impact from the building industry considerably.

Acoustics in building structures might have negative impact on the residents, if not favoured with their right importance and properly addressed to meet expectations. For lightweight structures like wood, if the design and the management of the projects fail, the impact is often more severe and the implications for the tenants are different compared to those in buildings with heavy structures. This thesis gives an overview of the work done by the author over the last 25 years. It started by adapting regulations to fit the new building technique in 1994, when the building regulations allowed multi storey buildings with wood, after lifting the one-hundred-year old ban of multi storey wood buildings in Sweden. It follows by a description of the complicated process to assimilate new findings into provisions. Results and knowledge are collected and available from several research projects[3] over the last fifteen years but still not introduced in any country but Sweden. In spite of clear research outcomes, results stay unused and the time prior to include changes into the building codes is very long (if ever). Therefore, one major finding from this work is that the design of wood buildings needs specific considerations in the building process and the development of helpful tools must continue to facilitate design of wood buildings. In addition, measured data for comparisons when modelling acoustics in buildings must become available for engineers to facilitate safe predictions and develop engineering calculation models. The developers of residential buildings must be aware of:

1. Which descriptors are applicable for sound insulation in the range of provisions?
2. Which target value should apply?
3. How to predict the sound insulation?
4. Risk for acoustic failure during erection of the building.

A safe design process is important for new housing developers or they will not take “risk” to use new materials and products, like wood, for multi storey residential buildings. This thesis discusses the challenges and opportunities for the wood industry in terms of acoustics in the building process. Specifically, the thesis concludes that designing a wood structure requires specific considerations at an early stage. It is also stated that knowledge far beyond specifications and standardised methods as referred to in mandatory documents are necessary. Finally, acoustics is one of the main design parameters for residential buildings, and therefore it should have raised priority during the entire building process.

[3] *AkuLite, AcuWood, Silent Timber Build, Aku20, COST action TU 0901 and COST Action FP 0702 (the two actions specifically providing research input from other European countries).*

POPULAR SCIENTIFIC SUMMARY

Lightweight materials are increasing in the structural systems of multi storey buildings. The term lightweight (structural) material is a wide concept covering for example wood and lightweight steel beams. However, specifically wood structures are developing fast due to several aspects, not least its environmental advantages. Wood stores carbon dioxide, it is renewable and it is a growing source of natural structural material. The wood industry has developed efficient methods for prefabrication in factories. That means quick erection of entire buildings on site, but also creating better work environment for workers and less waste of materials during the building process. Another advantage is the low weight, which opens up for reusing existing foundations or existing buildings by extension with several new storeys, often without additional reinforcement of the foundation. Furthermore, thanks to the low weight the number of transports from factory to building sites can be reduced dramatically, yet another benefit for the overall environment.

In 1994, the building regulations were revised in Sweden and the over 100 years old ban for wood in multi storey buildings was removed. It was the fire regulations that were revised allowing wood as structural material in multi storey buildings. It opened up for the building industry to use other materials than concrete and steel, a challenge that meant new opportunities for the building industry. For many types of buildings, the use of wood in the structure was easy to apply. However, when it comes to residential buildings, the regulatory framework was not fully adapted to the new wood building technique. For example, the chapter covering acoustic requirements was kept unchanged, in spite of new acoustical challenges.

Current acoustic building regulations and standards fit well to the most common traditional building techniques. Ever since 1945 (the time for the first regulations in Sweden) the development of building regulations and standards have been carried out in parallel to the development of the building industry, pre-assuming concrete in the structural building parts. The same is valid for any other countries. Therefore, all building acoustic theories, measurement methods and evaluation principles are adapted to a “heavy” building technique. From research presented in this thesis it is shown that the evaluation of the objective acoustic sound insulation criteria must change globally to fit the perceived sound insulation in multi storey residential buildings. A global change is important not least since the wood building industry is becoming more international, a building can be produced or designed in one country but aimed to be erected somewhere else. However, there is still a long way to go since the regulations are still “national”, comprising a number of specific national special rules.

Knowing which acoustic criteria that should apply for the building, the prediction of sound insulation is a key to success for the wood industry in future. The final acoustic quality of the building must meet the predicted values in terms of acoustics. From the work presented in this thesis, a procedure for verification of acoustic prediction models is developed and presented, specifically aimed to cover a large variety of possible wood floor assemblies.

This thesis concludes which aspects are necessary to consider during the management of wood building projects to ensure that the sound insulation requirements are fulfilled in the final building. It also describes the process to transmit knowledge for future improvements.

Contents

Nomenclature – Descriptors

BBR	Boverkets Byggregler (National Building Code in Sweden issued by The National Board of Housing, Building and Planning)
CPD	European Construction Productive Directive
ISO	International Organisation of Standardisation
CEN	European Committee for Standardisation
EN	European Norm
SIS	Swedish Standards Institute
SS	Swedish Standard
DIS	Draft International Standard
NKB	Nordic Committee on Building Regulations
COST	European network for researchers (European Cooperation in Science and Technology)
SNQ	Single Number Quantity
D_{nT}	Standardised level difference (normally displayed in 1/3 octave bands from 50 Hz to 5000 Hz)
$D_{nT,w}$	Weighted standardised level difference (descriptor where all 1/3 octave band values between 100-3150 Hz are weighted into a single number quantity according to ISO 717)
R	Laboratory sound reduction index (normally displayed in 1/3 octave bands from 50 Hz to 5000 Hz)
R_w	Weighted laboratory sound reduction index (descriptor where all 1/3 octave band values between 100-3150 Hz are weighted into a single number quantity according to ISO 717)
R'	Apparent sound reduction index (normally displayed in 1/3 octave bands from 50 Hz to 5000 Hz)
R'_w	Weighted apparent sound reduction index (descriptor where all 1/3 octave band values between 100-3150 Hz are weighted into a single number quantity according to ISO 717)

$R'_{w,8}$ Weighted apparent sound reduction index (an old descriptor where all 1/3 octave band values between 100-3150 Hz are weighted into a single number quantity according to ISO 717, including a specific 8.0 dB limitation in the evaluation)

C Spectrum adaptation term applicable for indoor noise sources, covering the frequency range 100-3150 Hz

$C_{50\text{-}3150}$ Spectrum adaptation term applicable for indoor noise sources, covering the frequency range 50-3150 Hz (used in Sweden)

$C_{50\text{-}5000}$ Spectrum adaptation term applicable for indoor noise sources, covering the frequency range 50-5000 Hz

$C_{100\text{-}5000}$ Spectrum adaptation term applicable for indoor noise sources, covering the frequency range 100-5000 Hz

C_{tr} Spectrum adaptation term applicable for traffic noise (sometimes used for improved protection against low frequency noise sources in general), covering the frequency range 100-3150 Hz.

L'_{nT} Standardised impact sound pressure level (normally displayed in 1/3 octave bands from 50 Hz to 5000 Hz)

$L'_{nT,w}$ Weighted standardised impact sound pressure level (descriptor where all 1/3 octave band values between 100-3150 Hz are weighted into a single number quantity according to ISO 71717)

L'_{n} Normalised impact sound pressure level (normally displayed in 1/3 octave bands from 50 Hz to 5000 Hz)

$L'_{n,w}$ Weighted normalised impact sound pressure level (descriptor where all 1/3 octave band values between 100-3150 Hz are weighted into a single number quantity according to ISO 717)

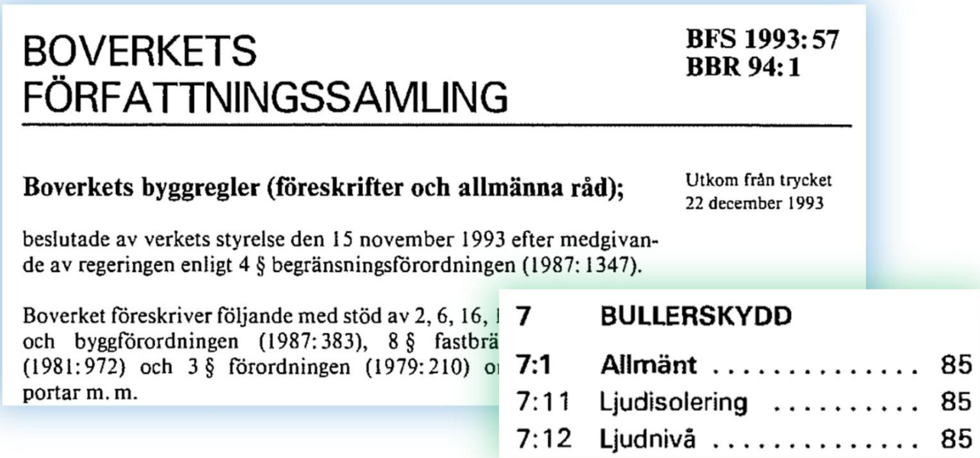
C_{I} Spectrum adaptation term applicable for impact noise sources, covering the frequency range 100-2500 Hz

$C_{I,50\text{-}2500}$ Spectrum adaptation term applicable for impact noise sources, covering the frequency range 50-2500 Hz (used in Sweden)

I. Introduction and Overview

1. Introduction

In 1994, The National Board of Housing, Building and Planning issued revised and extensively updated building regulations in Sweden, and for the first time, noise protection came up as a separate topic in the national building regulations, “Boverkets Byggregler” (BBR) [1]. Protection against noise was allocated a specific chapter (Chapter 7, “Protection against noise”) in BBR following the structure of the European Construction Productive Directive (CPD) [2], see figure 1.1. This was the first and very important step towards more attention to noise and an opportunity to raise the topic and its importance for the building sector.


BOVERKETS
FÖRFATTNINGSSAMLING

BFS 1993:57
BBR 94:1

Boverkets byggregler (föreskrifter och allmänna råd);

Utkom från trycket
22 december 1993

beslutade av verkets styrelse den 15 november 1993 efter medgivande av regeringen enligt 4 § begränsningsförordningen (1987:1347).

Boverket föreskriver följande med stöd av 2, 6, 16,
och byggförordningen (1987:383), 8 § fastbrä
(1981:972) och 3 § förordningen (1979:210) o
portar m.m.

7 BULLERSKYDD

7:1 Allmänt 85
7:11 Ljudisolering 85
7:12 Ljudnivå 85

Figure 1.1. Swedish building regulations were updated in 1994 in order to modernise the building code but also to facilitate high rise buildings with wood

The revision comprised a general update, to adapt the regulations to the new membership of the European Union but also to modernise the regulations in terms of introducing “functional requirements” [4] which facilitated and promoted tall multi storey buildings with wood. This created a fantastic opportunity for the forest sector in Sweden and of course other “forest” nations that experienced the same development. Still in 2017, clearance of forests is low, compared to the yearly

[4] Requirements not including specific target values, but instead comprising a regulatory text describing required function of a building, often attached advisory notes showing an example how to fulfil the regulatory text / requirement. Still, even if not following the advisory note identically, if verified, other technical solutions are acceptable to fulfil the regulatory text / requirement.

growth in the Swedish forests [5]. It is therefore a growing source of structural material implying substantial environmental advantages [6].

The most radical change in the building regulation, BBR, in 1994 was the update of the fire regulations. If the introduction of functional requirements facilitating the use of wood as structural material were obstructed, the over 100-year-old ban for wood in multi storey buildings would still be effectual. However, full focus was the update of the chapter regarding fire protection, without really considering the consequences for other technical areas, such as the new and recently highlighted section in the new building legislation "Protection against noise".

Protection against noise concerns several different noise sources. Noise from traffic and other outdoor activities often relate to severe annoyance. However, it can also be noise from neighbours, or even self-created noise from your own activities, that you yourself, think might be perceived as noise by your neighbours. Neighbour noise is a potential risk for severe annoyance if not considered [3], and one set of target values in the building code aims to protect from those sources. Correct acoustic target values in provisions are of great importance since tenants cannot evaluate the quality of sound insulation themselves prior to moving in, contradictory to many other accommodation quality aspects, often clearly visible. Hence, unsatisfactory sound insulation is a hidden source of annoyance. The above can be seen as the trigger for the research and development over the past 25 years presented in this thesis: sound insulation between dwellings in multifamily residential buildings made of wood.

1.1 Lightweight / wood building technique

Apart from their environmental benefits[7], wood constructions have many other advantages. First, and very important is that the wood industries have renewed the building industry to a large extent the last 20 years. Instead of building "on site" they are forerunners for prefabricating buildings, either in terms of flat building elements or entire rooms / apartments (volume elements). The higher the degree of prefabrication the more material is possible to save thanks to efficient and controlled production in a factory, see examples in figure 1.2. Additionally, it is a far more attractive production method for the workforce, who can work in a dry environment with better working atmosphere. To have an efficient production is a key to success for the future.

The fact that wood is a light material opens opportunities for usage in new applications, such as increasing the number of storeys on existing buildings without any reinforcement of the foundation. The lightness of the material also enables the construction of new buildings with simpler and cheaper foundations, i.e. less complicated foundation. The low weight also facilitates transportation of entire elements to the building site for very fast and efficient erection. Wood has also shown a positive effect

[5] Sweden is the 3rd largest country in the EU in surface covered by forest to 70 %. Out of that, 80 % is in forestry holding and only 1 % undergoes final logging. This has led to double the size of biomass over the past century. Source: Swedish forest industries.

[6] Advantages to use wood in the building industry in Sweden, is described in a report from Linköpings University (in Swedish), http://liu.diva-portal.org/smash/record.jsf?pid=diva2%3A1153498&dswid=7966

[7] Environmental benefits using wood include reduced carbon dioxide emissions and lower energy consumption in the building sector, amongst others. Additionally, wood stores carbon during its entire lifecycle and is easy to transport due to low weight. Wood is renewable. Source: Swedish Forest Industries.

on the tenants if the wood is exposed and visible in the building [4]. All in all, when wood is used correctly in buildings it can contribute to environmentally friendly, healthy, attractive and highly competitive buildings. Acoustically, wood and other lightweight materials, such as slender thin steel profile building systems, exhibit the same characteristics. However, in this thesis focus directs to wood due to its expected increased usage from the fact of the positive effects on the environment. Still, similar behaviour and future needs as the ones presented for the wood industry in this thesis, could be applied and followed for the lightweight building industry in general, in spite of not belonging primarily to the wood sector.

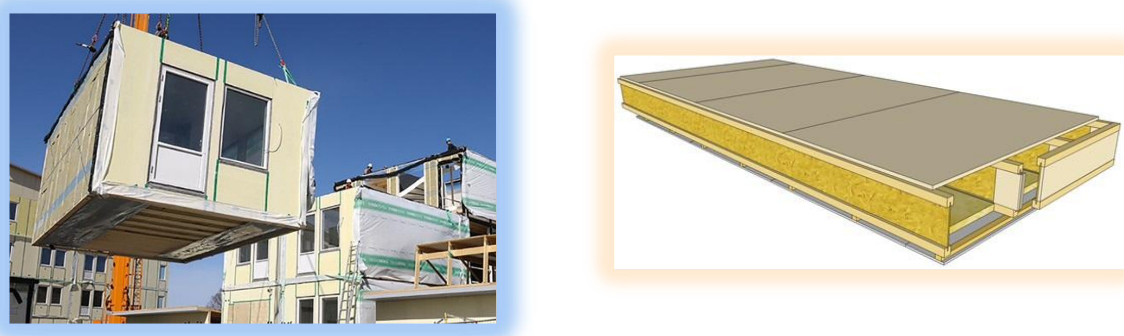


Figure 1.2 – Prefabricated elements; left, volume elements; right, flat elements

There are still challenges to overcome for the wood industry. It is preferable to use the wording "challenges" rather than "problems" since nowadays, raised knowledge has reduced the risk for failure, and hence it is less of a problem than 20 years ago. In this manner, one makes sure that the housing developers, and other partners involved in various projects are aware of the challenges, for which solutions should strive at. The solutions are available. One challenge is still to convince building industry actors and insurance companies that wood in a multi storey building is not equal to immediate damage in case of fire [8]. Another challenge is acoustics, specifically protection against noise from neighbours in multi-family wood buildings, and to optimise the solutions to fit to modern requirements and make the solutions economically attractive.

It is a major challenge to achieve a high level of acoustic quality in wood structures because the building regulations in most of the countries in the world are not at all adapted to buildings with light structural elements. Wood is light and their ability to resist low frequency sound transmission is therefore reduced considerably, compared to the ability of heavy structures. Historically, the regulations developed pre-assumed concrete or steel / concrete in the structural bearing system, focusing

[8] Organisations working for safety in case of fire (for example the Swedish organisation "Brandskyddsföreningen") and insurance companies support the development but require severe design to secure the fire safety, https://www.brandskyddsforeningen.se/om-oss/pressrum/pressmeddelanden2/garna-fler-trahus--men-forst-ett-bra-brandskydd/. By applying modern building technique safe houses can be designed [99]

exclusively on frequencies above 100 Hz in mandatory regulations almost everywhere in the world. Heavy structures offers good protection against noise below 100 Hz. For buildings made of wood and other light material, however, low frequencies (also below 100 Hz) must be accounted for when evaluating sound insulation to secure that the perceived acoustic quality is equal to the quality of heavy structural residential buildings [5, 6, 7] [9]. For that, the national building regulations are a key to facilitate correct design guidelines, fitted to any structural material, both concrete and wood.

In general, it requires more effort to achieve an acoustically successful building made of wood than one in concrete [10]. In specific cases, such as buildings erected by using certain volume elements, expected acoustic comfort is often fulfilled. However, the technical solutions are repeated in every new building and the systems are preceded of a thorough process of development, research, testing and experience prior to their introduction into the market. They have a management system fitted to the specific building system securing transmittance of knowledge to all parties involved during the building process, to secure the results for the finalised building.

1.2 Problem statement

Thanks to environmental benefits, efficient production methods and other advantages as already described, an increased use of wood in buildings is of interest and important to society. If the building methods are further developed, this might create opportunities for international exchange of products and an increased trade is to be expected. An obstacle for such a development is complicated national regulations aggravating unified and efficient building methods. Additionally, it is known that evaluation methods underrate the effect of low frequencies, specifically for impact sound, which might reduce acoustic comfort in wood buildings compared to heavy structure buildings. Therefore, an overview of national regulations is needed, to **adapt the regulations globally to human perception of noise**. Accordingly, striving for unified evaluation methods fitted to wood structures free from complicated national special rules can contribute to the development of the wood sector, advantageous for the future environment. Developing indicators for sound insulation and describing the complexity of building regulations and standards and their interaction in the building process is one key problem area of the research presented in this thesis. As the number of multi storey buildings with wood increase, this research has to be intensified.

New indicators adapted to a wider range of structural materials in buildings imply new ways to measure and predict sound insulation. For the traditional building industry using heavy materials the methods are in place since decades. Proven and familiar acoustic theories are applied and standardised prediction models with high accuracy exist since many years. For the housing developer it is therefore safe and predictable to choose concrete. For wood however, uncertainties are several and one way to reduce risks is to apply new indicators comprising a wider frequency range towards low frequencies. However, in low frequencies, prevailing acoustic theories are doubtful and the design has to adapt to

[9] Sweden is still (2017) the only country in the world with mandatory requirements in the building code starting at 50 Hz for residential buildings.
[10] An extensive literature review of current research regarding acoustics in wood buildings was carried out recently [100]

a new methodology. New design principles must apply, facilitating the choice of wood as structural bearing material. However, the diversity of possible wood structures complicate prediction. Nevertheless, prediction of sound insulation must improve and become accessible to minimise prototype testing and instead promote calculations and continual improvements of prediction models. The introduction of **practical methods for estimating sound insulation** in a diversity of wood floor assemblies is therefore one important area of research of this thesis.

Finally, for a healthy development of the wood industries, a global consensus for target values is important and, in addition, a fast development requires raised knowledge regarding design of low frequency sound insulation. It is necessary to cooperate between countries to collect sound insulation data (both objective and subjective data) and reuse these data as basis for further development of prediction models. Following this, the knowledge gained should be brought back to learn more about subjective annoyance and target values and to be able to improve modelling for any type of wood structures. Thus, adapting **the building process** for developing the industry will contribute to cost efficient, acoustically competitive and environmentally friendly buildings.

1.3 Aim and objective

The aim of this research is to advance knowledge regarding human response to noise in residential buildings and to improve its connection to regulations and standards. It is also aiming at developing practical methods for prediction of sound insulation for wood buildings and, finally, describing the building process for building projects to develop cost efficient, acoustically competitive and environmentally friendly wood buildings.

To fulfil the aims of this thesis the following research questions are stated:

1) Which sound insulation criteria should apply to conform to the human perception of noise in buildings with wood structures? (paper C and D)
2) Which obstacles must be enforced to update building regulations and standards accordingly? (Paper B)
3) How can the usage of modelling tools adapted to wood buildings in general be encouraged? (Paper E)
4) Which considerations are needed to adapt the building process to any type of wood building system? (Paper A)

Limitations

The main limitations of the thesis are related to the fact that surveys regarding perceived sound insulation have specific limitations. Generally, and almost exclusively, recent research involving field surveys consider residential buildings aimed for "normal families" [11]. Furthermore, the studies presented in this thesis are primarily carried out in Sweden and middle part of Europe and hence do not really consider potential cultural differences. Surveys regarding future expected living habits and demographic development are lacking. Currently in Sweden, almost half of the population is living in

[11] Families with various gender and a diversity of age living in medium size dwellings.

one-person households[12], probably even more in big cities like Stockholm, which might imply less risk for annoyance from specific sources. Another fact is that the population becomes older in the western part of the world, which will increase the need for multifamily houses to be adapted for an aging generation in the future. Student dwellings are another type of residential units with specific needs, and in addition sensitive to high costs. Hence, future expected living habits and their implications on the future housing market needs further elucidation prior to draw far-reaching conclusions for acoustic requirements, in general. The number of annoying noise sources might become lower or different in future housing units as the demographics changes and hence open up for less strict target values in several types of residential buildings. Since acoustics contributes considerably to the total cost of any building, an extensive overview of demographic development can contribute to lower the costs further for the building industry. That should also include cultural differences. This is, however, a very important research topic on its own. In the concluding remarks in this thesis, the limitations drawn up here are considered.

1.4 Outline of the thesis

The thesis is divided into two parts, Parts I and II as outlined in the following:

Part I

Part I comprises an introduction to the work. It summarises the basis for the thesis, as presented in the appended publications, and it provides an extensive background. The structure of part I is according to the following and figure 1.3:

Chapter 1 gives a brief introduction of the thesis and its aims and objectives.

Chapter 2 provides a brief history of the building regulations and their development in connection to the use of wood structures in the building industry. A description of the building process is included containing interpretation of acoustic regulations and challenges for different structural systems. An introduction to the complicated structure of regulations throughout Europe is given (Paper B).

Chapter 3 summarises the research regarding perception of noise between dwellings (i.e. considering sound insulation – noise from neighbours in dwellings). It is a compilation of results emanating from research carried out by the author [13]. The results from this research are essential input for future provisions (Paper C and Paper D).

Chapter 4 describes a tool or rather a methodology to verify calculation models by use of measured impact sound insulation data from a large number of floor structures in Europe, grouped in a specific

[12] SCB Statistiska Centralbyrån and PEW research center, http://fof.se/tidning/2014/10/artikel/ensamboendet-okar-i-hela-varlden-och-sverige-ligger-i-topp .

[13] The author´s licentiate dissertation (Lund University TVBA-3127, Sweden 2005) and its results are briefly described in the actual chapter, however not part of this thesis.

manner. Prediction of impact sound insulation in wood buildings is essential to promote a positive development of the entire wood industry. The grouping is used to verify calculation models of floor assemblies. From that, refining and optimisation of the floor assembly can take place, to fit the target value (Paper E).

Chapter 5 describes the management of building projects. The acoustic performance of wood building systems vary and is affected by the execution of the work on site (to different degrees depending on system). With efficient management of each building project, expected target values as modelled and verified can be fulfilled (Paper A).

Chapter 6 comprises a summary of appended papers and the author's contribution.

Chapter 7 concludes this work.

Part II

Part II compiles all scientific publications included in the thesis.

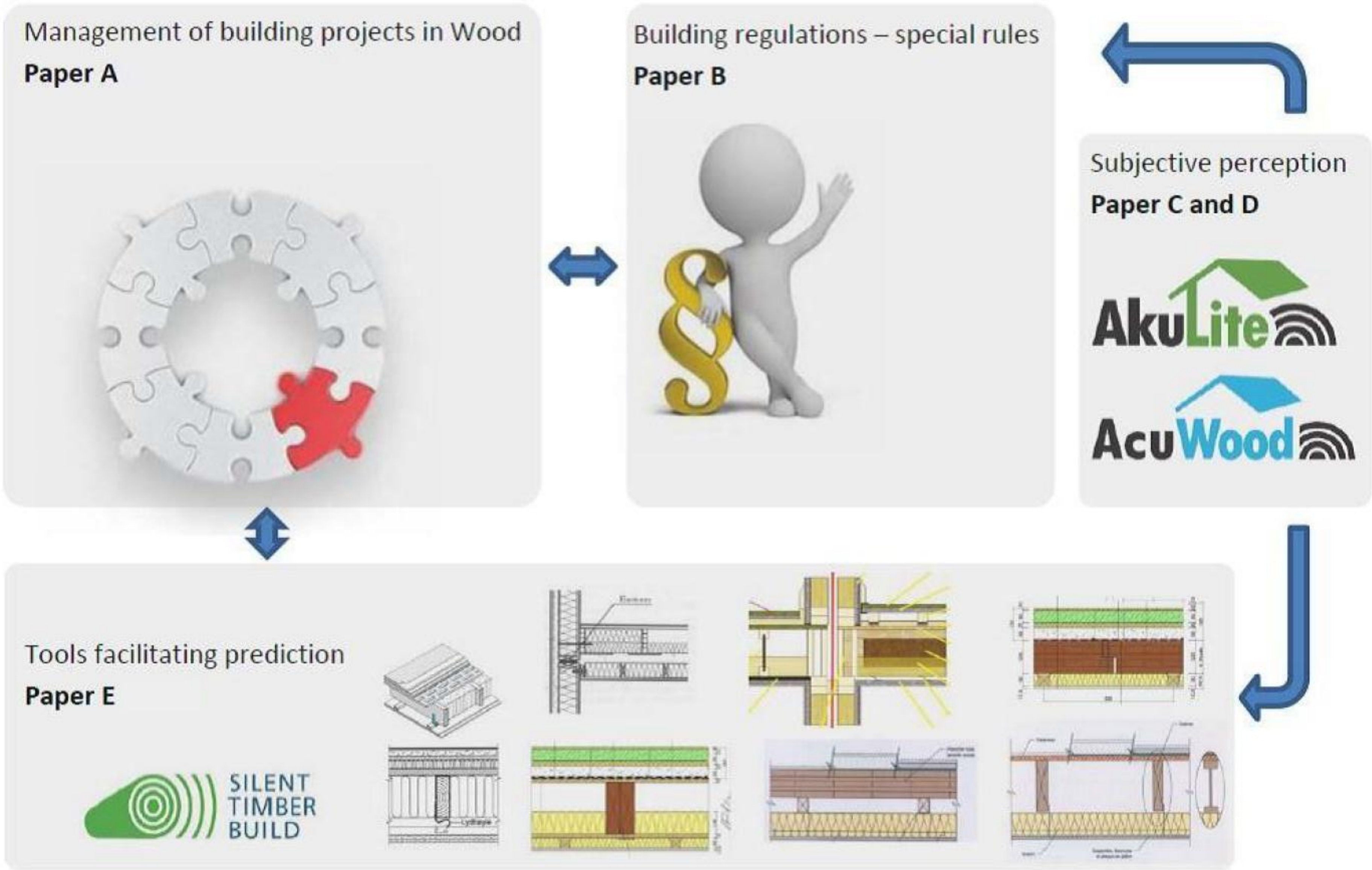


Figure 1.3. Outline of the thesis and the appended papers mutual interaction

2. Acoustic building regulations

Building regulations are important for the building industry. The building industry is highly affected by regulations from authorities and problems should not appear if a building fulfils the provision. So-called "Functional requirements" [14] opened up for new structural components made of wood, however the interpretation of functional requirements can vary and this often causes confusion within several technical aspects: *is it a real requirement or just a recommendation*? Regarding acoustics this confusion diminishes by introducing guidance documents and handbooks [8, 9, 10] describing the aim of the requirement and its intended application, and the direction for the industry to fulfil the requirements in the buildings. However, the regulations are often old-fashioned and certainly not up to date. Improvements and adaptations are necessary and the need for handbooks and guidance increases further, especially for small companies that are eager to develop their building technique. Mandatory national acoustic regulations for buildings are one specific and important example of a provision that needs to be updated.

Acoustic building regulations vary a lot throughout the world [3, 11], in spite of similar international evaluation standards. Even within the European Union requirements differ significantly between countries. Some countries still don´t have any quantified requirements at all related to impact sound insulation in buildings, and thus the final impact sound pressure levels remain unknown as a consequence of an acoustically uncontrolled building process. Therefore, the sound pressure levels from impact sound in buildings can become very high, and noise from neighbours might cause long-lasting annoyance. The lack of specific requirements might be a reason why people in many countries dream of having a quiet house of their own, where the only noise is caused by yourself and your family. This situation is more easily accepted since controlling the noise level then becomes much easier. To some extent, cultural differences regarding living habits and acceptance of noise levels exist and these differences can explain the diversity of regulations. Thus, it is difficult to find acceptable levels common to any country. However, in some cases the differences in regulations found today are neither possible to understand, nor possible to explain.

[14] See also note 4. Requirements where specific target values are excluded, but instead they comprise a regulatory text and often advisory notes showing an example how to fulfil the regulatory text / requirement. Still, even if not following the advisory note identically, if verified, other technical verified solutions are acceptable in order to fulfil the regulatory text [1].

2.1 Acoustic regulations – history

Building regulations were introduced in Sweden in 1946 [12], including the first acoustic regulations covering the frequency range 100 Hz – 3000 Hz[15]. Since then, a number of revisions were implemented, but still sound insulation requirements stayed almost unchanged in Sweden until 1999, even if life style (in terms of requirements from tenants and living conditions) indeed changed a lot during the same period. During the 1990´s, the national regulations in Sweden changed considerably and, as previously mentioned, a new set of building regulations based on functional requirements was enforced in 1994 [1]. The principal change (mainly regarding fire protection) in the 1994 edition positively affected the wood industry, since it enabled new opportunities to build multi storey buildings. However, in spite of the introduction of functional requirements allowing new structural materials in multi storey residential buildings, real changes in the new chapter 7, "Protection against noise", failed to arrive. This fact was a common line in all countries, which passed laws to promote new structural materials in multi storey buildings, securing necessary regulatory adaptations but failing to address the topic of acoustics. As a consequence, the industry has to continue to adapt their constructions to requirements that are old-fashioned and a remnant from the history.

Current sound insulation requirements should fit to a minimum standard where tenants, with a reasonably low probability, are not annoyed, i.e. only annoyed when the neighbours are far noisier than average. However, similar to fire protection in buildings with wood, the sound insulation characteristics and the preconditions become completely different in structures made of wood as compared to structures made of other materials, and this must be taken into account in any revision of the regulations. A great difficulty is the fact that acoustics does not cause any immediate mechanical damage or direct risk for injuries or death, i.e. these questions might be considered as less important compared to other aspects, such as mechanical resistance. However, noise annoyance demonstrably causes negative effects on humans (specifically at low frequencies), raising undefined costs for society [13, 14]. All of these influences are more difficult to calculate than immediate risk for damage. Noise emissions, no matter which, can cause a number of diseases depending on noise exposures and their duration [13, 14]. The complexity of the relation between noise and health makes it more difficult to motivate to take action and it is perhaps easier to consider the problem as being a consequence of people exaggerating.

To conclude, as conditions change in building regulations promoting new verified building techniques, it is of vital importance to undertake a general overview of the provisions, to make sure that all aspects, including acoustic performance, can be fulfilled under the updated regulations.

2.2 Sound transmission in buildings

On basis of the sound source (for example noise from music equipment, people talking or people walking), sound transmission can be classified as a) airborne sound or b) impact sound:

[15] Main household activities (speech, TV, radio, et.c.) are within this frequency range, at least historically.

a) Airborne sound is sound waves in the air hitting the surface of a building element and making it vibrate. Some of the vibrations in the element radiate on the opposite side and create a pressure difference, propagating as sound or noise. Sound sources creating airborne sound are typically speech, TV, HIFI equipment, kitchen appliances and similar. When the airborne sound insulation is to be evaluated, a noise source (loudspeaker) in one room creates high noise levels and the difference between one room (with the source) and the adjacent room is stated. Consequently, airborne sound insulation measures should be as high as possible for improved insulation (i.e. reducing the transmission).
b) Impact sound is noise caused by direct mechanical impact on the structure. The vibrations arising in the structure generate waves, which propagate through the structure and finally radiate and create sound in an adjacent room. Typical sources are walking, children playing, dropping things, chairs moving, rotating machines, vacuum cleaning and similar. Impact sound insulation is the ability to reduce structure borne sound described as the structural "impact sound pressure level". When the impact sound insulation of a structure is evaluated, a standardised force (ISO tapping machine) [16] is operating on the structure causing a noise level in the adjacent room. Consequently, the impact sound pressure level should be as low as possible in order to show high performance of impact sound insulation (i.e. reducing the transmission).

Unlike laboratory measurements or calculations on single elements, sound transmission in a building as specified in regulatory frameworks, comprises several transmission paths: direct transmission and a number of flanking paths, see figure 2.1. Depending on the structure, combination of materials and formation of junctions, the flanking contribution can vary substantially and the sound insulation values might reduce dramatically due to flanking transmission if not considered.

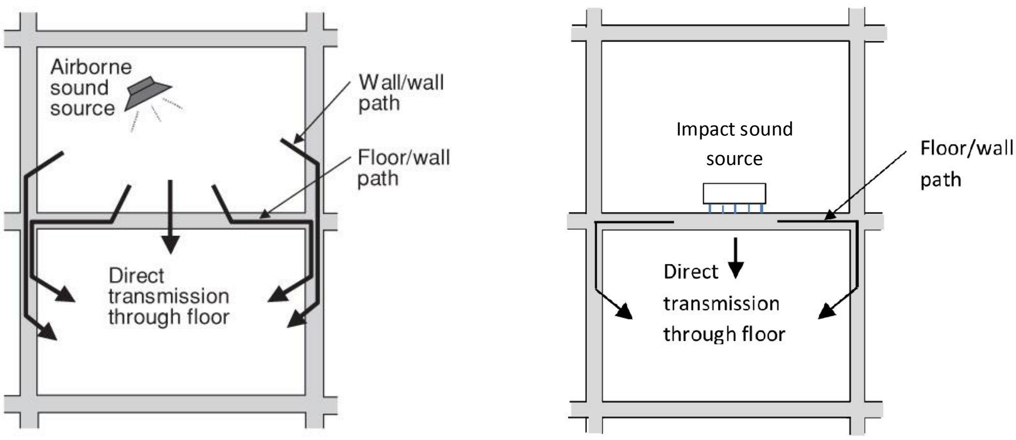


Figure 2.1. Sound transmission as considered in regulatory frameworks; left: airborne sound insulation; right: impact sound insulation

[16] A standardised impact sound source within ISO, widely used all over the world. It comprises five steel hammers that alternatively hit the floor. Other impact sources exists; Japanese ball, rubber tyre [79, 80]

Sound transmission in buildings varies with frequency. Generally, the lower the frequency the lower the sound insulation (both airborne and impact sound), specifically valid for wood constructions. This can be acceptable since low frequencies are less audible than high frequencies, i.e. the sound pressure level must be raised, to experience the same level as for high frequencies.

In general, heavy concrete structures, outperform wood structures in terms of sound transmission in low frequencies, since they exhibit a different behaviour compared to wood structures. When it comes to noise from normal housing activities it is sufficient to make sure that the impact sound pressure levels, e.g. chairs moving, children dropping toys and similar, are reduced enough to avoid high frequency noise for such heavy structures. The solution to reduce high frequency noise is very simple and straight forward since it is for example sufficient to add a thin resilient layer and parquet on top of the concrete [17]. Additionally, in the unlikely event of failure in the high frequency range it is very easy to make changes afterwards.

For wood structures however, it is the other way around; the sound produced at low frequencies can be audible and as soon as the noise is above the hearing threshold an increase in strength is more severe than at high frequencies, i.e. few dB can increase the perceived loudness substantially. Measures to improve sound insulation at low frequencies for wood structures are complex, or go against one of the advantages of wood structures (e.g. adding mass). In the event of failure in the low frequency range it is problematic to correct mistakes afterwards. However, unlike concrete, high frequencies do not really cause any problems for light structural materials, where the floor and wall assemblies take care of sound insulation at high frequencies.

2.2.1 ISO 717, part 1 and part 2

ISO 717 part 1 and 2 (2013) [15, 16], are two key standards often referred to in acoustic regulations for buildings. They state the principles for evaluation of sound insulation in buildings and hence, they are the basic documents used to define requirements for sound insulation in building regulations. The measured or calculated sound reduction indexes or impact sound pressure levels in sixteen different third octave bands between 100 Hz and 3150 Hz are, in each case, weighted into a single number quantity (SNQ) according to specific rules [18] in the standard series. The separate third octave band values are retrieved according to ISO 10140 [17] and ISO 16283 [18, 19], if measured values are considered, and according to ISO 15712 (EN 12354)[19] [20, 21] , if the values are calculated [20].

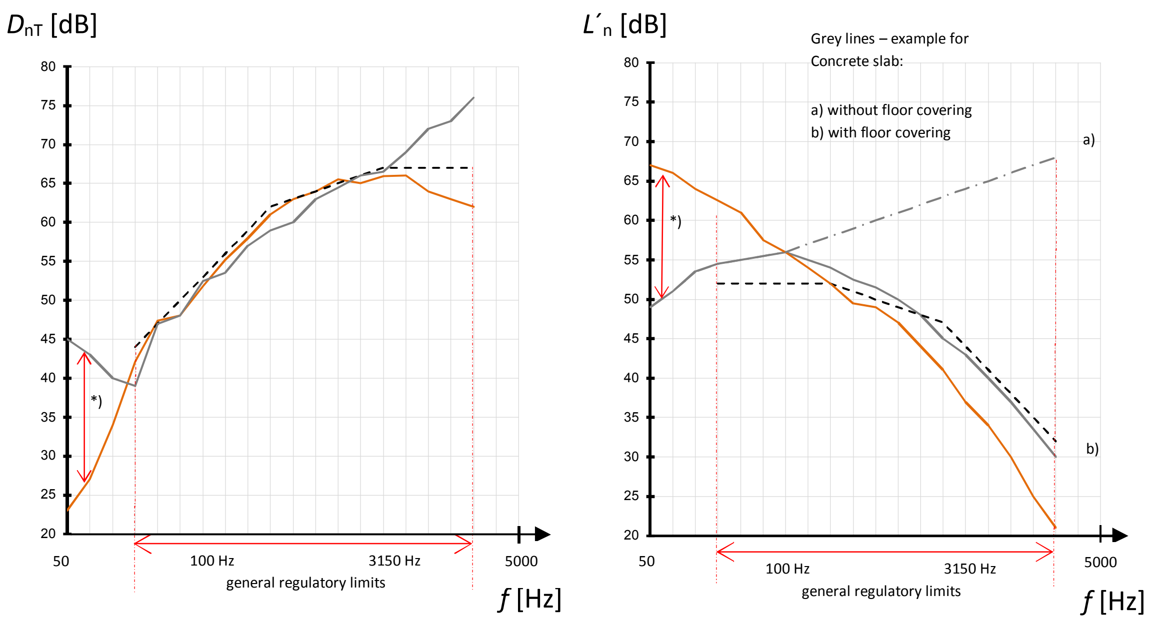
[17] Note that the weighted airborne sound insulation can decrease substantially due to resonant transmission at specific frequencies depending on the surface weight of the flooring and the spacing between concrete and the flooring mass/spring system. For a parquet layer 14 mm, on a 3 mm extruded LD polyethylene the resonance appear at 400 Hz.

[18] For evaluation, the reference curve (dotted grey line in figure 2.2) is shifted in steps of 1.0 dB towards the measured or calculated curve until the sum of unfavourable deviations are maximum, while not exceeding 32.0 dB. Unfavourable deviations appear when the measured or calculated curve is lower than the reference curve for airborne sound insulation and higher than the reference curve for impact sound pressure level. The weighted value is the placing of the reference curve at 500 Hz, after the shifting procedure [15, 16].

[19] Renamed to ISO 12354 in the updated standards in 2017 [74, 75].

[20] Several methods are available for calculations, as will be described later in this thesis. The standards EN 12354 [20,21] comprises an engineering method widely used for heavy structures.

Figure 2.2, below, shows two examples regarding evaluation of airborne sound insulation and impact sound insulation in two different buildings, emanating from normal floor assembly designs in a completed building (field values). The examples include measured data for one concrete floor assembly (grey line) and one wood floor assembly (orange line). In both examples (airborne and impact), the weighting curves (grey dotted lines), as defined in ISO 717:2013 [15, 16], are also displayed. The results imply that the concrete structure and the wood structure experience exactly the same SNQ, expressed as weighted standardised level difference ($D_{nT,w}$) and weighted standardised impact sound pressure level ($L'_{nT,w}$). The levels become 63 and 50 dB respectively, which can be considered as rather good sound insulation in both cases. However, as displayed in the diagrams, the measured curves exhibit huge differences (up to 20 dB) outside the frequency range 100-3150 Hz, from which the ISO weighted SNQs are evaluated.



*) Even if exactly the same SNQ value according to regulatory framework the difference in low frequencies is substantial and crucial

Figure 2.2. Airborne sound insulation and impact sound pressure level of a concrete structure (grey line) compared to a typical wood structure (red/orange line). Left: Airborne sound insulation; Right: Impact sound pressure level, displayed without (a) (as it can be expected, i.e. not measured) and with (b) floor covering for the concrete slab.

To conclude, sound insulation measures must focus above a certain frequency (around approximately 250 Hz) for heavy structures and below a certain (frequency below 250 Hz) for lightweight structures like wood, however always being aware that flanking paths can contain other frequencies.

In few countries, the evaluation standard ISO 717 is not prevailing, but often similar national standards replace the ISO standards and the basic principle for evaluation of SNQs regarding sound insulation is similar [21]. In 1996, ISO published an updated version of these two standards, to promote an extended frequency range when evaluating sound insulation. In the new versions, the ability to extend the frequency range to comprise also frequencies between 50 to 3150 Hz but also up to 5000 Hz was included. An extensive Swedish survey from 1985 [22, 23] was useful in the development of new descriptors. The results from [22] regarding impact sound, were evaluated within NKB [22] [5] and proved to exhibit high compliance with the new standard ISO 717-2 [24], when including frequencies from 50 Hz in the evaluation. In the same work within NKB, consequences of including various spectrum adaptation terms for airborne sound were carried out, to better understand part 1 of the standard [25].

However, the conformation of the updated standards was a political agreement implying several opportunities to evaluate the sound insulation. Still in 2017, the main core of the standard is unchanged [23]. The extension of the frequency range in the evaluation implies calculation of spectrum adaptation terms and then adding the one that fits best to the actual sound source to the weighted SNQ, e.g. $D_{\mathrm{nT,w}}+C_{50\text{-}3150}$ (airborne sound in Sweden). Hence, the simple choice for all countries was to keep their old SNQs, since the amount of adaptation terms enabled for all countries to fit the new SNQs to prevailing SNQs. Rasmussen describes an extensive overview of all opportunities [26]. Table 1 shows the overview of SNQs and the corresponding spectrum adaptation terms that ca be used for partitions between dwellings (acoustic descriptors).

[21] In spite of the fact that the tapping machine is widely used globally for generating impact sound, other sound sources are used, specifically in Japan and Korea as specified in standards [79, 80, 81, 82], consequently resulting in an alternative evaluation. The rubber ball is also part of latest version of the ISO measurement method, ISO 10140 [18] (part 5).

[22] NKB = Nordic Committee on Building Regulations, a committee working on order from Nordic ministry council. Active during 1990´s.

[23] Still in the latest revision (2013) the main core is unchanged 8 [15, 16].

Table 1*. Overview of various descriptors used inside buildings in Europe for evaluation of SNQs between dwellings [26]. The formulation of target values aims to combine the SNQ* **(A)** *with one of the spectrum adaptation terms* **(B),** *to adapt to the actual noise source and frequency range considered.*

Descriptors used for evaluation of sound insulation in the field in Europe according to ISO 717:2013 [15,16]	Airborne sound insulation between rooms a)	Impact sound insulation between rooms b)
Weighted quantities **(A)** c)	R'_w D_w (previously $D_{n,w}$) $D_{nT,w}$	$L'_{n,w}$ $L'_{nT,w}$
Spectrum adaptation terms used for partitions inside residential houses **(B)** c)	*None* C $C_{50\text{-}3150}$ $C_{100\text{-}5000}$ $C_{50\text{-}5000}$ C_{tr}	*none* C_I $C_{I,50\text{-}2500}$

a) The number of possible SNQs for partitions between dwellings is 3 × 6 = 18 [24] (*none* included).

b) The number of possible SNQs for partitions between dwellings is 2 × 3 = 6 (*none* included).

c) D_w is the weighted level difference (Previously also $D_{n,w}$, normalised to 10 m² absorption area); R'_w is the weighted field reduction index referring to the area of the partition; $D_{nT,w}$ is the weighted standardised level difference, standardised to 0,5 s reverberation time in the receiving room; $L'_{n,w}$ is the weighted field impact sound pressure level normalised to 10 m² absorption area; $L'_{nT,w}$ is the weighted impact sound pressure level standardised to 0,5 s reverberation time in the receiving room.

d) The spectrum adaptation terms are calculated according to a formula specified in (14, 15] and vary depending on sound source and frequency range covered. *C* is used when living activities are considered and if no frequency range is specified as in the first case, the frequency range covered by the spectrum adaptation term is 100-3150 Hz. C_{tr} implies that traffic noise is the source and if no frequency range is given, 100-3150 Hz automatically applies.

During implementation of the revised standard series ISO 717 in 1996 [24, 25], minor adaptations to fit the SNQ to lightweight structures, e.g. wood buildings, became possible within the framework of the standard. Specifically, the low frequency spectrum adaptation term for impact sound, $C_{I,50\text{-}2500}$, could be used to adapt the requirements to “the state of the art” at that time [5, 22]. By adding the spectrum adaptation term, the frequency range was extended to 50 Hz (previously 100 Hz). This was certainly one important regulatory framework improvement to drive the major changes in the national building code in 1999 [27] to better fit to the wood industry and their needs. As soon as the standard was introduced in 1996, a revision of the Swedish building code from 1994 [1] was initiated and low frequency spectrum adaptation terms both for airborne sound insulation and impact sound pressure levels were included in the mandatory framework, BBR 1999 [27]. Still after 20 years of usage of the standards, no other country has introduced the spectrum adaptation terms evaluating sound insulation from 50 Hz in the minimum requirements of their building regulations. Figure 2.3, displaying a measured impact sound insulation contour, illustrates the extension of the frequency range.

As mentioned above, low frequency protection regarding sound insulation for dwellings in multifamily houses made of wood is of great importance. Similar to experience from practice, this is valid primarily for “normal dwellings” and, in particular, for impact sound [25]. If the design focuses on achieving high

---

[24] C_{tr} is normally applied to facades (traffic noise) but is used in England and Wales for partitions between dwellings.

[25] Normal dwellings according to current research comprise families with a diversity in terms of gender and age.

sound insulation with regards to impact sound, the demands on airborne sound insulation are often also fulfilled. Extra attention to impact sound in the design process is therefore recommended.

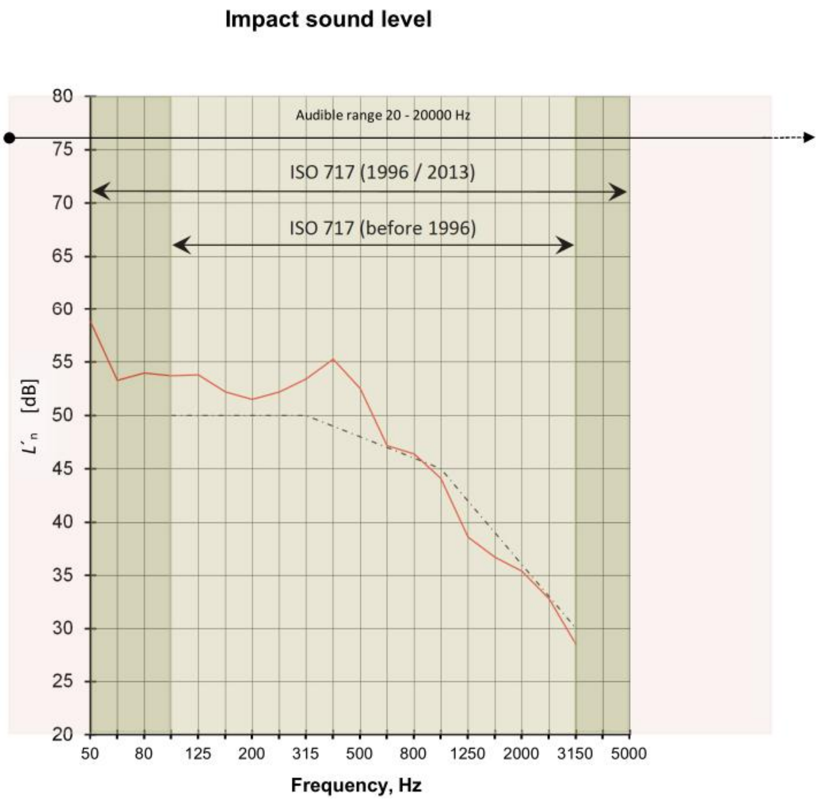


Figure 2.3. Frequency range for sound insulation in buildings. The extension to 5000 Hz is only valid for airborne sound insulation. For impact sound pressure level, as displayed in the picture, the extension is only towards low frequencies, covering the range 50-3150 Hz when $C_{I,50\text{-}2500}$ is applied.

Prior to the latest change of ISO 717, the working group within ISO, ISO / TC 43 / SC 2 / WG 18 [26], attempted to remove all spectrum adaptation terms and focus only on four different single numbers in a new set of standards aimed at replacing ISO 717, named *ISO 16717* part 1 (airborne sound insulation) and part 2 (impact sound insulation). Due to severe opposition the proposals were withdrawn in 2014. The idea was simply to replace the old equivalent with new single numbers without adaptation terms, hence reducing the various options considerably, see table 2. The background of the proposals is described in [28, 29].

[26] ISO = International Organisation of Standardisation; TC 43 = Technical Committee 43 (Acoustics); SC 2 = Sub Committee 2 (Building Acoustics); WG 18 = Working Group 18. https://www.iso.org/committee/48558.html.

***Table 2**. Overview of proposed SNQ within ISO / TC 43 / SC 2 / WG 18 (ISO 16717). It comprised an extensive and attractive simplification.*

New proposed SNQ		Old Equivalent	Comment	Frequency range [Hz]
R_{living}	Living noise sound reduction index	R_{w}-$C_{50\text{-}5000}$		50-5000
R_{traffic}	Traffic noise sound reduction index	R_{w}+$C_{\mathrm{tr},50\text{-}5000}$	Façade, outside scope of this thesis	50-5000
R_{speech}	Speech sound reduction index	R_{w}+C_{speech}	New measure, outside scope of this thesis	315-3150
R_{Impact}	Impact sound reduction index	L_{nw}+$C_{\mathrm{I},50\text{-}2500}$		50-3150

2.3 Acoustic regulations and sound classification – Swedish perspective

Minimum requirements of sound insulation are stated to make sure that a certain proportion of tenants is not annoyed. The level of the sound insulation requirements are judged as correct if a large majority of residents in multifamily houses perceive the sound insulation as “acceptable” [27] (typically around 80 %). In order to promote higher acoustic requirements, sound classification schemes could be an option. In Sweden, the first sound classification scheme had its introduction in the mid 1990-ies, in connection with the Swedish survey “Handlingsplan mot buller” [14]. It ended up in a Swedish standard SS 02 52 67 from 1996. This standard was revised in 1998 [30] and it became part of the Swedish building code by referring to the standard in the national regulations. Four sound classes, A-D, were defined, A being the highest performing. If sound class C was fulfilled the national regulations were automatically fulfilled. Many countries have introduced sound classification schemes, however all of them differ from each other. In 1997, the Nordic countries attempted to coordinate their standards into one single Nordic document [31, 32]. However, it ended up against adopting the standard.

To set the correct target values for the requirement levels corresponding to different sound classes in a classification standard, the sound classes should originate from surveys considering the perception of sound insulation. In 1998 Rindel [33, 34] [28] presented a summary regarding levels for acoustic quality based on existing surveys at that time.

2.3.1 Airborne sound

Rindel [33] concluded that when the weighted field sound reduction index, R'_{w}, equals 56 dB, the residents perceive the sound insulation as “acceptable, however not satisfactory” and would

[27] The limit (number of residents annoyed to a specific proportion) when the sound insulation should be considered as “acceptable” in terms of perception is not clearly defined.
[28] Based on existing social surveys by Langdon [83], Weeber [84], Bodlund[22, 23] and Bradley [85].

correspond to a performance judged as (statistically speaking) poor by 20 % and good by 50 % of the respondents. The level of the field sound reduction index, 56 dB, corresponds more or less to the minimum level of several countries in Europe ($R'_w \geq 55$ dB). For satisfactory conditions, an option is to use sound classification schemes introduced in several countries in Europe. In Sweden the minimum requirement is set to $D_{nT,w}$+$C_{50\text{-}3150}$ (abbreviated $D_{nT,w,50}$) ≥ 52 dB ≈ R'_w+ $C_{50\text{-}3150}$ (D_{nT} and R' are exactly equal when $0{,}32V_r/S_S = 1$) [29]. The target value has developed over the years, but the minimum level as it is today in Sweden, emanates from [5]. The work [5], carried out by the author of this thesis, included a substantial number of floor and wall assemblies for which various SNQs were calculated and then compared to find average values for spectrum adaptation terms, see table 3. In figure 2.4 the correlations between the SNQ, R'_w and the corresponding SNQs, $R'_w + C_{50\text{-}5000}$, $R'_w + C$ and $R'_{w,8}$ [30], respectively, are shown.

***Table 3**. Expected values of spectrum adaptation term $C_{50\text{-}3150}$ depending on type of construction [5].*

Type of construction	Number of measurements	$C_{50\text{-}3150}$ [dB] [a)]		
		Average	Min	Max
Concrete	9	-3.0	-4	-2
Porous concrete	23	-3.0	-5	-2
Wood, hardboard	15	-4.5	-7	-2
Gypsum board	19	-6.3	-15	-3

a) Originally, in the survey, the spectrum adaptation term $C_{50\text{-}5000}$ was calculated. The difference, $C_{50\text{-}5000} - C_{50\text{-}3150}$ = 1.0 dB.

From the study, it was concluded that it might be suitable to set the minimum requirements in the national building code to 52 dB (including the spectrum adaptaion term $C_{50\text{-}3150}$), implying slightly more severe requirements for light assemblies in order to raise the low frequency quality generally, see figure 2.4.

The sound insulation between dwellings may be characterized as satisfactory when 67 % (2/3) of the residents evaluate the conditions as good corresponding to R'_w = 60 dB [33], which means 4 dB difference between quality classes.

[29] $D_{nT} = R' + 10 \times \log(0{,}32V_r/S_S)$, where V_r (m^3) is the receiving room volume and S_S (m^2) is the area of the separating element. $D_{nT,w,50} = D_{nT,w}+C_{50\text{-}3150}$ in the current Swedish building code [36].

[30] $R'_{w,8}$ was used in BBR94 [1] and previous building codes to avoid large deviations between the measured or calculated curve and the reference curve in ISO 717, since it might cause annoyance from single frequencies. After shifting the reference curve, the single measured (or calculated) 1/3 octave bands must not deviate more than 8.0 dB from the reference curve. If exceeded, the reference curve shifts back until the maximum deviation is 8.0 dB.

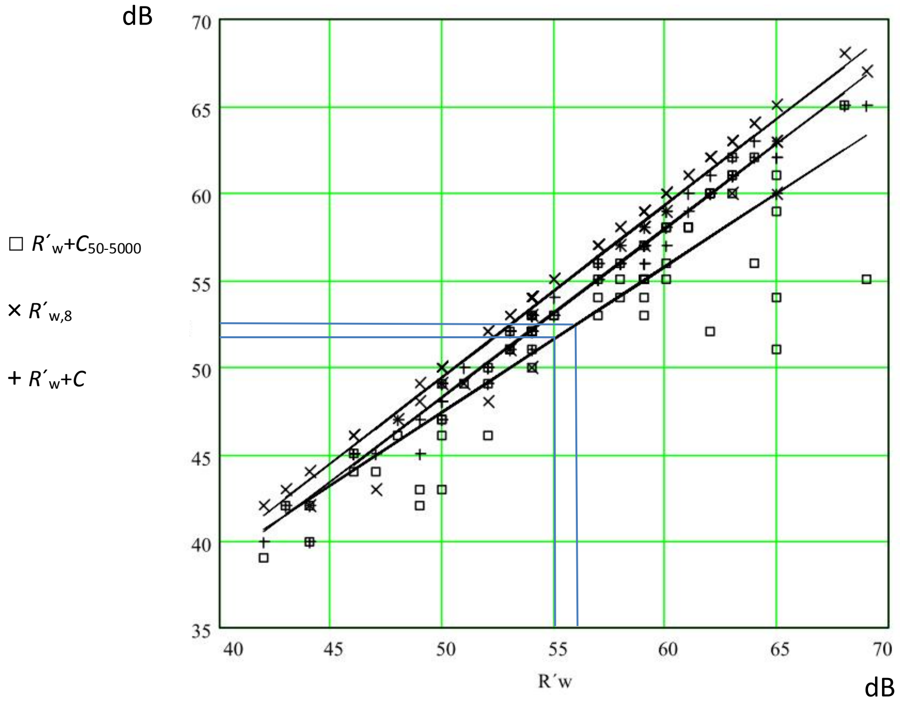


Figure 2.4. Correlation between each of the SNQs, $R'_w + C_{50\text{-}5000}$, $R'_w + C$, $R'_{w,8}$ and R'_w. Assuming requirement based on the weighted sound reduction index according to "tradition" and from [33], R'_w = 55-56 dB (see horizontal axis) corresponds to a SNQ, $R'_w + C_{50\text{-}5000} \approx$ 52-53 dB which equals $R'_w + C_{50\text{-}3150}$ 51-52 dB. From that, a requirement equal to $R'_w + C_{50\text{-}3150}$ = 52 dB is inherent.

2.3.2 Impact sound

Rindel requested further investigations regarding impact sound, and he concluded that it was not sufficient to propose new target values only based on one single field survey comprising 22 objects in Sweden [22]. Nevertheless, prior to introducing sound classification into provisions, the study regarding airborne sound insulation presented in table 3, also comprised spectrum adaptation terms for impact sound and their expected values for various structural systems, see table 4.

***Table 4**. Expected values of spectrum adaptation term $C_{I,50\text{-}2500}$ depending on type of construction [5].*

Type of construction [1)]	Number of measurements	$C_{I,50\text{-}2500}$ [dB]		
		Average	Min	Max
Heavy	27	-3.2	-11	1
Medium	53	1,5	-2	5
Light	62	2,4	-2	13

1) Heavy refers to homogeneous concrete; medium refers to hollow concrete; light refers to wood structures

The mandatory requirement in Sweden at that time was that the weighted normalised impact sound pressure level, must not exceed 58 dB ($L'_{n,w} \leq 58$ dB). Adding the spectrum adaptation term and keeping the same level the requirements for wood structures would imply an increased requirement by 3 dB. This results, together with the research results from [22] created basis for the updated regulations in Sweden 1999. To avoid that concrete structures will not deteriorate the weighted number without adaptation term remained, in addition.

In 2005, this single original survey [22] was extended and the new survey presented in the licentiate thesis of the author [6], included an attempt to state 3 minimum requirements and differences between classes for impact sound as well [6, 7], see figure 2.5.

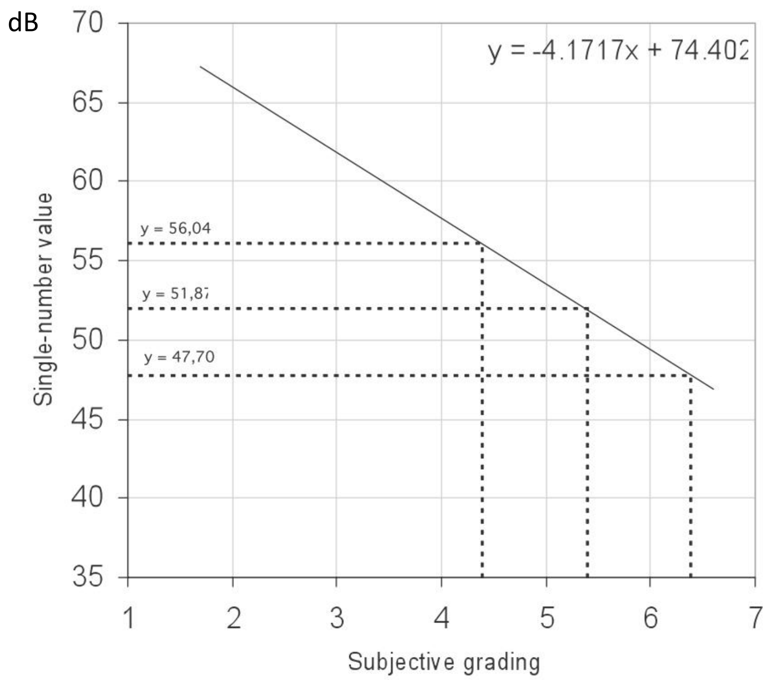


Figure 2.5. Proposed target levels for different classes from [7], based on the single number $L'_{n,w} + C_{I,50\text{-}2500}$ [31]. BBR, ≤ 56 dB; Class B, ≤ 52 dB; Class A, ≤ 48 dB. The levels form a basis for the classes in the updated Swedish sound classification standard SS 25267 [35].

[31] Today the requirement is stated using the standardised impact sound pressure level ($L'_{nT,w}$ and $L'_{nT,w}+C_{I,50\text{-}2500}$) instead of normalised impact sound pressure level. The relation between the normalised level, L'_n and the standardised level, L'_{nT} is the following; $L'_{nT} = L'_n - 10\times\log(0{,}032\times V_r)$, implying that big rooms have less hard requirements today, fitted better to subjective response [41].

2.3.3 Summary

The sound classes in Sweden regarding airborne sound insulation and impact sound pressure levels, as displayed in [35, 36], are set according to table 5. The standard also includes other parameters, which however, are outside of the scope of this thesis.

***Table 5**. Sound classes as displayed in the current Swedish classification standard SS 25267 (2015) [35] and minimum requirements in BBR [36].*

Sound Class in SS 25267 and BBR	*Descriptor* [dB]			
	$D_{nT,w,50} \geq$ a)	$D_{nT,w} \geq$	$L'_{nT,w,50} \leq$ b)	$L'_{nT,w} \leq$ b)
A	60		48	48
B	56		52	52
BBR	52		56	56
D		48		60

a) $D_{nT,w,50} = D_{nT,w}+C_{50\text{-}3150}$

b) $L'_{nT,w,50} = L'_{nT,w}+C_{I,50\text{-}2500}$ ($C_{I,50\text{-}2500} \geq 0$)

During many years, the Swedish classification standard and the building regulations referred to the descriptors "field sound reduction index", R', and "field normalised impact sound pressure level" L'_n. However, in order to fit better to reality and to the perceived sound insulation, the descriptors changed from scaling to a fixed absorption area to scaling to receiving room reverberation time. Over a period of 11 years, limitations of the ratio between the receiving room volume and the separating surface, V/S, for airborne sound insulation and for maximum volume of the receiving room, V, for the impact sound pressure level, was added; the descriptors changed in reality, but visually the "old" descriptors were kept the same [32]. The ratio V/S was limited to 3,1 and V was limited to 31 m^3 respectively. In practice, these hidden limitations implied that:

1. the weighted sound reduction index, R'_w, when calculated using this limitation, always becomes greater than or equal to the weighted standardised level difference $D_{nT,w}$
2. the $L'_{nT,w}$ value decided the level of $L'_{n,w}$ when the receiving room volume exceeds 31 m^3.

However, in the latest revision of the building regulations [36] [33] and in the classification standard SS 25267 (2013) [35], special rules were removed and, nowadays, the standardised SNQs fully apply. The consequences to transfer from sound reduction index, R', to standardised level difference, D_{nT}, and from normalised impact sound pressure level, L'_n, to standardised impact sound pressure level, L'_{nT}, for the provisions are described in [37, 38].

[32] These special rules were "hidden" in the text in the previous version (2004) of the Swedish sound classification standard SS 25267 [86].

[33] Later versions might exist, however not chapter 7 (2018).

2.4 Acoustic regulations and sound classification – European vision

Building regulations are national, but the building industry acts globally or at least within continents. Hence, mandatory building regulations would benefit from harmonisation to facilitate trade between countries and to reduce unnecessary administrative costs and design costs. Unfortunately, we are far from that as described in two papers from the conference Baltic Nordic Acoustic Meeting (BNAM) 2010, not least regarding sound insulation [39, 40]. However, in 2013 a draft proposal for harmonised regulations within Europe was prepared, as a result from the COST [34] action TU 0901 [41]. The main outcome was that the following quantities should apply, see also summary in table 6.

- D_{nT} – Good correlation to the subjective estimation of sound insulation. Adapted to field situation due to simple evaluation, no need to determine room volume or area of the separating element.
- L'_{nT} – Good correlation to the subjective estimation of sound insulation. Adapted to field situation due to simple evaluation, no need to determine room volume.
- The frequency range should be 50 – 3150 Hz. The extension to low frequency is necessary because it is important for wood constructions and floating floors. It is sufficient to keep 3150 Hz as the upper limit.

***Table 6**. Overview of acoustic descriptors for use in European provisions for partitions between dwellings, as proposed by TU 0901 [41]*

Aspect	Weighted quantity [dB]	Spectrum adaptation term [dB]	Frequency range [Hz]	Notation single number, in provisions *)
Airborne sound insulation	$D_{nT,w}$	$C_{50\text{-}3150}$	50-3150	$D_{nT,50}$
Impact sound insulation	$L'_{nT,w}$	$C_{I,50\text{-}2500}$	50-3150	$L'_{nT,50}$

*) The number is nothing but a practical and "visual" simplification, i.e only one single number must be written and the specific spectrum adaptation terms are hidden in the notation single number.

The results from COST were aimed to unify and simplify the building regulations in Europe. However, prior for the results to reaching the authorities for implementation in national mandatory building codes, problems arose. The intentions and agreements between researchers within the COST action, COST TU 0901, are only partly executed in the draft international standard (DIS) [35] [42], prepared after the completion of the COST action [41]. To minimise the risk that a mandatory extended frequency range would bring, the removal of the Vienna agreement [36] was agreed, i.e. it would not become a mandatory European standard. Additionally, only sound class A and B comprise descriptors including

[34] COST = European Cooperation in Science and Technology, http://www.cost.eu/.
[35] DIS = Draft International Standard is the last stage prior to become an International Standard, https://www.iso.org/stage-codes.html.
[36] Vienna agreement = Agreement on technical cooperation between ISO and CEN approved by the ISO Council resolution 18/1990 and the CEN General Assembly resolution 3/1990, https://boss.cen.eu/ref/Vienna_Agreement.pdf.

the adaptation terms, indicating that minimum requirements should only include frequencies from 100 Hz. This will remain for an unlimited time ahead. The agreement from COST TU 0901 to harmonise SNQs to include low frequencies at building code level thus failed to some extent and the obstacles to overcome are still almost the same prior to changing national minimum regulations throughout Europe. Nevertheless, for the future, the present standard proposal will perhaps encourage the industry within Europe to use the two highest classes including low frequency spectrum adaptation terms even if the levels are above normal standard. If not, it will complicate comparisons of sound insulation performances between buildings with different structural materials, since the objective values do not correlate well to the perceived sound insulation in wood buildings.

Mandatory requirements are different due to tradition and are deeply engrained in the minds of people. Not only that, over the years, each country in Europe has introduced national special rules (similar to Sweden as described in section 2.2) developed to adapt to specific building tradition at the time of introduction [39, 40]. Hence, apart from only changing descriptors, it is necessary to carry out an overview of each country´s special rules and its consequences, if removed.

To summarise, there is a huge inertia in the national legal systems, i.e. going from research results to introduction in national legal requirements. In the meantime, the industry manage building projects with historical requirements, still confident they produce buildings that exhibit acceptable living conditions. If the requirements do not cause immediate damage or loss of lives, there seem to be an increased inertia from research results to implementation in regulations. It is not only the authorities that hesitate to introduce new findings, but also acousticians themselves since the building acoustic theories used since early 1940 exhibit higher inaccuracy at low frequencies. Hence, the uncertainties grow, but still the challenges are there, the frequencies are audible and the requirements at least have to follow the development, even if the case should be, “to take the lead”. In the meantime, it is necessary to develop the building process such that it can handle acoustic building design for wood structures, to secure a residential standard providing healthy living conditions, similar to any other building system.

3. Subjective response

The foundation for regulatory framework on acoustics should have its basis on how humans perceive sound. In applied for heavy constructions, that is often the case. However, if extending the frequency range referring to ISO 717:2013 [15, 16], it might be sufficient to secure a proper residential acoustic standard in general, covering a wide range of housing formation, as it will be dealt with later on in this chapter. This chapter summarises research representing various surveys aimed to find the extent of residents' annoyance of sound in their homes. The results from the surveys are useful for development of regulations, but also to estimate the need for extension of the frequency range in the regulations (towards low and very low frequencies [37]), and when an extension should apply.

3.1 Research from 20th century

Due to the raised activity within the wood industry, boosted by the changes in regulations in 1994, to start building multifamily houses in wood, Lund University carried out research directly from the start, in several development projects [43, 44] ending up in an early design guide for wood constructions [45, 46]. The following research covered several fields within acoustics, subjective response to structure borne sound (e.g. impact sound) in wood buildings being specifically investigated. The conclusions were that the low frequency evaluation for impact sound according to ISO 717-2 [16] underestimates the annoyance even if the extended frequency range is included in the limit values. By keeping the frequency range 50-3150 but focusing more on low frequencies, the correlation between objective impact sound insulation measures and perceived sound insulation improved further, see figure 3.1 and 3.2 [6, 7] [38].

[37] Here, ´low´ means down to 50 Hz and ´very low´, down to 20 Hz.
[38] From the author licentiate dissertation in 2005 [6].

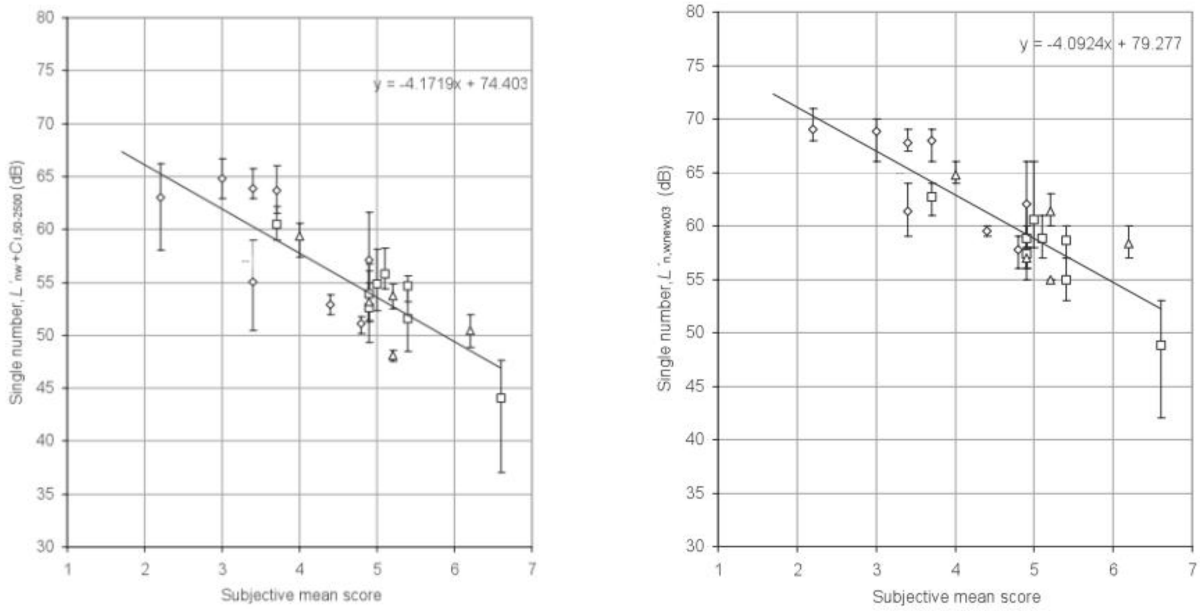


Figure 3.1. Linear regressions for the entire data sample; left; $L'_{n,w,new03}$ (and curve 04) vs subjective grading (r = 87 %[39]), and right; $L'_{n,w}+C_{I,50\text{-}2500}$ vs subjective grading [6, 7] (r = 84 %). The survey used a seven-point numerical scale. 1 corresponded to "quite unsatisfactory" sound insulation and 7 to "quite satisfactory" sound insulation.

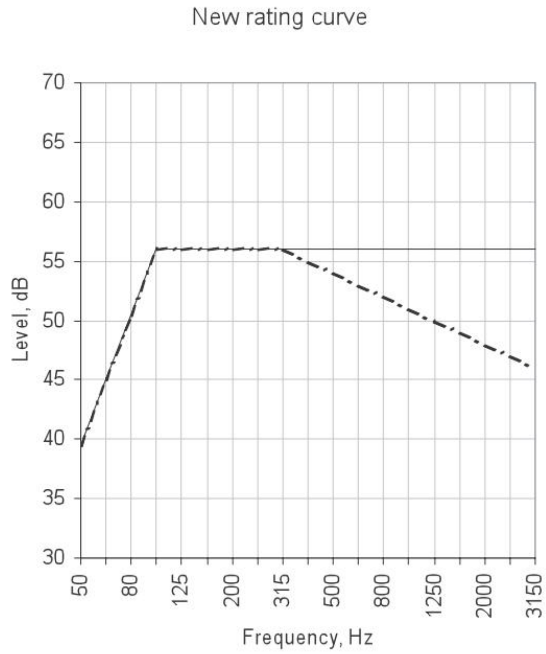


Figure 3.2. Reference curves (no 03 and 04) as proposed by Hagberg 2005 [6, 7]. Correlation between the subjective score and the objective measure raised from r = 84 % (ISO) to, r = 87 %[40].

[39] The correlation coefficient, r (and not the coefficient of determination R^2), was used in order to evaluate the results directly together with previous research from Bodlund [22, 23].

[40] The shifting procedure is similar to ISO 717 and the single number corresponds to the reference curve value at 500 Hz after the shifting [15, 16].

Similar to previous research [22], the new survey [7] comprised 22 different housing blocks. 11 of those were taken from [22, 23] (however, only floor assemblies included) and 11 new housing blocks using the results from floor assemblies only. The survey included buildings with various structural materials, solid concrete, hollow concrete, light steel beams and wood. The questionnaire comprised a seven-point numerical scale where 1 corresponded to "quite unsatisfactory" sound insulation and 7 to "quite satisfactory" sound insulation. The survey results indicated that the spectrum adaptation term for impact sound pressure level $C_{I,50\text{-}2500}$ did not compensate enough for the low frequencies. The correlation between all objective SNQs (various standardised SNQs and two SNQs proposed in [6, 7]) and the subjective scores are shown in table 7. Hence, the results imply that the best correlation appears after a complete change of the shape of the reference curve, and in this case omission of the spectrum adaptation term.

Table 7. *Different SNQs and their correlation coefficient, r* [41], *related to subjective experience [7]*

Single number	Reference	Frequency range [Hz]	Correlation	Comment
$L'_{n,w}$	[23, 15] ISO 717 (1996/2013)	100-3150	*r* = 74 %	Still most common globally
$L'_{n,w} + C_I$	[23, 15] ISO 717 (1996/2013)	100-3150	*r* = 79 %	Not used much
$L'_{n,w} + C_{I,50\text{-}2500}$	[23, 15] ISO 717 (1996/2013)	50-3150	*r* = 84 %	Extended to 50 Hz (Sweden, 1999)
$L_{Bodlund}$	[22] (1985)	50-1000	*r* = 83 %	Basis for ISO 717
$L_{Hagberg}$	[7] (2005)	50-3150	*r* = 87 %	Extra "penalty" in low frequencies

3.2 Recent research

A "state of the art" survey took place in Sweden 2007 [47] where several Swedish research institutions were involved, and a few years later also in Austria (2011) [48]. Their aims were to clarify the direction for further research regarding acoustics in the wood building sector. The results from the Swedish survey led to a funding decision for a project with the title *AkuLite* [42]. The project aim was to further study subjective response, however focusing on lightweight structures including wood. The project started in 2009 and finished 2013. In parallel, a European project was running, *AcuWood* [43], with identical aim, but comprising residential buildings in other countries in Europe.

Two different surveys were used in the two different projects; 1. one survey using measured data and questionnaires from a number of different housing blocks, to correlate subjective response with objective evaluation to find an optimised single number rating for building structures with wood (and

[41] The correlation coefficient, *r* (and not the coefficient of determination, R^2), was used in order to evaluate the results directly together with previous research from Bodlund [22, 23].
[42] The entire project is compiled in ten different reports [8, 49, 87, 88, 89, 90, 91, 92, 93, 94].
[43] The entire project is compiled in five different reports [50, 95, 96, 97, 98].

some light steel structures), but also applicable to concrete structures; 2. one other survey employed listening tests, based on recordings as described in [49, 50].

The questionnaire surveys in housing blocks in the two research projects were similar to the previous Swedish research projects [7, 22], however using an updated and unified 11-point numerical scale ranging from 0 – not at all bothered, disturbed or annoyed to 10 – extremely annoyed, including face symbols to characterize the two extremes of the scale. The questionnaire containing questions related to annoyance from indoor noise sources such as structural noise (impact sound) and airborne noise from neighbours. It follows the ISO method [51] and European researchers in the COST action, COST TU 0901, participated in its development. The questionnaire was translated into several European languages.

The outcome and the results from the *AkuLite* and *AcuWood* projects are not identical, although similar final statements emerged from both projects. It was clear that the main parameter causing annoyance was noise caused by impact sound, more pronounced than any other parameter. That is in compliance with previous research [6, 7]. From *AkuLite* the results included yet another proposal for a new descriptor for impact sound insulation, best fitted to the questionnaire results from 10 different residential blocks. The outcome from *AcuWood* on the other hand comprises an extensive test of different available single numbers / descriptors, both standardised descriptors and such descriptors as proposed by researchers over the years. The results were based on questionnaire survey in the field and laboratory listening tests at Fraunhofer Institute for Building Physics (IBP), Germany. During the survey, the perceived annoyance from various noise sources was compared to the perceived annoyance from objective measures, following a procedure as described in [50].

The SNQ from *AkuLite,* giving the best correlation between the perceived annoyance and the objective measures, is simply an addition of frequency weighted 1/3 octave bands (the descriptor becomes the weighted single number with a new spectrum adaptation term added, similar to the procedure described in ISO 717 [15, 16]). The best correlation was found for a spectrum adaptation term starting at 20 Hz, including additional weighting in the 1/3-octave bands below 50 Hz and above 400 Hz, added to the standardised weighted value $L'_{n,w}$, as displayed in figure 3.

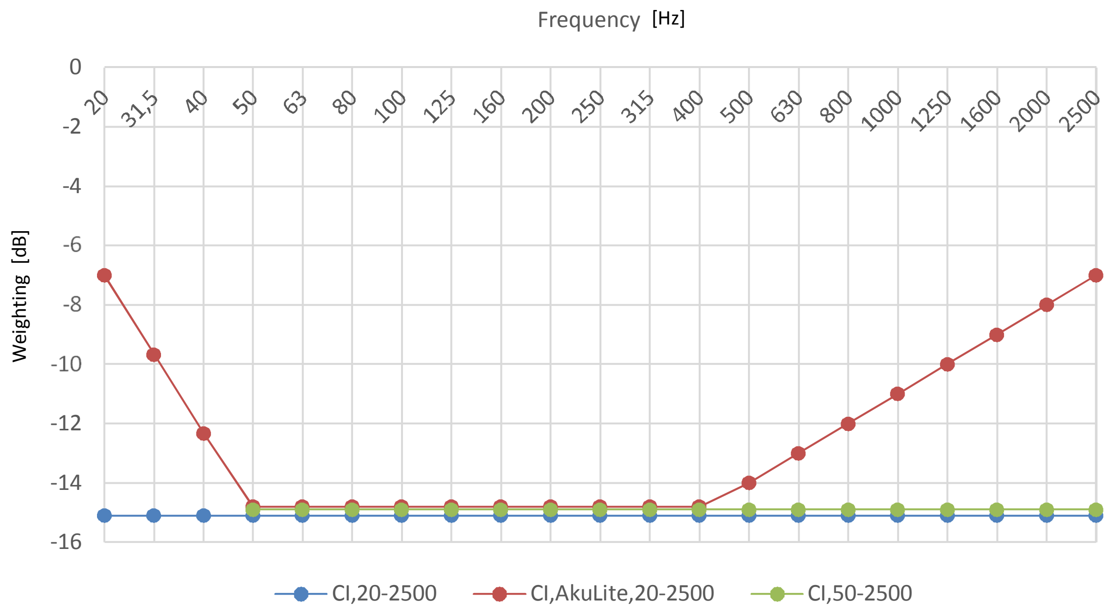


Figure 3.3. Frequency weighting of three spectrum adaptation terms; blue – flat term down to 20 Hz; green – ISO 717-2; red – as proposed from *AkuLite* results

Hence, the final SNQ showing the best coefficient of determination compared to perceived sound insulation, from the field survey answered by residents in *AkuLite* is:

- $L'_{n,w} + C_{I,AkuLite,20\text{-}2500}$ (R^2 = 85 %)

The *AkuLite* adaptation term implies strong attention to low frequencies in the evaluation procedure, see figure 3.3 above. The coefficient of determination was raised from 26 % when only considering frequencies above 100 Hz ($L'_{n,w}$) and from 32 % when starting from 50 Hz ($L'_{n,w} + C_{I,50\text{-}2500}$).

Another interesting comparison can be made by dividing the correlation into two frequency groups; 1. Considering frequencies between 50-3150 Hz following ISO 717 and its extended frequency range ($L'_{n,w} + C_{I,50\text{-}2500}$) and 2. Considering only frequencies outside this range, e.g below 50 Hz. The coefficient of determination considering only the very low frequencies (20, 31.5, 40 and 50 Hz) is convincing, see the results as displayed in figure 3.4. For buildings made with wood structures the lowest frequencies certainly have an impact on the perceived impact sound insulation. Therefore, using techniques to reduce noise in these frequencies will resolve many potential problems. In addition, potential problems at high frequencies are more or less resolved by themselves.

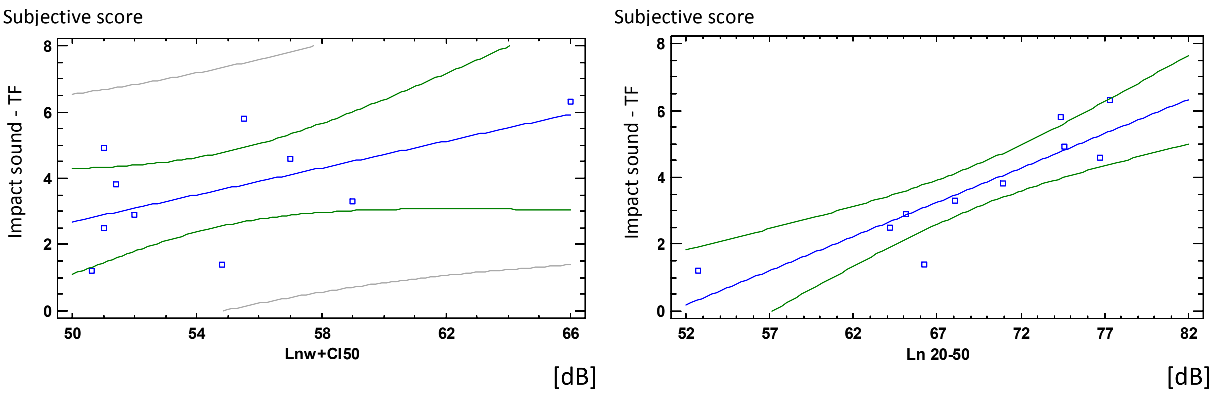


Figure 3.4. Coefficient of determination between single number (horizontal axis) and subjective score (vertical axis), top floor excluded (TF). 1. Left diagram; considering ISO 717-2 from 50 Hz ($L'_{n,w}$+ $C_{I,50\text{-}2500}$), R^2 = 32 %, and; 2. Right diagram; considering only frequencies below 50 Hz, $L'_{n,20\text{-}50}$, R^2 = 78 %

The questionnaire survey from *AkuLite* indicates that low frequencies strongly influence the perceived annoyance in dwellings with wood structures. The buildings in the survey aimed at meeting at least the Swedish minimum requirements for impact and airborne sound, implying that the impact sound pressure level must not exceed $L'_{nT,w}$+ $C_{I,50\text{-}2500}$ = 56 dB [7], see figure 2.5 in previous section. Still, few (three out of ten) measurements exhibit too high values, see left diagram in figure 3.4.

An overview of the single numbers and their correlation to walking noise as evaluated from field survey and listening tests in laboratory, during the *AcuWood* project, is displayed in table 8. The correlation represents a comparison between recorded signals representing different single numbers and annoyance due to human walking noise.

Table 8*. The coefficient of determination, R^2, between different single numbers (tapping machine as a source) and perceived annoyance of walking noise.*

Single number	R^2	**Frequency range [Hz]**
$L'_{nT,w}$	0,38	100-3150
$L'_{nT,w}$ + $C_{I,100\text{-}2500}$	0,48	100-3150
$L'_{nT,w}$ + $C_{I,50\text{-}2500}$	0,58	50-3150
$L'_{nT,Bodlund}$	0,58	50-1000
$L'_{nT,Hagberg}$	0,63	50-3150
$L'_{nT,Fasold}$	0,56	50-5000
$L'_{n,w}$ + $C_{I,AkuLite,20\text{-}2500}$	0,56	20-3150
$L'_{nT,w}$ + $C_{I,AkuLite,20\text{-}2500}$	0,57	20-3150

Concluding the findings from *AcuWood,* results in the statement that; if walking noise is the main excitation source, the frequency range starting from 50 Hz is sufficient in order to describe an objective impact sound pressure level that corresponds well to perceived sound level. Still it is clear that it is necessary to include frequencies between 50 – 100 Hz, at least for the typical ordinary housing units included in the surveys.

Another recently finalised research project, *Aku20*, managed from Luleå University of Technology (Sweden) is of interest in the present context [52]. The aim of that project was to gather additional acoustic data together with subjective data, using the same principle with questionnaires and measurements as in the previous project *AkuLite.* By adding a substantial number of new residential blocks and including them in the material, the statistical significance became stronger. In total, thirteen new residential blocks were included, five of those were heavy structures (concrete) and eight of them were different types of wood structures. The coefficients of determination for different objective evaluations, as related to perception of noise from footsteps, are given in table 9 [52]. In addition, a complementary listening test was made to verify the results [53].

Table 9*. Coefficient of determination, R^2, between different single numbers (tapping machine as a source) and perceived annoyance of walking noise, from the project Aku20 [52].*

Single number	R^2	Frequency range [Hz]	Weight 20-40 Hz [a)]
$L'_{nT,w}$	0,18	100-3150	
$L'_{nT,w,50}$	0,49	50-3150	
$L'_{nT,w,40}$	0,53	40-3150	
$L'_{nT,w,31}$	0,64	31-3150	
$L'_{nT,w,25}$	0,72 [b)]	25-3150	
$L'_{nT,w,20}$	0,71	20-3150	
$L'_{nT,w,25}$	0,75	25-3150	1
$L'_{nT,w,20}$	0,67	20-3150	1
$L'_{nT,w,25}$	0,77	25-3150	2
$L'_{nT,w,20}$	0,65	20-3150	2
$L'_{nT,w,25}$	0,75	25-3150	3
$L'_{nT,w,20}$	0,61	20-3150	3

a) The weighting concerns increased dB per third octave band relative to -15 dB.

b) If one outlier is removed because it exhibited strange results due to the high age of the respondents, the coefficient of determination increases up to 0.85, exhibiting almost similar coefficient of determination as the *AkuLite* proposal (0.86).

To conclude, the adaptation term as proposed in the project *AkuLite* seems to overestimate the low frequency impact, generally speaking. As more residential blocks are included and other surveys are added to the considerations, the very low frequencies are still important, however less important than what was concluded from the limited number of residential blocks as presented in *AkuLite*, which comprised almost only lightweight structures. Consequently, very low frequencies are very important but still more research is needed to verify to what extent.

From the two projects *AkuLite* and *Aku20* together, Öqvist concluded [52] that the spectrum adaptation term $C_{I,25\text{-}2500}$ should be used creating the single number $L'_{nTw,25}$, for low frequency evaluation. Additionally, it is perhaps not necessary to push the limits below 50 Hz at present, since a holistic view on wood as building material is important, e.g. impact sound insulation is only one characteristic amongst others to consider.

Then, if $L'_{nT,w,50}$ is used, and if current research is used to convince the global community that it is a suitable and general requirement for impact sound insulation for any structural material, on a global market, it will bring a great benefit. The building industry will gain much more than if one small country introduces even more strict regulations. Promoting the ISO descriptor ($L'_{nT,w}$+$C_{I,50\text{-}2500}$) has several advantages:

1. It is globally standardised.
2. A lot of data and experience are collected and are already available regarding this descriptor.
3. The industry will unify their efforts in the same direction.
4. Though not perfect in terms of low frequencies, it is proven to be far better than $L'_{nT,w}$ or $L'_{n,w}$ and, simultaneously, a moderate step is taken that can be accepted globally within a limited amount of years.

Still the limitations as elaborated in section 3.3, must be taken into account.

3.2.1 Additional research – subjective perception

Over time several national surveys have been carried out in different countries, however not directly connected to timber frame structures or not using the widely used ISO tapping machine as a source.

In Canada, subjective laboratory tests were conducted in 2011 from which similar outcomes as stated in previous section can be identified [54]. In Korea, Jeong carried out research with heavy impact ball and characterised $L_{A,max}$ as a good estimate for impact sound pressure level for improved subjective perception [55]. In 2011 Ryu et.al. carried out research using heavy ball as a source [56] and concluded that the Japanese standardised single-number quantities using the A-weighting curve as a rating curve were excessively influenced by frequencies below 100 Hz. In Finland, subjective response for various flooring on concrete structures were investigated by performing listening tests, showing that the low frequency impact sounds are significant in the subjective rating also for concrete floors [57]. A survey was carried out in Norway and the conclusion was that the low frequency spectrum adaptation term, $C_{I,50\text{-}2500}$, should be included in order to improve the correlation between annoyance and measurements in multifamily houses [58]. In the French project Acubois a questionnaire survey was made recently, concluding that it is important to consider low frequency impact sound in the evaluation (from 50 Hz) [59]. There is also a survey from 1970 in the Netherlands [60]. Hence, there are a number of surveys available for further evaluation in a common context.

For airborne sound insulation, some studies have been carried out lately [61-69], summarised by Rindel in [70]. Rindel concludes, contradictory to the papers he reviewed, that they prove that the low frequency components are of great importance and that it would be beneficial to provide SNQs adapted to the source of sound, i.e. one SNQ to protect from music comprising bass tones and one

SNQ for other sources comprising less sound in low frequencies. However, if the main purpose of the SNQ for airborne sound insulation in dwellings is to define a minimum level of sound insulation that can ensure a reasonable protection against annoying sounds from the neighbours, then it is sufficient to have the stronger of the two requirements.

3.3 Limitations

As discussed in section 1.3, the questionnaire surveys referred to above suffer from limitations, also noted in [52]. They all refer to "normal size flats", and in spite of a diversity of tenants in terms of age and gender, they still represent rather ordinary households. In future, there will be more need for dwellings for the elderly and the percentage of single-person households might increase. Therefore, surveys should comprise expected demographic changes and in addition cultural differences (many countries). This, in turn, implies that other requirements and considerations than those taken in the previously mentioned studies could be of interest. If adapting requirements for one type of dwellings and then transmit those to other types of dwelling with other preconditions, the costs might rise without any verified benefits.

Historically, low frequencies have not been part of the evaluation in building acoustics. The lower limit has always been 100 Hz but nowadays many countries at least measure and evaluate down to 50 Hz even if there are no requirements in building regulations. There are uncertainties and difficulties to measure in the low frequencies, as described in [52, 71], that have to be taken into account when stating requirements and developing prediction tools. However, with an increased amount of wood in the building sector, the low frequencies have to be included in the development of the industry.

4. Tools to facilitate Prediction

Prediction of sound insulation with enough accuracy is of high importance to promote housing developers to use wood. However, low frequency design down to the third octave bands 40, 31, 25 or even 20 Hz requires new methodologies. Frequencies around 20 Hz can be characterised as being something in between felt vibrations and low frequencies causing sound. These phenomena are connected such that the perceived annoyance of e.g. noise can be more severe if, at the same time a vibration is sensed (or possibly the noise is perceived as being more annoying if no other sensation, such as the vibration, can be coupled to it). Negreira [72] gives a meticulous description of low frequency prediction using Finite Element Method (FEM). However, for management of *ongoing* building projects, applicable and simplified tools for direct use are necessary.

Since year 2000, standardised engineering prediction tools are available [20, 21]. The standards describe how to combine partitions (walls, floors, ceiling and their junctions) in a building in order to include flanking transmission. However, there is one shortcoming, the standards are mainly fitted to heavy structures. They are based on Statistical Energy Analysis (SEA) theory, which does result in inaccurate results / predictions for wood buildings, due to, among other things, low modal density in the low frequencies. Therefore, other methods can be used [72], complementary to SEA. Nevertheless, during the last few years this standard series has been revised and updated to include some junctions that can be used for timber structures. The standards are, however, still very limited and hence they do not cover the huge diversity of different options for floor and wall assemblies in wood nor the various types of junctions that might appear. An update of ISO 15712 (EN 12354) [44], has been ongoing for many years and an extensive work was carried out within the COST action, COST FP 0702, "Net-Acoustics for timber based lightweight buildings and elements" [73].

4.1 Model verification

Measurements are exclusively the dominant verification procedure for structural systems in a building. When modelling using software, the software model validity should of course be verified by comparing the results with measured data. However, the huge variety of wood building components, complicate the verification procedure due to lack of available measurement data. New solutions enter the market every day and reliable input data to provide satisfactory predictions are lacking, [101], and the question is how we can help developers to optimise their proposals?

[44] Renamed to ISO 12354 in the updated standards in 2017 [74, 75]

Silent Timber Build [45] is a recently finished project, which comprised of several parts:

1. Model development covering the standardised frequency range (50-3150 Hz)
2. Model verification
3. Grouping of measurement data from various European floor assemblies
4. Display of solutions in a European ATLAS comprising floor and wall assemblies

Software systems are available for utilizing models of various floor and wall assemblies. By combining Statistical Energy Analysis (SEA) and the Finite Element Method (FEM) the full frequency range can be covered with a high degree of compliance. The Silent Timber Build project used this approach. However, to promote modelling and prediction in practice, a verification procedure must exist to confirm the validity of prediction models. Historically, new building systems develop by building "full scale" models, which implies high costs and limited input for further development.

By collecting existing data from a large number of different building sites and laboratories, compiling the data in a well-defined and structured manner, a basis for verification of theoretical models was established within the project Silent Timber Build. Providing an extensive set of data for different assemblies facilitates modelling and continuous improvements as more data are acquired / added to the database.

4.1.1 General verification by grouping

The dimensions of a building and its building parts are of great importance during the building process. Thicknesses of floor assemblies influence the final height of the building and therefore an early prediction is important, not least since acoustical characteristics create the basis for dimensions needed from a structural point of view, at least for dwellings but also for many other buildings with high sound insulation requirements. Hence, in many European countries the requirements regarding sound insulation are high enough in order to prescribe the dimensions of any construction assembly needed for the building. This means it is neither the strength, the fire resistance nor any other technical regulation, but rather the vibration resistance or the sound insulation requirements (either the airborne sound insulation or the impact sound insulation) that prescribe the dimensions of floor and wall assemblies. This is actually true for any structural material used for the building, no matter if the material is heavy like concrete or if it is light like wood. However, the structural dimensions always have to be considerably larger for wood structures compared to heavy weight structures to fulfil the acoustical minimum requirements for residential buildings, at least in the Nordic countries, see example in figure 4.1. The sizes displayed in figure 4.1 can serve as an early prediction when following the Swedish sound classification standard [35], for sound class B, a very common quality level in Sweden.

[45] www.silent-timber-build.com, WoodWisdomNet project WWN+ in the 4th joint call (2013-2017)

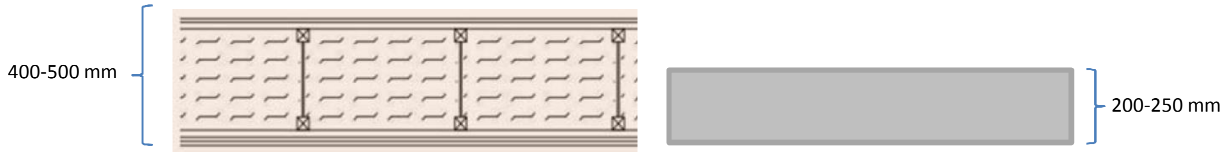


Figure 4.1. Structural bearing system and their dimensions. Left; wood. Right; concrete. Approximate structural floor height for a typical wood structure (left) and heavy concrete structure (right) to fulfil minimum requirements in Swedish building regulations.

Since sound insulation very often prescribes the structural dimensions of a building, it is a high priority design parameter, or at least it should be. In addition, careful framing of junctions and connections is necessary.

In a building project, modelling of sound insulation characteristics is of great importance to reduce the risks for the developer and other parties involved. Often, the design is carried out by using experience and previous results from similar buildings / floor assembles. Another manner, more useful for the wood industry development since it allows further optimisation of the assembly, is to make a model by using SEA and/or FEM software. However, the complexity and the diversity of available wood floor assemblies require a verification procedure of the model. To provide a verification procedure, a model of grouping various floor assemblies based on their acoustic characteristics, was prepared by the author of this thesis. The grouping is based on a large number of different floor assemblies, divided into groups and subgroups depending on their composition of material. The grouping is aimed for verification of a calculation model of an actual floor assembly, to secure that the calculated sound insulation (impact sound pressure level) end up in the expected range. The grouping is useful, since it creates a basis for further future development and analysis if kept up and running. The different groups identified, based on a relation between the mas per unit area and their structural build-ups, are displayed in figure 4.2.

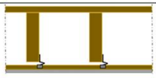
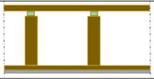
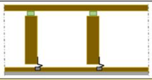
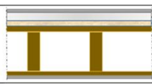
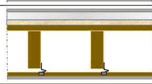
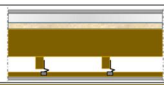
Floor Assembly group	Name	Assembly	
Group A	Wood Joist	FS-CS	
		FS-CR	
		FS-CN	
		FR-CS	
		FR-CR	
Group B	Hybrid Wood Joist	FS-CS	
		FS-CR	
		FR-CS	
		FR-CR	
Group C	Massive wood	FS-CS	
		FS-CR	
		FS-CN	
		FR-CS	
		FR-CR	
Group D	Hybrid Massive element	FR-CS	
		FR-CR	

Figure 4.2. Main groups (A-D) and subgroups (assembly) identified from where a specific relation between the mass per unit area (*mpua*) and the single number, $L_{n,w}+C_{I,50\text{-}2500}$, could be identified. Each subgroup is identified by the floor and the ceiling and their fixing to the structural element. FS = Floor Stiff; FR = Floor Resilient; CS = Ceiling Stiff; CR = Ceiling Resilient; CN = Ceiling None (decoupled)

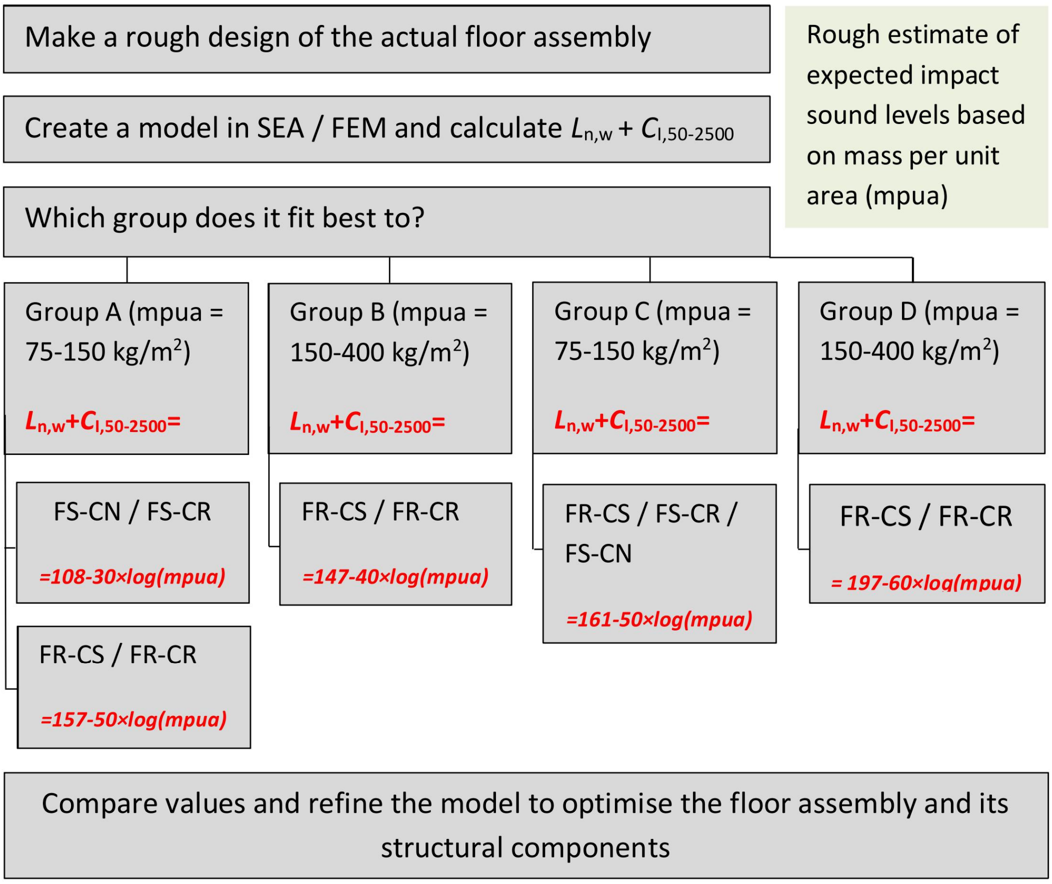


Figure 4.3. After dividing into subgroups the single number $L_{n,w}+C_{I,50\text{-}2500}$ was related to the floor assembly mass per unit area (*mpua*). As new systems develop, the grouping and the calculations can be updated and refined – an iterative learning process.

The grouping is a tool facilitating immediate use of advanced software models amongst engineers and consultants. The grouping model can be further developed, and the results will be useful as input for further development of standardised calculation tools. As mentioned previously, standardised calculation tools are lacking, at least to cover all upcoming floor and wall assemblies and conceivable junctions for wood buildings. However, in 2017 an update of the standard series ISO 15712 (EN 12354) renamed to ISO 12354 was published [74, 75], allowing wood floor and wall assemblies including new junctions to small extent. However, still with a limited scope and, of course, not covering all possible options within the wood sector. The listing of the standard series and its usage in the building process map out in several surveys, overall described consistently by Simmons [71].

The usage of ISO 12354 [74, 75] and general models for wood structures are still a “grey zone”, due to a huge variety of structural elements, complex compositions and a diversity of junctions. Therefore, new and additional considerations are still required prior to have a standardised model, applicable to wood and easily accessible for acoustic engineers.

5. Project management

As also described earlier in section 2, the importance of unimpeachable acoustic design is even more evident when it comes to wood structures. For such structures specifically low frequencies have to be considered since a minor failure in the design stage or erection phase can cause high costs at a late stage compared to traditional heavy concrete structures. A “low frequency failure”, as might appear in a wood structure, is complex and, in addition, difficult to trace while a “high frequency failure”, as might appear for instance in a concrete structure, is easier to correct and to trace. It might even become impossible to mitigate the effects of the low-frequency failure of the wood structures. Minor errors can cause unforeseen sound transmission also in other frequencies since wood structures comprise a diversity of products interacting to exhibit expected (according to the project requirements) sound insulation performance. One misplaced screw can cause severe sound transmission at specific frequencies. Such mistakes must be avoided either by educations of workers, or by regular checks during the building phase, following specific processes adapted to the system provider. If not, all mistakes visible during erection, are easily hidden behind topper compounds and painting after finishing.

To avoid failures, easily accessible tools should be available. In 2008 the Swedish National board of housing, building and planning published an extensive handbook [76]. In this handbook, it is fully described how to manage acoustics throughout the entire building process for any building system. The handbook is now prepared for an update (2018) due to recently revised acoustic regulations in Sweden (not yet published). The purpose of the handbook is to facilitate the management of building projects in terms of acoustic issues. This means reducing uncertainties due to poor cooperation between parties involved. It is written in Swedish by the author and Simmons, however a summary of the first edition is displayed in Paper A in this thesis. For wood houses, additional more specific handbooks / system descriptions need to be developed since the diversity of systems complicate the design process even further.

To facilitate the use of wood in small multifamily houses, specifically for local developers with a limited budget, a new design guide for small wood houses was prepared in 2013, [8], also partly described in a paper presented at Internoise 2012 [9].

An example: Masonite Flexible Building System, Industrial Constructive Cooperation (MICC)

MICC is a form of cooperation between different parties involved in industrial wood construction with MFB - Masonite Flexible Building System. The MICC model is the work procedure that is practiced, collaborating throughout the construction process (from design to finished houses) based on industrial methods with prefabrication at the factory, close collaboration and partnership. MICC included development of the entire building design chain, from the wood I-beam manufacturer (system developer) to the element producer and components included. In addition, the interface to the technical design, architect, acoustic designer and static designer was included. Specifically, the importance of acoustic design was put into high priority due to the system complexity and its low weight, see figure 5.1 [77].

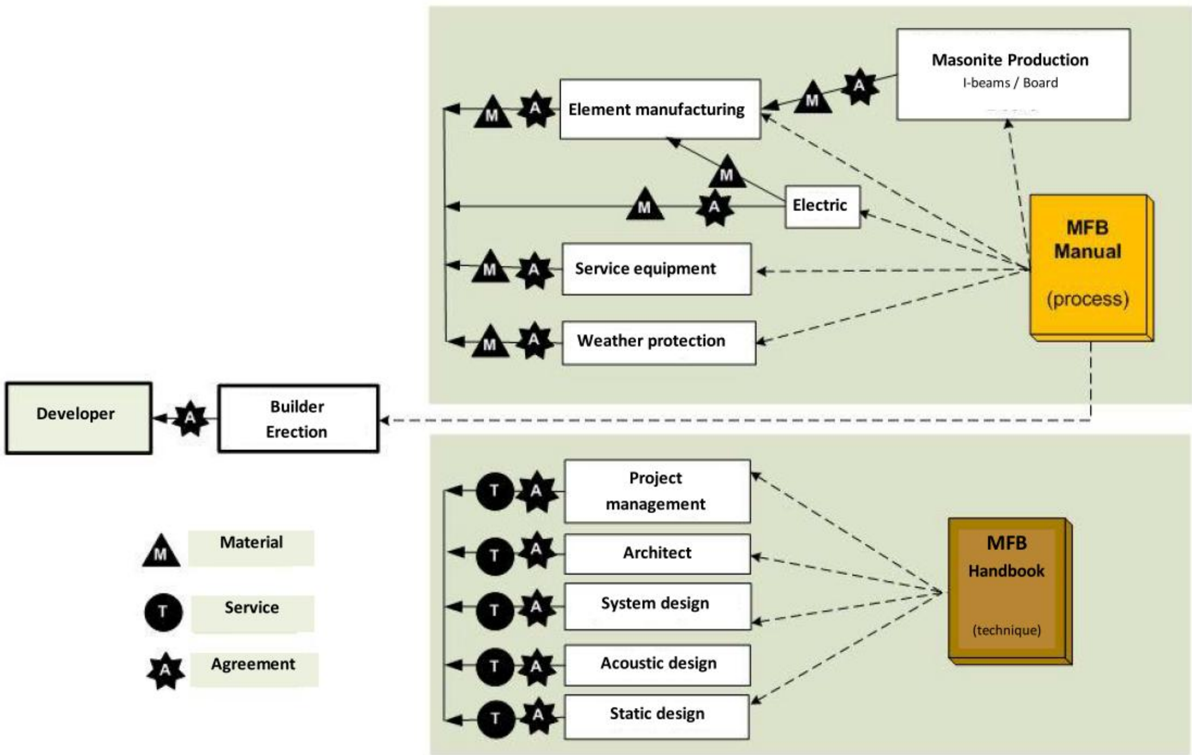


Figure 5.1. MICC business model showing the interaction between the parties involved

The project resulted in a handbook and one finalised building project in Nordmaling on the north east coast of Sweden. Depending on manufacturer the process can vary, however it is always necessary to include acoustic design as a key topic in the process.

Opportunities

If acoustics is highlighted in the design process this can be added to all positive effects that is connected to the use of wood. By using all the knowledge gained from the research projects *AkuLite* (Sweden), *AcuWood* (Europe) and *Silent Timber Build* (Europe) as managed by the author, include the results into the building process, the wood sector will become stronger in terms of acoustics. Then, adding results from other research projects referred to in this thesis, will further strengthen the building sector. If the developers do not hesitate to use wood due to acoustics, the focus can be elevated to broadcast all opportunities for use of wood.

Firstly, wood is a renewable material with low weight. The low weight opens up for applications where heavy materials cannot compete such as densification of buildings by adding additional storeys and making use of construction sites with specific foundation issues.

Secondly, wood buildings allow a high degree of prefabrication. This implies a unique opportunity to develop processes for increased efficiency within the building sector that will have several benefits:

- Improved work environment for the workers.
- Less waste of material → reduced costs.
- Minimising the risk for building site adjustments after completion of the building.
- Reducing the number of people needed on the building site → minimising interference between different duties.
- More quiet conditions during erection compared to building sites with concrete structures.
- Less storage of material on site.

Thirdly, the prefabricated elements are easily transported to the building site for fast, dry and efficient erection. All these opportunities are of great importance to modernise the building sector and reduce cost for production of residential buildings.

Finally, wood is a natural material and in terms of indoor acoustics, it is shown to bring wellbeing to residents [4].

Challenges

The low weight of wood creates opportunities, however in terms of acoustics it also creates new challenges for the building industry. More focus to evaluate low frequencies require specific knowledge outside the "comfort zone" for the people involved in the projects. The low weight also complicates the calculation of flanking transmission for many building systems comprising wood. Wood assemblies require more space (larger dimensions) to fulfil the same acoustic requirements compared to similar buildings made with concrete. Thus, prior to taking decisions regarding the structural system, possible limitations of city plans and building permits have to be considered.

Knowledge regarding acoustics in wood buildings is a challenge for the future. Education of new engineers, directed to the wood sector must increase. The industry itself often identifies acoustics as a key challenge for further development of the wood sector [46].

[46] Several companies and developers have defined acoustics and vibration as a main challenge to overcome, afflicted to severe uncertainties. NCC presented their thoughts at a seminar in Stockholm 23 May 2017, https://www.svenskttra.se/om-oss/events/2017/5/ingenjorsmassigt-byggande-i-tra/ .

Tasks

The wood industry itself is often aware of the challenges ahead, implying it is important to continue the development and show good examples. However, new solutions often appear, not at all optimised in terms of acoustics. The main tasks to secure future success for the wood industry is:

- Put high priority to acoustics – acoustic performance sets the dimensions of the building components.
- Set the correct target value.
- Decide building system for the actual building.
- From that, decide the procedure to manage the building to reach the targeted results.

6. Appended publications

Below, a summary of the appended publications, and the author´s contribution to each of them, is given. Furthermore, other publications contributed to the content in this thesis are found in a separate list in section 6.2 and as references in the text in chapters 1 to 5 (see reference list after section 7).

6.1 Summary of the appended scientific papers

6.1.1 Paper A

A Handbook on the Management of Acoustic Issues During the Building Process

Klas G. Hagberg and Christian Simmons

Journal of Building Acoustics, Volume 17, no 2, p 143-150

In 2008, the author of this thesis and Simmons wrote a handbook commissioned by the National Board of Housing Building and Planning, titled *Noise prevention of Dwellings and Commercial premises* (however the full book only in Swedish – *Bullerskydd i bostäder och lokaler*). The purpose of the handbook is to facilitate the management of building projects in terms of building acoustics issues. That is to reduce the uncertainty in design and the conclusive of a building due to poor cooperation amongst parties involved in the building process. The handbook covers all types of buildings, no matter lightweight structures or heavy. In 2015 a revision of the handbook was prepared, however not yet published. The paper appended in this thesis gives a summary of the content in the handbook.

Contribution:

The author of the thesis has written the handbook together with Simmons. The handbook is based on research and development connected to acoustics in the building process. The author of this thesis has specifically contributed for those parts that connect to lightweight and wood structures. The author also prepared the article submitted to and reviewed by Building Acoustics.

6.1.2 Paper B

Sound Insulation Descriptors in Europe—Special Rules Complicate Harmonization within Lightweight Industry

Klas G. Hagberg and Delphine Bard

Journal of Building Acoustics, Volume 17, no 4, p 277-290 (2010)

The acoustic descriptors differ more than what is obvious by a quick comparison between different countries and their mandatory requirements and classification standards. The different descriptors are a heritage from the past, visually kept to avoid confusion but successively adapted to the building industry in each country and their certain traditions in building technique. To fulfil national interests and to fit to new design trends of housing units, etcetera, the descriptors involve small local adaptations/national "corrections" within each country. These local adaptations are not easy to find and require careful reading of the provisions, often in the local language. This causes unnecessary translation problems and costs since the building industry is not restricted physically to national boundaries anymore. The paper describes those differences between some countries within Europe. If all European countries would be involved it is expected to increase the diversity even more.

Contribution:

The author of the thesis has made the survey as a whole by collecting data from different countries, and has written the article. The co-author, Bard, proof read the article and gave suggestions for changes and presented initial results at conferences.

6.1.3 Paper C

Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound

Fredrik Ljunggren, Christian Simmons and **Klas G. Hagberg**

Journal of Applied Acoustics, 85, p 57-68 (2014)

In a survey carried out in real housing blocks several vibrational and acoustical parameters were determined, by applying an extensive measurement template. In total, the survey included ten Swedish buildings of various constructions. In the same buildings, the occupants were asked to rate the perceived annoyance from a variety of natural sound sources. The highest annoyance score concerned impact sounds, mainly in the buildings with lightweight floors. Statistical analyses between the measured parameters and the subjective ratings revealed a useful correlation between the rated airborne sound insulation and $R'_{w}+C_{50\text{-}3150}$ while the correlation between the rated impact sound insulation and $L'_{n,w}+C_{I,50\text{-}2500}$ was weak. However, by applying a modified spectrum adaptation term starting at 20 Hz, the correlation exhibited considerable improvement.

Contribution:

The author of the thesis contributed to this paper in four ways; 1. By providing the basis for the research in which the survey was carried out since the basic idea for the research was initiated by the author and also by designing the objective measurement procedure; 2. By developing the methodology for the field survey, together with the co-authors; 3. By providing input to the evaluation of the collected data and; 4. By writing and proof reading the article.

6.1.4 Paper D

Subjective and Objective Evaluation of Impact Noise Sources in Wooden Buildings

Moritz Spaeh, **Klas G. Hagberg**, Olin Bartlomé, Lutz Weber, Philip Leistner and Andreas Liebl

Journal of Building Acoustics, Volume 20, no 3, p 193-214 (2013)

The project, *AcuWood*, comprised an extensive a series of measurements and recordings on different intermediate timber floor assemblies in the laboratory and in the field, covering a wide range of modern intermediate timber floors. Additionally, one intermediate concrete floor with different floor coverings was included in the study. Besides the standardised tapping machine, the modified tapping machine and the Japanese rubber ball and "real" sources formed part of the survey. Subjective ratings from listening tests were evaluated and correlated to many technical single number descriptors such as the standardised descriptors and non-standardised proposals. It was found that the Japanese rubber ball represents walking noise in its characteristics and spectrum best, taking into account the practical requirement of a strong enough excitation for building measurements. The standardised tapping machine, with an appropriate single number descriptor, leads also to an acceptably high coefficient of determination between the descriptor and the subjective ratings. Additionally, based on the subjective ratings, assessment of conceivable requirements for the suggested single number ratings is possible.

Contribution:

The author of the thesis contributed to this paper in four ways; 1. By providing basis for the research, in which the surveys was carried out, meaning developing the basic idea for the research including taking into account residents cultural differences and designing the objective measurement procedure; 2. By developing the methodology for the field survey together with the co-authors and providing basis/input for the non-standardised single number evaluation to the research; 3. By providing input to evaluation of the collected data; 4. By writing the text in the article and proof reading of the content.

6.1.5 Paper E

Impact sound insulation of wooden joist constructions: Collection of laboratory measurements and trend analysis

Anders Homb, Catherine Guigou-Carter, **Klas G. Hagberg** and Hansueli Schmid

Journal of Building Acoustics, p 1-20 (2016)

Wood building systems are becoming more common. Consequently, a variety of complex floor assemblies exists on the market. The floor assemblies normally become the weakest part due to impact load from walking persons. So far, there are no reliable standardised calculation models available regarding prediction of impact sound in the entire frequency range. Therefore, the design is addicted to previous experiences and available measurements. For the development of prediction models, the first approach is to carry out a grouping of various available floor assemblies to provide basis for comparable measurements. From that, the aim is to trace similarities and carry out simplifications. Correlation is found within various groups between the single number $L_{n,w}$+$C_{I,50\text{-}2500}$ and the mass per unit area. The data is available for further processing and will be an helpful tool in prediction and for optimisation of wood floor assemblies.

Contribution:

The author of the thesis contributed to this paper by carrying out extensive measurements used for input as measured data from Swedish buildings. The author actively co-wrote the article, and finally, concluded the results by providing the grouping principle, an important model to simplify verification of prediction models. The author has also contributed by setting up the entire research programme of the project Silent Timber Build, from which this article emanates. The research is a consequence of a study of future needs for wood buildings [78].

6.2 List of publications not included in the thesis

Licentiate dissertation

- *Evaluation of sound insulation in the field,* Engineering Acoustics, Hagberg, K LTH TVBA-3126, Sweden (2005)
- *Evaluating Field Measurements of Impact Sound*, Journal of Building Acoustics, Hagberg, K., Volume 17, No 2, p. 105-128 (2010)

Conference papers

2012 - Design principles of small multi storey wooden houses
Proceedings of the international conference on Acoustics, Internoise 2012, 19 Aug – 22 Aug 2012, New York, USA

2011 – Acoustically robust lightweight constructions require controlled building process
Proceedings of the international conference on Acoustics, Internoise 2011, 4 Sept – 7 Sept 2011, Osaka, Japan

2010 - Impact sound insulation descriptors in the Nordic building regulations – Overview special rules and benefits of changing descriptors
Proceedings Baltic Nordic Acoustic meeting, Bergen, Norway, May 10-12, BNAM 2010

2010 - Sound insulation descriptors in Europe - Special rules complicate harmonization within lightweight industry
Proceedings of the International Symposium on Sustainability in Acoustics, ISSA 2010, 29-31 August 2010, Auckland, New Zealand

2010 - Uncertainties in standard impact sound measurement and evaluation procedure applied to lightweight structures
Proceedings of 20 the International Congress on Acoustics, ICA 2010, 23-27 August 2010, Sydney, Australia

2009 - Design of lightweight constructions - risks and opportunities
Proceedings of the international conference on Acoustics, Internoise 2009, Ottawa, Canada

2008 - MFB-Wooden building system with high sound insulation
Proceedings of the international conference on Acoustics, Internoise 2009, Shanghai, China

2006 - Evaluation of impact sound in the field
Proceedings of the conference on Acoustics in South Pacific, WESPAC IX, Seoul, Korea

2006 - Consequences of new building regulations for modern apartment buildings in Sweden
Presentation of a development project for the National Board of Housing Building and Planning in Sweden. Proceedings of the international conference on Acoustics, Internoise, Honolulu 2006

2004 - Evaluation of impact sound in the field situation, research at Lund University
Proceedings of the international conference on Acoustics, ICA 2004, Kyoto, Japan

2002 - Aspects concerning lightweight constructions in Swedish residential building with high sound insulation (class B according to SS 02 52 67)
Proceedings of the international conference on Acoustics, Forum Acusticum 2002, Sevilla, Spain

2001 - Ratings adapted to subjective evaluation for impact and airborne sound and its application in building regulations
Proceedings of the international conference on Acoustics, ICA 2001, Rome, Italy

1998 - New sound insulation requirements in the Swedish building Code
Proceedings of the international conference on Acoustics, Internoise 1998, Christchuch, New Zealand.

7. Conclusions

Although research within the field of acoustics of wood buildings has increased during the last two decades, much is still left to do to facilitate the management of wood buildings as they increase rapidly in numbers, specifically the last three to five years. Further research is needed regarding building acoustics to assure authorities, but also future acousticians, that updated building regulations comprising a wider frequency range and free from special rules have to be implemented, to facilitate for the building industry in general and the wood building industry specifically. In the meantime, an explicit management procedure to secure that expected sound insulation target values are fulfilled in each wood building project is a key factor. Three major goals connected in achieving this were the focus of this thesis

1. Gaining increased insight into perception of sound insulation in multifamily houses.
2. Provide input to building authorities and organisations for standardisation.
3. Giving insight to specific management procedure for design of wood buildings, including engineering design tools, no matter which type of wood structure.

7.1 Scientific contributions

The research reported in this thesis aimed at being able to describe the impact of low frequency sound in buildings made of wood and to facilitate the design by using available prediction tools and develop them further in the context of a continually improving building process. The results provided input into three basic research areas: a) research on human perception, as input for future target values in building regulations and standards; b) research regarding the complexity of building regulations and standards and their application in various countries; c) collection of sound insulation data, as basis for engineering application of prediction tools.

Finally, the building process to interconnect these research areas is described, for further development of the wood industry.

- **Human perception of sound insulation**

    1. In **Paper C**, research results regarding human perception of sound insulation in Swedish wood / lightweight buildings are presented. The research comprised a questionnaire survey in real buildings, extensive measurements in the same buildings and development of an alternative rating for impact sound insulation
    2. The research in Sweden was followed by a European project, *AcuWood*, to collect knowledge from residents outside Sweden. The results are presented in **Paper D** and

emanate from a questionnaire survey as in bullet point 1 and a laboratory listening test. A number of evaluation methods for impact sound insulation were investigated in the project.

- **Building regulations and standards**

  1. The complexity of national regulations and the importance of harmonising the regulations within Europe are described in **Paper B**. It is concluded that the wood industry will gain from increased harmonisation by; 1. Removing special rules; 2. Harmonising regulations. Instead, the tendency is increased complexity due to less cooperation at authority level.

- **Specific management procedure**

  1. As modern requirements are lacking, modelling considering future requirements are necessary. For that, input data from an extended frequency range have to be collected to form basis for model verification. **Paper E** contains a collection of a large number of floor assemblies grouped to provide comparable values for impact sound insulation for different groups of floor assemblies within Europe. The grouping is used to verify calculation models down to 50 Hz and it can be further developed if considered in a management process.
  2. The complex building process, which is the core in the process of continual improvements, is described in **Paper A** (regarding acoustics). The building process must develop in parallel to the development of the lightweight (wood) industry.

Development of the national building regulations and new design tools including all parties must be part of the building industrial development as for any other industry. The wood industry and the parties involved are already working at a European level and specific national rules in the acoustic regulations are creating obstacles for the future development of the industry. It also complicates an increased trade between countries. In figure 7.1, the interaction to develop the industry is visualised, also summarising this work.

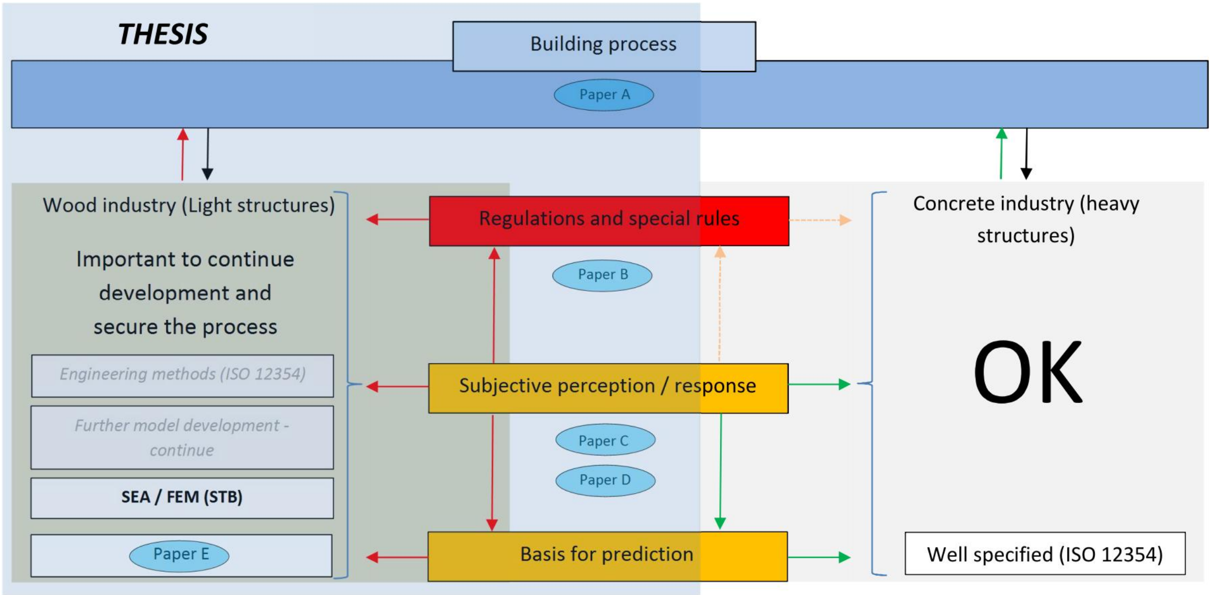


Figure 7.1. A summary of the interaction between different areas as presented in this thesis. Yellow rectangles: New input always needed for improvements and further development and optimisation; Red rectangle: Convince authorities and the community to remove unnecessary and cost raising rules. Red arrows: Far more input required prior to create "safe design" on engineering level. Green arrows: the knowledge is satisfactory and the system exchange works adequately. Orange broken arrow: Concrete industry would gain from less special rules as well. Finally, rectangles with italic font, we are on the way but still obstacles to overcome. Always make sure that the building process is deliberate prior to start a project.

7.2 Future work

The next step in the development of wood structures to increase their competitiveness, is to raise the knowledge regarding calculation models considerably, see figure 7.1, and make them accessible on an engineering level. From research presented in this thesis a tool to verify models at an engineering level is presented. Although this will facilitate modelling, it is still far from standardised and the uncertainty of material characteristics, junction behaviour etc. must be further reduced. The huge increase in high rise CLT buildings raises the topic even more, since it is necessary to deliver cost efficient solutions fulfilling expected requirements. The uncertainties create doubts amongst many housing developers. Every builder or developer wants to know in advance which quality they can be expected. If not, it is easier to choose a structural material where the building quality is predictable in advance, e.g. concrete.

Future research should also focus on more investigations regarding perceived noise in dwellings, starting with an extensive compilation of data from projects throughout the globe comprising scientific conclusions as input for the community (authorities, industry, acousticians). A summary was compiled in Italy [100] but a more extensive analysis of the outcomes should be carried out. Since there is an extreme inertia for changes in national provisions, the surveys also must include demographic development in order to create real basis for future regulations and standards. The surveys carried out so far are limited to specific “normal” households.

Authors final remarks:

My view on changes in regulatory frameworks is rather modest, not least due to limitations as discussed in chapter 3. A huge step will be taken the day when the ISO SNQ $L'_{nT,w}+C_{I,50\text{-}2500}$ will become mandatory for use in most countries. After that, each country can choose level. Just by introducing frequencies down to 50 Hz will help to think differently, without exaggerating for buildings that might not need stricter low frequency requirements. For airborne sound insulation it might be acceptable for specific applications to keep the frequency range as used in many countries still, corresponding to the SNQ, $D_{nT,w}$. After many years in different research constellations, my view is that we should simplify the regulations considerably and aim for the most important. That is, to consider impact sound pressure levels down to 50 Hz, and really focus on that. Caution will also help to avoid exaggerations when designing dwellings with less risk for annoyance, such as dwellings for elderly, student dwellings and similar. Probably lower requirements might be acceptable in these types of dwelling, however we do not know for sure yet.

References

[1] BBR 1994:1, Boverkets Författningssamling – Boverkets byggregler, Föreskrifter och allmänna råd; BFS 1993:57 (in Swedish)

[2] The European Union Construction Product Directive (CPD, 89/106/EEG)

[3] Rasmussen, B. *Sound insulation between dwellings – Requirements in building regulations in Europe,* Applied Acoustics 71(4), 373-385 (2010)

[4] Yrsa Cronjort et al., *Competitive wood-based interior materials and systems for modern wood construction*. WWN+ project Wood2New, 4th joint call.

[5] Hagberg, K., NKB report 1996:02, *Ljudkrav med stöd av ISO/DIS 717*, Nordic Committee on building regulations (only in Swedish) (1996). Eng. *Sound requirement according to ISO / DIS 717,* Nordic Committee on building regulations (1996)

[6] Hagberg, K, *Evaluation of sound insulation in the field,* Engineering Acoustics, LTH TVBA-3126, Sweden (2005)

[7] Hagberg, K., *Evaluating Field Measurements of Impact Sound*, Journal of Building Acoustics, Volume 17, No 2, p. 105-128 (2010)

[8] Hagberg, K., *Tre exempel på akustiklösningar i träbyggande* (SBUF) (only in Swedish), AkuLite Report no 10, SP Rapport 2013:41, ISBN 978-91-87461-29-3 (2013).

[9] Hagberg, K., Bard, D., *Design principles of small multi storey wooden houses*. Proceedings at Internoise 2012, New York, USA (2012)

[10] Hammer, P., Brunskog, J., *En designvägledning för lätta konstruktioner*, TVBA-3084, Lund University (1996) (only in swedish). *A design guide for lightweight constructions,* TVBA-3084, Lund University (1996)

[11] Rindel, J.H., Rasmussen, B., *Building Codes: Comparisons between countries and future requirements*, Acustica, Acta Acustica, Vol 82 (1996), suppl 1 (1996).

[12] Kungliga byggnadsstyrelsens anvisningar 1946:1 *Anvisningar till byggnadsstadgan Byggnadsstadgan* (7 dec. 1945).

[13] Socialstyrelsen, *Buller – Höga ljudnivåer och buller inomhus*, ISBN 978-91-85999-30-9, Folkhälsomyndigheten (2008) (only in Swedish). *Noise – High sound levels and indoor noise*, The Public Health Agency of Sweden (2008).

[14] SOU 1993:65, *Handlingsplan mot buller, Betänkande av utredningen för en handlingsplan mot buller* (1993) (only in Swedish). *Action plan against noise, Report from the commission of inquiry on an action plan against noise.*

[15] ISO 717-1 (2013); *Acoustics – Rating of sound insulation in buildings and of building elements – part 1 airborne sound insulation*

[16] ISO 717-2 (2013); *Acoustics – Rating of sound insulation in buildings and of building elements – part 2 impact sound insulation*

[17] ISO 10140 part 1 to part 5; *Laboratory measurements of sound insulation of building elements*

- Part 1; Application rules for specific products
- Part 2; Measurement of airborne sound insulation
- Part 3; Measurement of impact sound insulation
- Part 4; Measurement procedures and requirements
- Part 5; Requirements for test facilities and equipment

[18] ISO 16283-1 (2014); *Acoustics – Field measurement of sound insulation in buildings and of building elements - Part 1; Airborne sound insulation*

[19] ISO 16283-2 (2015); *Acoustics – Field measurement of sound insulation in buildings and of building elements - Part 2; Impact sound insulation*

[20] ISO 15712-1:2005 (EN 12354-1:2000); *Building acoustics – Estimation of acoustic performance of buildings from the performance of elements - Part 1: Airborne sound insulation between rooms* (2005)

[21] ISO 15712-2:2005 (EN 12354-2:2000); *Building acoustics – Estimation of acoustic performance of buildings from the performance of elements - Part 2: Impact sound insulation between rooms* (2005)

[22] Bodlund, K., *Alternative reference curves for evaluation of the impact sound insulation between dwellings*, Journal of sound and vibration 102 (3), 381–402 (1985)

[23] Bodlund K., and Eslon L., *En kartläggning av ljudklimatet i några moderna svenska bostäder*, Teknisk rapport SP-RAPP 1983:37 (1983) (only in Swedish). *An investigation of the sound climate in some modern residential housing in Sweden*, Technical report SP-Rapp 1983:37 (1983)

[24] ISO 717-2 1996; *Rating of sound insulation in buildings and of building elements – part 2; impact sound insulation*

[25] ISO 717-1 1996; *Rating of sound insulation in buildings and of building elements – part 1; airborne sound insulation*

[26] Rasmussen, B; Rindel, J.H.; *Sound insulation between dwellings – Descriptors in building regulations in Europe*, Applied Acoustics 71, 171-180 (2010)

[27] BBR 7, Boverkets Författningssamling – Boverkets byggregler, Föreskrifter och allmänna råd; BFS 1998:38 (in Swedish only)

[28] Scholl, W., Lang, J., Wittstock, V., *Rating of Sound Insulation at Present and in Future. The Revision of ISO 717*, Acta Acustica United with Acustica, Vol. 97, p. 686 – 698 (2011)

[29] Scholl, W., *Revision of ISO 717: Why Not Use Impact Sound Reduction Indices Instead of Impact Sound Pressure Levels?*, Acta Acustica United with Acustica, Vol. 97, p. 503 – 508 (2011)

[30] SS 02 52 67 (edition 2); Swedish standard SS 02 52 67, *Sound Classification of spaces in buildings – Dwellings*, Swedish Standards Institute SIS (1998)

[31] INSTA-B Draft Proposal 122:1997 *Sound classification*. Norwegian Council For Building Standardisation, Oslo (1997)

[32] Rindel, J.H., Turunen-Rise, I., *Sound classification of dwellings in the Nordic countries*, Proceedings, Institute of Acoustics, Windermere, UK (1997)

[33] Rindel, J.H., *The relationship between sound insulation and acoustic quality in dwellings*. Proceedings from Internoise 1998, Christchurch, New Zealand (1998)

[34] Rindel, J.H., Rasmussen, B., *Assessment of airborne and impact noise from neighbours*, Proceedings from Internoise 1997, Budapest Hungary (1997).

[35] SS 25267 (edition 4), Swedish standard SS 25267, *Sound Classification of spaces in buildings – Dwellings*, Swedish Standards Institute SIS (2015).

[36] BBR 20, Boverkets Författningssamling – Boverkets byggregler, Föreskrifter och allmänna råd; BFS 2013:14 (in Swedish only)

[37] Boverkets Byggkostnadsforum, Bostäder och nya ljudkrav, ISBN 978-91-85751-43-3, Karlskrona, Sweden (only in Swedish) (2007)

[38] Hagberg, K., Simmons, C., *Consequences of new building regulations for modern apartment buildings in Sweden*, Proceedings at Internoise 2006, Honolulu, Hawaii, USA (2006).

[39] Hagberg, K., Rasmussen, B.; *Impact sound insulation descriptors in the Nordic building regulations—Overview special rules and benefits of changing descriptors*. BNAM, Bergen, Norway, 2010.

[40] Helimäki, H., Rasmussen, B.; *Airborne sound insulation descriptors in the Nordic building regulations—Overview special rules and benefits of changing descriptors*. BNAM, Bergen, Norway, 2010.

[41] B. Rasmussen et.al., COST Action TU 0901, *Towards a common framework in building acoustics throughout Europe*, ISBN 978-84-616-7124-3 (2013)

[42] ISO / TC 43 / SC 2; ISO / DIS 19488:2017 (Draft International Standard) - *Acoustics — Acoustic classification of dwellings*. ISO ref no ISO/DIS 19488:2017(E) (2017)

[43] Hammer, P., *Sound insulation in multistorey wooden house: Orgelbänken*, Lund University, TVBA-3084B (1996).

[44] Hammer, P., *Sound insulation in multistorey wooden house: Wälludden*, Lund University, TVBA-3084A (1996).

[45] Hammer, P., Brunskog, J., En designvägledning för lätta konstruktioner, TVBA-3084, Lund University (1996) (only in swedish). A design guide for lightweight constructions, TVBA-3084, Lund University (1996).

[46] Hammer, P., Nilsson, E., *On subjective grading of impact sound transmission through lightweight floor structures*, Proceedings at Internoise 97, Budapest, Hungary (1997).

[47] Forssén, J., Kropp, W., Brunskog, J., Ljunggren, S., Bard, D., Sandberg, G., Ljunggren, F., Ågren, A., Hallström, O., Dybro, H., Larsson, K., Tillberg, K., Sjökvist, L.G., Östman, B., Hagberg, K., Bolmsvik, Å., Olsson, A., Ekstrand, C.G., Johansson, M., *Acoustics in Wooden Buildings. State of the art 2008.* Vinnova project 2007-01653, Technical Research Institute of Sweden. Report 2008:16. Stockholm, Sweden (2008).

[48] Stani, M. et.al., LowFreCon – Feasability study, report no 11527/AB – *Sound Insulation in the Low Frequency Range, Prospects and Recommendations to keep the Building with Wood Industry competitive*, Versuchsanstalt Akustik und Bauphysik, Vienna, Austria (2011)

[49] Thorsson, P., *Laboratory listening tests*, AkuLite Report no 7, Calmers report 2013:5, Chalmers University of Technology, Division of Applied Acoustics, ISBN 978-91-87461-22-4, Göteborg, Sweden (2013)

[50] Liebl, A., Spaeh, M., Leistner, P., *Acoustics in wooden buildings – Evaluation of acoustic quality in wooden buildings: Listening tests and questionnaire field study*, AcuWood Report no 3, SP report 2014:16, ISBN 978-91-87461-66-8, Borås, Sweden (2014)

[51] ISO TS 15666; *Assessment of noise annoyance by means of social and socio-acoustic surveys* (2013).

[52] Öqvist, R., *Measurement and Perception of Sound Insulation from 20 Hz between Dwellings*, Doctoral Thesis, Engineering Acoustics Luleå Technical University, ISBN 978-91-7583-869-4 (pdf), Luleå, Sweden (2017).

[53] Öqvist, R., Ljunggren, F., Johnsson, R., *Walking sound annoyance vs. impact sound insulation from 20 Hz*, Applied Acoustics 135 p. 1-7 (2018).

[54] Gover, B. N., Bradley, J. S., Zeitler, B., Schoenwald, S., *Objective and Subjective Assessment of Lightweight Wood-Framed Floor Assemblies in Response to Footstep and Low-Frequency Impact Sounds*, proceedings Internoise 2011, Osaka, Japan (2011).

[55] Jeong, Jeong Ho, *Heavy/soft impact sound criteria and regulation in Korea*, proceedings Internoise 2014, Melbourne Australia (2014).

[56] Ryu, J.K., Sato, H., Kurkata, K., Hiramitsu, A., Hirota, T., *Relation between annoyance and single-number quantities for rating heavy-weight floor impact sound insulation in wooden houses*, Journal Acoustic Society of America 129(5) p. 3047-3055 (2011).

[57] Kylliäinen, M., Hongisto, V., Oliva, D., Rekola, L., *Subjective and objective rating of impact sound insulation of a concrete floor with various coverings - a laboratory listening experiment*, Acta Acustica united with Acustica, 103 p. 236-251 (2017).

[58] Høsøyen, C-O., Rindel, J.H., Løvstad, A. Klaeboe, R., *Impact Sound Insulation and Perceived Sound Quality*, Proceedings at Internoise 2016 in Hamburg (2016).

[59] Guigou-Carter, C., Balanant, N., Villenave, M., *Acoustic comfort evaluation in lightweight woodbased buildings,* proceedings Forum Acusticum, Krakow, Poland (2014).

[60] Gerretsen, E., *A new system for rating impact sound insulation*. Applied Acoustics 1976:9 (1976).

[61] Park, H. K., Bradley, J. S., *Evaluating signal-to-noise ratios, loudness, and related measures as indicators of airborne sound insulation*. J. Acoust. Soc. Am. 126 p. 1219–1230 (2009).

[62] Rychtáriková, M., Muellner, H., Chmelík, V., Roozen, N. B., Urbán, D., Garcia, D. P., Glorieux, C., *Perceived loudness of neighbor sounds heard through heavy and lightweight walls with equal* $R_w + C_{50–5000}$. Acta Acutica united with Acustica 102 p. 58–66 (2016).

[63] Monteiro, C., Machimbarrena, M., de la Prida, D., Rychtáriková, M., *Subjective and objective acoustic performance tanking of heavy and light weight walls*. Applied Acoustics 110 p. 268–279 (2016).

[64] Virjonen, P., Hongisto, V., Oliva, D., *Optimized reference spectrum for rating airborne sound insulation in buildings against neighbor sounds.* Proceedings of InterNoise 2016, Hamburg, Germany, 964–969 (2016).

[65] Hongisto, V., Oliva, D., Keränen, J., Subjective and objective rating of airborne sound insulation – Living sounds. Acta Acustica united with Acustica 100 p. 848–863 (2014).

[66] Bailhach, S., Jagla, J., Guigou, C., *CSTB-Project Environnement et ambiances: effet des basses fréquences sur le confort acoustique – tests psychoacoustiques*. Report USC-EA-D1_A2.1.4_2 (2014).

[67] Bailhach, S., Guigou, C., *Etude perceptice de la prise en compte des basses fréquences dans les indices de performance acoustique*. Proceedings of CFA, Poitiers, France, 22–25 April (2014).

[68] Hongisto, V., Mäkilä, M., Suokas, M., *Satisfaction with sound insulation in residential dwellings – The effect of wall construction*. Building and Environment 85 p. 309–320 (2015).

[69] Kylliäinen, M., Takala, J., Oliva, D., Hongisto, V., *Justification of standardized level differences in rating of airborne sound insulation between dwellings*. Applied Acoustics 102 p. 12–18 (2016).

[70] Rindel, J.H., *A Comment on the Importance of Low Frequency Airborne Sound Insulation between Dwellings*, ACTA Acustica united with Acustica, Vol 103 p 164-168 (2017)

[71] Simmons, C., *Managing uncertainty in building acoustics – Comparisons of predictions using EN 12354 standards and measurements*, Doctoral Thesis, Luleå University of Technology, ISBN 978-91-7439-028-5, Luleå, Sweden (2009).

[72] Negreira, J., *Vibracoustic Performance of Wooden Buildings – Prediction and Perception*, Doctoral Thesis, Engineering Acoustics, Lund University, ISBN 978-91-7623-643-7 (pdf), Lund, Sweden (2016).

[73] Villot, M., et. al., COST Action FP 0702 "Net-Acoustics for Timber based lightweight buildings and elements", *E-Book*

- **Chapter 1**; WG1 – Prediction methods for sound and vibration performances
- **Chapter 2**; WG2 – Measurement methods for sound and vibration performances
- **Chapter 3**; WG3 – Comfort assessment for sound and vibration
- **Chapter 4**; WG4 – Building acoustic design
- **Chapter 5**; Overview of research at the main member institutes

[74] ISO 12354-1:2017, *Building acoustics - Estimation of acoustic performance of buildings from the performance of elements - Part 1: Airborne sound insulation between rooms* (2017).

[75] ISO 12354-2:2017, *Building acoustics -- Estimation of acoustic performance of buildings from the performance of elements -- Part 2: Impact sound insulation between rooms* (2017).

[76] Boverket, *Bullerskydd i bostäder och lokaler*, handbok, ISBN 978-91-86045-41-8 (2008, revision prepared 2017) (only in Swedish). National Board of Housing Building and Planning, *Noise protection in dwellings and premises*.

[77] Hagberg, K., Persson, T., *Design of lightweight constructions – risks and opportunities*, proceedings, Internoise 2009, Ottawa, Canada (2009).

[78] Hagberg, K., *2011 - Building With Wood Workshop - Acoustics and Vibration in Wood Construction*, Stockholm 17-18 October, 2011; SP report 2011:72

[79] JIS A 1418-2 *Acoustics – Measurement of floor impact sound insulation in buildings and of building elements; Part 2: Method using standard heavyweight impact source* (2000)

[80] KS F 2810 *Method for field measurement of floor impact sound insulation. Part 2: method using standard heavy impact sources* (2012)

[81] JIS A 1419-2 *Acoustics – Rating of floor impact sound insulation in buildings and of building elements; Part 2: Floor impact sound insulation* (2000)

[82] KS F 2683-2 *Rating of floor impact sound insulation for impact source in building elements; Part 2: Floor impact sound insulation against standard heavy impact source* (2012).

[83] Langdon, F.J., Buller, I.B., Scholes, W.E., *Noise from neighbours and the sound insulation of party walls in houses*, Journal of Sound and Vibration 79, p. 205-228 (1981).

[84] Weeber, H., Merkel, H., Rossbach-Lochmann, H., Buchta, E., Gösele, K., *Schallschutz in Mehrfamilienhäusern aus dem Sicht der Bewohner*, F 2049, IRB Verlag, Stuttgart Germany (only in German), (1986)

[85] Bradley, J.S., *Subjective rating of the sound insulation of party walls (a pilot study)*, Building Research Note no. 196, National Resarch Council Canada, Ottawa (1982)

[86] SS 25267 (edition 3), Swedish standard SS 25267, *Sound Classification of spaces in buildings – Dwellings*, Swedish Standards Institute SIS (2004).

[87] Simmons, C., Hagberg, K., Backman, E., *Acoustical Performance of Apartment Buildings – Resident's Survey and Field Measurements*, AkuLite Report no 2, SP report 2011:58, ISBN 978-91-86622-88-6 (2011).

[88] Simmons, C., *Uncertainties of room average sound pressure levels measured in the field according to the draft standard ISO 16283-1 - Experiences from a few case studies*, AkuLite Report no 3, SP report 2012:28, ISBN 978-9187017-42-1 (2012).

[89] Bard, D., Jarnerö, K., Negreira, J., Sjökvist, L-G., Trollé, A., *Physical and psycho-vibratory testing of wooden floor,* AkuLite Report no 4, SP report 2012:29, ISBN 978-91-87017-43-8 (2012).

[90] Negreira, J. , Trollé, A., Jarnerö, K., Sjökvist, L-G., Bard, D., *Psycho-vibratory evaluation of timber floors – Existent criteria, measurement protocols, analysis of objective data and determination of design indicators of vibration acceptability and vibration annoyance,* AkuLite Report no 5, SP report 2013:25, ISBN 978-91-87461-10-1 (2013).

[91] Jarnerö, K., Bard, D., Simmons, C., *Vibration Performance of Apartment Buildings with Wooden Lightweight Framework – Residents Survey and Field Measurements*, AkuLite Report no 6, SP report 2013:17, ISBN: 978-91-87461-02-6 (2013).

[92] Ljunggren, F., Backman, E., *Data från byggakustiska fältmätningar och enkätundersökningar i flerfamiljshus*, AkuLite Report no 8 (only in Swedish), LTU report 2013, Luleå Technical University, Division of Applied Acoustics, ISBN 978-91-87017-94-0, (2013).

[93] Negreira, J., Bard, D., *Finite Element Modelling of a Timber Volume Element Based Building with Elastic Layer Isolators*, AkuLite Report no 11, SP report 2013:27, ISBN 978-91-87461-12-5 (2013).

[94] Jarnerö, K., Höök, M., Hagberg, K., *AkuLite – Sammanställning av resultat för industrin (AkuLite – Compilation of results for the industry)*, AkuLite Report no 12 (only in Swedish), SP report 2013:26, ISBN 978-91-87461-11-8 (2013).

[95] Spaeh, M., Liebl, A., Lesitner, P., *Acoustics in wooden buildings – Measurements in the Laboratory and in Single Family Houses*, AcuWood Report no 1, SP report 2014:4, ISBN 978-91-87461-64-4 (2014).

[96] Spaeh, M., Liebl, A., Lesitner, P., *Acoustics in wooden buildings – Field Measurements in Multi-Storey Buildings*, AcuWood Report no 2, SP report 2014:15, ISBN 978-91-87461-65-1 (2014).

[97] Spaeh, M., Liebl, A., Lesitner, P., *Acoustics in wooden buildings – Correlation analysis of subjective and objective parameters*, AcuWood Report no 4, SP report 2014:17, ISBN 978-91-87461-67-5 (2014).

[98] Hagberg. K., Simmons, C., *Acoustics in wooden buildings – Summary of results AcuWood – including a comparison of the parallel project AkuLite*, AcuWood Report no 5, SP report 2014:18, ISBN 978-91-xxxxx-67-5 (2014). *(Not yet published)*

[99] Östman, B., et.al., *Fire Safety in Timber Buildings – Technical Guideline for Europe*, SP report 2010:19, ISBN 978-91-86319-60-1 (2010).

[100] Caniato, M., Bettarello, F., Ferluga, A., Marsich, L., Schmid, C., Fausti, P., *Acoustic of lightweight timber buildings: A review*, Renewable and Sustainable Energy Reviews 80, p. 585-596 (2017).

[101] Caniato, M., Bettarello, F., Fausti., P., Ferluga, A., Marsich, L., Schmid, C., *Impact sound of timber floors for sustainable buildings*, Building and Environment 120 p. 110-122 (2017).

PART II – Appended publications

Paper A

A Handbook on the Management of Acoustic Issues During the Building Process

by

Klas G. Hagberg and Christian Simmons

Reprinted from

JOURNAL OF
BUILDING ACOUSTICS
Volume 17 · Number 2 · 2010

MULTI-SCIENCE PUBLISHING CO. LTD.
5 Wates Way, Brentwood, Essex CM15 9TB, United Kingdom

A Handbook on the Management of Acoustic Issues During the Building Process

Klas G. Hagberg[1] and Christian Simmons[2]
[1]*ÅF Sound & Vibration, Box 1551, SE-401 51 Göteborg, Sweden*
klas.hagberg@afconsult.com
[2]*Simmons akustik & utveckling AB/Luleå Univ. of Technology,*
Krokslätts Fabriker 1, SE – 431 37 Mölndal, Sweden
christian.simmons@euromail.se

(Received 8 October 2009 and accepted 19 July 2010)

ABSTRACT
A new handbook has been published by the Swedish National Board of Housing, Building and Planning. This handbook describes the building process from an acoustical point of view. It focuses on the conversion of functional requirements on the performance of the building to appropriate designs of a building. This type of requirement allows all kinds of solutions to be applied, but is also requires coordination of acoustic issues between the parties involved during the entire building process. Hence, the handbook addresses detailed information to each party. Functional requirements and acoustic issues are complex by nature, because they affect many building elements, they are handled by several parties and they must be considered during several phases of the building process. Typical errors come from building designs (floor plans), product designs (input data of elements), calculation models, quality of workmanship (during the construction phase) and uncertainties in field measurements. The aim is to help the commissioner manage the responsibility for these issues. The handbook also covers a large field of practical applications to support the acoustic expertise. It is expected that this handbook will encourage developers and contractors to deal with acoustic issues more efficiently. If the noise environment is not considered in the design process for new residential areas and other building facilities, the satisfaction of tenants, the health costs for the society and the building values will be affected. If verifications are made only at a late stage of the building process, errors are normally discovered too late. They are then expensive to correct for and it is difficult to find out who is responsible. When the verifications are made effectively during the process, costs are minimized.

1. INTRODUCTION

This paper summarizes the content of a new handbook, which includes; a description of the process to handle acoustical issues during the building process; practical advice to all parties involved in the process and interpretations of functional requirements in sound classifications standards that are referred to by the Swedish building regulations. However, this paper does not discuss scientific theory. The aim is rather to describe a practical way to deal with acoustics throughout the building process, from the interpretation of the functional requirements, the early stage design, the purchase of building elements to the finalized building.

The modern building process is complicated. For those who deal with acoustic issues in the design phase or the construction phase, this is obvious for several reasons. New buildings are often erected at complicated sites in the city centres. Hence, they are often exposed to high sound levels and ground vibrations from various types of traffic. High requirements on sound insulation between the interior spaces are frequent, e.g. between residential apartments and premises for public activities (shops, restaurants, theatres, cinemas etc) and these requirements tend to be raised further in future. Furthermore, new architecture and new building products are often suggested, which require a lot of knowledge to use since empirical experience is not always at hand for these specific solutions.

There is now a need to transfer acoustic knowledge directly to our building industry, since the teaching of building acoustics at our universities has been significantly reduced. It is too expensive to retain acoustic laboratories at the universities, since they are not efficiently used, hence converted and used for other purposes. Furthermore, the governmental grants to research and teaching have been reduced which has resulted in fewer civil engineers graduated with even basic knowledge in acoustics.

At the same time, modern buildings become more and more complicated, and the building acoustic demands from inhabitants and commercial developers are increasing. Lightweight structures (e.g. wood or steel) are being used more frequently in multi storey residential buildings, which present large challenges to the acousticians.

The possibility to use various building products is now easier than some decades ago, partly because the requirements are based on performance of the building (or spaces therein) instead of the properties of individual products. Performance based building codes may be regarded as an "open system" compared to codes based on specific dimensions and constructions.

However, an important disadvantage of a performance based building code is the need for conversion from the performance of products to the expected performance of buildings. Requirements on dimensions and constructions are more "straight forward" to apply and to verify by inspection *in situ*. However, the advent of EN 12354 [1] and extensive laboratory tests have helped the acousticians to make rational choices and decisions with respect to combinations of products, at least in those cases where the standardized calculation models are applicable. There are now an increasing number of innovative products and structural elements that might be combined in order to meet the requirements stated by the client or the national building codes.

Furthermore, the requirements are often changed. In Sweden (as well is in some other countries), the requirements by authorities or clients normally refer to the sound classification standards or similar publications. The Swedish standard SS 25267 [2] addresses requirements for dwellings and the SS 25268 [3] addresses spaces in hospitals, schools, offices, hotels and institutional premises. The idea behind a classification system is to offer the developer a choice of a level of acoustic quality (sound class) that is appropriate for the actual performance level considering the acceptable cost level. The sound class may vary in different projects, from renovation of old buildings (low sound class) to very high ambitions (luxury apartments).

Acoustic issues affect many building constructions, several parties must handle them and they influence several phases during the building process. Typical errors come from building design (floor plan), product design (data), calculation models, assemblies in the building (construction phase) and uncertainties in field measurements.

1.1 A new handbook

On the initiative of the National Board of Housing Building and Planning (Boverket), a new handbook has been issued, in an attempt to facilitate the management of building projects with respect to the acoustic issues. The handbook is written to meet the following needs:

- to describe how the commissioner (e.g. a developer or a proprietor) can specify the responsibility for different parties involved during the building process. Each party then gets specific targets to facilitate his handling of acoustic issues.
- to present interpretations and application examples on the Swedish sound classification standards, based on a large number of real questions and detailed examples from the building industry, universities and consultants.
- to complement other guidelines and advisory notes from the National Board of Housing Building and Planning used by local authorities.

The handbook consists of seven sections:

- Sections 1 and 2 address information to all participants in the building process who may come in contact with acoustic issues, for example proprietors, developers, authorities, designers, manufacturers, building contractors, experts, quality controllers etc. They give general background information and a description of which parties should take responsibility during each phase of the building process.
- Section 3 recommends the commissioner to engage an acoustic expert to monitor all phases of design, drawings, building details at the site, as well as the verification measurements in partly finalized or in the finalized building. As a result, the acoustic documentation is assembled. This documentation is a living document that may support the other parties of the project team during the building process.
- Section 4 is primarily addressed to experts within acoustics, involving detailed advices on risks and interpretation aspects on the sound requirements.
- Section 5 gives information to manufacturers on how they should test and present the acoustical technical properties of their products, as well as supplementary information on how to ensure that the product fits to connecting structures, handling issues, mounting advice etc.
- Section 6 gives general advice to building contractors. The advice address several aspects which should be considered to avoid raised costs due to poor workmanship and a lack of precision during the construction phase.
- Section 7 clarifies the most important tasks to verify the acoustic performance of the building. It has become clear that the international standards for sound testing

at the sites (ISO 140-series) are not detailed enough. Uncertainty may be reduced with complementary instructions, e.g. to minimize arbitrary choices of measurement locations etc.

However, the handbook does not cover all conceivable acoustic problems, nor does it give a general review of theoretical acoustics. It is intended to facilitate the management and the probability to fulfil the intended sound class, and to clarify responsibilities to all parties involved in each stage. It does give reference to papers and books on theory etc. that may be of interest to some parties, e.g. manufacturers of service equipment or building elements.

It is a well known fact that if technical aspects, i.e. acoustics, are *not* considered at an early stage this might lead to raised costs in the end of the building project, as illustrated by the figure 1.

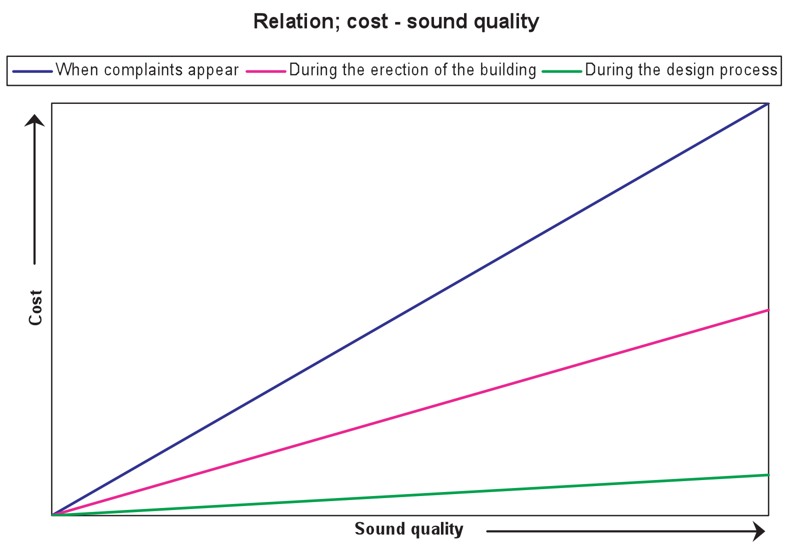


Figure 1. The relation between costs for acoustic (or other) measures and sound quality depending on when the technical issues are considered during the building process.

2. THE COMPLEXITY OF THE BUILDING PROCESS

There are often conceptual confusions within the building industry and between the parties of a project process, with respect to the variety of type of agreements, c.f. figure 2. In an attempt to simplify the process the purposes of different participants in the process are emphasized, no matter who is responsible for a specific task at a specific time during the progress of a project. The handbook describes which parts should be managed and by whom: the developer, the experts, the designers, the manufacturers, the building contractors or the authorities.

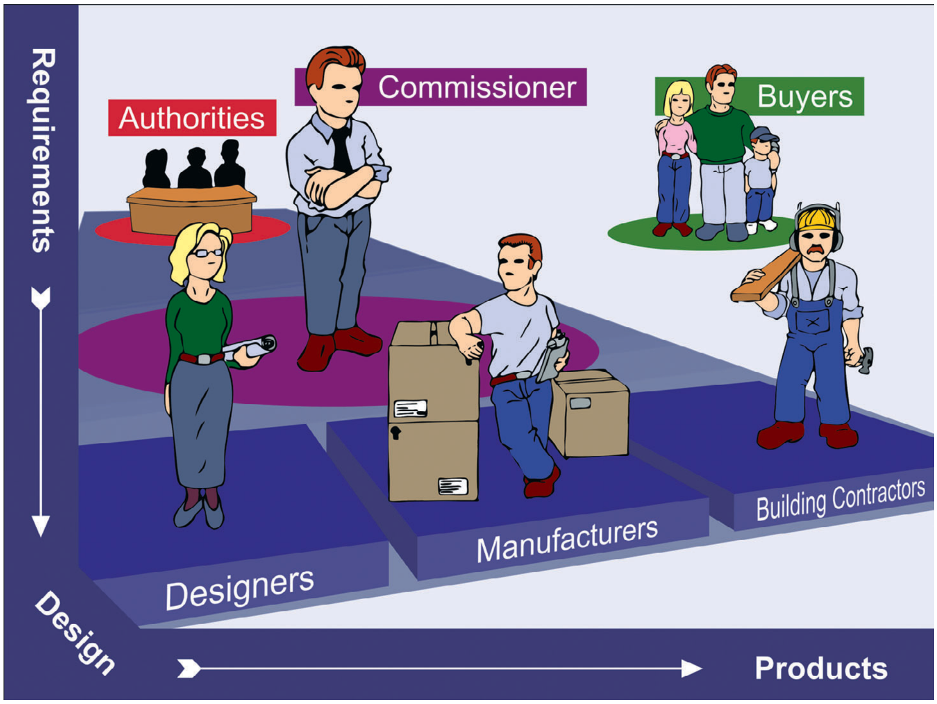


Figure 2. The complex matrix of actors involved in a building project. General performance based requirements (sound class) stated by the Authorities and the Developer must be interpreted by the Designer to constructions and to products. The Manufacturers must present correct input data to the Designer. The Contractor must follow all instructions carefully and handle risk constructions consciously. The final Buyer (or tenant) is often not involved at all during the planning, design and construction phases.

3. THE STRUCTURE OF THE HANDBOOK

3.1 Acoustic documentation – created by the expert

Frequently, there is no acoustician involved during the very early phases of a building process. They may be commissioned during the later stage of the design process or sometimes just to perform measurements in the finalized building or when a problem has occurred. However, the handbook advises the commissioner to engage an acoustician during all phases of the project. Then, all acoustical risks may be clarified and handled early, and all parties involved may be assisted by the acoustic documentation, updated throughout the process. Furthermore, an acoustic consultant knows where the acoustic efforts are most beneficial and may guide the client through the building process. The communication with the authorities is made easier by the assistance of an experienced acoustician.

The expert should establish an acoustic documentation with a structure described in section 3 of the handbook. In general the documentation may cover the following topics:

- ***Part 1*** specifies the sound requirements established by the developer (particularly if they deviate from the recommendations given by the sound classification standards). In this phase, the input data regarding exterior noise levels should be specified, as well as the façade elements (walls, doors and windows) that must attenuate noise from the exterior. In public premises, the requirements may be adapted to fit the needs of the current clients/tenants. In multi storey residential buildings, relaxation of the requirements may be appropriate, for example on the impact sound insulation of staircases that are only intended for evacuation purposes.

- ***Part 2*** contains recommendations for the design of the building (documented by drawings and product descriptions) such that it fulfils the current sound class (requirement). The risks should be highlighted, considering known issues with the actual structural elements (light weight or heavy structure, prefabricated or in-situ manufactured etc) as well as the specified building products.

- ***Part 3*** describes the procedure for review and verification within different stages of the project.

3.2 Other sections

Section 4 is primarily addressed to designers and acousticians and it has the same basic structure as the Swedish sound classification standards. The content of section 4 gives background, interpretations and examples in order to increase the understanding and to facilitate the application of the standards. Its content is written on the basis of real questions and contains statements that reflect frequent attitudes by the building industry, universities, consultants etc. As an example, a developer is certainly free to pick single requirements from various acoustic properties in the different sound classes as long as the minimum national requirements are fulfilled. But the handbook explains why this is not recommended, i.e. it explains that the perceived sound level will be determined by the weakest part of the building. Hence, in some respects the building will be either worse or better than expected which is, of course, not cost efficient.

Section 5 describes current requirements, standards and methods applicable to manufacturers in order to deliver product data usable in the calculation standard series EN 12354 (also issued as ISO 15712) [1] which are of particular significance. The section also emphasizes the importance of good workmanship of field adapted assembly instructions, e.g. structures made of lightweight material.

Section 6 addresses building contractors and involves, amongst others, description of risk level, description of sensitive details, typical acoustical problems with regard to service equipments etc. Such descriptions are cumbersome to establish, because the variety of constructions and possible problems in intersections makes it virtually impossible to cover all risks that may occur. Hence, also the contractor must have some basic understanding of acoustics and be able to identify risks that have not yet been described.

3.3 Verification

Suitable verification procedures are necessary to produce a final building which actually meets the contracted sound class (or any requirement). Traditionally, acousticians are involved at a late stage performing measurements in the building. This is too late if something is wrong, see Figure 1. If involved very late, the acoustician's knowledge of the project is very limited which further complicates efficient measures. Undoubtedly, costs are minimized when the verification is carried out throughout the building process. As soon as decisions have been made or the work is already in progress, the verification should cover

- Requirement level, type of project contract, responsibility management
- Traffic density, type of traffic, sound pressure levels at the facade
- Structural framework, products in the building, final drawings
- Visits to the building site
- Measurements in the completed building

Depending on each project, its location, its form for contract, the choice of structural material etc the need for verification within each part above vary and should be stated in the acoustic documentation.

The intention of this part of the handbook is to clarify the need for surveillance carried out continuously throughout the process, and not solely relying on acoustical measurements. Continuous visual inspections during the construction phase and documentation of products which form a part of the building is important in order to take actions if something appears to be wrong – correcting measures may then be carried out immediately.

Furthermore, during the building process current basic prerequisites for the design have to be laid down. One such issue is to define the traffic conditions (traffic density, number of heavy vehicles etc) in order to choose the right windows and façade. The handbook also contains information on safety margins during design in order to manage the final requirements with sufficient probability, based on calculations which are compared to measurements presented in a Nordtest report NT Tec 603 [4] and a report from the Forum for building costs [5, 6].

4. CONCLUSIONS

There is a need for a shake-up regarding knowledge of aspects that cause acoustical problems in buildings. Every mistake not corrected as early as possible costs a lot of money and the final product quality may deteriorate more than necessary. A new Swedish handbook has been issued by our national authorities, to provide help to those who work in projects to secure the acoustical quality of buildings.

To promote acoustic knowledge directly to the building industry has become an even more important task during the last decade (or decades) since the teaching of building acoustics at the universities has been reduced. At the same time, modern buildings have become more and more complicated, and the building acoustic demands from inhabitants are increasing. Lightweight structures (e.g. by wood or steel) are increasingly being used in multi storey residential buildings, which present huge future challenges to the industry and to the acousticians.

The handbook is presently available in Swedish only. However, some countries have shown interest to translate the handbook into their language and of course it would be interesting to publish it in other languages, primarily in English.

5. REFERENCES

1. EN 12354 Building acoustics - Estimation of acoustic performance of building from the performance of elements. Parts 1-6. The parts 1-4 have been published by ISO without changes (ISO 15712 1-4)
2. SS 25267 Acoustics - Sound classification of spaces in buildings - Dwellings
3. SS 25268 Acoustics - Sound classification of spaces in buildings - Institutional premises, rooms for education, preschools and leisure-time centres, rooms for office work and hotels
4. NT Tech 603, Simmons C., "Reproducibility of measurements with ISO 140 and calculations with EN 12354." ISSN: 0283-7234. Nordic Innovation Centre, Oslo (2005), www.nordicinnovation.net/nordtest.cfm.
5. National Board of Housing Building and Planning, *"Bostäder och nya ljudkrav"*. ISBN: 978-91-85751
6. Hagberg K., Simmons C., "Consequences of new building regulations for modern apartment buildings in Sweden" *Proceedings of INTER-NOISE 06*, 2006. This paper gives is a brief summary of reference 5.

Paper B

Sound Insulation Descriptors in Europe—Special Rules Complicate Harmonization within Lightweight Industry

Klas Hagberg(1,2,3), Delphine Bard(2,3)
(1)ÅF Ingemansson, Box 1551, SE-40151, Göteborg, Sweden
(2)Engineering Acoustics, Lund University, Box 18, SE-22100, Lund, Sweden
(3)SP Technical Research Institute of Sweden, Box 857, SE-501 15 Borås, Sweden

ABSTRACT
Many European countries have a sound classification standard connected to the building regulations in order to specify minimum requirements. The various national standards have a lot of similarities, however the acoustic descriptors differ more than what is obvious by a quick comparison of current classification standards. The different descriptors in each country are to some extent a heritage from the past, successively adapted to the building industry in each country and their certain traditions in building technique. The descriptors and the requirements are necessarily not based subjective experience. Furthermore, to fulfil national interests and to fit to new design trends of housing units etc, the descriptors involve small local adaptations to each country. These local adaptations are not easy to find unless the standards are read carefully. This causes problem since the building industry is not restricted to national boundaries anymore. Many companies have activity in countries adjacent to each other and in future the probability for increased activity all across Europe and also outside Europe is to be expected, unless regulations restrict this development. Combining national special rules and some severe uncertainties in the measurement and evaluation procedures of sound insulation, the situation is more critical for lightweight structures. This is partly due to the fact that the development of building systems are made in one country, the production takes place in production plants, i.e. the production and the process are fitted to local regulations and are "standardized". The standardized process is fast and dry but also needed due to lack of prediction models. And once the light weight system and the system process are established in one country it is complicated and expensive to adapt them to other countries. In this paper an overview of special national rules in some European countries and major problems connected to lightweight construction are presented.

INTRODUCTION
This paper considers sound insulation descriptors, requirements and special rules in some European countries. The paper focuses on multi-storey housing and briefly describe the differences between building codes in different European countries and their effect on the lightweight building industry, see also [1, 2, 22, 23]. It is partly based on a work within Building With Wood BWW with the acronym "LowFreCon",

All European countries have sound insulation requirements specified either in the building regulations and/or in sound classification schemes. In some countries the sound classification schemes and the regulations are closely connected since the regulations referre to national standards (classification schemes). The schemes and the regulations are normally based on similar descriptors, originating from the international standards ISO 140 and ISO 717 [18,19]. However, the descriptor in the regulations are completed with additional national rules and consequently they differ more than what is obvious at the first glance. The details and differences from seven European countries will be described more in detail further on in this article. A summary of current legislation in these particular seven European countries is given in table 1.

During different periods in history attempts have been made to coordinate the sound insulation requirements in some countries. In the Nordic countries a far-reaching attempt was made during the mid 90's. The work was partly funded by a joint governmental organization called "the Nordic Committee on Building Regulations", see reports and by a Nordic standardization organization, Inter Nordic STAndardization—Building (INSTA-B). However, the work did not fully succeed even though an equal basic system for sound classification was presented. All Nordic countries agreed upon four classes (A, B, C and D) and that sound class C should correspond to the minimum requirement according to national building regulations. Nevertheless, today there are huge differences between the requirements in each country, both regarding descriptors and their evaluations but also values for different classes. Furthermore, even if the figures or the descriptors, really appears to be equal at a glance, they might actually be rather different due to national special rules.

Analyzing all differences, a coordination of National regulations across all Europe would be a huge challenge and probably not exhaustively possible. However it would be of great benefit, if at least the descriptors could be similar, which is also one of the main goals within the ongoing COST action (European Organization of Scientific and Technical Research), COST TU 0901. In parallel, there is some ongoing, simplification work within ISO/TC 43/WG 18, revision of ISO 717 [18]. If successful, this would be very helpful for the industry and their future development and trade, in particular for the lightweight industry. With regard to building regulations, the market is indistinct today, thus impeding exchange of building systems and products. It is an important task for acousticians working in the field of building acoustics today to overcome national protectionism and politics in order to encourage and simplify the trade between the countries in an "open Europe". Unfortunately, the unnecessary differences in acoustic regulations create a trade barrier which is more extensive and expensive than necessary with regard to cultural differences between countries.

Instead of cooperation and coordination and strict use of current standards based on knowledge, revisions of the building codes have been adapted to current building tradition and to former requirements due to national experiences solely, i.e. changes have been made by adding special rules to the international standards [18, 19], to fit to national regulations or classification standards. Additional special rules were introduced and included, for example as notes or rules explained somewhere in the document-not necessarily in the tables with limit values-or even in other documents like e.g. guidelines. The reason is, in many cases, that no one wants to make changes that

Table 1. Sound insulation of dwellings. Overview building codes and sound classification schemes in some European countries—july 2010.

Country	Building code (BC)	Classification scheme (CS)	BC link to CS	BC Reference to CS	BC References	CS References
Sweden (SE)	BBR 2008	SS 25267:2004	+	Class C(1)	[7]	[17]
Finland (FI)	RAKMK C1:1998	SFS 5907:2004	(+)	(Class C)(1)	[4]	[14]
Austria (A)	OIB Guideline V:2007 and Building Codes federal states referring to ÖNORM B 8115-2: 2006	in preparation as ÖNORM B 8115-5	(+)	Class C	[11, 12]	[–]
Germany (D)	Musterbauordnung (MBO) 2002, 2008	DIN 4109	–	–	[8]	[9, 10]
Switzerland (CH)	SIA 181:2006 (Schallschutz im Hochbau)(2) SIA 260–267(2)	SIA 181:2006	Complementary	Complementary	[–]	[–]
Denmark (DK)	BR 2008	DS 490:2007	+	Class C(1)	[3]	[13]
Iceland (IS)	Byggingarreglugerd Nr. 441/1998	IST 45:2003	(–)	Class C(1) recommended	[5]	[15]
Norway (NO)	TEK'97	NS 8175:2008	+	Class C (1)	[6]	[16]

(1)Class denotations A/B/C/D indicated in descending order, i.e. the best class first.

(2)Switzerland does not have a building code master document. The Swiss building code is made of a series of standards. The different standards in the series deal with distict building aspects. The documents in the series all start with the letters SIA (Schweizerische Ingenieur- und Architektenverein) and are numbered: E.g. SIA 265:2003 regulates the structural issues of timber buildings. Similar SIA standards exist for masonry, concrete etc. They do not contain reference values of other standards in the series but may refer to the relevant SIA standard. Sound insulation issues are regulated in SIA 181:2006 (covers the sound requirements of all types of construction) can affect the local industry negatively even if the best would to encourage improved constructions and to simplify trade. Today, the industry put a lot of energy to adapt building systems to various regulations without any scientific reason.

BUILDING REGULATIONS REGARDING LIGHTWEIGHT STRUCTURES

The use of the extended frequency range down to 50 Hz is a topic which is currently frequently discussed all across Europe. In, Sweden it has been mandatory to apply spectrum adaptation terms ($C_{50\text{-}3150}$ and $C_{I,50\text{-}2500}$) from 50 Hz in the building code since 1999. The main reason for the revision at that time was to secure the development of an increasing amount of lightweight structures, primarily in wood.

It should be favourable for the lightweight structural development if the rest of Europe introduces frequencies down to 50 Hz according to current standard. Nevertheless, in the mean time several issues might require further analysis and discussion especially concerning

1. the predicting performance methods
2. reproducibility problems of the laboratory and field measurement methods
3. Transfer the results from theory to practice (the process [27])

in order to improve accuracy of measurements, calculations and evaluation of single numbers [20, 21, 24]. But still it is necessary to include low frequencies for lightweight structures since they are prevailing regarding subjective experience [25].

Hence, even if there are practical problem such as measurement uncertainties, it is of importance that current legislation is adapted to the future development of building technique. Building technique that includes very light structures. If not, the development will not go in the right direction, Today, the evaluation principles are certainly not adapted to these new structures and there is a potential risk for failure and product development towards "old fashioned" measures which might cause big problems for the industry in future [26]. Hence, there is a need for fast implementation of new regulations but also a need for extended research directed to lightweight structures. The acoustic research has to be more oriented to solutions for lightweight industry rather than problems.

The quantity of buildings using lightweight structures for multi storey residential buildings is increasing and it is going fast. For example, in Sweden more than 15% of all new multi-storey residential buildings are built with lightweight structure (the main part with wooden structural material). This is increasing due to several factors, for example

1. governmental support
2. its highly industrialized production
3. environmental issues et.c.

Furthermore the knowledge regarding fire resistant and stability is mainly solved. It is possible to build rather high rise buildings (at least eight storeys) in wood today, fulfilling current regulations. A lot of effort has been made in order to adapt the fire resistance regulations to promote wooden structures in multi-storey family houses. This has been necessary since no one wants the inhabitants to experience severe fire damage with high risk for human life. Furthermore, no one expect damage or structural break emanating from lack of strength. Nevertheless, still the sound insulation requirements are a remnant from the history and not adapted to current development of new systems. The risk of failure during the process is also a big risk when introducing lightweight structures adding yet another risk factor, see [28].

MAIN REASONS FOR INCLUDING LOW FREQUENCIES IN THE EVALUATION PROCEDURE

Poor sound insulation is not a problem that is obvious to those who will buy an apartment immediately. They will become aware of it after they have moved into their new housing unit. In case the problem becomes severe and involves diffuse low frequencies and perhaps also includes disturbing vibrations it might cause long term effects on human beings. In case it is high frequency problems it might be irritating but often these problems will be solved more easily even if the inhabitants have already moved in. It could be some leakage problem, sound transmission through ducts high frequency impact sound etc. As soon as the failure is detected it is easy to solve.

Unfortunately, lightweight structures normally exhibit behaviour involving diffuse low frequency problems and in case of failure it is very difficult to accomplish sufficient measures afterwards. Hence, in order to prevent an adverse development of the lightweight building industry in general there is a need for quick action regarding target values and evaluation principles for sound insulation, and then in particular low frequency impact sound and vibrations caused by household activities.

In order to consolidate the future position of lightweight residential buildings compared to heavy weight buildings there is a need for future development of the acoustic evaluation methods and raised knowledge within the industry regarding vibrations and material characteristics. As far as concerned, the most immediate needs are also important in order to actually fulfil the essential requirement “Protection against noise” of the European Construction Productive Directive (CPD). First of all it is absolutely necessary to establish well founded criteria for evaluation of impact sound insulation in order to make minimum requirements and various sound classes in classification schemes reasonably comparable to the corresponding requirements of heavy building structures [26]. In this context it is important to consider the vibration behaviour due to household activities and its effect on the experienced low frequency impact sound. The lightweight industry is also in need of quick implementation of new criteria in International and European standards (i.e. ISO 717) in order to facilitate the trade of lightweight building systems. The systems complexity, the difficulties to replace single products and the lack of calculation models make this issue even more urgent. But still, there is a need for research in parallel in order to improve the figures in future and to promote and support an advisable development of new lightweight building systems.

CURRENT BUILDING REGULATIONS IN EUROPE

Within Europe, Sweden is the only country which has adopted the low frequency spectrum adaptation term for sound insulation as a mandatory requirement in the national building regulations [7]. The sound insulation indices used in Sweden are (some special rules should be applied additionally, see table 2 and 3):

1. $R'_{w} + C_{50\text{-}3150}$
2. $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$

The reason for this was to adapt the requirement as far as possible using current international standards to new building technique for multi storey houses, with lightweight structures. However, research work indicates that the introduction of the low frequency spectrum adaptation terms is not harsh enough in order to prevent bad constructions to enter the market [28], at least for impact sound. It is necessary to rather quick create completely new measures or new evaluation curves for impact sound and perhaps introduce some sort of requirement regarding vibrations from household activities.

Current situation regarding sound insulation requirements in some other European countries are presented in table 2 and table 3. Apart from different single numbers there exist national special rules which are not immediately discovered in the regulations, see next section. For those companies working in different European countries these additional special rules further complicate the trade, quite contradictory to the aim of European Union.

For vibrations, no strict minimum requirement exists, hence in case of annoying vibrations there is no building code taking care of this except in parts of Austria, where OIB Guideline V is introduced (OIB Guideline V - sub-clause 4) demands a protection against vibrations. Due to these facts there is a need for a reconsideration of current evaluation of impact sound but also to consider vibrations. This is of immediate interest since

- The experienced sound insulation is normally worse than the objective value exhibit, perhaps reinforced due to combined low frequency noise and vibrations
- The sound class for a lightweight construction do not correspond to the sound class for a heavy weight construction even if the objective values are identical
- The lightweight industry is rapidly increasing its market share. Hence, in case current objective measures retain, the risk of increased numbers of bad constructions entering the market grows

Perhaps, new evaluation principles are not necessary for all types of living accommodations. For some certain types of housing units current evaluation principles might work. However, there is certainly a need for raised knowledge regarding modern living habits in order to state well founded criteria in those cases. Hence the results might become different single numbers applicable to various multi storey residential building.

SPECIAL RULES

Compliance with Regulations

Apart from the differences stated above, some further additional differences might confuse the market, and these differences and their effect on the national adaptations for various systems is far from clarified. Typical users might think that each measured value must fulfil the requirements. However, it is not always perfectly

Table 2. Regulatory requirements for impact sound insulation between dwellings in seven european countries including remarks of national special rules—july 2010.

		Requirements impact sound	
Country	**Requirements found in**	**Impact sound [dB]**	**Remarks–National special rules [1]**
SE	CS (Class C)	$L'_{n,w} \leqslant 56$	$V_{r,max} = 31$ m^3 → $L'_{n,w} = L'_{nT,w}$ when $V_r \leqslant 31$ m^3
		$L'_{n,w} + C_{I,50\text{–}2500} \leqslant 56$	Bathrooms are excluded from requirement in case the level from service equipment is kept below some certain limits. Also floor (1 m^2) immediately inside the entrance door is excluded.
FI	BC or CS (Class C) (Identical limits)	$L'_{n,w} \leqslant 53$	Volume limit in: $V_{r,max} = 60$ m^3 → $L'_{n,w} = L'_{nT,w} + 3$ dB when $V_r \geqslant 60$ m^3 Bathrooms are excluded from requirement
A	BC (federal states referring to ÖNORM and OIB Guideline)	$L'_{nT,w} \leqslant 48$ (row houses $L'_{nT,w} \leqslant 43$, special requirements in buildings with commercial units)	—
D	DIN 4109	$L'_{n,w} \leqslant 53$	National special rules (additional rules compared to ISO 140-7)
CH	SIA 181:2006 Schallschutz im Hochbau	$L' \leqslant 53^{(1)}$ $L' \leqslant 48$	bedroom (in case of normal sensitivity to noise) school (in case of normal sensitivity to noise)

(Continued)

Table 2. Regulatory requirements for impact sound insulation between dwellings in seven european countries including remarks of national special rules—july 2010. *(Continued)*.

Country	Requirements found in	Requirements impact sound	
		Impact sound [dB]	**Remarks–National special rules [1]**
DK	CS (Class C)	$L'_{n,w} \leqslant 53$	Balconies and floors in rooms with floor area less than 2.5 m^2 do not need to fulfil the requirements. This is stated directly in DS 490 just above the Table with limit values. For light-weight constructions it is recommended to extend the frequency range down to 50 Hz, applying $L'_{n,w} + C_{I,50\text{-}2500} \leqslant$ 53 dB. This recommendation is found in a separate guideline
IS	BC	$L'_{n,w} \leqslant 58$ Row housing: $L'_{n,w} \leqslant 53$	$L'_{n,w}$ is calculated by applying the former "8-dB max rule" ($L'_{n,w,8dB} \leqslant 58$). It is expected to disappear in the next revision of the building code. Classification scheme is not yet referred to in the BC
NO	CS (Class C)	$L'_{n,w} \leqslant 53$	Volume limit $V_{r,max} = 100\ m^3$ ➔ $L'_{n,w} = L'_{nT,w} + 5$ dB when $V_r \geqslant 100\ m^3$ It is recommended to include $C_{I,50\text{-}2500}$

[(1)] $L' = L'_{nT,w} + C_I + C_V$ (as in ISO 717-1). C_I can be given either for the frequency band 100–3150 Hz or 50–2500 Hz. The frequency band is mentioned in the index, e.g. $C_{I,\ 50\text{–}2500}$. ➔ Converted and expressed as $L'_{n,w}$ a L' of 50 dB is around 52–45 dB.

Table 3. Regulatory requirements for airborne sound insulation between dwellings in seven european countries including remarks of national special rules—july 2010.

		Requirements airborne sound insulation	
Country	Requirements found in	Airborne sound insulation [dB]	Remarks–special national rules [2]
SE	CS (Class C)	$R'_w + C_{50\text{-}3150} \geqslant 53$	Relation V/S must not exceed 3.1 m when evaluating the single number, R'_w (i.e D_{nTw}). Hence, $R'w$ in Sweden corresponds to $D_{nT,w}$ when $V/S > 3.1$.
FI	BC or CS (Class C) (Identical limits)	$R'_w \geqslant 55$	Receiving room volume limitation in the evaluation, $V_{r,max} \leqslant 60$ m^3
A	BC (federal states referring to ÖNORM and OIB Guideline)	$D_{nT,w} \geqslant 55$ (row houses $D_{nT,w} \geqslant 60$)	special requirements in buildings with commercial units
D	DIN 4109	$R'_w \geqslant 53/54$	National special rules (additional rules compared to ISO 140-4)
CH	SIA 181:2006 Schallschutz im Hochbau	$D_i \geqslant 52$ dB$^{(1)}$ $D_i \geqslant 57$ dB	bedroom (in case of normal sensitivity to noise) school (in case of normal sensitivity to noise)
DK	CS (Class C)	$R'_w \geqslant 55$	If the area of the common part of the partition between two rooms is less than 10 m^2, the area applied is largest of the values of the actual area and the receiving room volume divided by 7.5. If there is no common area, the normalized level difference D_n is applied instead of R' It is recommended to include $C_{50\text{-}3150}$ at the same level and in particular for light-weight constructions (walls < 100 kg/m^2 and floors < 250 kg/m^2) it is recommended to extend the frequency range down to 50 Hz and apply $R'_w + C_{50\text{-}3150} \geqslant 53$ dB The special rules are found in SBi Guideline 216 and 217

(Continued)

Table 3. Regulatory requirements for airborne sound insulation between dwellings in seven european countries including remarks of national special rules—july 2010. *(Continued)*

		Requirements airborne sound insulation	
Country	**Requirements**	**Airborne sound insulation [dB]**	**Remarks–special national rules [2]**
IS	BC	$R'_w \geqslant 52/55$	R'_w is calculated with old "8 dB max rule" as in old I_a-value. $R'_{w,8dB}$ = Ia (it is expected that this wilkl disappear in the next revision). Min. value 52 dB, recommended 55 dB for apartments, min. value 55 dB for row-houses
NO	CS (Class C)	$R'_w \geqslant 55$	Receiving room volume limitation in the evaluation, $V_{r,max} \leqslant 100$ m^3 It is recommended to include $C_{50-3150}$ at the same level. If the partition contains a door, and the total dividing surface is smaller than 10 m^2, then $S = 10$ m^2. If there is no common partition between the rooms, then $S = 10$ m^2. In this case, it is the normalised level difference, $D_{n,w}$, that is determined (see NS-EN ISO 140-4). The resulting value of $D_{n,w}$ is then compared with the limit value set for R'_w.

(1) D_i ($D_i = D_{nT,w} + C - C_v$ (as in ISO 717-1)) ⟶ Converted and expressed as R'_w a D_i of 54 dB is around 54–57 dB

clear, if each single measured value really must comply with the requirement. In some countries, deviations in single values are accepted as long as the mean value from a number of measurements, fulfil the requirement. The number of measurements needed to fulfil the requirement in each country is - or should be - stated in each national standard.

In addition to the issue of measurement uncertainty and related national compliance rules, other factors might influence whether a building system fulfils the regulations or complies with a specific limit or not. As earlier mentioned impact sound insulation and airborne sound insulation, field results or rather the modified field results can depend on the national special rules.

It would be a great advantage, if the rules and procedures could be minimized and/or further clarified in the international standards and thus harmonized between countries. In addition to the before-mentioned special rules, there might be other national special rules related to limit values. Hence, it is of course also relevant and probably even more important to review descriptors and limit values. Furthermore, there are differences in requirements between countries depending on the type of living accommodation, dwellings for elderly, normal dwellings etc.

In spite of different building practices, there seems to be no scientific reason for various national requirements and special rules, since people in living in the countries represented in this paper are considered to have approximately the same living habits and equal expectations of their home environment. The reason for differences is rather traditions in each country and lack of cooperation.

Complaints from residents in light-weight housing indicate a need to include lower frequencies in the evaluation for such construction types. Low frequencies in lightweight structures might cause new disturbances from vibrations, implying a need to also developing regulations for vibrations. However, there is a lot of issues in need for clarification in order to finally state proper and predictable procedure to measure, evaluate and compare the results to a suitable value in the building code [26].

Benefits of Reviewing Sound Insulation Descriptors, Limits and Rules

More work on the findings stated in this paper, cooperation and implementation would have the following benefits:

1. Increased exchange of knowledge—better understanding regarding the basis for national special rules
2. Less complicated national adaptations—some adaptations might be unnecessary with regard to subjective response
3. Facilitate and encourage more cross country trade between countries
4. Lower costs for the building industry
5. Less risk for mistakes due to the fact that some special rules may not be discovered by consultants and other parties involved

The need for some of the special rules may be caused by a non-optimal choice of descriptors. Thus, it is important to understand the reasons and to investigate if other descriptors are more optimal.

The building industry today is not national any more. Almost all building companies and manufacturers are working all across Europe or at least in limited parts of Europe, for instance on the Nordic market. Each company makes their own investigations and expensive, national adaptations in order to enter new markets or to market new products. Besides, if the national adaptations are not discovered when transferring building systems or building products from one country to another, the costs will raise even more afterwards. Often, it is necessary to involve consultants from each country in order to understand and clarify the differences for the developer.

SUMMARY

This paper is summarizing national special rules for sound insulation requirements in the building regulations in some European countries.

In terms of coordination the Nordic countries were rather close to meet an agreement in the mid 90's. However, lack of consensus and the asynchronous revisions of building regulations led to stop of cooperation soon after. Since then, differences between the Nordic countries have increased. Descriptors and other rules differ more than what is obvious at the first glance, when comparing the regulations or classification standards. When comparing the diversified requirements and standards existing now—approximately fifteen years later—it seems to be time to reconsider the situation and reopen cooperation to the benefit of the residents of dwellings, building industry and development of building constructions. The largest differences in requirements and classes are found for impact sound insulation. Adding potential national special rules from the rest of Europe will probably make the picture even more complicated. The present situation impedes development and creates trade barriers, and there seems to be a high interest for all parties involved in the building process to change the situation.

It is concluded that more close cooperation could contribute to identify the most important special rules, and it would be proper to prepare a document with an overview of all national building acoustic requirements (including special rules) and classes in the European countries, starting with dwellings. The document should state the reason for special rules and identify which of the current rules are important to retain, if any. The document would then include 1; proposals for change of descriptors to fit also to the lightweight structures, 2; evaluation if there is a need for certain special rules for lightweight structures to be included in ISO standards, 3; perhaps further work directed to lightweight industry in particular. The results of such work is urgent and could provide useful input for the revision of ISO 717, and for the work within the COST Action TU 0901 aiming at harmonization of descriptors and classification schemes in Europe.

REFERENCES

1. K Hagberg and B Rasmussen, "Impact sound insulation descriptors in the Nordic building regulations—Overview special rules and benefits of changing descriptors". BNAM, Bergen, Norway, 2010.
2. H Helimäki and B Rasmussen, "Airborne sound insulation descriptors in the Nordic building regulations—Overview special rules and benefits of changing descriptors". BNAM, Bergen, Norway, 2010.

3. Building Regulations 2008, Danish Enterprise and Construction Authority, Danish Ministry of Economic and Business Affairs.
4. RakMK C1:1998, The National Building Code of Finland: C1 Sound insulation and noise abatement in building, Regulations and guidelines.
5. Byggingarreglugerd Nr. 441/1998.
6. Teknisk Forskrift 1997 (TEK'97) Technical Regulations under the Planning and Building Act 1997, National Office of Building Technology and Administration, Norway
7. BBR 2008, Boverket 2008
8. Musterbauordnung—MBO—Fassung November 2002. Online Ressource: http://www.is-argebau.de
9. DIN 4109 :1989-11, Schallschutz im Hochbau; Anforderungen und Nachweise
10. DIN 4109 Beiblatt 2: 1989-11, Schallschutz im Hochbau; Hinweise für Planung und Ausführung; Vorschläge für einen erhöhten Schallschutz; Empfehlungen für den Schallschutz im eigenen Wohn- oder Arbeitsbereich
11. OIB Guideline V: 2007, Schallschutz; OIB, Vienna
12. ÖNORM B 8115-2: 2006 Schallschutz und Raumakustik im Hochbau Teil 2: Anforderungen an den Schallschutz; Österreichisches Normungsinstitut Wien
13. DS 490:2007, "Lydklassifikation af boliger". (Sound classification of dwellings), Denmark.
14. SFS 5907:2004, "Rakennusten Akustinen Luokitus", Finland. English version "Acoustic classification of spaces in buildings" published in July 2005.
15. IST 45:2003, "Acoustics—Classification of dwellings", Iceland. Note: Under revision, cf. Draft IST 45:2010, "Acoustic conditions in buildings - Sound Classification of Various Types of Buildings" (publication expected in 2010).
16. NS 8175:2008, "Lydforhold i bygninger, Lydklassifisering av ulike bygningstyper" (Sound conditions in buildings—Sound classes for various types of buildings), Norway.
17. SS 25267:2004, "Byggakustik—Ljudklassning av utrymmen i byggnader—Bostäder". (Acoustics—Sound classification of spaces in buildings—Dwellings). Sweden.
18. ISO 717, Acoustics—Rating of sound insulation in buildings and of buildings elements
    - Part 1: Airborne sound insulation, 1996.
    - Part 1 Amd. 1: Rounding rules related to single-number ratings and single-number quantities, 2006.
    - Part 2: Impact sound insulation, 1996.
    - Part 2 Amd. 1: 2006.
19. ISO 140, Acoustics—Measurement of sound insulation in buildings and of building elements

- Part 2: Determination, verification and application of precision data, 1991.
- Part 4: Field measurements of airborne sound insulation between rooms, 1998.
- Part 5: Field measurements of airborne sound insulation of facade elements and facades, 1998.
- Part 7: Field measurements of impact sound insulation of building elements, 1998.
- Part 14: Guidelines for special situations in the field, 2004.

Note: ISO 140 consists of more parts. The above parts are those relevant to field measurements.

20. Kylliäinen, M. Uncertainty of impact sound insulation measurements in field. Report 125, Tampere University of Technology, 2003
21. Christian Simmons, "Managing uncertainty in building acoustics: comparisons of predictions with the 12354 standards to measurements". Dissertation, Luleå University of Technology, 2009.
22. .*"Sound insulation between dwellings—Descriptors in building regulations in Europe"* by Birgit Rasmussen & Jens Holger Rindel. Applied Acoustics, 2010, 71(3), 171–180.
23. *"Sound insulation between dwellings—Requirements in building regulations in Europe"* by Birgit Rasmussen. Applied Acoustics, 2010, 71(4), 373–385.
24. Hagberg, K., Thorsson, P. "Uncertainties in standard impact sound measurement and evaluation procedure applied to lightweight structures", Proceedings, International conference on Acoustics, ICA 2010.
25. Hagberg, K. "Evaluation field measurements of impact sound", Building Acoustics, Volume 17, no 2, 2010, p.105–128.
26. Hagberg, K. ¨Acoustic development of lightweight building system", Proceedings Euronoise 2009
27. COST "MICC-Flexible industrialized open lightweight building systems require a good process to make them robust, COST TU0901 meeting Florens 2011

Paper C

Applied Acoustics 85 (2014) 57–68

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound

Fredrik Ljunggren [a,*], Christian Simmons [b,a], Klas Hagberg [c,d]

[a] Luleå University of Technology, 97187 Luleå, Sweden
[b] Simmons akustik och utveckling, Chalmers Teknikpark, 41288 Gothenburg, Sweden
[c] WSP Acoustics, Ullevigatan 19, 41140 Gothenburg, Sweden
[d] Lund University, Box 118, 22100 Lund, Sweden

ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 2 April 2014
Accepted 7 April 2014

Keywords:
Impact sound insulation lightweight
building acoustic

ABSTRACT

Traditionally, multi-family houses have been constructed using heavy, homogenous materials like concrete and masonry. But as a consequence of the progress of lightweight building systems during the last decades, it has been questioned whether standardized sound insulation evaluation methods still are appropriate.

An extensive measurement template has been applied in a field survey where several vibrational and acoustical parameters were determined in ten Swedish buildings of various constructions. In the same buildings, the occupants were asked to rate the perceived annoyance from a variety of natural sound sources. The highest annoyance score concerned impact sounds, mainly in the buildings with lightweight floors.

Statistical analyses between the measured parameters and the subjective ratings revealed a useful correlation between the rated airborne sound insulation and $R'_w + C_{50-3150}$ while the correlation between the rated impact sound insulation and $L'_{n,w} + C_{I,50-2500}$ was weak. The latter correlation was considerably improved when the spectrum adaptation term with an extended frequency range starting from 20 Hz was applied. This suggests that frequencies below 50 Hz should be considered when evaluating impact sound in lightweight buildings.

1. Introduction

Multi-storey residential buildings in Europe are conventionally constructed with heavy materials like concrete/steel or masonry. After new findings, e.g. in material combinations leading to improved fire safety, wooden framework is nowadays an alternative in the design of multi-family houses. In Sweden, the building regulations have permitted high-rise wooden residential buildings since 1994.

The acoustical consequences were not taken properly into account by then and it soon turned out that lightweight constructions with wooden or thin profiled steel joists often resulted in poor sound insulation at low frequencies. Since 1999, the requirements in Sweden prescribe measurements and evaluation in the extended frequency range 50–3150 Hz, whereas in other countries the standardized range 100–3150 Hz is used. Despite that new lightweight multi-family houses typically fulfil the sound insulation requirement, their occupants often perceive the impact sound insulation as being insufficient while occupants in heavy concrete buildings, having the same single number values, are satisfied [1]. Hence, the standardized single number evaluation of impact sound insulation according to ISO 717-2 cannot be considered as neutral with respect to building technique and materials.

A number of initiatives to increase the knowledge regarding low frequency sounds in multi-family houses have been taken. An extensive field study performed by Bodlund [2], led to the suggestion of new single number ratings of which some were introduced to ISO 717-2:1996 [3]. Cooperation between the Nordic building authorities (NKB) resulted in a field study regarding the application of single numbers [4]. Bodlund's investigation was further analysed by Hagberg [5] and examples of more field studies have been summarized by Rindel [6]. All the referred studies concluded that frequencies below 100 Hz must be considered regarding impact sound in lightweight buildings. This indicates that the informative

* Corresponding author. Tel.: +46 920 491286.
E-mail address: fredrik.ljunggren@ltu.se (F. Ljunggren).

http://dx.doi.org/10.1016/j.apacoust.2014.04.003
0003-682X/

annex of the current standard, ISO 717-2:2013 [7], that defines the single number quantity $L'_{n,w} + C_{I,50-2500}$, should be mandatory in building regulations.

The mentioned results from various studies together with the accumulated experiences from the academy as well as from the building industry and consultants resulted in the establishment of the Swedish research programme AkuLite, 2009–2013. One of its main objectives was to find neutral single number values for sound insulation that are independent of the building technique, i.e. parameters that do not favour one type of structural material to another. This paper describes the methods applied together with the main results. The steps were to (1) identify a number of relevant multi-family buildings, (2) measure several acoustical and vibrational parameters in these buildings, (3) ask the occupants, by means of a questionnaire, how they rate the sound insulation at home and (4) find out which measured quantities correlate well with the subjective ratings, by means of statistical analyses. The study is restricted to the relation between sound insulation performance and the mean subjective rating given by the occupants. Other factors, although not considered here, may influence the rating, e.g. personal sensitivity or specific sound generated in a neighbouring apartment.

2. Building objects

Ten building objects of various constructions were involved in the study which comprises both field measurements and questionnaire surveys. All of them may be considered relatively modern as all are less than ten years old. A majority of the buildings are designed with lightweight loadbearing structures. Four objects are based upon a traditional wooden framework and flooring boards (here denoted *wood*), one object utilizes a cold-formed thin-walled steel framework (denoted *thin steel*), four objects are made of cross laminated timber (denoted *CLT*) and one object has walls and floors made of massive concrete cast in situ (denoted *concrete*). The objects are located in various Swedish cities according to Table 1.

3. Field measurements

3.1. Method – measurement template

Within the AkuLite project, a special measurement template (procedure) was developed. The idea behind the template is to collect data and knowledge of a large variety of building acoustic parameters, including data which normally are not covered by standardized measurements. An overview is given here but the template is fully described in [8]. The template is divided into two parts; (1) General measurements and (2) Additional measurements. The procedure for each building object is to perform numerous general measurements between adjacent apartments/rooms in vertical direction, preferably up to ten, and to perform additional measurements for one of these cases. A special feature of all measurements is the low frequency content.

Table 1
Building objects.

No	City	Construction	New building	Existing building
1	Upplands Väsby	Wood	X	
2	Östervåla	CLT	X	
3	Umeå	Concrete		X
4	Växjö	CLT		X
5	Växjö	CLT		X
6	Falun	CLT		X
7	Alingsås	Wood		X
8	Lindesberg	Wood		X
9	Örebro	Thin steel		X
10	Varberg	Wood	X	

3.1.1. General measurements

The general measurements include airborne and impact sound insulation using the ISO tapping machine as the source but also sound and vibration measurements using the ISO heavy/soft rubber ball (ISO 10140-1 [9]).

(a) Impact sound insulation using the standardized impact tapping machine.
Measurement and evaluation according to ISO 140-7 [10], ISO 717-2 [3] and SS 25267 [11] but in an extended frequency range: 20–5000 Hz.
$L'_{n,w}$ and $C_{I,50-2500}$ are to be reported.
(b) Airborne sound insulation.
Measurement and evaluation according to ISO 140-4 [12], ISO 717-1 [13] and SS 25267 [11] but in an extended frequency range: 20–5000 Hz.
R'_w and $C_{50-3150}$ are to be reported.
(c) Impact sound using the rubber ball.
Excitation in the centre of the sending room where the ball is dropped from 1.0 m height. Measurement in two positions in the receiving room, in the centre and in one arbitrary selected corner with a microphone height of 1.0 m. Frequency range: 20–500 Hz.
Total L_{max} (with instrumentation time constant *F*, fast), linear and A-weighted are to be reported.
(d) Floor vibrations using the rubber ball.
Excitation of the floor by dropping the ball in the centre of the room from 1.0 m height. The response is measured in two points, 0.5 m from the source in orthogonal directions.
Total a_{max} (maximum acceleration with time constant fast) and fundamental frequency of the floor are to be reported.

3.1.2. Additional measurements

The additional measurements include vibration across junctions and over the floor surface. Natural frequencies of walls and static deflection of the floor are covered as well.

(a) Flanking vibrations on three sides of a junction using the ISO tapping machine (frequency range: 10–3150 Hz) and the ISO heavy/soft rubber ball (1–500 Hz).
Acceleration is measured along two perpendicular walls, in total 30 points on upper floor, lower ceiling and lower wall.
Mean accelerations from each surface are to be reported.
(b) Attenuation of floor vibrations using the tapping machine (10–3150 Hz) and the rubber ball (1–500 Hz).
Measurement is effected in total 10 points along two perpendicular lines, from the excitation in the centre of the floor towards the flanking walls.
Acceleration in each point is to be reported.
(c) Wall response.
Two walls in the room are excited separately by an impact hammer and the response is measured in two positions for each wall.
The lowest natural frequencies of the walls are to be reported.
(d) Static deflection of the floor.
The deflection due to a 1 kN point load in the weakest point of the floor is measured and reported.

3.2. Results

The results in the following diagrams are presented as the mean value for each of the ten objects presented in Table 1, where each mean value represents data from one to ten measurements. All original data is available in [14]

3.2.1. Airborne sound

The airborne sound insulation results are shown in Fig. 1. Taking R'_w (a) defined between 100 and 3150 Hz as a reference, it is clearly seen that the declared sound insulation drops when the spectrum adaptation term $C_{50-3150}$ (b) is added. When the frequency range is further extended, down to 20 Hz, $R'_w + C_{20-3150}$ (c), there is practically no difference from previous case. Since the ISO L_{ij} terms [13] of the trial spectrum adaptation term $C_{20-3150}$ is not defined for frequencies 20–50 Hz, these terms must be calculated. Based upon A-weighting a successive drop of 4–6 dB is obtained for each one third octave band below 50 Hz. To get a hint of the building objects' low frequency performance, the sound reductions were energetically summed up within the narrow range 20–100 Hz on one third octave band basis (d). In this respect, the concrete building, object No. 3, shows the highest sound insulation.

In terms of $R'_w + C_{50-3150}$ (b), the mean results of the ten objects span from 48 to 62 dB.

3.2.2. Impact sound using the tapping machine

Results from the measured impact sound insulations are presented in Fig. 2. Note that the normalized single number rating $L'_{n,w}$ is evaluated according to the Swedish standard [11] in which the volume of the receiving room is restricted not to exceed 31 m^3. Thus, in any case where the real room is larger than 31 m^3, the volume 31 m^3 is used in the calculation of the normalized impact sound pressure level L'_n according to

$$L'_n = L_i + 10\log\left(0.016\frac{V}{T}\right), \tag{1}$$

where L_i is the impact sound pressure level, V is the room volume and T is the reverberation time. For the specific room size of 31 m^3, $L'_{n,w}$ is effectively equal to the standardized impact sound level $L'_{nT,w}$. In larger rooms, $L'_{n,w}$ shows somewhat lower value when evaluated according to the Swedish standard compared to ISO [3]. The difference is 3 dB in 60 m^3 rooms and 5 dB in 100 m^3 rooms.

Starting with $L'_{n,w}$ (a), defined from 100 to 3150 Hz, it is seen – similar to the airborne sound case – that the impact sound level increases for a large majority of the objects as the $C_{I,50-2500}$ (b) is added. It can also be seen – in contrast to the airborne sound case – that the impact sound level increases even more when the frequency range is extended down to 20 Hz (c). Here, the frequency weight of $C_{I,20-2500}$ was set to -15 dB for the one third octave bands 20–40 Hz as for all other frequencies 50–2500 Hz [3]. The concrete building, object No. 3, is again unaffected by the lowest frequencies which also is indicated by the lowest result when the impact sound levels between 20 and 100 Hz are summed up (d).

In terms of $L'_{n,w} + C_{I,50-2500}$ (b), the mean results of the ten objects span from 51 to 66 dB.

3.2.3. Alternative measurements related to impact sound

In Fig. 3, the results from measurements with alternative sources related to impact sound insulation are presented. Two examples of sound level from the ISO rubber ball (measurement template (c), Section 3.1.1) can be seen; A-weighted sound level measured in the centre of the receiving room (a) and linear sound

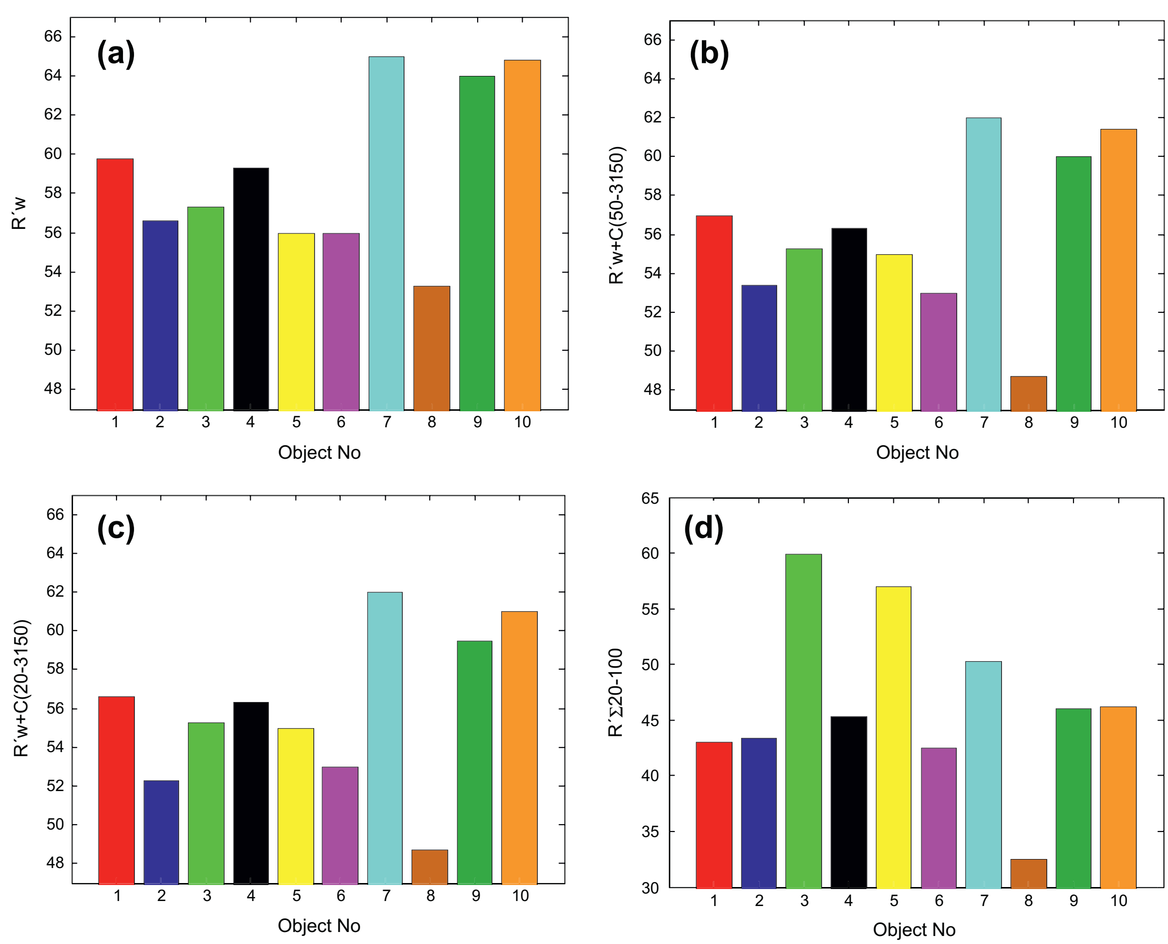


Fig. 1. Airborne sound insulation; (a) R'_w, (b) $R'_w + C_{50-3150}$, (c) $R'_w + C_{20-3150}$ and (d) $R'_{\sum 20-100}$.

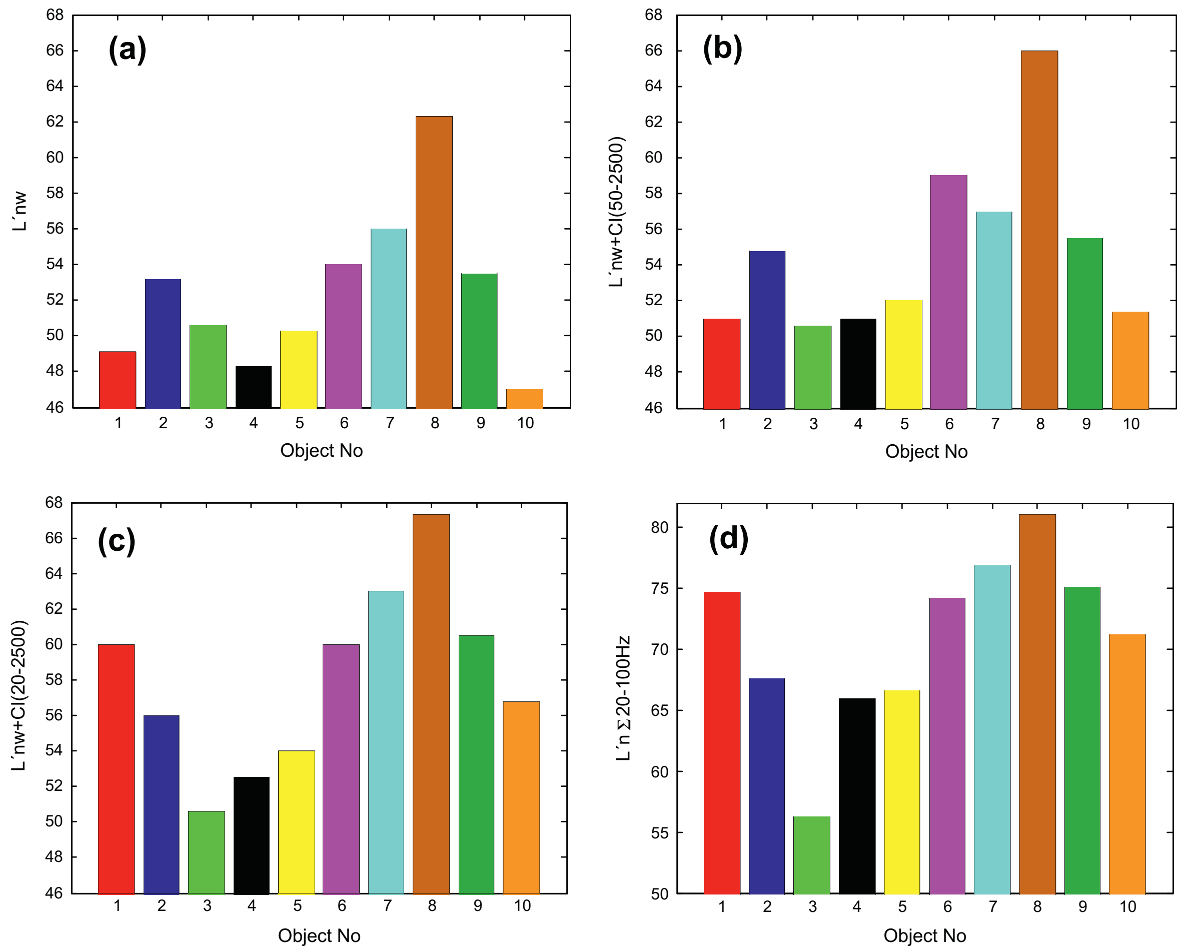


Fig. 2. Impact sound insulation; (a) $L'_{n,w}$, (b) $L'_{n,w} + C_{I,50-3150}$, (c) $L'_{n,w} + C_{I,20-3150}$ and (d) $L'_{n,\sum 20-100}$. ($L'_{n,w}$ is evaluated according to the Swedish national standard.).

level measured in a corner of the room (b). The variation of the weighted level from the centre position is large, from about 35 to 85 dB(A) while the linear levels from the corner positions are somewhat more homogenous, from about 70 to 105 dB. The obtained variations are probably higher compared to if a spatial averaging of the sound pressure levels in the room had been carried out [15].

The floor acceleration (template (d), Section 3.1.1) is presented as the mean value from the two measurement positions (c) with a variation from about 3 to 30 m/s^2. The static deflection (template (h), Section 3.1.2) has a spread from about 0.1 to 1.4 mm which can be seen in (d). Note that the latter case only represents one measurement per building object since it originates from the additional part of the measurement template. Also note that results from two of the objects (Nos. 5 and 6) are missing for this parameter.

4. Subjective perception by the occupants

4.1. Method – questionnaire

The COST action TU0901 [16] was established in 2009 in order to gather researchers from the member states of the European Union to develop a harmonized sound classification scheme. One goal of this COST action is to establish a questionnaire template for socio-acoustic surveys in dwellings. There is a need for a uniform and easy translatable questionnaire which can be applied for comparisons between measured quantities and occupants' ratings. For this purpose a questionnaire based upon the international technical specification ISO/TS 15666 [17] was developed [18], see Fig. 4. A Swedish version was used for the surveys reported in this paper.

The questionnaire contains 15 questions on the annoyance of airborne sounds coming through walls and floors, music with low frequency sounds, footstep noise, sounds from staircases and balconies, traffic noise, sounds from service equipment and more. It employs an 11-point numerical scale ranging from 0 – *not at all bothered, disturbed or annoyed* to 10 – *extremely annoyed* including face symbols to characterize the two extremes of the scale.

A great advantage of making a questionnaire study in occupied dwellings, as compared to listening tests with a small group of test subjects being exposed to short bursts of noise in a laboratory, is that most answers are based upon a realistic time of living in the actual house. All buildings in the study were occupied for a minimum period of six months.

There is a natural variation in the occupants' exposure to noise which depends partly upon the type of building construction and partly upon the neighbours' activities. This implies a greater uncertainty compared to listening tests which are conducted in artificial and well controlled environments. When the questionnaires were distributed to occupants, it included a cover letter that emphasized that the purpose of the survey was to find out about the building construction's acoustic performance. Note: The questionnaire has been further evaluated and developed and a final version is available in several languages on the TU0901 website [16].

4.1.1. Evaluation of the occupants' ratings

The evaluation of the occupants' ratings refers to the obtained mean value of the annoyance for each individual question, either

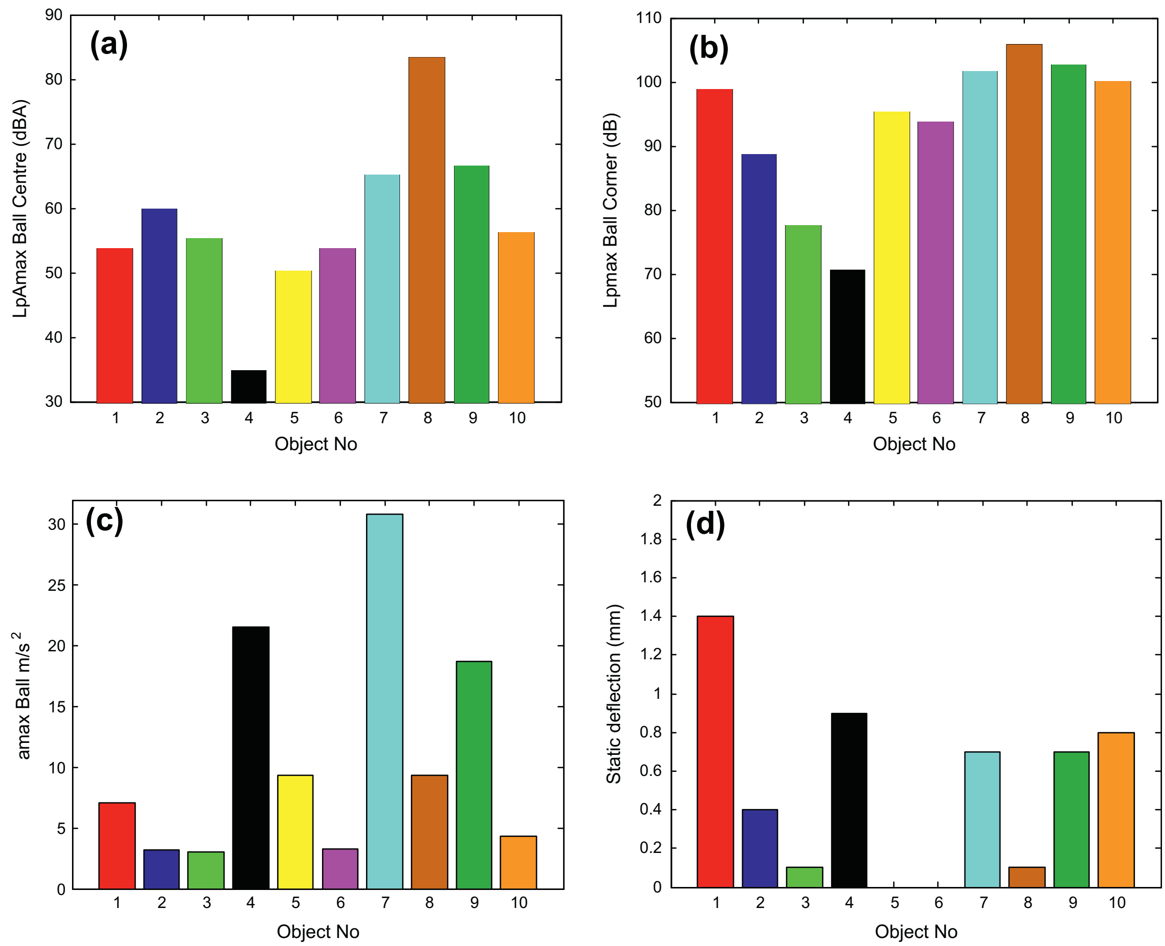


Fig. 3. Alternative measurements; (a) rubber ball, A-weighted sound in the centre of the receiving room (b) rubber ball, sound in one corner of the receiving room, (c) rubber ball, floor vibrations and (d) Static deflection due to a 1 kN load.

in terms of mean annoyance of the separate objects or in terms of the overall mean annoyance representing the average of all the ten objects' means. Other possible evaluation parameters have been considered, e.g. the percentage of the accumulated answers where occupants returned ratings 3 or higher, 5 or higher and 8 or higher. However, in the correlation analyse no significant differences were found between the mentioned evaluation parameters. This was also supported in a previous study [1] based upon a draft version of the same questionnaire. Since the actual questionnaire is relatively new, the obtained figures of annoyance cannot be calibrated.

Furthermore, when evaluating question No. 5, related to impact sound, all answers from occupants living on the uppermost floor of the buildings were excluded since impact sounds from above then do not occur.

The number of answers among the building objects varied between 13 and 79 with a reply rate of 33–83%.

4.2. Results

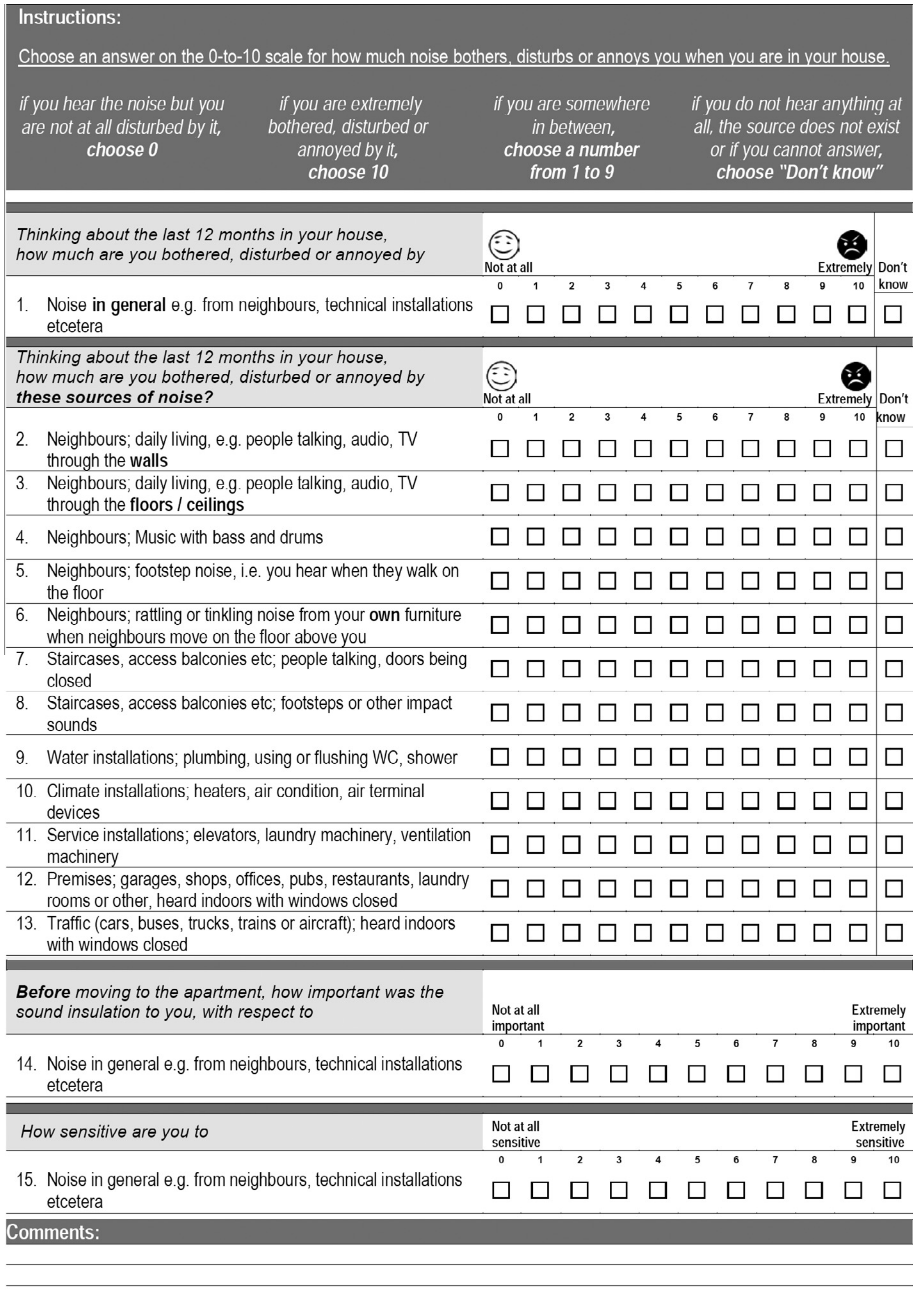
For a majority of the questions related to specific issues, question (Q) 2–13, the declared annoyance is fairly low with overall mean ratings about 2 on the scale ranging from 0 to 10, see Fig. 5. However, one of the questions stands out, the one about walking neighbours, Q5. Here the mean annoyance is 3.7, about twice as high compared to the others. The remaining matters of the questionnaire about the noise in general (Q1), the importance of noise (Q14) and the sensitiveness of noise (Q15) resulted in mean ratings of 2.4, 6.6 and 3.6 respectively. Thus, sound insulation is indeed an important factor for any potential occupant and impact sound seems to be especially crucial in lightweight buildings.

The pooled standard deviation, obtained by – for each question – combining the standard deviations from all the ten objects, was found to be about 2 for all individual questions, Q1-15. A number of matters (Q 1, 3, 4 and 5) are presented in Fig. 6 to get an idea of the spread between the individual building objects. Although the question related to impact sound (Q5) resulted in an overall mean score of 3.7 it can be seen (d) that allocated to the individual building objects, several of them are given men annoyance rating of about 5 or higher, with a total range from 1.2 to 6.3. The lowest value refers to the concrete building (object No. 3) and the highest value refers to a traditional wooden framed building (object No 8). The corresponding lowest-highest mean value is 0.6–4.3 for the overall annoyance (Q1) (a), 0.1–3.0 for the airborne sound through floors (Q3) (b) and 0.2–4.8 for the low frequency music (Q4) (c).

The complete results, including all individual questionnaires, are available in [14].

4.2.1. Assessment of the occupants' ratings

The subjective ratings in term of mean annoyance of each building object were presented above. The mean annoyance often takes a numerical value of 0.5–5.0 which could seem to be low compared to the maximum value "10". However, when the individual questionnaires are studied it is clear that the data is not normally distributed but shows a more bipolar characteristic [14]. Many occupants tend to be either practically not disturbed at all (ratings 0–2) or considerably disturbed (rating 8–10), i.e. despite a comparatively low



Instructions:

Choose an answer on the 0-to-10 scale for how much noise bothers, disturbs or annoys you when you are in your house.

if you hear the noise but you are not at all disturbed by it, ***choose 0***	*if you are extremely bothered, disturbed or annoyed by it,* ***choose 10***	*if you are somewhere in between,* ***choose a number from 1 to 9***	*if you do not hear anything at all, the source does not exist or if you cannot answer,* ***choose "Don't know"***

Thinking about the last 12 months in your house, how much are you bothered, disturbed or annoyed by	0 Not at all	1	2	3	4	5	6	7	8	9	10 Extremely	Don't know
1. Noise **in general** e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Thinking about the last 12 months in your house, how much are you bothered, disturbed or annoyed by ***these sources of noise?***	0 Not at all	1	2	3	4	5	6	7	8	9	10 Extremely	Don't know
2. Neighbours; daily living, e.g. people talking, audio, TV through the **walls**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Neighbours; daily living, e.g. people talking, audio, TV through the **floors / ceilings**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Neighbours; Music with bass and drums	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Neighbours; footstep noise, i.e. you hear when they walk on the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Neighbours; rattling or tinkling noise from your **own** furniture when neighbours move on the floor above you	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Staircases, access balconies etc; people talking, doors being closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. Staircases, access balconies etc; footsteps or other impact sounds	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9. Water installations; plumbing, using or flushing WC, shower	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10. Climate installations; heaters, air condition, air terminal devices	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11. Service installations; elevators, laundry machinery, ventilation machinery	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12. Premises; garages, shops, offices, pubs, restaurants, laundry rooms or other, heard indoors with windows closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13. Traffic (cars, buses, trucks, trains or aircraft); heard indoors with windows closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Before *moving to the apartment, how important was the sound insulation to you, with respect to*	0 Not at all important	1	2	3	4	5	6	7	8	9	10 Extremely important
14. Noise in general e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

How sensitive are you to	0 Not at all sensitive	1	2	3	4	5	6	7	8	9	10 Extremely sensitive
15. Noise in general e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Comments:

Fig. 4. Questionnaire (early version by COST TU0901).

mean value, the fraction of occupants that are substantially annoyed cannot be ignored.

5. Correlation between field measurements and occupants ratings (questionnaire surveys)

5.1. Method – statistical analyses

Statistical analyses in terms of principal component analyses and linear regressions were performed to reveal correlations between the field measurements and the subjective ratings from the questionnaires regarding airborne and impact sound insulation. The overall mean annoyance for respective question has been used as the subjective parameter throughout the analyses and correspondingly the overall mean value of respective measured quantity from the ten building objects has been used as the field measurement parameter. Two questions from the questionnaire are directly related to airborne sound insulation, sounds transmitted through the walls (Q2) and through the floors/ceilings (Q3). The mean annoyance of these two questions correlates well with each other even though the mean annoyance is almost twice as high for the latter. The transmission through floors is then used as the subjective parameter for correlation against airborne sound insulation measurements. For impact sound measurements, the question of footstep noise (Q5) has been used.

5.2. Results

5.2.1. Airborne sound

The coefficient of determination (R^2, equivalent to the square of the correlation coefficient) from linear regression analyses regarding airborne sound is presented in Table 2 together with the

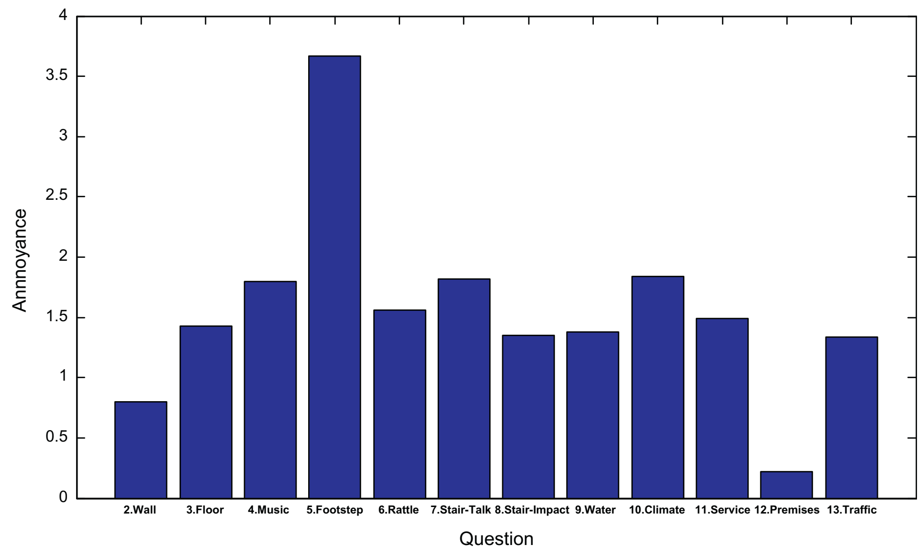


Fig. 5. Overall mean annoyance from question Nos. 2–13 of the questionnaire.

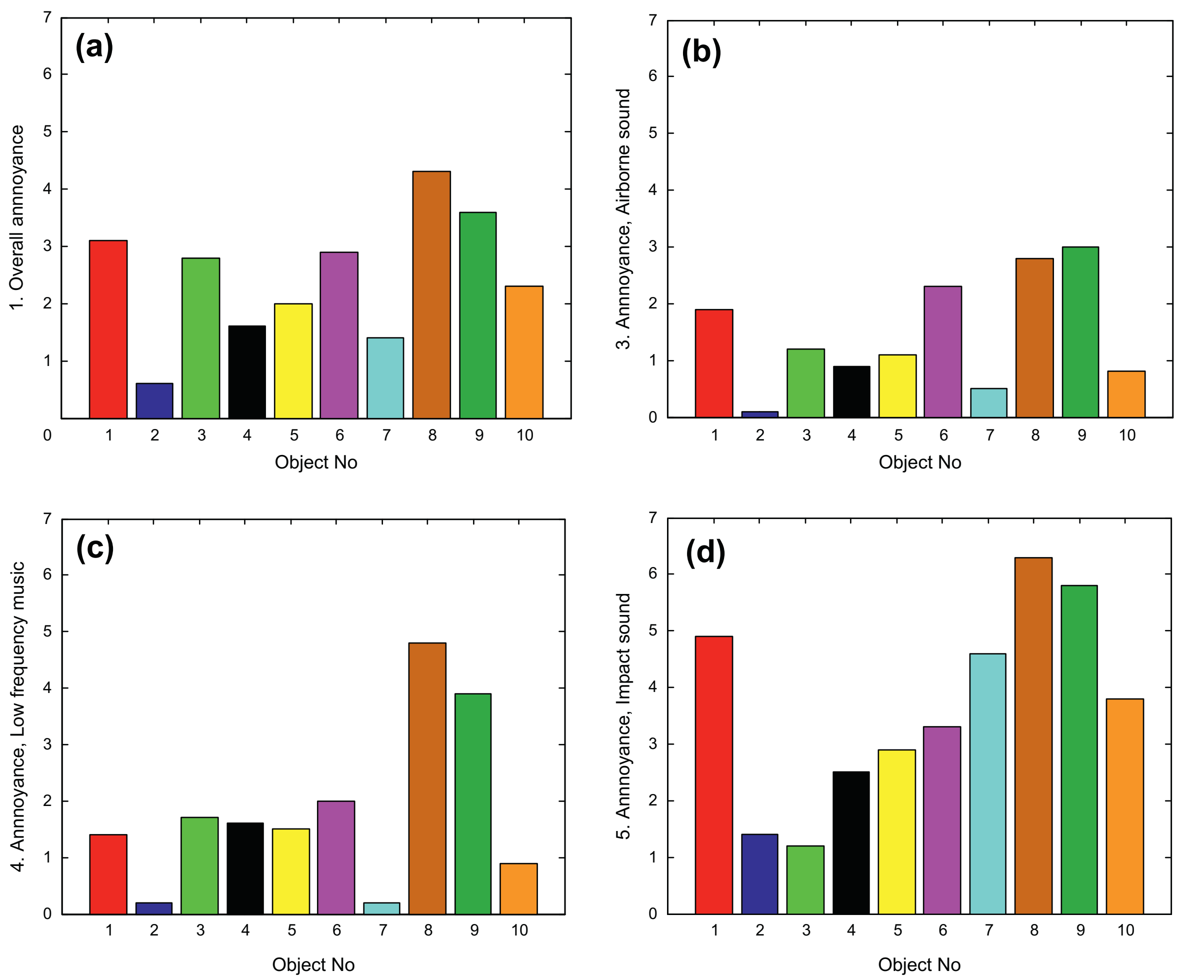


Fig. 6. Mean annoyance for selection of matters from the questionnaire: (a) overall annoyance, (b) airborne sound, (c) low frequency music and (d) impact sound.

coefficients a and b in the linear equation $Y = a + bX$, where Y represents the annoyance and X represents the measured quantity. The 95% confidence interval of the slope, b, is also given together with an indication whether the actual measured parameter shows any statistic significant relation (Stat. rel.) to the annoyance, i.e. whether or not the slope "0" is included in the interval.

When taking all 10 objects into consideration, a poor correlation is obtained between subjective ratings and measurements. This is mainly caused by two objects showing abnormal properties. Referring to the linear regression in Fig. 7, object No. 2 shows considerably lower subjective annoyance than expected. This is a new building where a great majority of the occupants are 65 years or older. It is reasonable to assume that these occupants generate less noise than an average occupant. And if less noise is generated, the complaints are few even if the construction does not offer top class sound insulation. Object No. 9 on the other hand is a house of student rooms occupied by young people. Here, it can be assumed that more noise is generated than on the average, i.e. despite approved sound insulation it is not good enough to get satisfactory protection against noise from the neighbours. Noise from corridors and other common areas might also have affected the ratings for this specific object. Therefore, complementary analyses – probably with better relevance – have been performed with these two outliers withdrawn.

The coefficient of determination, R^2, when R'_w is matched against annoyance is 58%. R^2 increases to 73% when the spectrum adaptation term from 50 Hz is added, $R'_w + C_{50-3150}$. For the correlation maintained with an ever further extension down to 20 Hz, $R'_w + C_{20-3150}$, R^2 = 75%. Note that the rated annoyance generally is low, 3 or less according to Fig. 6. It might therefore be inaccurate to extrapolate the results for predictions outside this range.

In a trial experiment, the impact sound pressure level obtained by the ISO rubber ball was correlated against the rated airborne sound annoyance. Due to the poor R^2, 11% and 17% using linear and A-weighted sound levels respectively, the ball cannot be suggested to be used as a uniform "hybrid source" applicable for both airborne and impact sound insulation.

5.2.2. Impact sound

The coefficient of determination together with other statistical parameters from linear regression analyses regarding impact sound is shown in Table 3. Here all ten building objects are included.

The coefficient of determination, when $L'_{n,w}$ is matched against annoyance is just 26%. This is marginally improved to 32% when the spectrum adaptation term from 50 Hz is added, $L'_{n,w} + C_{I,50-2500}$, but when the frequency range is extended to include 20–50 Hz a remarkable improvement can be seen, R^2 = 74% for $L'_{n,w} + C_{I,20-2500}$.

When the ISO rubber ball is used as the impact sound source, with a single microphone position, the correlation is still respectful. Taking the measurement in the corner, R^2 = 64% for linear weighting, which drops to 43% when A-weighting is applied. The static deflection shows practically no correlation to the perceived annoyance from impact sound since R^2 = 5%.

6. Ideas for improved impact sound spectrum adaptation terms

6.1. Experiences about the present use of $L'_{n,w} + C_{I,50-2500}$

The spectrum adaptation term $C_{I,50-2500}$ is defined by ISO 717-2 [3] according to:

$$C_{I,50-2500} = 10\log\left(\sum 10^{L'ni/10}\right) - 15 - L'_{n,w}, \quad (2)$$

where L'_{ni} is the normalized impact sound pressure level in the one third octave band i. Thus, $C_{I,50-2500}$ is the numerical differential between two evaluation procedures, the summation of the normalized impact sound pressure levels, L'_{ni} (−15), and $L'_{n,w}$. This term was introduced in the Swedish building regulation (1999) in order to prevent lightweight separating floors with poor impact sound insulation at low frequencies from being used in residential buildings.

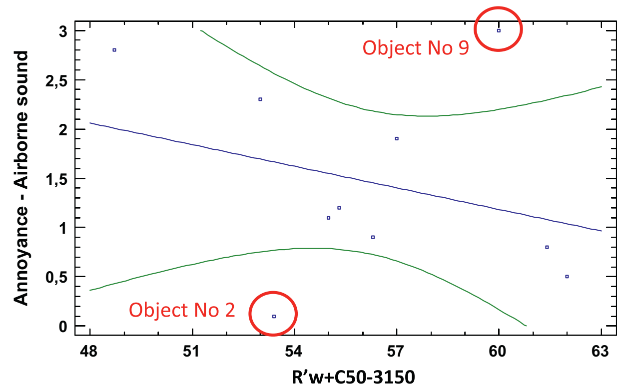


Fig. 7. Linear regression of airborne sound annoyance vs. $R'_w + C_{50-3150}$ including 95% confidence intervals. Two outliers are highlighted within the circles.

However, the requirements were shortly thereafter amended such that *both* $L'_{n,w}$ and $L'_{n,w} + C_{I,50-2500}$ have to fulfil the stipulated limit, i.e. negative values of $C_{I,50-2500}$ must not be taken into account. Otherwise, this would have been favourable for a concrete slab covered by flooring with a negligible reduction of impact sound at higher frequencies, e.g. ceramic tiles or linoleum carpets without acoustic underlays. In such cases $L'_{n,w} + C_{I,50-2500}$ can be 10 dB less than $L'_{n,w}$, i.e. $C_{I,50-2500}$ = −10 dB. Practical experiences showed that occupants did not accept such floors because the impact related noise was clearly audible and annoying, e.g. from walkers with hard shoes and chairs being moved on the floor.

The collected experience from 1999 has indicated that $L'_{n,w}$ in combination with $L'_{n,w} + C_{I,50-2500}$ generally work quite well as a regulatory parameters although they do not prevent unsatisfactory sound insulation in every type of building construction.

6.2. Frequency extension to 20 Hz, $C_{I,20-2500}$

As already discussed, when a constant frequency weighting of −15 dB in the range of 50–2500 Hz is used to define a spectrum adaptation term, in analogy with the $C_{I,50-2500}$, the coefficient of determination R^2 was improved from 0.32 for $C_{I,50-2500}$ to 0.74 for $C_{I,20-2500}$. In fact, using only the narrow frequency range 20–100 Hz for the frequency weighting resulted in R^2 = 0.78. Although it is not realistic to evaluate the impact sound insulation in general in such a narrow frequency range, the need for consideration of low frequencies is clearly indicated.

6.3. A-weighted difference between tapping machine and living activities, $C_{I,20-2500,AwLiving}$

One interesting approach is to define new frequency weights to replace the constant value of −15 dB, on the basis of spectra from living activities that may be assumed to act on floors in dwellings,

Table 2
Statistics in terms of linear regression $Y = a + bX$, where Y is the annoyance of airborne sound and X is the measured parameter.

Airborne sound	R^2 (%)		a	b	95% conf. interval (b)	Stat. rel. (b)
R'_w	4[a]	58	10.0	−0.146	[−0.266 −0.026]	Yes
$R'_w + C_{50-3150}$	9[a]	73	10.4	−0.160	[−0.254 −0.066]	Yes
$R'_w + C_{20-3150}$	9[a]	75	10.7	−0.166	[−0.258 −0.074]	Yes
ISO Ball corner	19[a]	11	−0.590	0.0218	[−0.0378 0.081]	No
ISO Ball corner (A)	18[a]	17	−0.103	0.0256	[−0.0283 0.0795]	No

[a] Denotes value with two outliers included.

Table 3
Statistics in terms of linear regression $Y = a + bX$, where Y is the annoyance of impact sound and X is the measured parameter.

Impact sound	R^2 (%)	a	b	95% conf.interval (b)	Stat. rel. (b)
$L'_{n,w}$	26	−6.65	0.197	[−0.072 0.466]	No
$L'_{n,w} + C_{I,50-2500}$	32	−7.41	0.202	[−0.033 0.437]	No
$L'_{n,w} + C_{I,20-2500}$	74	−13.4	0.294	[0.154 0.434]	Yes
ISO Ball corner	64	−7.69	0.121	[0.047 0.195]	Yes
ISO Ball corner (A)	43	−2.15	0.0952	[0.008 0.183]	Yes
Static deflection	5	3.19	0.983	[−3.23 5.20]	No

e.g. from walking persons, chairs moved, toys dropped on the floor etc. The impact sound pressure levels obtained with the ISO standardized tapping machine could hypothetically be "translated" into a single number value being representative for the sound pressure level from daily life impact sounds. Following the procedure in ISO 717-2, this translation could be made by means of adding a spectrum adaptation term, $C_{I,20-2500,AwLiving}$, to the normalized single number value $L_{n,w}$ measured with the tapping machine. The sum $L_{n,w} + C_{I,20-2500,AwLiving}$ would then be assumed to represent the A-weighted sound pressure level of such living sources. The $C_{I,20-2500,AwLiving}$ is calculated as:

$$C_{I,20-2500,AwLiving} = 10\log\left(\sum 10^{(L'ni - X_i - Aw)/10}\right) - L'_{n,w}, \quad (3)$$

where L'_{ni} is the sound pressure level measured with the ISO tapping machine in the one third octave band i. X_i is the difference between L'_{ni} and a level chosen to represent an upper estimate of sound pressure levels that may come from a variety of typical 'living sources'. This difference is A-weighted according to IEC 61672 [19] and denoted "A-weighted sound pressure level difference".

It should be noted that this approach may be questioned since it is only applicable to force sources having considerably higher force mobility than the mobility of the floor assembly. The influence of the source and floor mobility on the injected structure-borne sound power is described in the European standard EN 12354-5 and the force source assumption is explained in [20]. The possibility of translating impact sound levels obtained with one specific source to the sound level due to another source, e.g. the ISO tapping machine and walking persons respectively was analysed in [21]. It was there concluded that the source and receiver mobility must be taken into account. The data indicated that the force source approximation works reasonably well for wooden floors at medium and low frequencies (approximately below 1 kHz), but for concrete floors with soft carpets the approximation may be erroneous above about 100 Hz (depending of the stiffness of the carpet). This certainly restricts the applicability of the "translation" concept in buildings with such floorings, but it may still be useful if a single number values with a modified spectrum adaptation term would correlate better to the annoyance experienced by the occupants compared to the standardized term. The force source approximation could thus be expected to be approximately valid at low frequencies for the small and light sources, when they act on hard floorings typical for most (Swedish) dwellings. But discrepancies may be expected at higher frequencies where the source mobility from falling hard objects increases to be of the same order as the mobility of the floor assembly.

To obtain the necessary frequency weights, a number of laboratory measurements of various impact sound sources [22–24] were analysed.

Results are displayed in Figs. 8 and 9 as A-weighted differences in sound pressure level between various living sources and the tapping machine, for various floor types. The differences shown in Fig. 8 are largely scattered, especially for the floors with concrete tiles or massive concrete and they are diverging even more at higher frequencies. The differences shown in Fig. 9 indicate that rather large variations between different activities may be expected as well, even between walkers. However, even if the results are somewhat dissatisfying, the curves have in general a similar shape, which justify the attempt to find a better spectrum adaptation term.

The frequency weights X_i for Eq. (3) are plotted in Figs. 8 and 9. The weights were chosen such that $L_{n,w} + C_{I,20-2500,AwLiving}$ could be assumed to be higher than the A-weighted sound pressure level from most living sources and many typical floor constructions, according to the results of Figs. 8 and 9. Hence, the slope of the weighting curve was defined positive in contrast to the constant value of −15 dB in the ISO spectrum adaptation term $C_{I,50-2500}$. A similar idea, although restricted to high frequencies, has been proposed previously [25] in terms of a slope of 2 dB per one third octave band starting from 400 Hz. The purpose was to handle sounds from hard floorings (e.g. tiles on concrete slabs).

When $L'_{n,w} + C_{I,20-2500,AwLiving}$ is correlated to the ratings given by the occupants with respect to the annoyance of impact sounds (Q5), the coefficient of determination R^2 is 0.39, This is somewhat higher than for the standardized sum $L'_{n,w} + C_{I,50-2500}$, but still not satisfactory for a potential regulation requirement applicable to all types of buildings.

6.4. Further increased weights at low frequencies, $C_{I,AkuLite,20-2500}$

Indications of the importance of low frequencies combined with the special high frequency consideration [25], discussed in previous section, lead to the suggestion of a spectrum adaptation term denoted $C_{I,AkuLite,20-2500}$. It is defined as:

$$C_{I,AkuLite,20-2500} = 10\log\left(\sum 10^{(L'_{ni} - X_i)/10}\right) - L'_{n,w}, \quad (3)$$

where X_i here are the new proposed frequency weights in third octave bands 20–2500 Hz. In the range 50–400 Hz, the weights are −15 dB as in ISO 717-2. They increase by 2 dB per one third octave band below 50 Hz. At frequencies above 400 Hz the weights increase 1 dB per one third octave band, see Fig. 10.

Applying $L'_{n,w} + C_{I,AkuLite,20-2500}$, the correlation against the subjective impact sound rating (Q5) leads to an improved coefficient of determination of 85%. The linear regression can be seen in Fig. 11.

A compilation of the obtained R^2 for the cases where frequencies from 20 Hz are included is given in Table 4.

7. Discussion including examples of other closely related findings within AkuLite

7.1. Improved correlation of impact sound by low frequency extension

Adding more weight to the low frequency sounds, in contrast to the present ISO evaluation method, improved the correlation against subjective ratings given by occupants in the light-weight residential buildings. One hypothesis to explain this strong influence on impact sounds at 20–50 Hz, is that the perceived sound in the buildings varied from barely audible to clearly audible and even annoying. The linear sound pressure levels obtained with the tapping machine varied from 66 dB to 81 dB in the one third

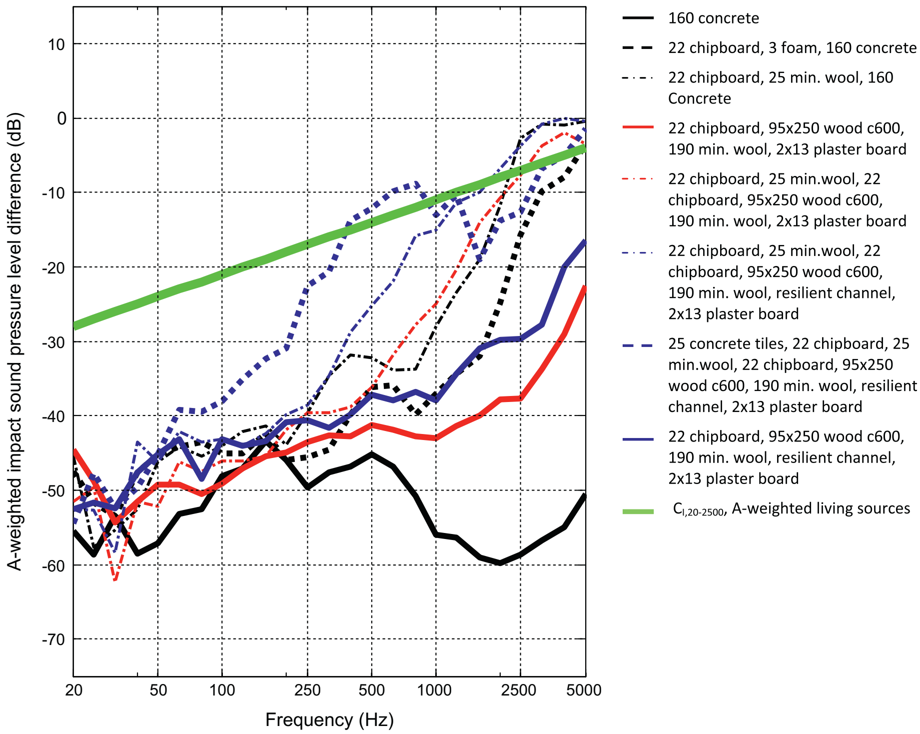


Fig. 8. A-weighted differences between normalized impact sound pressure levels from a male person walking on *various floor constructions*.

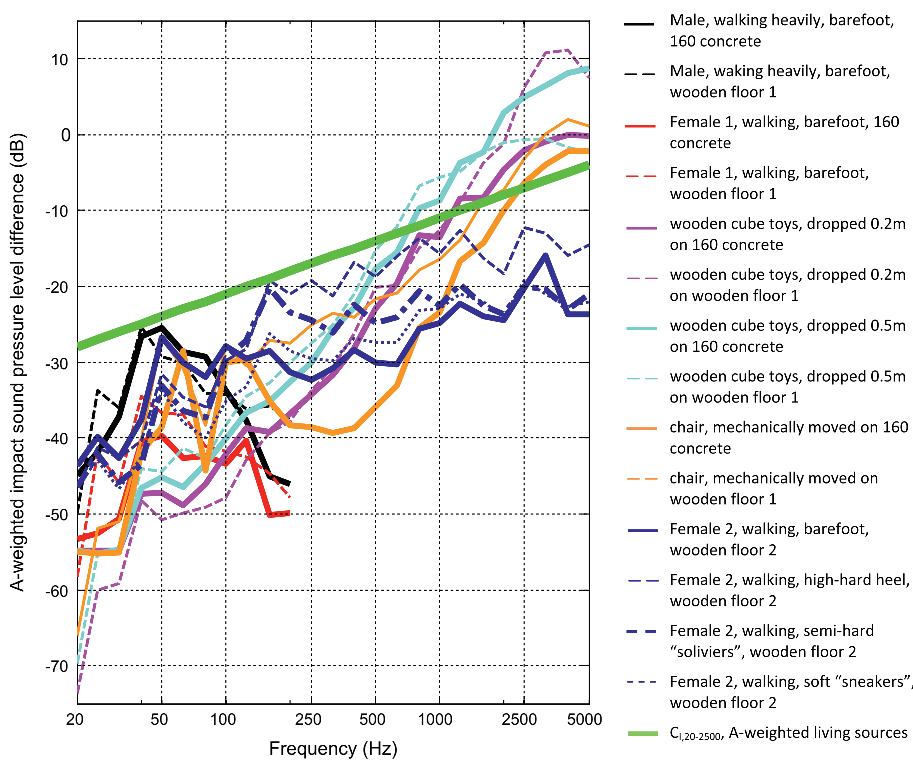


Fig. 9. A-weighted differences between normalized impact sound pressure levels measured with *various impact sources* and the levels obtained with the tapping machine.

octave bands within 20–100 Hz as was shown in Fig. 2d (omitting the concrete building).

According to the standardized isophon curves in ISO 226 [26], this 15 dB raise of the impact sound level, starting at 66 dB, corresponds to a change from slightly below the auditory threshold to exceed 15–20 phons, which make these impact sounds clearly audible. Since these isophon curves were developed for the perceived loudness of pure tones, they are not necessarily applicable to this interpretation, but they may at least be taken as an indication and basis for further research on the sensitivity to impact sounds.

The authors' experience is that when walking occurs at a normal, gentle speed, the impact sound is often barely audible but as soon as the walking speed, and thereby also the force, increases,

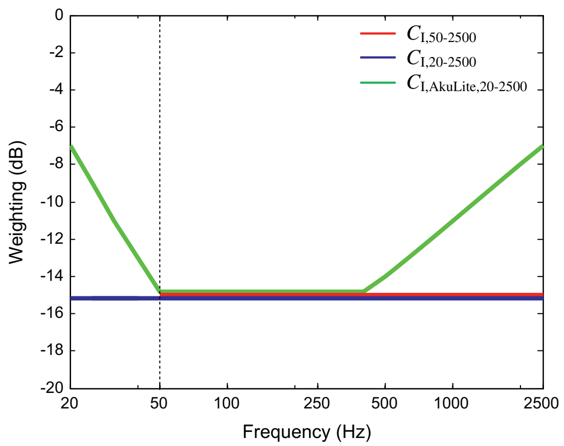


Fig. 10. Frequency weights of three spectrum adaptation terms.

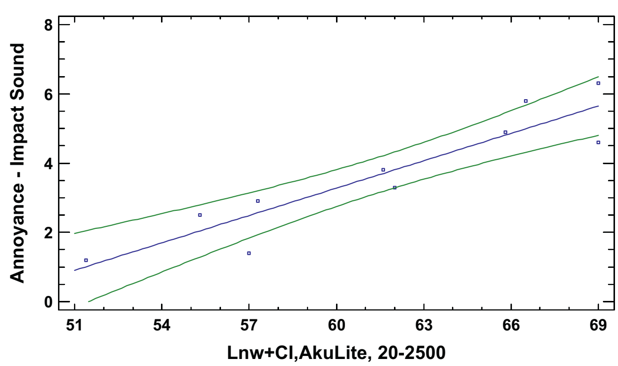


Fig. 11. Linear regression of impact sound annoyance vs. $L'_{n,w} + C_{I,AkuLite,20-2500}$ including 95% confidence intervals.

the impact sound quickly becomes very disturbing. It can therefore be suspected that this dynamic range is very narrow, as is indicated by the shape of the isophon curves. This, in turn, means that listening tests should be performed with realistic background levels and with impact sound pressure levels as they were determined in field.

7.1.1. Tapping machine vs. rubber ball

The subjective rating of impact sounds was correlated against various measured parameters in Table 3. Accordingly, the evaluations based upon the ISO tapping machine show better correlation than the correspondent ISO rubber ball measurements. But while the tapping machine measurements strictly follow the appropriate ISO standards in terms of number of measurement positions (tapping machine and microphones), the measurements using the ball was performed in a more simplified way using only one excitation point and one microphone position. In that respect, the results are not fully comparable and thus it cannot be concluded, from this study, that any of the impact sources is to prefer ahead of the other.

7.2. Low frequency measurements

Performing indoor sound measurements at low frequencies, typically below 100 Hz, might be more erroneous compared to measurements at higher frequencies. The reason is mainly due to the lack of a diffuse sound field in the room where the dimension of the wavelengths is comparable with the dimensions of the room. Within the frequency region where the first standing waves appears, the strength of sound field varies due to low modal overlap which requires an expanded amount of sampling positions in order to represent the mean sound pressure in the room. On the other hand, at the very lowest frequencies, below the first mode of the room, the sound pressure can again be assumed to be more uniformly distributed.

In the actual ISO standards [10,12], special guidance is given when dealing measurements in the low frequency bands. E.g. it is stated that sampling of the sound field should take place in an increased number of microphone positions, the averaging time should increase and the number of loudspeaker configurations when performing airborne sound insulation should increase from two to three.

For the present paper, the ISO guidance was applied when collecting the low frequency sound data according to the measurement template. But since the ISO standards cover frequencies down to 50 Hz (through the spectrum adaptation terms), additional arrangement might be necessary in order to guarantee a satisfactory measurement procedure down to 20 Hz in possible forthcoming recommendations. Some investigations into the effect of different methods of spatial averaging have been reported previously [15].

7.3. Listening test

A listening test was performed within the AkuLite project in order to evaluate the subjectively perceived loudness of recorded footsteps [23]. It was conducted in two ordinary office rooms where the test subjects were exposed to various footstep sounds emitted by a hidden loudspeaker system, including or excluding sounds in the frequency ranges 20–50 or 20–100 Hz. Sound recordings from a person walking on one timber framed floor and one concrete floor were used for pair comparison tests, “A–B”. The results indicate that when frequencies below 50 Hz are filtered out from the timber floor (floor “B”), the test subjects add about 4–7 dB to make the sound equally loud compared to the unfiltered recording (floor “A”). In the case where the frequencies below100 Hz part was removed, the test subjects added 16–20 dB to make the sound equally loud. When the timber framed floor recording was compared to a recording from a concrete floor with similar $L'_{n,w} + C_{I,50-2500}$ (57 dB and 56 dB respectively), the test subjects compensated by adding 8–12 dB to the concrete floor in order to make the sound equally loud. Filtering below 50 Hz had no effect on the subjectively perceived level from the concrete floor. These listening tests suggest – independently from the other findings in this paper – that impact sounds of 20–50 Hz play an important role as it affect the subjective rating.

Table 4
Statistics in terms of linear regression $Y = a + bX$, where Y is the annoyance of impact sound and X is the measured parameter starting from 20 Hz.

Impact sound	R^2 (%)	a	b	95% conf. interval (b)	Stat. rel. (b)
$L'_{n,w} + C_{I,20-2500}$	74	−13.4	0.294	[0.154 0.434]	Yes
$L'_{n,w} + C_{I,20-2500,AwLiving}$	39	−10.2	0.267	[−0.002 0.536]	No
$L'_{n,w} + C_{I,AkuLite,20-2500}$	85	−12.5	0.263	[0.175 0.351]	Yes

7.4. Vibration annoyance

A separate survey was carried out in nine of the ten building objects (No. 8 omitted) specifically addressing the annoyance of floor springiness and vibrations from daily activities [27]. Similar methodologies as for the previously described questionnaire and analysis were applied. The results indicate that vibrations are perceived as annoying from numerous sources like neighbours walking on their floor or on the stairs, closing the doors as well as family members walking on their own floor.

The annoyance rating from "Vibrations in the floor or in the furniture, in general" correlated to the static deflection of the floors with a coefficient of determination, R^2, of 85%. The lowest annoyance ratings were obtained in the concrete building (No. 3) while the highest annoyance was obtained in one of the lightweight wooden framed buildings (No. 1). The remaining five objects had all similar ratings and deflections and in order to establish a more confident relationship, additional stiffer and weaker floors would be needed to achieve a wider range of data.

8. Conclusions

The presented results indicate that low frequencies are of essential importance when evaluating sound insulation in lightweight buildings.

An extension of the frequency range down to 20 Hz improved the correlation of measurements to occupants' rating of annoyance from impact sounds. The coefficient of determination, R^2, increased from 32% using $L'_{n,w} + C_{I,50-2500}$ to 85% when including the new spectrum adaptation term $L'_{n,w} + C_{I,AkuLite,20-2500}$. This finding has also been supported by a separate listening test, conducted independently.

Regarding airborne sound insulation, it was indicated that the frequency range covered by $R'_w + C_{50-3150}$ Hz is adequate as compared with subjective perception. It is important though, that the frequency range start at 50 Hz since R^2 decreased from 73% to 58% with R'_w solely, i.e. when starting from 100 Hz. In this case, no further improvement was obtained with a frequency extension down to 20 Hz.

Due to the limitations in the number of building objects, and thereby also in the variety of data, the findings are only valid within the actual data range, extrapolation to higher or lower value could be erroneous. And although several of the relations between annoyance and the measured parameters are proven to be statistically significant, this is not the case regarding the difference in between the corresponding correlation coefficients, for the same reason. For validation purpose, it is therefore important to gather complementary information from other type of buildings, preferably on international bases.

Acknowledgements

The authors gratefully acknowledge the financial support by the Swedish research authorities Formas and Vinnova as well as all academic and industrial partners of the project AkuLite.

References

[1] Simmons C, Hagberg K, Backman E. Acoustical performance of apartment buildings – resident's survey and field measurements, AkuLite Report 2, SP Report 2011, vol. 58, 2011. ISBN 978-91-86622-88-6.
[2] Bodlund K. Alternative reference curves for evaluation of the impact sound insulation between dwellings. J Sound Vib 1985;102.
[3] Rating of sound insulation in buildings and of building elements – Part 2: impact sound insulation. 1996. ISO 717-2.
[4] Ljudkrav med stöd av ISO/DIS 717, Nordiska kommittén för byggbestämmelser NKB, Rapport 1996, vol. 02, 1996. ISBN 951-53-0781-3.
[5] Hagberg K. Evaluating field measurements of impact sound. J Build Acoust 2010;17.
[6] Rindel JH, Rasmussen B. Assessment of airborne and impact noise from neighbours. In: Proc. internoise. Budapest Hungary; 1997.
[7] Rating of sound insulation in buildings and of building elements – Part 2: impact sound insulation. 2013. ISO 717-2.
[8] Ljunggren F, Ågren A A. How to match building acoustic measurements with subjective judgements?. In: Proc. internoise. New York (USA); 2012.
[9] Laboratory measurement of sound insulation of building elements – Part 1: application rules for specific products. 2010. ISO 10140-1.
[10] Measurement of sound insulation in buildings and of building elements – Part 7: field measurements of impact sound insulation of floors. 1998. ISO 140-7.
[11] Sound classification of spaces in buildings – dwellings, Swedish standards institute. 2004. SS 2526.
[12] Measurement of sound insulation in buildings and of building elements – Part 4: field measurements of airborne sound insulation between rooms. 1998. ISO 140-4.
[13] Rating of sound insulation in buildings and of building elements – Part 1: airborne sound insulation. 1996. ISO 717-1.
[14] Ljunggren F, Backman E. Data from building acoustic measurements and questionnaire survey in multi-family houses, AkuLite Report 8, LTU Report 2013, SP Report 2013, vol. 10, 2013. ISBN 978-91-87017-94-0.
[15] Simmons C. Uncertainties of room average sound pressure levels measured in the field according to the draft standard ISO 12683-14. Noise Control Eng 2012;60.
[16] Integrating and harmonizing sound insulation aspects in sustainable urban housing constructions. COST TU0901. <http://www.costtu0901.eu, 2013-10-14>.
[17] Assessment of noise annoyance by means of social and socio-acoustic surveys. 2013. ISO/TS 15666.
[18] Simmons C, Hagberg K, Gallego A. A questionnaire for correlation of subjective evaluation of dwellings with their objective building acoustic parameters, In: Proc. forum acusticum. Aalborg Denmark; 2011.
[19] Electroacoustics – sound level meters – Part 1: specifications. 2013. IEC 61672-1.
[20] Building acoustics – estimation of acoustic performance of building from the performance of elements – Part 5: sounds levels due to the service equipment. 2009. EN 12354-5.
[21] Scholl W, Ciszewski R, Wittstock V. Revision of ISO 717: why not use impact sound reduction indices instead of impact sound pressure levels? Part 2: application to different impact sources. Acta Acustica United Acustica 2013;99.
[22] Nilsson E, Hammer P. Subjective evaluation of impact sound transmission through floor structures. Report TVBA-3103. Lund University of technology, 1999.
[23] Thorsson P. Laboratory listening tests on footfall sounds. AkuLite Report 7. Chalmers University of Technology Report 2013, vol. 5, 2013. ISSN 1652-9162.
[24] Amiryarahmadi N, Kropp W, Bard D. Time-domain model of a tapping machine. In: Proc. Forum Acusticum, Aalborg Denmark; 2011.
[25] Gerretsen E. A new system for rating impact sound insulation. Appl Acoust 1976;9.
[26] Normal equal-loudness-level contours. 1987. ISO 226.
[27] Jarnerö K, Bard D, Simmons C. Vibration performance of apartments buildings with wooden framework – residents survey and field measurements, AkuLite Report 8, SP Report 2013, vol. 17, 2013. ISBN 978-91-87461-02-6.

Paper D

Subjective and Objective Evaluation of Impact Noise Sources in Wooden Buildings

by

Moritz Späh, Klas Hagberg, Olin Bartlomé, Lutz Weber, Philip Leistner and Andreas Liebl

Reprinted from

JOURNAL OF
BUILDING ACOUSTICS
Volume 20 · Number 3 · 2013

MULTI-SCIENCE PUBLISHING CO. LTD.
5 Wates Way, Brentwood, Essex CM15 9TB, United Kingdom

Subjective and Objective Evaluation of Impact Noise Sources in Wooden Buildings

Moritz Späh*, Klas Hagberg, Olin Bartlomé***, Lutz Weber*, Philip Leistner*, Andreas Liebl***

Contact address: moritz.spaeh@ibp.fraunhofer.de

**Fraunhofer Institute for Building Physics*

Nobelstrasse 12, 70569 Stuttgart, Germany

***SP Wood Technology and Engineering Acoustics,*

Lund University, Box 857, 501 15 Boras, Sweden

****Lignum, Holzwirtschaft Schweiz*

Mühlebachstrasse 8, 8008 Zürich, Switzerland

(Received and 3 December 2013 and accepted 7 February 2014)

ABSTRACT

Multi-storey timber buildings up to 6 and more floors are increasingly built in many European countries. The challenge with these buildings can be that with traditional intermediate floor constructions in timber it can be difficult to fulfill the standard requirements and even when they are met, low frequency transmission can still cause complaints. Additionally it is difficult to develop appropriate light weight floor constructions since it is well known that the correlation between the standardized evaluation methods using the tapping machine and the human perception of impact noise can be poor, especially in buildings with light weight structures. In the AcuWood project, measurements and recordings on different intermediate timber floor constructions in the laboratory and the field were performed covering a wide range of modern intermediate timber floor constructions. Additionally, one intermediate concrete floor with different floor coverings was included in the study. Besides the standardized tapping machine, the modified tapping machine and the Japanese rubber ball and "real" sources were employed. Subjective ratings from listening tests were correlated to many technical single number descriptors including the standardized descriptors and non-standardized proposals. It was found that the Japanese rubber ball represents walking noise in its characteristics and spectrum best, taking into account the practical requirement of a strong enough excitation for building measurements. The standardized tapping machine, with an appropriate single number descriptor, $L'_{nT,w} + C_{I,50\text{-}2500}$ or slightly better, $L'_{nT,w\ Hagberg\ 03}$, leads also to an acceptably high determination coefficient between the descriptor and the subjective ratings. Additionally, the study delivered data, from which proposals for requirements for the suggested single number ratings are deduced, based on the subjective ratings.

Keywords: Impact Noise, Correlation, Listening test, Single number rating, Annoyance, Requirements, Timber Construction, Low Frequencies, Residential Buildings.

1. INTRODUCTION

Multi-storey residential buildings with up to 6 and more floors in timber are becoming more and more popular in Europe. Driving forces are new building regulations (based on extensive research on fire safety), better sustainability and the development towards industrialization of building elements and with that cost reduction, excellent construction-accuracy and unbeaten short construction time. However, noise and vibration disturbances experienced by residents are often an issue within these buildings even if the building code requirements are fulfilled. Therefore, sound and vibration issues might become the hindrance for further development of multi-storey timber buildings.

The current acoustic requirements of residential buildings are based on experience in heavy weight massive constructions, since these structures have dominated the European market historically and timber multi-storey buildings were uncommon in Europe until 10-15 years ago. The perceived acoustic quality in lightweight buildings can be different to heavy weight buildings. In particular, low frequency sound transmission impact sound sources can lead to complaints in timber buildings [1].

The currently applied single number ratings for building acoustics were developed in the 1950's for massive constructions used at that time. In 1996 the introduction of the spectrum adaptation terms according to ISO 717 [2], enabled ratings that include low frequencies down to 50 Hz. Until today low frequency spectrum adaptation terms have been mandatory in national requirements only in one European country, namely Sweden, and used in national classification schemes in only a few European countries [3].

In the AcuWood project the main aim was to find technical descriptors for different impact sound sources taking several European countries (building traditions, cultural differences etc.) into account [4]. The methodology used was to correlate technical descriptors of different floor constructions to subjective ratings, gained by listening tests, similar to methods used to evaluate sound quality [5]. A graph of the approach is shown in figure 1.

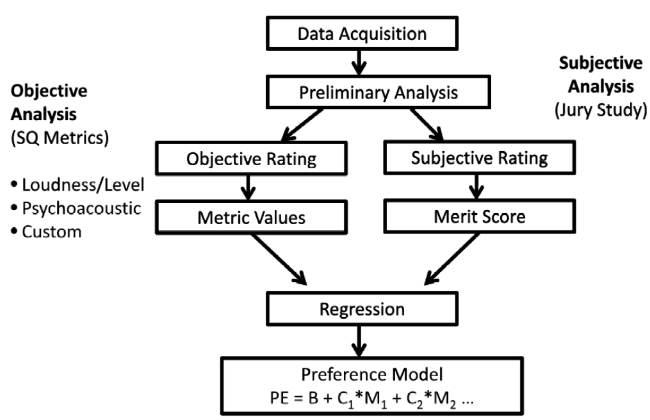


Figure 1: Process of data analysis in the AcuWood project, typical for sound quality processes [5]

2. MEASUREMENTS

Microphone recordings of impact noise measurements were conducted in different floor testing facilities of the Fraunhofer IBP and in the field in both Germany ("DE") and Switzerland ("CH"). For the measurements different impact noises sources were employed. In the laboratory different floor coverings were used. In parallel, binaural recordings with a dummy head were conducted in the receiving rooms. All recordings with the dummy head were made in a similar position in all receiving rooms near a corner of the room at a height of 1.2 m, representing a sitting person. The binaural recordings were then used for the listening tests. From the microphone recordings third-octave band values were extracted, on which the evaluation of the technical descriptors are based.

2.1 Impact Noise Sources

Different impact noise sources were examined in all described measurements. First of all, the standardized tapping machine according to ISO 10140-5 [7] annex E was used. The measurements were conducted in the laboratory according to ISO 10140 and in the field according to ISO 140-7 [8]. The number of microphone positions in the receiving room was 6. In general, four excitation positions on the floor were measured, giving a number of 24 independent measurements in the receiving room. The levels of the 6 microphones were energetically averaged. Some deviations from the standards were necessary in two field measurements, where the distance of microphones to the surrounding walls was reduced. In one of the field measurements the sending room was very small (10 m^3) and the number of excitation positions was accordingly reduced. In addition, the modified tapping machine according to ISO 10140-5 annex F1 method b was applied. This was performed by using the standardized tapping machine placed on 12.5 mm thick elastic pads. The hammers were falling onto elastic interlayers of 12.5 mm thickness, as described in ISO 10140-5. The measurements were conducted at the same positions and with the same procedure as for the standardized tapping machine. Additionally, the Japanese rubber ball described in ISO 10140-5 annex F2 was used. The ball was dropped from a height of 1 m, according to the standard. Here the $L_{F,max}$ value was evaluated in third octave bands from the recordings. The ball drop was repeated in the laboratory and in the field measurements from Switzerland ("CH") 10 times, and in the German field measurements ("DE") the number of ball drops was reduced to 5. The same positions as for the standardized tapping machine were excited by the ball.

Furthermore, "real" sources (walking persons with different footwear) were examined. In all field measurements the same male walker was engaged with the same footwear (shoes and socks). In the laboratory measurements, not always the same walking persons were engaged, giving differences in the walking styles and excitation etc. In the laboratory on all floors three walking persons were engaged, a male walker with normal shoes, a male walker on socks and a female walker with hard heeled shoes. The walkers were walking in a circle across the four excitation positions of the tapping machine; the frequency of steps was about 2 Hz. The walking noise was recorded for 60 s. In cases of background noise during recordings, parts with high background noise were excluded in the analysis of the data.

The second “real” source in all measurements was a chair drawn across the floor. The chair was a four-leg modern chair with plastic seat and backrest. The chair was drawn by a rope for a length of approximate 1 m, giving a signal of about 5 s in the receiving room. The excitation was repeated in the laboratory and the Swiss field measurements (“CH”) 10 times. In the German field measurements (“DE”) the number of iteration was reduced to 5. The same positions as for the standardized tapping machine were excited. The main excitation mechanism of the chair is the stick-slip effect of the feet on the floor. In the measurements of floors with carpet, this source mechanism changed, so that the chair became essentially a different source with much less energy input into the floor and with a different excitation spectrum. This has to be kept in mind when analysing the results of the chair.

2.2 Laboratory Measurements

Two building acoustics test facilities were used to perform the measurements. Both of them are located in IBP (called P8 and P9) and comply with the requirements of ISO 10140-5. Laboratory P8 is used to test intermediate timber floor constructions. It consists of concrete walls and floors and contains a frame where lightweight floors are installed. Laboratory P9 is a concrete construction with a 140 mm thick concrete floor. In both laboratories linings in the sending and receiving room with resonance frequency between 60 and 80 Hz reduce flanking transmission between sending and receiving room at frequencies above approximately 100 Hz.

The laboratory P8 was equipped with a standardized intermediate timber floor according to ISO 10140-5 (Appendix C floor C1). This floor is a lightweight wooden beam floor with a weighted sound reduction index R_w = 45 dB and a weighted normalized impact sound pressure level $L_{n,w}$ = 74 dB. This floor represents a basic floor construction not found in modern buildings with wooden floors. Therefore, further measurements were conducted on the floor equipped with a standard dry floating floor consisting of 18 mm thick gypsum fibre board laminated on 10 mm thick wood fibre board for impact insulation. The bare floor combined with the dry floating floor had a R_w = 54 dB and a $L_{n,w}$ = 68 dB. Additionally, different floor coverings were installed on the dry floating floor in the laboratory to simulate real floor situations. The floor coverings are described in Table 1.

Table 1. Floor coverings used in the laboratory

Number	Floor covering	Interlayer	DLw [dB]
1	7 mm laminate	ribbed foam	20
2	13 mm parquet	foam interlayer	15
3	8 mm tiles + 2 mm tile adhesive	decoupling layer	16
4	4 mm standard carpet	none	23

For practical reasons all floor coverings were not glued to the floating floor and covered only parts of the floor area. The influence of the additional floor coverings on the airborne sound reduction was considered to be low. As the measurements were conducted in laboratories with homogeneous heavy weight flanking walls and linings, the correction of the impact noise levels by airborne sound transmission was not necessary.

As an additional measure in order to increase the acoustic performance of intermediate timber floors, elastically suspended ceilings are often installed. Therefore, the above described floor of laboratory P8 was altered by removing the lowest sheet of gypsum board and replacing it by a suspended ceiling with 40 mm spacers and elastic interlayer and additional 2 x 12.5 mm gypsum boards. On top of the intermediate floor the dry floating floor remained. For this floor construction the measured weighted sound reduction index was R_w = 63 dB, and the weighted normalized impact sound pressure level of the floor was $L_{n,w}$ = 53 dB. Again, for this floor similar measurements were conducted as before on the bare floor and with the same floor coverings described in Table 1.

The measurements in the laboratory P9 were included in this study to give a benchmark for homogeneous heavy weight concrete floors. Additionally, including concrete floors in the correlation analysis was necessary as the proposal for an adequate rating system should comprise all building constructions, including light weight, massive and hybrid constructions. The intermediate floor of P9 measured was a homogeneous floor slab of 140 mm concrete according to ISO 10140-5. Additionally, a standard floating floor with a 50 mm concrete screed on 25 mm mineral wool impact sound insulation (dynamic stiffness s' ≤ 9 MN/m^3) was installed. For this intermediate floor the weighted sound reduction index was R_w = 64 dB, the weighted normalized impact sound pressure level was $L_{n,w}$ = 41 dB. Again, similar measurements as on the standardized intermediate timber beam floor were conducted with the same floor coverings described in Table 1. This floor does not represent modern heavy weight concrete floors any more. Nowadays, normal concrete floors have a thickness between 200 and 240 mm and are therefore much heavier than the one considered. Nevertheless, the floating floor installed is up to date for German building constructions. It is assumed that the intermediate concrete floor with floating floor considered in this study has mainly a similar frequency spectrum compared to contemporary intermediate concrete floors, however the level of the impact noises are slightly higher (approximately 3-5 dB) than for contemporary intermediate concrete floors.

2.3 Field Measurements

The field measurements were conducted in a manner similar to the laboratory measurements. The measurements comprised modern Swiss multi-storey and multi-family residential timber buildings where the intermediate floors have to fulfill increased legal requirements. Additionally, modern German two-storey single family houses with typical intermediate floors were measured.

The investigated timber buildings in Switzerland comprised four popular intermediate timber floor constructions. In detail: 1. a hollow box floor with ballast and floating floor (height of floor h_f = 269 mm, mass of unit area m_f' ≈ 208 kg/m^2, impact insulation mineral wool of thickness d_i = 30 mm and dynamic stiffness $s' < 9$ MN/m^3 with a floating floor made of calcium sulphate screed with thickness d_s = 55 mm and m_s' = 110 kg/m^2); 2. a timber-concrete composite floor with floating floor (h_f = 220 mm,

$m_f' = 308$ kg/m^2, impact insulation mineral wool, $d_i = 17$ mm and $s' < 9$ MN/m^3 with a floating floor made of cement screed with $d_s = 80$ mm and $m_s' = 176$ kg/m^2); 3. a solid timber floor (Brettstapel) with ballast and floating floor ($h_f = 245$ mm, $m_f' \approx 220$ kg/m^2, insulation EPS, $d_i = 40$ mm and $s' > 30$ MN/m^3 with a floating floor made of cement screed with $d_s = 85$ mm and $m_s' = 180$ kg/m^2); 4. a ribbed wooden floor of glulam timber with ballast, floating floor and suspended ceiling ($h_f = 337$ mm, $m_f' \approx 81$ kg/m^2, impact insulation mineral wool, $d_i = 40$ mm and $s' < 9$ MN/m^3 with a floating floor made of calcium sulphate screed with $d_s = 60$ mm and $m_s' = 115$ kg/m^2, suspended ceiling with space of 45 mm, partly filled with mineral wool and 2x15 mm gypsum boards with $m' = 26.4$ kg/m^2). All measured intermediate floors had a floor covering of parquet. In all Swiss buildings two floors (rooms) in the same flat with the same build-up but different surface sizes where measured to investigate any differences due to workmanship etc.

The field measurements in Germany were mainly conducted in exhibition houses of prefabricated house companies. All houses were recently erected, therefore they reflect modern single family houses with up to date constructions, thermal insulation etc. One of these timber houses was individually planned and built. In this building two intermediate floors of different sizes were measured. In all other houses one intermediate floor situation was measured. Four of the houses were equipped with intermediate timber beam floors with 240 mm beams and mineral wool filling; two houses had solid timber intermediate floors with 240 mm and 140 mm thickness respectively. One of the intermediate floors with timber beams was additionally equipped with ballast with $m' = 64$ kg/m^2. All houses had floating floors of anhydride or cement with a thickness of the screed between 50 and 65 mm. In most cases impact insulation material was installed underneath the floating floor, in one case it was much stiffer thermal insulation material. The measurement results showed in some cases higher high-frequency impact noise levels, suggesting problems in the proper installation of the floating floor (possibly with sound bridges via installations etc.). Therefore they include results of a wide range of modern floors in buildings.

3. LABORATORY LISTENING TESTS

The laboratory listening tests were conducted for all above described floors in a series of two tests with similar procedure and technique (n=18; n=22). The signals of a length between 5 and 20 s were recorded by dummy head and played to the subjects by calibrated headphones. To confirm the comparability of the two listening test results, the set of one of the field measurements was included in both listening tests. Statistical analysis showed that the answers of both series were comparable and therefore could be combined. The listening tests included questions to the individual noise sensitivity on an 11 point rating scale from “not at all” to “extremely”, the subjective annoyance of the signals on a 11 point rating scale according to ISO/TS 15666 [9], the subjective loudness on a 51 point rating scale according to ISO 16832 [10]. Additionally the question was asked if the signal would be judged annoying when imagine reading a newspaper, magazine or book (answer yes or no). Details and more information on the listening test are described by Liebl [11]. In addition to the listening tests described, questionnaire surveys in single family houses in Germany and in multi-family houses in Switzerland were performed. Because of practical reasons, the questionnaires were not performed in the same houses as the measurements, except two multi-family houses in Switzerland. Results of the questionnaire surveys are reported by Liebl [11].

4. SINGLE NUMBER RATINGS

For the technical description of the measured impact spectra there are numerous single number ratings available. Besides the standard weighted single number ratings for the standardized tapping machine $L_{n,w}$ and $L_{nT,w,}$ including the spectrum adaptation terms $C_{I,\ 100\text{-}2500}$ and $C_{I,\ 50\text{-}2500}$ according to ISO 717, a number of different ratings have been proposed in the past. Most of them are based on the ISO 717 rating method, with a different rating curve in terms of slope and frequency range. Lately, proposals have been made in the AkuLite Project in Sweden [12, 13], but also by Hagberg [14]. Other proposals were given by Bodlund [15], Fasold [16] and Gösele [17]. Additional methods are described in the Japanese Standard JIS A 1419-2 [18] and the Korean Standard KS F 2863-2 [19]. As single number value for all applied impact noise sources the A-weighted standardized sound pressure level $L_{nT,A}$ with a reference to a reverberation time of 0.5 s in the receiving room was calculated from the third octave band spectrum values. This was calculated for two different frequency ranges of $L_{nT,A,50\text{-}2500\ Hz}$ and $L_{nT,A,20\text{-}2500\ Hz}$. For the Japanese rubber ball this was altered to $L_{F,max,nT,A,50\text{-}2500\ Hz}$ and $L_{F,max,nT,A,20\text{-}2500\ Hz}$. Furthermore, two additional single number rating methods were tested in the correlation analysis. Both are based on the standard method of ISO 717, altering only the reference curve. First the reversed A-weighting curve from 50 to 3150 Hz was used as reference curve. Additionally, the hearing threshold curve of ISO 389-7 [20] for a diffuse sound field, was applied as a reference curve. The frequency range from 20 to 5000 Hz was used for this reference curve.

5. CORRELATION ANALYSIS

With the correlation analysis of subjective and objective parameters for the given dataset, three questions can be answered:

- Which of the technical sources is most appropriate to represent walking noise and chair moving noise?
- Which single number descriptor for the given technical source correlates best with the subjective annoyance of the analyzed real sources?
- What requirement levels can be proposed based on the subjective ratings for walking noise?

In this study two “real sources” were investigated, walking person and moving of a chair. For the walking noise signals, different persons were engaged and the levels and the subjective ratings on the same intermediate floor (with the same floor covering) were averaged. As technical sources the standardized tapping machine, the modified tapping machine and the Japanese rubber ball were used. The results of the listening tests showed a high correlation of the loudness and the annoyance judgements. Therefore, loudness and annoyance analysis give essentially similar results. The following analysis is based on the annoyance ratings.

5.1 Representative Sources

In order to clarify which of the technical sources is the most representative for walking noise a correlation between the subjective rating of the technical sources and the subjective rating of walking noise was made. The result for the standard tapping machine is shown in figure 2.

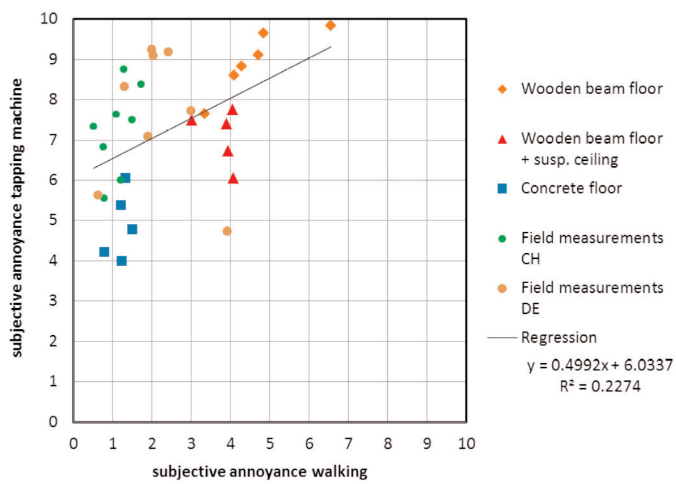


Figure 2: Correlation of the subjectively rated annoyance of the standardized tapping machine with the annoyance of walking noise

For the correlation a linear dependency was assumed. The data points of the different intermediate floors in the laboratories (with different floor coverings) and of the different field measurements together with the regression line and the regression parameters are shown. According to expectations, the annoyance of the tapping machine is much greater than the annoyance of walking noise. Clearly, the annoyance of the standard tapping machine on the intermediate timber floors in Switzerland ("CH") are rated much higher than the annoyance of the same source on the intermediate concrete floor, even though the subjective annoyance of walking noise on both types of floor are rated with quite similar values i.e, ranging only between 0.5 and 1.73. Also for the intermediate timber beam floors in the lab and in the field ("DE"), the spread of the annoyance of the tapping machine is big even when the annoyance rating of walking on the same floor is similar. This leads to a poor determination coefficient of R^2=0.23. The same analysis considering the annoyance of the Japanese rubber ball is shown in figure 3.

The correlation between the annoyance of the Japanese rubber ball and the annoyance of walking noise shows quite a good linear dependency with a determination coefficient of R^2=0.80. For this source the subjective ratings of the acoustically superior intermediate timber floors in Switzerland and of the intermediate concrete floor are quite similar. Only for the field measurements in Germany ("DE") the annoyance ratings of walking noise shows slightly larger spread. Both outliers, the data points from

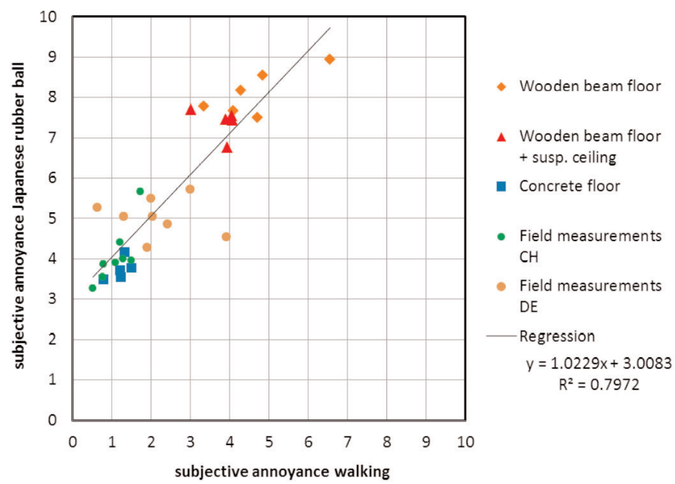


Figure 3: Correlation of the subjectively rated annoyance of the Japanese rubber ball with the annoyance of walking noise

the field measurements ("DE") with the lowest subjective rating and the one with the highest rating were measurements on floors with carpet. The one with the highest subjective rating (3.93/4.5) included high background noise and a rather low walking noise signal. Therefore, for this outlier an increased subjective annoyance rating caused by the raised background noise is assumed. The second outlier with the lowest subjective annoyance rating (0.64/5.3) was an intermediate floor with deep-pile carpet, where the walking noise was reduced by the carpet but the Japanese rubber ball seemed much less affected by the floor covering (the same intermediate floor partly covered by tiles was also investigated, the data point for this floor was (2.01/5.5) in figure 3).

The regression line in figure 3 shows a slope close to 1. This tells us that an increase of annoyance of walking noise by one rating number leads to a similar annoyance increase for the Japanese rubber ball. The overall shift to higher annoyance ratings for the ball can be explained by the stronger excitation (with higher loudness and annoyance) of the rubber ball. For building measurements this stronger excitation is advantageous, as the signal to noise ratio is much greater for the ball than for the other technical sources.

The same analysis was performed for the moving chair noise. An overview of the results for all combinations is shown in table 2. Note that for the regression analysis of the moving chair noise all intermediate floors with carpet as floor covering were excluded.

The results of the correlation between the annoyance of the technical and the "real" sources show that the Japanese rubber ball gives the highest determination coefficient for walking noise. Additionally, the slope of the regression is close to 1. The modified tapping machine gives much higher determination coefficient then the standard tapping machine. Unfortunately, the modified tapping machine is relatively weak in its excitation and gives practical problems at building site measurements because of a low

Table 2. Linear regression coefficients between subjective annoyance of technical source against subjective annoyance of walking noise and chair moving noise

technical source	"real" source	Linear regression coefficients y=ax+b		Determination coefficient
		a	b	R^2
tapping machine	Walking	0.50	6.03	0.23
rubber ball	Walking	1.02	3.01	0.80
modified tapping machine	Walking	0.83	1.45	0.71
tapping machine	Chair	0.71	4.08	0.53
rubber ball	Chair	0.99	0.68	0.72
modified tapping machine	Chair	0.88	-0.72	0.76

signal to noise ratio. For walking noise the Japanese rubber ball is therefore the most appropriate and practical technical source.

Regarding noise from the moving of the chair, the situation is less clear. Here the rubber ball, resulting in R^2=0.72 and a slope near 1, is an appropriate source. Nevertheless, the highest determination coefficient is given by the modified tapping machine with R^2=0.76. The standardized tapping machine gives a much higher determination coefficient then for walking, but with R^2=0.53 it is still lower than for the modified tapping machine and the Japanese rubber ball.

5.2 Single Number Descriptor

In spite of the shortcomings regarding the standard tapping machine and its subjectively rated annoyance due to living noises, it is almost the only technical noise source used in the past in Europe. However, in addition to the rating methods given in ISO 717, the Japanese standard JIS A 1419-2 [18] and the Korean standard KS F 2863 [19] give rating methods for both the standard tapping machine and the Japanese rubber ball.

The most common rating method applied in Europe is the method described in ISO 717. To evaluate if the standard frequency range (100-3150 Hz) single number rating is appropriate to assess walking noise, this single number value ($L'_{nT,w}$) of ISO 717 is correlated to the subjective annoyance of walking noise. The result is shown in figure 4.

For the weighted standardized impact sound pressure level $L'_{nT,w}$ the correlation to the subjective annoyance gives a low determination coefficient of R^2=0.38. For the field measurements in Switzerland ("CH") and Germany ("DE"), the spread of the single number value can be quite high (more than 10 dB) for the same subjective annoyance rating. Additionally, the Swiss intermediate timber floor constructions have much higher $L'_{nT,w}$ values compared to the intermediate concrete floor with similar subjective annoyance ratings. This results in a low determination coefficient showing the problem when rating timber constructions using $L'_{nT,w}$ or $L'_{n,w}$. Taking into account the spectrum adaptation term $C_{I,50\text{-}2500}$ (frequencies from 50 Hz), the results from the correlation analysis are shown in figure 5.

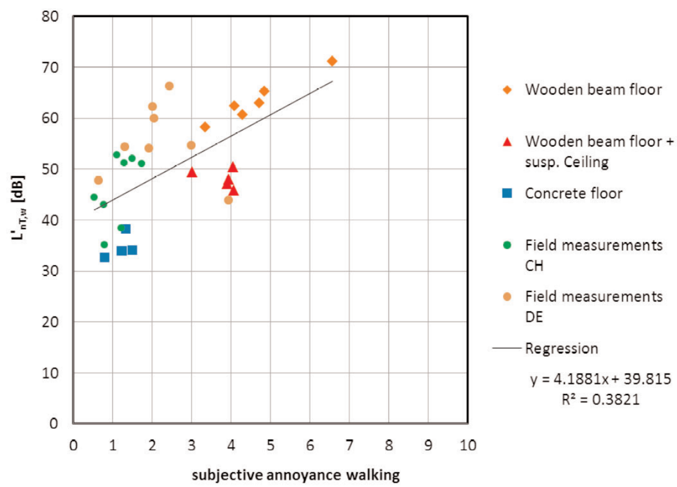


Figure 4: Correlation of the weighted standardized impact sound pressure level $L'_{nT,w}$ with the annoyance of walking noise

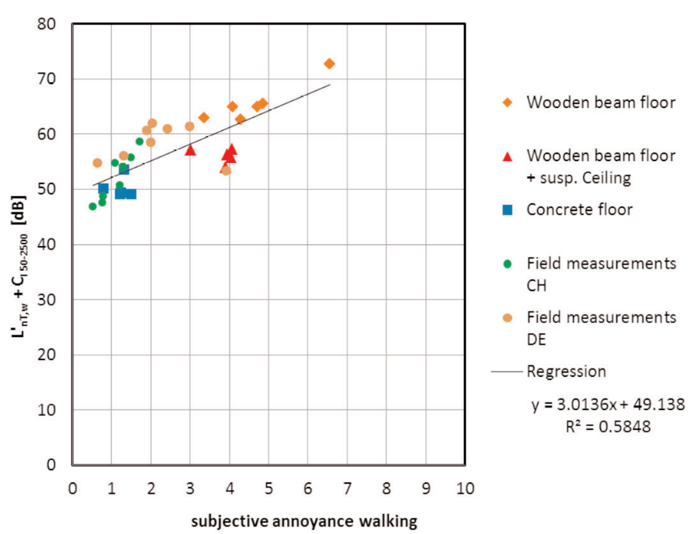


Figure 5: Correlation of the weighted standardized impact sound pressure level $L'_{nT,w} + C_{I,50\text{-}2500}$ with the annoyance of walking noise

Taking the spectrum adaptation term $C_{I,50\text{-}2500}$ into consideration, the determination coefficient increases to R^2=0.58. The data points follow much better the linear relationship assumed. It is interesting that the technical descriptor for all the intermediate floors with suspended ceiling in the laboratory lie below the regression curve. For these intermediate floors the main impact noise (highest levels of the A-weighted third octave band spectrum) occurs below 50 Hz and is therefore not included in the spectrum adaptation term.

A similar linear regression analysis was conducted for different single number descriptors, based on the normalized impact sound pressure level in the receiving room. Most of the rating systems are based on the evaluation rules according to ISO 717, but instead use an altered reference curve in terms of shape and frequencies. The different rating curves based on the ISO 717 method are shown in figure 6.

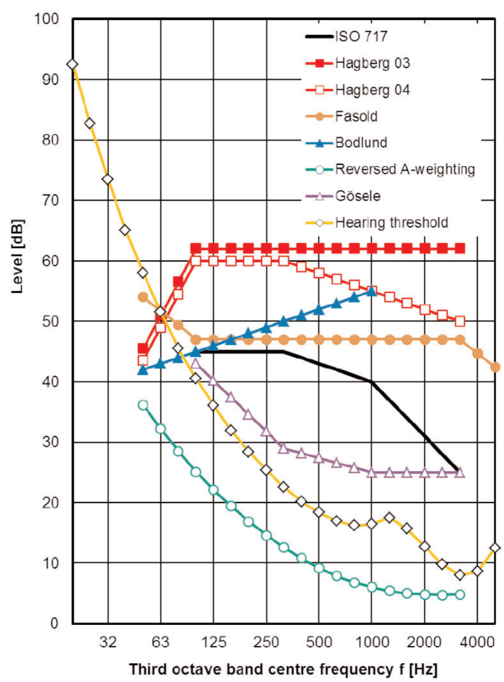


Figure 6: Rating curves used for the different rating methods, based on the evaluation rules according to ISO 717 method

Additional rating methods were taken from JIS A 1419-2. They are somewhat different to the ISO rating method, as they refer to octave band values. The rating curves have high values at low frequencies and lower values at higher frequencies, similar to the shape of the Gösele-curve. Additionally, a proposal of the AkuLite project for a rating method, based on the sum level of the normalized impact sound pressure level and a frequency dependent weighting function was also tried [13]. The results of the determination coefficient for those different rating methods are given in Table 3.

Table 3. Linear regression determination coefficients R^2 between different rating methods of the tapping machine and the subjective annoyance of walking noise

rating method	R^2	rating method	R^2	rating method	R^2
$L'_{nT,w}$ ($L'_{n,w}$)	0.38 (0.41)	$L'_{nT,Fasold}$ [16]	0.56	$L'_{nT,hearing\ threshold}$	0.31
$L'_{nT,w}+C_{I,100–2500}$ ($L'_{n,w+}C_{I,100–2500}$)	0.48 (0.51)	$L'_{n,w}+$ $C_{I,AkuLite,20\text{-}2500}$ [13]	0.56	JIS $L_{i,A}$ [18]	0.35
$L'_{nT,w}+C_{I,50–2500}$ ($L'_{n,w}+C_{I,50–2500}$)	0.58 (0.61)	$L'_{n,w}+$ $C_{I,AkuLite,20\text{-}2500,hf}$* [13]	0.56	JIS $L_{i,A,F}$ [18]	0.29
$L'_{nT,Hagberg03}$ [14]	0.63	$L'_{n,w}+$ $C_{I,AkuLite,20\text{-}2500,Sweden}$** [13]	0.57	JIS $L_{i,A,w}$ [18]	0.29
$L'_{nT,Hagberg04}$ [14]	0.62	$L'_{nT,Gösele}$ [17]	0.36	$L'_{nT,A\ 20\text{-}2500}$	0.36
$L'_{nT,Bodlund}$ [15]	0.58	$L'_{nT,reversed\ A\text{-}weighting}$	0.36	$L'_{nT,A\ 50\text{-}2500}$	0.36

* AkuLite method with additional high frequency (hf) adaptation

** AkuLite method with restriction to room volume of 31 m^3

The results show that all methods including low frequencies at least down to 50 Hz, Hagberg, Fasold, Bodlund and AkuLite, with the exception of the reversed A-weighting and the hearing threshold, result in relatively high determination coefficients. The best for the given data is the method of Hagberg 03, which has a strong focus on the low frequencies between 50 and 100 Hz with a steep declining reference curve from 100 Hz to 50 Hz. Additionally, the reference curve of Bodlund has a declining reference curve between 50 and 1000 Hz, with a slope not as steep as for the Hagberg 03 reference curve. On the other hand the reversed A-weighting and the hearing threshold curve where the curve is inclining to lower frequencies the determination coefficient is much lower. The Japanese methods with an inclining reference curve towards low frequencies produce also a low determination coefficient.

Additionally, the A-weighted sum level of the tapping machine $L'_{nT,A}$ for both frequency ranges gives low determination coefficients, which can be explained by the fact that the spectrum of the tapping machine is very different to the spectrum of walking noise.

A similar correlation analysis can be made for the Japanese ball and the modified tapping machine. In this case, less single number rating methods are available. The results are shown in table 4

Table 4. Linear regression determination coefficients R^2 between different rating methods of the Japanese rubber ball and the modified tapping machine against subjective annoyance of walking noise

rating method Japanese Ball	R^2	rating method Japanese Ball	R^2	rating method modified tapping machine	R^2
JIS $L_{i,A}$ [17]	0.62	$L'_{F,max,nT,A,\ 20\text{-}2500}$	0.75	$L'_{nT,A\ 20\text{-}2500}$	0.83
JIS $L_{i,A,Fmax}$ [17]	0.69	$L'_{F,max,nT,A\ ,50\text{-}2500}$	0.69	$L'_{nT,A\ 50\text{-}2500}$	0.76
JIS $L_{i,A,w}$ [17]	0.62	KS $L_{i,avrg,Fmax\ 63\text{-}500}$ [18]	0.64	-	-

The results in table 4 show for the Japanese rubber ball and the modified tapping machine that the A-weighted sum level including the very low frequencies from 20 to 2500 Hz gives the highest determination coefficient R^2. All values of R^2 are much higher than for the standard tapping machine, as the spectrum of the rubber ball is much better related to the walking noise.

For the moving of the chair, similar analysis has been conducted. In the following analysis, the intermediate floors with carpet were excluded (on carpet, the chair changes its source behavior as the stick-slip-effect causing the typical moving noise do not occur).

Taking the standardized tapping machine as a technical source to represent the chair, $L'_{nT,w}+C_{I\ 50\text{-}2500}$ gives almost the highest determination coefficient of R^2=0.72. Only $L'_{nT,Fasold}$ lies slightly higher with R^2=0.73. All other methods give slightly lower R^2. For this source, all methods tend to work equally well. Considering the rubber ball as source for chair noise, the highest determination coefficient was found for $L'_{F,max,nT,A\ 20\text{-}2500}$ with R^2=0.82. For the modified tapping machine, $L'_{nT,A\ 20\text{-}2500}$ gave a R^2=0.82, $L'_{nT,A\ 50\text{-}2500}$ resulted in a R^2=0.84. For the moving of the chair noise and the modified tapping machine as representative noise source, the consideration of the very low frequencies below 50 Hz gives lower determination coefficient than $L'_{nT,A\ 50\text{-}2500}$. This can be explained by the circumstance that the moving of the chair has less very low frequency components, and this is also true for the modified tapping machine.

5.3 Requirement Levels for Single Number Descriptors

In the listening tests the question was asked if the signal is annoying when reading a newspaper, magazine or book. The percentage of test persons perceiving the signal as annoying was correlated to the subjective annoyance rating. This correlation analysis showed very similar linear correlation for both sources alone, the walking noise and the moving of the chair noise. For the walking noise alone the determination coefficient was R^2=0.94. The moving of the chair alone gave a determination coefficient R^2 of 0.79. The data of both sources combined is shown in figure 7.

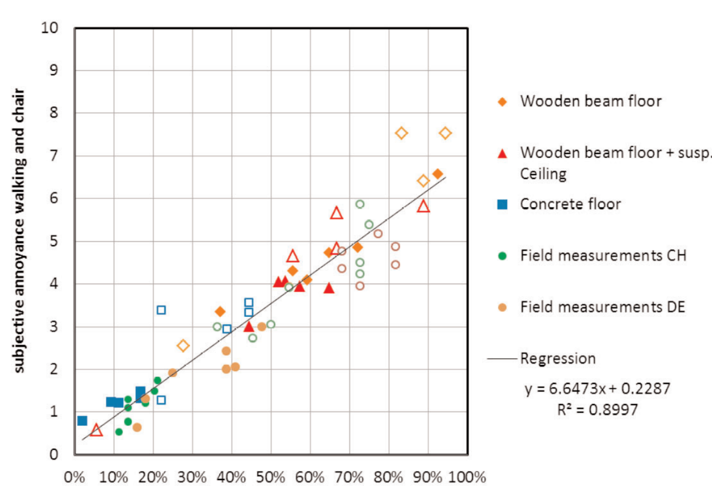


Figure 7: Correlation of the percentage of annoyed persons with the annoyance rating of walking noise (full symbols) and moving of the chair (hollow symbols)

The determination coefficient of the regression is then R^2=0.90. The 50% mark of annoyed persons correspond to an annoyance rating of 3.6.

A relationship between a subjective rating scale and a percentage of annoyed or dissatisfied persons has been established in the field of thermal comfort in the 1960s by Fanger [21]. This approach proved successful to formulate requirements based on the predicted percentage of dissatisfied index PPD. A similar approach can be used also to deduce requirements for impact noise.

When recommending requirement levels based on the percentage of annoyed persons, the following question has to be answered: Which kind of noise needs to be addressed by the requirements? The field survey conducted in this project and reported by Liebl [11], can answer this question. The mean judgment of noise annoyance in multi-storey timber buildings in Switzerland with acoustically superior floors was 2.1 on a scale from 0 to 10 for neighbours' walking. This was the highest annoyance judgment for any single noise source addressed (neighbours' music and drums: 1.0; neighbours' rattling of furniture: 1.0; talking in staircases: 1.4; outside traffic: 1.6; water installations: 1.1). Even though the values are quite low, walking noise of neighbours in the flats above are found to be the most prominent source of annoyance. Therefore, the following requirements are focusing on walking noise.

With the high correlation between the subjective annoyance rating and the percentage of annoyed persons, shown in figure 7, it seems reasonable to correlate the single number ratings directly to the percentage of annoyed persons. The correlation and linear regression for the impact sound pressure level $L'_{nT,w} + C_{I,50\text{-}2500}$ is shown in figure 8:

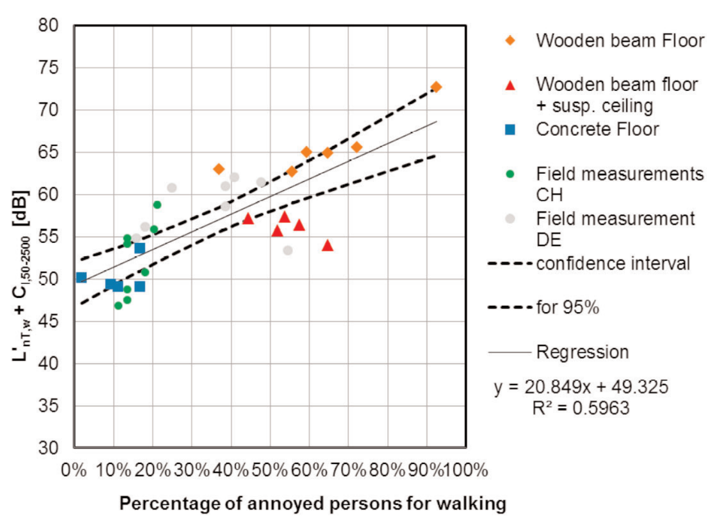


Figure 8: Correlation of the weighted standardized impact sound pressure level $L'_{nT,w} + C_{I,50\text{-}2500}$ with the percentage of annoyed persons for walking noise and linear regression with confidence interval for 95% confidence limit.

The determination coefficient R^2 is slightly higher than for the regression of the annoyance rating in figure 5. The confidence interval for 95% confidence limit shows at low single number values and low percentage of annoyed persons a spread of about 5 dB and at a mid-percentage of 40% a spread below 3 dB. At higher percentage of annoyed persons a bigger spread occurs, due to the lower number of measurement points and the higher deviation of the single measurement point (92.6%/72.7 dB) from the linear regression line.

This analysis can similarly be performed for other single number values. Then, given requirements of standards or recommendations can be related to the percentage of annoyed persons. The most recent recommendations in Germany are given in VDI 4100 [22] for $L'_{nT,w}$. With a linear regression similar to the one in figure 8, the percentage of annoyed persons can be related to the requirements of VDI 4100 [22], shown in Table 5.

Table 5. Requirements of VDI 4100, annoyance rating and percentage of annoyed persons for three levels of acoustic requirements

VDI 4100 (2012)	L´nT,w	Percentage of persons annoyed by walking noise $y = 31.4*x + 39.2; R^2 = 0.46$
SST I	51 dB	38%
SST II	44 dB	15%
SST III	37 dB	-7%

The recommendation of SST III of VDI 4100 leads to a negative value for the corresponding percentage of annoyed persons, as the value of $L'_{nT,w}$ of 37 dB corresponds to an extrapolated negative value of the annoyance rating. This can be interpreted as an excessive requirement, but also as a safety margin for the relatively low determination coefficient of R^2=0.46 of the linear regression.

An additional analysis of the German DIN 4109 requirements of $L'_{n,w}$ of 53 and 46 dB leads to a percentage of 38% and 14% annoyed persons, when using the correlation between $L'_{n,w}$ and the percentage of annoyed persons.

On the other hand, proposals for requirements can be given, based on the percentage of annoyed persons.

For a minimum requirement a percentage of 40% annoyed persons, and two steps for increased acoustic performance of 20% and 0% annoyed are proposed. Taking the regression formula of figure 8 for $L'_{nT,w}+C_{I,50\text{-}2500}$ and a regression formula from a similar correlation analysis for $L'_{n,w}+ C_{I,50\text{-}2500}$, this leads to the corresponding single number values shown in table 6.

Table 6. Requirements for the different rating methods for the standardized tapping machine representing walking noise

Rating method for the standard tapping machine	Linear regression formula single number value versus percentage of annoyed persons	Determination coefficient R^2	Requirement for percentage of annoyed persons in dB		
			40%	20%	0%
$L'_{nT,w} + C_{I,50\text{-}2500}$	y = 20.8x + 49.3	0.60	58	53	49
$L'_{n,w} + C_{I,50\text{-}2500}$	y = 21.0x + 50.8	0.59	59	55	51

Table 7. requirements given by Hagberg [14] for three stages of acoustic quality

Rating method for the standard tapping machine	Requirement three stages in dB		
	Stage I	Stage II	Stage III
For rooms of V < 31 m^3: requirement for $L'_{n,w} + C_{I,50–2500}$ and $L'_{n,w}$ and for Rooms of V > 31 m^3: requirement for $L'_{nT,w} + C_{I,50–2500}$ and $L'_{nT,w}$	56	52	48

The comparison of the requirements given in Table 6 with the ones of Hagberg in Table 7 shows that the Hagberg requirements are somewhat stricter with values of 1 or 2 dB lower than given in Table 6 for $L'_{nT,w}+C_{I,50\text{-}2500}$. In the database of the AcuWood project, only one Swiss intermediate floor reached stage III of the Hagberg requirement with $L'_{n,w}+C_{I,50–2500}$ = 46.7 dB. Therefore the requirements of Hagberg might be a bit ambitious. There is, however, a potential for optimization of the investigated intermediate floors, for example adding more ballast or a suspended ceilings with low resonance frequency etc., which had not yet been performed.

Additionally, again based on the percentage of annoyed persons, requirements for the Japanese rubber ball and the modified tapping machine are derived similarly to the standard tapping machine and are given in Table 8 and 9 respectively.

Table 8. Requirements for the proposed rating method for the Japanese rubber ball representing walking noise

Rating method for the Japanese rubber ball	Linear regression formula single number versus percentage of annoyed persons	Determination coefficient R^2	Requirement for percentage of annoyed persons in dB		
			40%	20%	0%
$L'_{nT,A,F,max,20\text{-}2500\ Hz}$	y = 24.8x + 46.9	0.74	57	52	47
$L'_{nT,A,F,max,50\text{-}2500\ Hz}$	y = 27.6x + 44.3	0.69	55	50	44

Table 9. Requirements for the proposed rating method for the modified tapping machine representing walking noise

Rating method for the modified tapping machine	Linear regression formula single number versus percentage of annoyed persons	Determination coefficient R^2	Requirement for percentage of annoyed persons in dB		
			40%	20%	0%
$L'_{nT,A,20\text{-}2500\ Hz}$	y = 29.1x + 25.2	0.82	37	31	25
$L'_{nT,A,50\text{-}2500\ Hz}$	y = 29.0x + 23.9	0.75	36	30	24

The choice of three levels of acoustic quality and the given percentage of annoyed persons was related to the proposals of VDI 4100 and Hagberg [14].

5.4 Transferability of the Listening test Data to Real Buildings

Important for the above derived proposals for requirements is the transferability of the laboratory listening test data to the subjective annoyance of living noise in real building situations. The annoyance of living noise in buildings was addressed in the questionnaire surveys in single family houses in Germany and in multi-family houses in Switzerland. Evidence was found that the annoyance ratings in the listening test in the laboratory correspond to the annoyance ratings in real multi-family buildings. The same rating scale was used in the laboratory listening test and the questionnaire field survey. Following from that direct comparison of listening test and questionnaire results were possible for two Swiss multi-family buildings. For both buildings, the annoyance ratings of the listening test and the field survey were similar. The results are discussed in [11].

6. CONCLUSIONS

In the AcuWood project the impact noise of "real" sources of walking noise and chair moving noise and of technical sources, the standardized tapping machine, the modified tapping machine and the Japanese rubber ball have been measured and recorded in different laboratory and field situations. Additionally, these different noise sources were subjectively evaluated by performing laboratory listening tests.

The most appropriate technical source to represent walking noise turned out to be the Japanese rubber ball. In its characteristics and spectrum, it is very similar to real walking noise. Additionally, there are no restrictions regarding floor covering materials, unlike for the other technical sources. The best correlating single number rating for the Japanese rubber ball is $L'_{F,max,nT,A\ 20\text{-}2500}$, with a determination coefficient of R^2=0.75. Based on the percentage of annoyed persons, requirement values for this single number rating are given.

The modified tapping machine represents walking noise very well and has an even higher R^2=0.83 for the single number rating of $L'_{nT,A\ 20\text{-}2500\ Hz}$. Nevertheless, the modified tapping machine is rather unpractical for real building measurements due to low signal to noise ratio.

The standardized tapping machine can also be utilized as impact noise source. $L'_{nT,w}+ C_{I,50\text{-}2500}$ is an acceptable single number descriptor with a determination coefficient of R^2=0.58. The best single number descriptor when evaluating the standard tapping machine was $L'_{nT,w\ Hagberg\ 03}$ with R^2=0.63. For single number ratings in an extended frequency range according to ISO 717, $L'_{n,w}+ C_{I,50–2500}$ and $L'_{nT,w}+ C_{I,50\text{-}2500}$, requirements are given, again based on the percentage of annoyed persons.

Regarding the frequency range to be considered for the single number rating, the results showed that frequencies at least down to 50 Hz have to be included. This is the case for $L'_{nT,w}+C_{I,50–2500}$ and $L'_{nT,w\ Hagberg\ 03}$ evaluating measurements using the standardized tapping machine. For the sum levels of $L'_{F,max,nT,A\ 20\text{-}2500\ Hz}$ and $L'_{nT,A,\ 20\text{-}2500\ Hz}$ evaluating measurements using the Japanese rubber ball and the modified tapping machine respectively, frequencies down to 20 Hz have been found to give slightly better correlation than considering frequencies down to 50 Hz. In this study this finding is caused by intermediate timber floors with suspended ceilings, since they exhibit relevant sound transmission below 50 Hz. Therefore, excluding frequencies below 50 Hz in the single number rating will always carry the risk of excluding relevant sound transmission at very low frequencies.

For the single number descriptors investigated, requirements are deduced from the percentage of annoyed persons. This approach has been proved useful by Fanger [21]. He describes the PPD index for the evaluation of thermal comfort. Acoustical requirements based on the percentage of annoyed persons seem to be more easily understood by builders, clients, lawyers, politicians and other people involved in the building process, even without acoustical knowledge. Evidence was found that the annoyance rating of the listening tests were similar to annoyance ratings in multi-family houses in Switzerland. This evidence still has to be confirmed by comparison of more data sets of multi-family buildings in the future.

REFERENCES

1. Forssen, J., Kropp, W. e.a.: Acoustics in wooden buildings. State of the art 2008. *Vinnova project 2007-01653*, Stockholm (2008).
2. EN ISO 717-2 (1996): Acoustics – Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation. International Organization for Standardization ISO, Geneva, Switzerland.
3. Rasmussen, B.: Sound insulation between dwellings – Requirements in building regulations in Europe. *Applied Acoustics* **71**(4), 373–385 (2010).
4. Hagberg, K.: AkuLite and AcuWood finish what happens now? In: *Proc. INTER-NOISE 2013*
5. Pietila, G, Lim, T.C.: Intelligent systems approaches to product sound quality evaluations – A review. Applied Acoustics 73, 987-1002 (2012).
6. Späh, M., Liebl, A., Weber, L., Leistner, P.: Subjective and Objective Evaluation of Impact Noise Sources in Wooden and Heavy-weight Floor Constructions. In: *Proc. ICSV19* (2012).

7. EN ISO 10140-5 (2010): Acoustics – Laboratory measurements of sound insulation of building elements – Part 5: Requirements for test facilities and equipment. International Organization for Standardization ISO, Geneva, Switzerland.
8. EN ISO 140-7 (1998) Acoustics – Measurement of sound insulation in buildings and of building elements – Part 7: Field measurements of impact sound insulation of floors. International Organization for Standardization ISO, Geneva, Switzerland.
9. ISO/TS 15666 (2003): Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys, International Organization for Standardization ISO, Geneva, Switzerland.
10. ISO 16832 (2006): Acoustics - Loudness scaling by means of categories, International Organization for Standardization ISO, Geneva, Switzerland.
11. Liebl, A.: Evaluation of acoustic quality in wooden buildings. In: *Proc. INTER-NOISE 2013*
12. Ljunggren, F., Simmons, C., Hagberg, K. H.: Findings from the AcuLite project: Correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings. In: *Proc. INTER-NOISE 2013*.
13. Ljunggren, F., Simmons, C., Hagberg, K. H.: Findings from the AcuLite project: New single number for impact sound 20-5000 Hz based on field measurements and occupant's survey. In: *Proc. INTER-NOISE 2013*.
14. Hagberg, K.: Evaluating Field Measurements of Impact Sound. *Building Acoustics* **17**(2), 105–128 (2010).
15. Bodlund, K.: Alternative Reference Curves for Evaluation of the Impact Sound Insulation between Dwellings. *Journal of Sound and Vibration* **102**(3), 381–402 (1985).
16. Fasold, W.: Untersuchungen über den Verlauf der Sollkurve für den Trittschallschutz im Wohnungsbau. *Acustica* **15**, 271–284 (1965).
17. Gösele, K.: Zur Bewertung der Schalldämmung von Bauteilen nach Sollkurven. (Evaluation of sound reduction in building structures by means of grading curves) *Acustica*, 1965, 15 (5), 264-70.
18. JIS A 1419-2 (2000): Acoustics - Rating of sound insulation in buildings and of building elements - Part 2: Floor impact sound insulation. Japanese Standards Association, Tokyo, Japan.
19. KS F 2863-2: Rating of floor impact sound insulation for impact source in building and of building elements. Part 2: Floor Impact sound insulation against heavy impact source. Korean Standards Association, Seul, Korea.
20. ISO 389-7 (2005): Acoustics - Reference zero for the calibration of audiometric equipment - Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions, International Organization for Standardization ISO, Geneva, Switzerland.

21. Fanger, P. O, Thermal Comfort. Danish Technical Press, 1970 (Republished by McGraw-Hill, New York, 1973). ISBN8757103410, 9788757103410.
22. VDI 4100 (2012): Sound insulation between rooms in buildings - dwellings - Assessment and proposals for enhanced sound insulation between rooms. Verein Deutscher Ingenieure e.V. VDI, Düsseldorf, Germany. Beuth Verlag GmbH, Berlin.

Paper E

Article

BUILDING ACOUSTICS

Building Acoustics
1–19

DOI: 10.1177/1351010X16645971
bua.sagepub.com
SAGE

Impact sound insulation of wooden joist constructions: Collection of laboratory measurements and trend analysis

Anders Homb[1], Catherine Guigou-Carter[2], Klas Hagberg[3] and Hansueli Schmid[4]

Abstract

Wooden building systems are becoming more common. Still, there are a huge variety of floor assemblies in the market. The floor assemblies normally become the weakest part due to impact load from walking persons. So far, there are no reliable standardized calculation models available regarding prediction of impact sound in the entire frequency range. Therefore, the design is always based upon previous experiences and available measurements. For the development of prediction models, the first approach is to carry out a grouping of various available floor assemblies. From that, the aim is to trace similarities and carry out simplifications. Correlation is found between the single number $L'_{nT,w} + C_{I,50\text{-}2500}$ and the mass per unit area. It is also found that the ceiling system is useful in order to optimize the construction. The data will be further processed and used in the model development and to propose optimization of wooden floor assemblies.

Keywords

Lightweight, timber, impact sound insulation, building acoustics, floor

Introduction

Lightweight building technique

In traditional lightweight buildings, walls and floors are rigidly connected, but the ceiling is often elastically connected to the beams and sometimes completely separated. Regarding the upper floor construction, a more or less resilient solution is common but actually depending on the requirement level in each country. When concentrating on the floor construction itself and laboratory

[1]Building and Infrastructure, SINTEF, Trondheim, Norway
[2]CSTB, St Martin d'Hères, France
[3]WSP Sweden AB, Malmö, Sweden
[4]Lignum, Zürich, Switzerland

Corresponding author:
Anders Homb, Building and Infrastructure, SINTEF, Høgskoleringen 7B, NO-7465 Trondheim, Norway.
Email: anders.homb@sintef.no

measurements, the effect of supporting walls and flanking transmission is not included. The effect of these contributions is therefore outside of this study. The majority of a timber floor construction is so far typically erected on site under different conditions and workmanship. It is difficult to document the consequence of this with respect to the sound insulation, but it will probably increase the spreading of the properties as shown by Johansson[1] and Ljunggren and Ågren.[2] When considering research and studies from some years ago and from different countries, a lot of laboratory measurement results are actually available. It includes some comprehensive parametric studies performed on specific timber floor constructions, see for instance Warnock and Birta,[3] Sipari et al.,[4] Fothergil and Royle[5] and Johansson,[6] besides measurements from unpublished projects.

Sound insulation requirements

The building code in many countries was developed when lightweight structures were rarely used or not even permitted for multi-storey residential buildings. Thus, requirements are adapted to heavyweight structural behaviour, that is, current single number ratings presuppose structures which actually have very good low-frequency sound insulation and are not sensitive to perceived vibrations, at least not to vibrations from normal private activities. Lightweight structures often exhibit poor low frequency behaviour, and if using a single number rating without spectrum adaptation term as shown in EN-ISO 717-2:1996,[7] there is no consideration at all for frequencies below 100 Hz. A few countries have extended the sound insulation requirements or recommendations using the ISO (International Organization for Standardization) spectrum adaptation terms from 50 Hz. New lightweight building techniques are growing, and so more countries need to incorporate this either formally or by recommendations, at least for residential buildings. Table 1 shows impact sound insulation requirements and recommendations given in different countries participating in this project.

Objective

This article presents results from numerous well-controlled sound insulation measurements performed in laboratory. As the impact sound insulation tends to be the most significant problem for the wooden floor construction building technique,[8,9] such measurements are in focus. The main objective is to highlight some specific phenomena, in order to see in what way structural differences related to the grouping of the constructions affect the sound insulation properties. An objective is also to deliver well-controlled and systematically performed experimental results that can

Table 1. Impact sound insulation requirements and recommendation/certification.

Country	Impact sound insulation	
	Legal requirement	Recommendation/certification
Austria	$L'_{nT,w} \leqslant 48dB$	–
France	$L'_{nT,w} \leqslant 58dB$	$L'_{nT,w} \leqslant 55dB$
Germany	$L'_{n,w} \leqslant 53dB$	$L'_{n,w} \leqslant 46dB$
Norway	$L'_{n,w} \leqslant 53dB$	$L'_{n,w} + C_{I,50–2500} \leqslant 53dB$
Sweden	$L'_{nT,w} \leqslant 56dB$ and $L'_{nT,w} + C_{I,50–2500} \leqslant 56dB$	–
Switzerland[a]	$L'_{n,w} \leqslant 50dB$	$L'_{n,w} \leqslant 45dB$

[a]Intermediate values.

verify solutions and give input for better prediction tools for lightweight floor constructions. To this end, results included in this article are first presented by country since floor construction is specific to each country: typical construction will depend on regulation requirements and local expertise. However, it will be seen that floor configuration grouping is possible across the European countries considered.

Floor assemblies

Introduction

In the following section, typical timber floor assemblies for residential buildings will be presented The information will be given for each contributing country in alphabetic order. The data collection presented in this article concentrates mainly on typical national solutions, but divided into different groups depending on structural differences. The grouping of constructions has been based on work in the Silent Timber Build (STB) project (see Homb[10]). Floor assemblies presented in this article are the following main types according to these grouping:

- *Construction group A*: wooden joist constructions;
- *Construction group B*: hybrid wooden joist constructions with gravel or concrete.

From the different countries, quite different solutions are found but also in some cases there are identical constructions when considering the principal solutions given by the grouping of the constructions. Due to traditions, it is not surprising that many of the same solutions in Sweden and Norway are found; however, also in France, similar floor assemblies are detected. Also due to traditions, Switzerland and Germany are often using a combination of concrete and wood. Therefore, such solutions dominate the findings when we collect laboratory measurement data from these countries. Even if France has some floor assemblies similar to Scandinavia, they are also using a combination of concrete on various wooden joist solutions.

France

In France, wooden joist constructions have not been that common in modern residential buildings, and therefore, common solutions have been based on a stiff top floor solution of chipboards, that is, group A constructions or even concrete with soft floor coverings on top, that is, group B constructions. In order to fulfil French regulation for residential buildings, separating floors are mounted with a resilient top floor (composed generally of mineral wool as resilient layer and of either boards or cast-in-place screed). Common for these solutions is a ceiling solution based on steel suspension products, often non-spring types but also resilient systems. The first mentioned solution is in the following coded as FS-CS solutions (corresponding to Floor Stiff–Ceiling Stiff meaning stiff top floor and stiff suspended ceiling) and the second one as FS-CR (Floor Stiff–Ceiling Resilient meaning stiff top floor and resilient suspended ceiling). The ceiling commonly incorporates a layer of mineral wool. A principal drawing of this construction type is presented in Figure 1(a). From both construction groups, there also exist laboratory measurement results with no coupling between the joist construction and the ceiling construction (independent double frame for the floor and ceiling), that is, solutions with the code FS-CN (Floor Stiff–Ceiling No coupling) similar to that commonly found in Swedish and Norwegian solutions. A principal drawing is presented in Figure 1(b).

Hybrid floors with an important concrete layer, falling into group B constructions, are not so much used yet for apartment buildings in France.

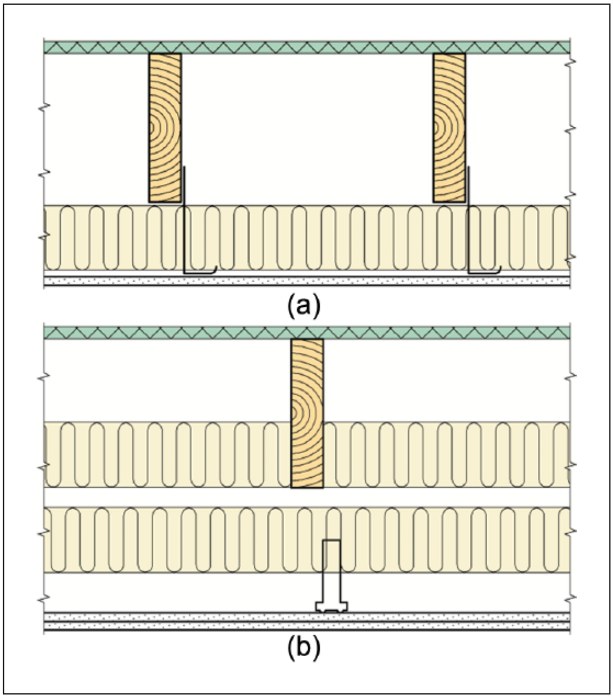


Figure 1. Common types of French wooden joist constructions: (a) type A, FS-CS and (b) type A, FS-CN.

Germany

In Germany, timber floor constructions are rarely used. But it is an increasing interest and examples and documentation exist based on solutions developed in Austria and Switzerland. Due to traditions and requirement level, these solutions normally have been based on a hybrid Timber-concrete composite floor solution (tccf) with concrete layer on the sub-floor (plywood/osb panel), that is, construction type B, FR-CS (Floor Resilient–Ceiling Stiff), with either prefabricated concrete elements which are directly laid on the floor joist members or more common as concrete on top of the sub-floor. The ceiling can either consist of plasterboard on rigidly fixed laths or of a suspended ceiling on resilient hangers. In the following, these solutions are encoded as hybrid FR-CS or hybrid FR-CR (Floor Resilient–Ceiling Resilient) solutions (concrete with a resilient top floor and resilient suspended ceiling). Principal drawings of these floor assemblies are presented in Figure 2(a) and (b).

Norway

In Norway, three main wooden joist constructions have been common in the last 10–20 years. The major choice has been using solutions based on resilient profiles in the ceiling and a resilient top floor solution. Different types of steel springs or resilient steel channels have been mounted underneath the timber beams. At the floor, floating floor on mineral wool products with a certain limit of dynamic stiffness has been the most common. Similar to the Swedish solution, these are encoded as FR-CR solutions (resilient floor and resilient ceiling). A principal drawing of this construction type is presented in Figure 3(a). Previously, it has also been very common to build similar floors without a resilient layer at the floor, coded as FS-CR solutions.

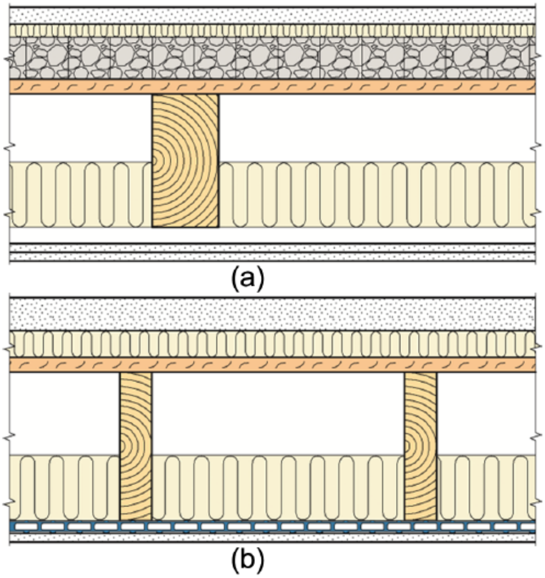


Figure 2. Common types of German wooden joist constructions: (a) type B, FR-CS and (b) type B, FR-CR.

The third solution with increased market share in the last 5 years has been prefabricated three-dimensional (3D) module-based solutions (usually referring to factory-built modules transported to the site and stacked to create a multi-family building). This construction type implies separate independent wood beams system for the floor from the upper module and for the ceiling from the lower module. This solution is similar to the Swedish one presented below, coded as FS-CN solutions (no coupling between joists and ceiling construction). In these solutions, it has not been common to use floating floors on mineral wool products nor use resilient profiles for mounting the ceiling. Different from many Swedish module-based buildings, it has not been common to use vibration insulation products between peripheral frames of superposed modules in Norway. A principal drawing of this construction type is presented in Figure 3(b).

Sweden

In Sweden, three main wooden joist constructions have been common in the last 5–10 years. The most common type has been a solution based on resilient profiles in the ceiling and more or less resilient top floor solutions. Relatively stiff underlayer in the top floor was applied sometimes, but very often floating floors on mineral wool products with a certain upper limit of dynamic stiffness have been used. In the following, these are coded as FR-CR solutions (resilient floor and resilient ceiling). This solution is more or less identical with construction type presented in Figure 3(a).

As mentioned previously, another solution with rapidly increased market share has been prefabricated 3D module-based solutions, briefly presented in section ‘Norway’. For such solutions, floating floor on mineral wool products is rarely used and not resilient profiles below the ceiling beams. But due to flanking transmission from the lightweight load-bearing walls, it has been more and more common to use vibration insulation products between peripheral frames of superposed

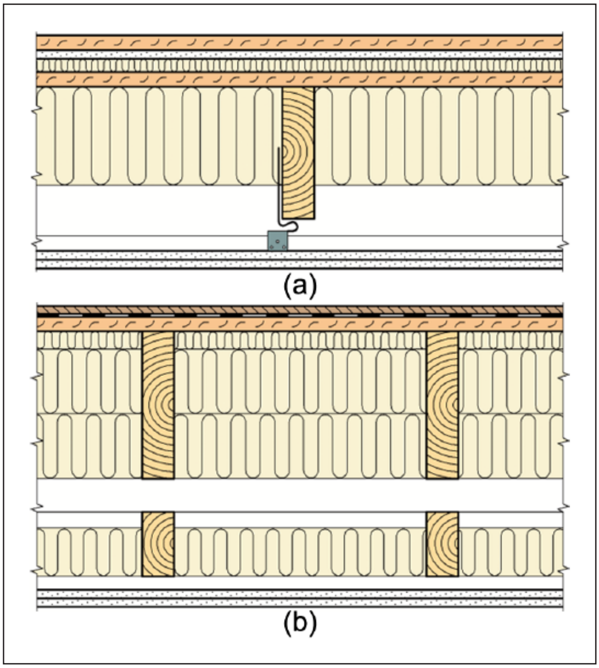


Figure 3. Common types of Norwegian wooden joist constructions: (a) type A, FR-CR and (b) type A, FR-CN.

modules, either point elastic solutions or line elastic solutions. Presentation of these solutions with measurement results and limitation is presented by Ljunggren and Ågren.[2] But due to the concept of complete 3D solutions, it is not possible to find laboratory measurements with the separate constructions itself. In the following, we assign the codes FS-CN or FR-CN (Floor Resilient–Ceiling No coupling) for those solutions (no coupling between beams and ceiling construction). This solution is more or less identical with construction type presented in Figure 3(b).

The third and also upcoming solution in Sweden is based on a hybrid solution with cross-laminated timber (CLT) elements on beams. The most successful solution has been developed by Martinsons of which a lot of in situ measurement results exist as well as some laboratory measurements. In fact, the complete solution for residential buildings is based on separate beams for the ceiling. Due to a combination with CLT elements in the load-bearing walls, it has also been necessary to use elastic interlayers between the floor element and the lower load-bearing wall. In the following, this floor assembly is also coded as a hybrid FS-CN solution (no coupling between joist and ceiling construction). A principal drawing of this construction type is presented in Figure 4.

Impact sound insulation properties

Measurement method and data

The impact sound insulation measurements were carried out according to ISO 140-6, versions valid at the time of measurements. Major part of measurements after 1995 has been carried out in the frequency range from 50 Hz. The measured normalized impact sound pressure levels in the frequency range 50–5000 Hz (or 100–3150 Hz) are presented as graphs in the following sections.

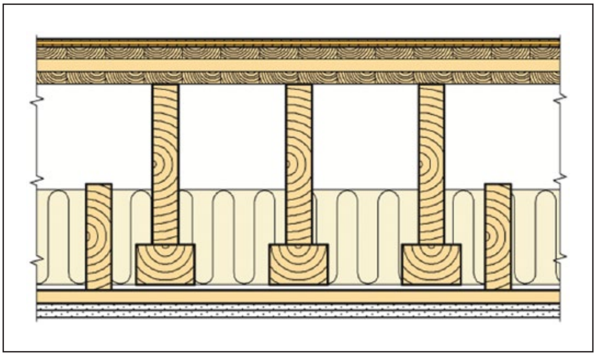


Figure 4. Common type of Swedish wooden joist constructions: type A, hybrid CLT and wooden joist construction, FS-CN.

From the test result, different single number quantities for rating the impact sound insulation were calculated, that is, $L_{n,w}$, the spectrum adaptation term, $C_{I,50\text{-}2500}$ and the sum of these, $L_{n,w}+C_{I,50\text{-}2500}$; see EN-ISO 717-2:1996.[7]

In the following sections, measurement results compiling comparable laboratory measurement data from the different countries are presented. Totally, approximately 170 laboratory measurement data have been collected and evaluated. However, for each construction group, a limited number of records will be reported. The idea has been to extract results only from the most comparable solutions. In section 'Construction group A: wooden joist constructions', impact sound insulation data from solution type A, measured in Germany, Finland, France, Norway, Sweden and Switzerland, are presented. In section 'Construction group B: wooden joist constructions with gravel or concrete', impact sound insulation results from solution type B, measured in France, Norway, Germany and Switzerland, are presented. For all presented data, the total mass per unit area (kg/m^2, denoted mpua) of the floor construction is given.

Through the analysis of this measurement results compilation, it is expected to observe and deduce what effect has the most influence on the floor performance in terms of impact noise. Indeed, it could be expected that mpua, ceiling mounting type and floor covering system are of importance.

Construction group A: wooden joist constructions

Laboratory measurement results of wooden floor constructions with stiff top floor and stiff suspended ceiling are presented in Figure 5. Even if the material specification may vary, it is an impressive correlation between measurements from Germany and Norway. The French measurement deviates with more than 10 dB, but this solution cannot be considered as fully comparable to the other two. The reason for this is the mounting of the ceiling (stiff suspended but) based on steel furring channels attached to steel hangers connected to the joists (rather than wood battens for the German and Norwegian systems). This mounting obviously introduced some flexibility between the joist and the ceiling. Such solutions will of course reduce the sound radiated from the ceiling. The measurement curve therefore verifies the effect of this more flexible ceiling suspension, with result similar to solutions with resilient steel profiles as presented in Figures 6 and 7.

Laboratory measurement results of floor constructions with stiff top floor and resilient suspended ceiling are presented in Figure 6. In Figure 6(a), results are given for solutions with mpua

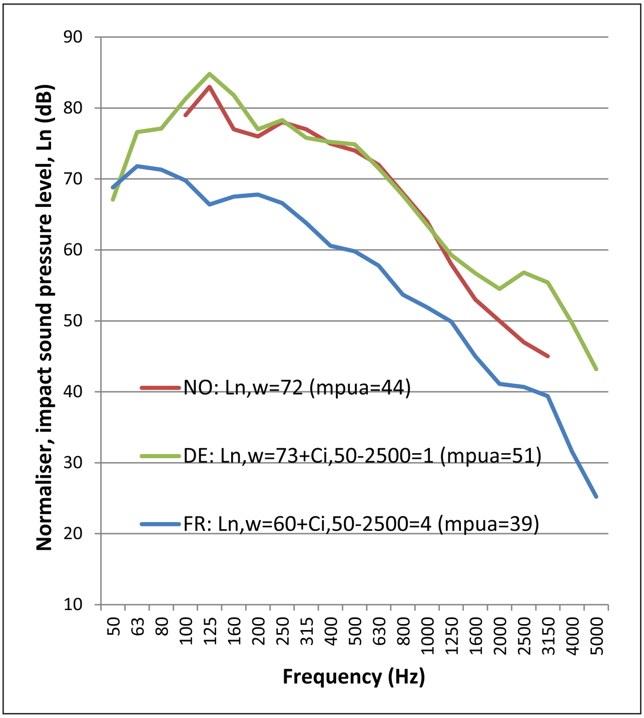


Figure 5. Measurement results from construction type A, FS-CS NO,[11] DE[12] and FR.[13]

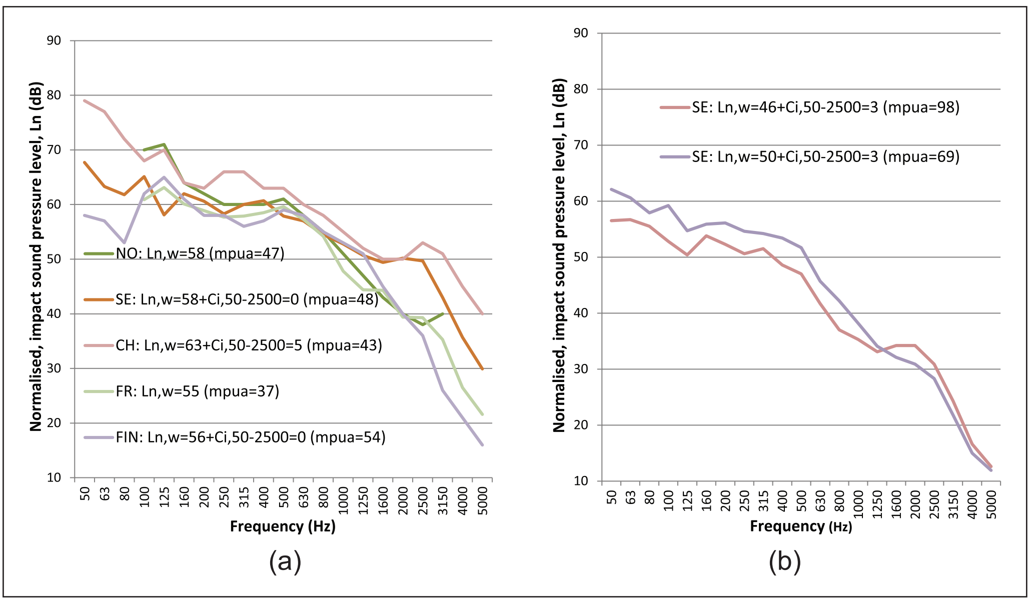


Figure 6. Measurement results from construction type A, FS-CR: (a) NO from Homb et al.,[14] SE from Nilsson,[15] CH from Lignum,[16] FR from Bois-AcouTherm[17] and FIN from Sipari et al.,[4] and (b) 2 × SE from Nilsson.[15]

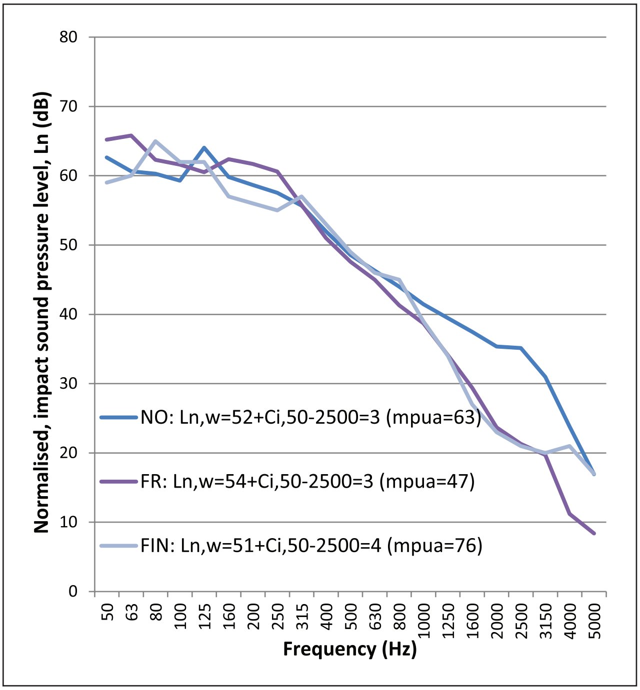


Figure 7. Measurement results from construction type A, FS-CN NO from Homb,[18] FR from Acoubois[13] and FIN from Sipari et al.[4]

of below approximately 50 kg/m^2. The results deviate considerably in the frequency range below approximately 160 Hz and above 1600 Hz. The deviation in the high-frequency range is not important in this article because it depends very much on the softness of the floor covering and the fact that the impact sound insulation anyway is good in this frequency range. The deviation in the low-frequency range needs to be investigated due to a significant increase (more than 2–3 dB) of the $L_n + C_{I,50\text{-}2500}$ value. A hypothesis is an effect of the joist and floor stiffness and modal behaviour. In the middle part of the frequency range, the result seems to correlate well with the mpua. This effect is also clearly shown in Figure 6(b).

Laboratory measurement results of floor constructions with stiff top floor and a fully independent ceiling uncoupled from the load-bearing joist construction are presented in Figure 7. The results show a relatively good correlation between the different measurements in the whole frequency range below approximately 1250 Hz. The deviation in the low-frequency range seems to correlate with the mpua. Different softness of the floor covering probably explains the deviations in the high-frequency range.

Laboratory measurement results of floor constructions with floating screed on resilient layer and a stiff suspended ceiling are presented in Figure 8. The results show deviation of 5–10 dB between the curves in the most important frequency range below 400 Hz even if the mpua is comparable. It is obvious that the properties of the resilient layer are of importance, but another reason could be related to the ceiling solution details and sound radiation from the ceiling. It probably explains huge deviations observed in the high-frequency range, but this is normally of minor importance with respect to the single number quantity.

Laboratory measurement results of floor constructions with floating screed on resilient layer and resilient suspended ceiling are presented in Figure 9. The results show deviation of

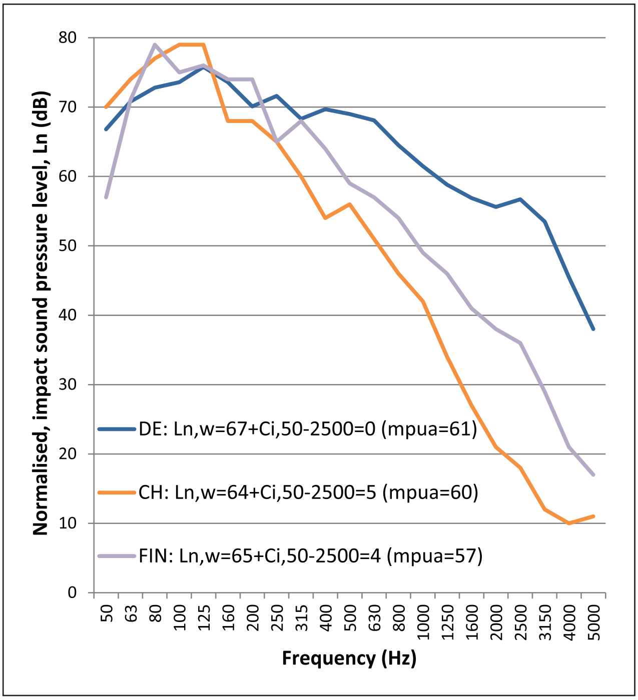


Figure 8. Measurement results from construction type A, FR-CS DE from Späh et al.,[12] CH from Lignum[16] and FIN from Sipari et al.[4]

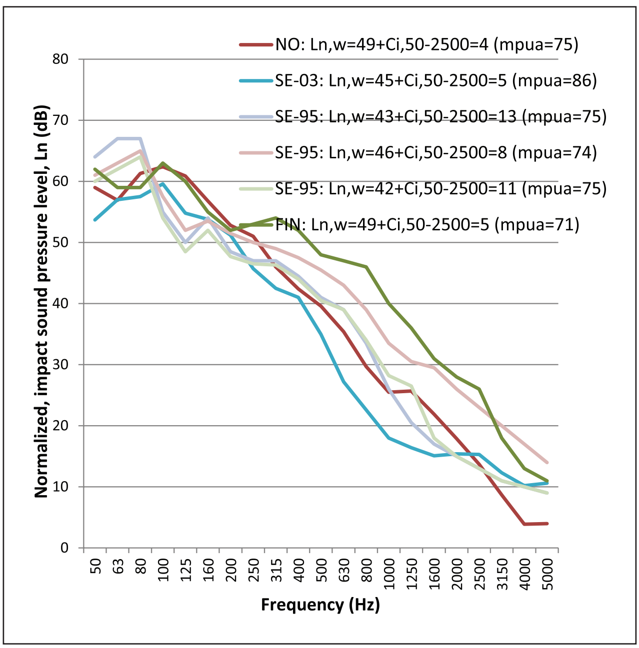


Figure 9. Measurement results from construction type A, FR-CR NO from Nemko,[19] SE-03 from Nilsson,[15] 3 × SE-95 from Johansson[6] and FIN from Sipari et al.[4]

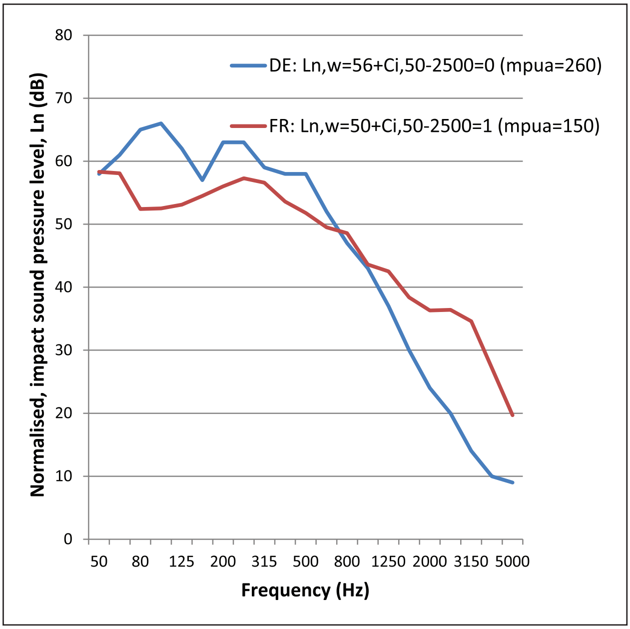


Figure 10. Measurement results from construction type B, FS-CS DE from Lignum[16] and FR from Acoubois.[13]

approximately 10 dB between the curves in the whole frequency range below 400 Hz, but with respect to single number quantities, the maximum difference of $L_{n,w}+C_{I,50\text{-}2500}$ is 6 dB. The results partly correlate with the mpua, as shown by curve SE-03 with the highest mpua and lowest single number quantity. With increasing number of layers, resilient products and possible combination of sheet layers, it is not surprising that such spreading will occur. But it is important to investigate the deviations between the different solutions in the low-frequency range, due to the necessity to limit the sound pressure level in the low-frequency range and to optimize solutions. Such investigations should at least include the joist and floor stiffness in combination with the effect of resilient top floor behaviour.

Construction group B: wooden joist constructions with gravel or concrete

Laboratory measurement results of wooden floor constructions with stiff top floor, added mass and a ceiling on rigidly fixed laths or stiff steel hangers are presented in Figure 10. In the frequency range below 800 Hz, the deviation between the curves appears to be relatively high because of the steel hangers and increased cavity depth of the FR case from Acoubois.[13] The results therefore show apparently a negative effect of the relatively high mpua of the DE case, from Lignum.[16] As mentioned before, the sound pressure level is sensitive to connections and radiated sound from the stiff suspended ceiling.

Laboratory measurement results of floor constructions with stiff top floor, added mass and a ceiling decoupled from the load-bearing joist construction are presented in Figure 11. The results exhibit low impact sound pressure level except in the frequency range below 100 Hz. Further studies should be focused on prediction of the impact sound insulation when adding alternative masses to these wooden floors.

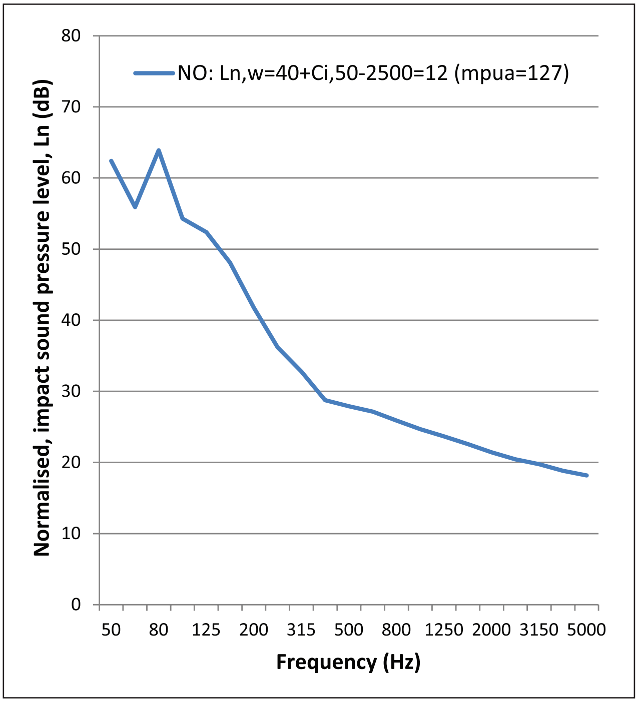


Figure 11. Measurement results from construction type B, FS-CN NO from Homb[18] and FR from Acoubois.[13]

Laboratory measurement results of floor constructions with a resilient top floor and a ceiling on rigidly fixed laths are presented in Figure 12. The results presented in Figure 12(a) (mpua < 200 kg/m^2) show deviation of approximately 5–15 dB in the frequency range below 800 Hz. Some part of this deviation is explained by differences of the mpua. Similar to other objects with stiff suspended ceiling, connections and sound radiation from the ceiling may be an important reason for differences between these measurement curves. The results presented in Figure 12(b) (mpua > 200 kg/m^2) show deviation of approximately 5–20 dB in the frequency range below 630 Hz. But looking into the single number quantity, $L_{n,w} + C_{I,50\text{-}2500}$, a strong correlation between the mpua and single number quantity is achieved. For these heavy solutions with use of gravel to increase the mass, variations due to the ceiling solution seem to be, in this case, of minor importance.

Laboratory measurement results of floor constructions with a resilient top floor and a suspended ceiling on resilient hangers are presented in Figure 13. In the middle frequency range, there are significant differences between the NO result from IGP[20] and CH results from Lignum[16] (see Figure 13(a)). A possible explanation is the position of the gravel. The gravel is at a sub-board for the NO case and above chipboard on the wooden beams for the CH cases. The deviation between the two CH cases correlates well with the differences of the mpua in the low-frequency range. The results presented in Figure 13(b) show a total spreading of 9 dB with respect to the $L_{n,w} + C_{I,50\text{-}2500}$, but these variations do not correlate with the mpua levels. The deviation occurs at frequencies below approximately 200 Hz, but it is difficult to point out a reliable explanation of these results. In the NO case from Homb,[21] concrete tiles have been installed on a relatively stiff resilient layer, while the concrete in the DE case from Lignum[16]

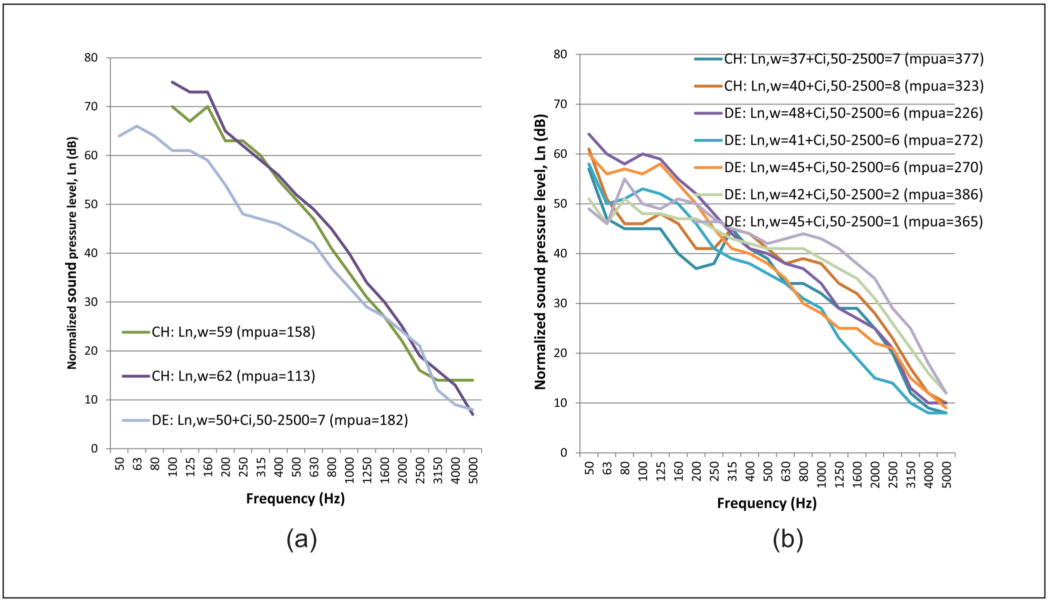


Figure 12. Measurement results from construction type B, FR-CS: (a) 2 × CH from Lignum[16] and DE from Lignum,[16] and (b) 2 × CH from Lignum[16] and 5 × DE from Lignum.[16]

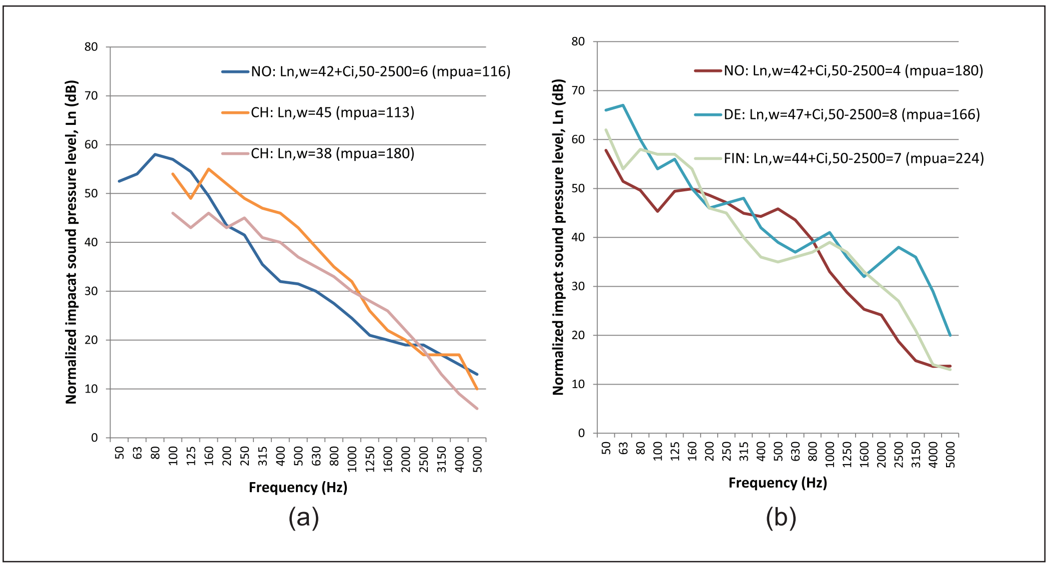


Figure 13. Measurement results from construction type B, FR-CR: (a) NO from IGP[20] and 2 × CH from Lignum,[16] and (b) NO from Homb,[21] DE from Lignum[16] and FIN from Sipari et al.[4]

has been installed on a soft resilient layer. In the DE case, a sharper peak level at the resonance frequency of the system can be expected compared to the NO case. In the FIN case from Sipari et al.,[4] a relatively thin resilient layer may explain poor results in the low-frequency range compared to the high mpua.

Table 2. Main results, impact sound insulation from construction type A.

Type A	$L_{n,w}$ (dB)	$C_{I,50\text{-}2500}$ (dB)	Sum (dB)	Mass per unit area (kg/m^2)	Source
FS-CS	60	4	64	39	FR
FS-CS	72	–	–	44	NO
FS-CS	73	1	74	51	DE
FR-CS	65	4	69	57	FIN
FR-CS	64	5	69	60	CH
FR-CS	67	0	67	61	DE
FS-CR	55	–	–	37	FR
FS-CR	63	5	68	43	CH
FS-CR	58	–	–	47	NO
FS-CR	58	0	58	48	SE
FS-CR	56	0	56	54	FIN
FS-CR	50	3	53	69	SE
FS-CR	46	3	49	98	SE
FR-CR	49	5	54	71	FIN
FR-CR	46	8	54	74	SE
FR-CR	43	13	56	75	SE
FR-CR	49	4	53	75	NO
FR-CR	42	11	53	75	SE
FR-CR	45	5	50	86	SE
FS-CN	54	3	57	47	FR
FS-CN	52	3	55	63	NO
FS-CN	51	4	55	76	FIN

FS-CS: Floor Stiff–Ceiling Stiff; FR-CS: Floor Resilient–Ceiling Stiff; FS-CR: Floor Stiff–Ceiling Resilient; FR-CR: Floor Resilient–Ceiling Resilient; FS-CN: Floor Stiff–Ceiling No coupling.

Result evaluation

Main results

In the following, the main results from previous sections are given. Table 2 shows single number values and corresponding mpua of construction type A. Figure 14 shows the $L_{n,w}+C_{I,50\text{-}2500}$ values as a function of the mpua for solutions with resilient ceiling or separate ceiling. The figure also includes a curve based on a ratio between the $L_{n,w}+C_{I,50\text{-}2500}$ values and the mpua of −30 log (mpua). The −30 log term refers to the basic equation of impact sound insulation of homogeneous floors.

Table 3 shows single number values and corresponding mpua of construction type B. Figure 15 shows the $L_{n,w}+C_{I,50\text{-}2500}$ values as a function of the mpua for solutions with resilient top floor. The figure also includes a curve based on a ratio between the $L_{n,w}+C_{I,50\text{-}2500}$ values and the mpua of −40 log (mpua). The −40 log term refers to the basic equation of impact sound insulation of homogeneous floors including the effect of a resilient sub-floor.

Result evaluations

Comparing laboratory measurements for similar floor assemblies, sometimes the frequency domain results coincide rather well and sometimes they coincide rather poorly. Table 4 shows an overview of similarities in the frequency domain when influences of the mpua are taken into account.

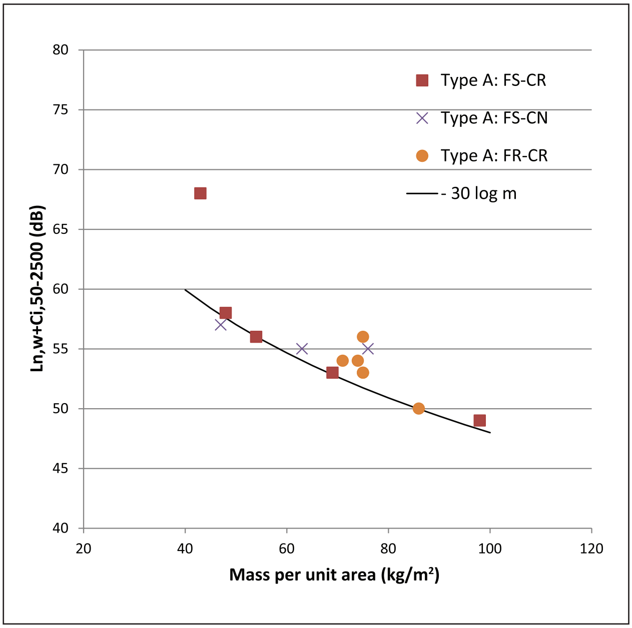


Figure 14. Single number values as a function of mass per unit area, construction type A.

Table 3. Main results, impact sound insulation from construction type B.

Type B	$L_{n,w}$ (dB)	$C_{I,50\text{-}2500}$ (dB)	Sum	Mass per unit area (kg/m^2)	Source
FS-CS	50	1	51	150	FR
FS-CS	56	0	56	260	DE
FR-CS	62	–	–	113	CH
FR-CS	59	–	–	158	CH
FR-CS	50	7	57	182	DE
FR-CS	48	6	54	226	DE
FR-CS	45	6	51	270	DE
FR-CS	41	6	47	272	DE
FR-CS	40	8	48	323	CH
FR-CS	45	1	46	365	DE
FR-CS	37	7	44	377	CH
FR-CS	42	2	44	386	DE
FR-CR	45	–	–	113	CH
FR-CR	42	6	48	116	NO
FR-CR	47	8	55	166	DE
FR-CR	42	4	46	180	NO
FR-CR	38	–	–	180	CH
FR-CR	44	7	51	224	FIN
FS-CN	40	12	52	127	NO

FS-CS: Floor Stiff–Ceiling Stiff; FR-CS: Floor Resilient–Ceiling Stiff; FR-CR: Floor Resilient–Ceiling Resilient; FS-CN: Floor Stiff–Ceiling No coupling.

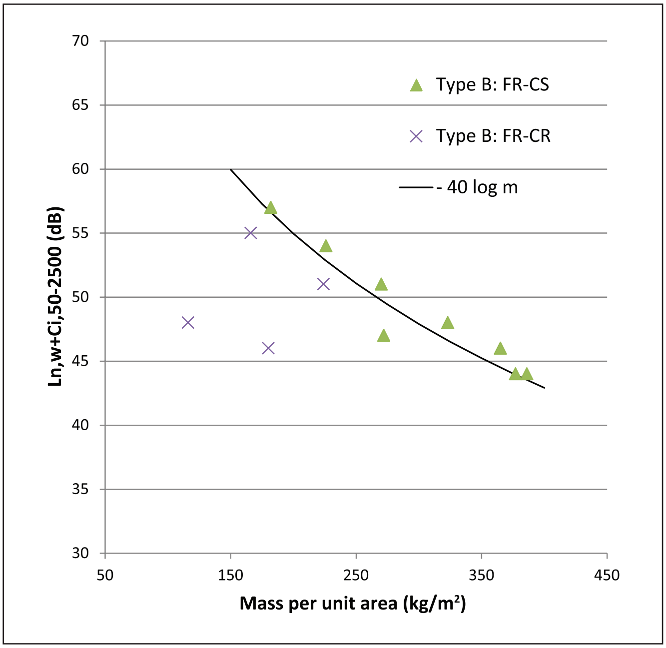


Figure 15. Single number values as a function of mass per unit area, construction type B.

Table 4. Similarities in the frequency domain between different measurement objects.

Frequency domain similarities	Type A	Type B
High or medium	FS-CS, Figure 5 FS-CN, Figure 7 FR-CS, Figure 8	FS-CN, Figure 11
Low	FS-CR, Figure 6(a) FR-CR, Figure 9	FS-CS, Figure 10 FR-CS, Figure 12 FR-CR, Figure 13

FS-CS: Floor Stiff–Ceiling Stiff; FS-CN: Floor Stiff–Ceiling No coupling; FR-CS: Floor Resilient–Ceiling Stiff; FS-CR: Floor Stiff–Ceiling Resilient; FR-CR: Floor Resilient–Ceiling Resilient.

The overview presented in Table 4 shows that all constructions of type A without resilient ceiling present high or medium similarities in the frequency domain, which means that the results are more or less independent of details, products and laboratory conditions. But the comparison shows that the resilient ceiling system itself or in combination with the joist construction and assembly gives a high spread of the impact sound insulation properties in the frequency domain.

Looking into single number quantities, results given in Figure 14 show a high correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mpua (–30 log mpua) of FS-CR solutions except in the low mpua region. An explanation may be similar (or equal) properties of the resilient profiles used in the Nordic countries. For other floor assemblies, it is not possible to establish a reliable correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mpua from the collected data.

The compilation also shows that all constructions of type B show poor similarities in the frequency domain, except the solution with a separate ceiling (uncoupled floor and ceiling).

The comparison shows that all types of connections between the joist construction and floor or ceiling elements have an important influence and give a high spread of the impact sound insulation properties in the frequency domain. Considering single number quantities, results given in Figure 15 show a high correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mpua (–40 log mpua) of FR-CS solutions. This means that the resilient layer at the top floor used in the different countries may have similar properties with respect to dynamic stiffness. Regarding the FR-CR solutions, results given in Figure 15 show a poor correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mpua (–40 log mpua). The difference in performance between the various type B FR-CR solutions (more than 10 dB) is most probably related to the resilient support used to mount the ceiling.

Conclusion

This article presents the results of numerous well-controlled sound insulation measurements of wooden joist constructions conducted in the laboratory. Comparison of results with different solutions, different products and from different laboratories is of course challenging. But the grouping of constructions has been a very helpful tool to compare and analyse the results.

Considering the total collection of wooden joist construction data (i.e. construction group A), $L_{n,w}+C_{I,50\text{-}2500}$ results from 74 to 49 dB from objects with mpua from approximately 40 to 100 kg/m^2 are found. Similarly, the total collection of data from hybrid wooden joist constructions with gravel or concrete (i.e. construction group B) shows $L_{n,w}+C_{I,50\text{-}2500}$ results from 57 to 44 dB from objects with mpua from approximately 80 to 380 kg/m^2. It means that it is possible to choose solutions within a wide range of impact sound insulation properties and weight of the floor construction.

In the frequency domain, results regarding construction type A show high or medium similarities except objects with resilient ceiling. The comparison shows that the resilient ceiling system itself or in combination with the joist construction and assembly gives a high spreading of the impact sound insulation properties in the frequency domain.

The compilation also shows that all constructions of type B show poor similarities in the frequency domain, except the solution with a separate decoupled ceiling. The comparison shows that all types of connections between the joist construction and floor or ceiling elements have an important influence of the impact sound insulation properties in the frequency domain.

With respect to single number quantities, the picture is a bit different. Regarding construction type A objects, results show a high correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mpua (–30 log mpua) of FS-CR solutions except in the low mpua region.

Regarding construction type B objects, results display a high correlation between the single number quantity and the mpua (–40 log mpua) of FR-CS solutions. For all other floor assemblies, it is not possible to establish a reliable correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mpua from the collected data.

The collection of data and result analysis highlight some basic phenomena. For instance, how structural differences related to the grouping of the constructions change the frequency distribution of the impact sound level and the single number quantities. Another significant result is the influence of the mpua of the floors. The mounting of the ceiling also plays an important role in the floor performance. Within the STB project work, these data and results will give us the possibility to optimize existing solutions or develop new floor construction with respect to the impact sound insulation properties itself, geometrical or mass per unit load limitations and other physical issues. Results from this work will also be used for verification of the ongoing research on prediction tools.

Acknowledgements

The authors would like to acknowledge all R&D partners of Silent Timber Build project representing the following countries: Sweden, France, Germany, Austria, Norway and Switzerland.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

This work was supported by Wood Wisdom Net for recommending financing of this project, and additionally, the financing organizations in each of the involved countries.

References

1. Johansson C. Field measurements of 170 nominally identical timber floors – a statistical analysis. In: *Proceedings of the InterNoise 2000*, Nice, 27–30 August 2000, pp. 4072–4075.
2. Ljunggren F and Ågren A. Potential solutions to improved sound performance of volume based lightweight multi-storey timber buildings. *Appl Acoust* 2011; 72: 231–240.
3. Warnock ACC and Birta JA. *Summary report for consortium on fire resistance and sound insulation of floors: sound transmission class and impact insulation class results*. Internal report IRC-IR-766, 1998. http://archive.nrc-cnrc.gc.ca/obj/irc/doc/pubs/ir/ir766/ir766.pdf
4. Sipari P, Heinonen R and Parmanen J. *Acoustic properties of wooden floor slabs* (VTT Publications 345). Espoo: VTT Technical Research Centre of Finland, 1998.
5. Fothergil LC and Royle P. The sound insulation of timber platform floating floors in the laboratory and field. *Appl Acoust* 1991; 33: 249–261.
6. Johansson C. Low-frequency impact sound insulation of a light weight wooden joist floor. *Appl Acoust* 1995; 44: 133–147.
7. EN-ISO 717-2:1996. Acoustics – rating of sound insulation in buildings and of building elements – part 2: impact sound insulation.
8. Simmons C, Hagberg K and Backman E. *Acoustical performance of apartment buildings – resident's survey and field measurements*. SP report 2011, http://www.simmons.se/Filer/PDF-filer/SP%20Rapport%202011-58%20Acoustical%20performance%20of%20apartment%20buildings%20-%20residents%20survey%20and%20field%20measurements.pdf
9. Guigou-Carter C and Balanant N. Acoustic comfort evaluation in lightweight wood-based and heavy weight concrete-based building. *Proceedings of the InterNoise 2015*, San Francisco, CA, 9–12 August 2015.
10. Homb A. Grouping of wood constructions. Silent Timber Build document, April 2015.
11. SINTEF. Unpublished laboratory measurement results. 1983.
12. Späh M, Liebl A and Leistner P. *Acoustics in wooden buildings – measurements in the Laboratory an in Single Family Houses*. AcuWood Report 1, SP Report 201414. Borås: SP Technical Research Institute of Sweden.
13. Acoubois Etapes 2 and 3. Measures Acoustiques en laboratoire. Qualitel, FCBA & CSTB. Rapport V2.0, France, June 2014 (in French).
14. Homb A, Hveem S and Strøm S. *Sound insulating structures: data collection and calculation method* (Anvisning 28). Oslo: Norges byggforskningsinstitutt, 1983 (in Norwegian).
15. Nilsson L. *SBUF-Projekt: wood joist floors*. Commissioned by Skanska Teknik AB. SBUF report nr. 1033. Lund: Laboratory measurements at Engineering Acoustics, Lund University (in Swedish), April 2003.
16. Lignum. Database, 2015, www.lignum.ch
17. Bois-AcouTherm. *Final report*, FCBA and partners. Boredeaux: November 2010 (in French).
18. Homb A. *Low frequency sound and vibrations from impacts on timber floor constructions*. Doctoral Thesis, IME Faculty, Department of Electronics and Telecommunications, Norwegian University of Science and Technology, Trondheim, 2006, vol. 132.

19. Nemko Report. *Sound insulation measurements of wooden joist floors*. Commissioned by Arbor Hattfjelldal AS, ABU0057/03. Trondheim: Classified (in Norwegian), 4 November 2003.
20. IGP AS. *Wooden joist floor with gravel: Impact sound insulation measurements* Commissioned by Norske Skog, report 215223. Trondheim: Classified (in Norwegian), November 1995.
21. Homb A. *Laboratory sound and vibration measurements of open web joist supported timber floors*. Project report O 14168, Norwegian building research institute for 'Norske Takstolprodusenters Forening' (not published), June 2003. Trondheim (in Norwegian).