1 Description of the research that has been carried out

Although a bit delayed due to the pandemic, the project must be considered as significant step forward in knowledge and methods. It has resulted in new knowledge regarding new methods for measurements and evaluation of impact sound in timber buildings, a lot of useful test data for the future, several journal papers, strong ideas for future progress and not least new research relationships. The research made in Sweden at RISE and LNU is related to the work packages:

- Work package 2 – Reverberation time at low frequencies
- Work package 3 – Simulation of low-frequency impact sound insulation
- Work package 4 – Psycoacoustics of floors.

The aim of WP 2 "Reverberation time at low frequencies was to improve measurement methods for estimation of sound absorption in rooms in low frequencies, especially in the range from 20 Hz to 100 Hz. This frequency range is below the range of the methods commonly used today within building acoustics and it is a range where they are not working well. This frequency range is of particular interest for multi-story timber buildings, since this is where they tend to have their highest impact sound transmission levels. This is one of the more challenging areas within timber construction, to secure accurate sound and vibration comfort. Measurements of sound absorption is important to gain knowledge about the acoustic environment and to accurately measure the sound insulation within buildings. The main obstacle today for reverberation time measurements, when estimating the sound absorption, is the frequency filters in the sound analyzers. Both analog and digital band-pass filters are too slow in lower frequencies to be able to present accurate one-third octave results, for normal rooms (with not excessively long reverberation times). After some consideration a few different methods of evaluation were chosen.

- Avoiding conventional filters, such as Butterworth filters, by using the Fast Fourier Transformation (FFT) algorithm.
- To use a reference sound source to estimate the sound absorption in the room.
- To use modal damping extraction by means of "modal analysis" of the sound field.

RISE took lead in the first method of the three above. For the FFT method interrupted noise signals with known frequency content were produced (both sinusoidal oscillations and random noise). The method was shown to be successful give an accurate decay pace if the dynamic range was sufficient. To achieve the desired one-third octave results, it was seen that a frequency resolution of 2 Hz is a feasible compromise between resolution and required dynamic range in the signals. A weakness is when the FFT calculates the initial part that covers both steady state noise and the decay. Since this part is not useful for classical regression calculation of the reverberation, the part is lost, and the dynamic range is narrowed. However, the benefit would be great if one could use this initial part as well or even instead of the linear decaying part for the reverberation time estimation. The benefit would be that both high frequency resolution could be achieved, and less dynamic range would be needed. It took some resources to develop the mathematics and programming to enable this. To program stable end detectors for the regression analysis required several improvements, to work in most conditions with difficult signals. The detectors are important parts in the outcome and the statistical stability of the results. If a detector is used that is not good in finding the start and endpoint of the regression analysis, the statistical quality of the method will not be accurate. Still, there was also a problem in accuracy due to spectral leakage in signals, which happens when signals are not periodic and it increases at strongly decaying signals. Due to the difficulties to keep track of the leakage, this version of the FFT method was abandoned. However, the work resulted in a published article in Applied Acoustics [1]. Later in the project further attempts were made in order to decrease the need for dynamic range and yet obtain the desired one-third octave results. The method may be used to more accurately extract acoustic damping in the low frequencies in the low 20 Hz one-third octave band and for short reverberation times (down to 0.1 s). This work has resulted in a submitted conference paper to the Forum Acusticum 2023 Conference [2]. The Incremental FFT script has also been packed as a Matlab demo script / function to make it accessible for a wider audience. The script / demo is free to be used and to modified by anyone.

The reference sound source and “modal analysis” to extract the modal damping. If the sound power radiated from a reference sound source is known, the steady state average sound pressure will give the information of the sound power in the room and the sound absorption of the room, since the sound power in the room is proportional to the absorbed / dissipated sound effect. Linnaeus university (LNU) took lead in this work. To measure the radiated sound effect in low frequencies is difficult. Anechoic chambers work down to around 80 Hz, as lowest usually. Here the main range of interest is between 20 Hz to 100 Hz. To be able to measure only the radiated sound, all reflected sound must be omitted. This may be done outside. A hard ground like concrete or tarmac reflects most of the sound (high impedance). The sky does not reflect sound, so it is a perfect absorber. Thus, a semi anechoic measurement setup for low frequencies is possible outdoors. A half-sphere measurement grid of thin rods was designed in an iterative process at LNU. The sphere has a radius of 5.0 m, and 20 microphones are mounted on along the sphere radius. The joints between the rods are 3D-printed to obtain the right shape. First mounting tests were made in a badminton sports arena in October 2021. After evaluation and further improvements, a last test mounting was made in the spring 2022. Preparations was made to measure with the half-sphere rig in summer of 2022. The location was Kosta old military runway outside of Växjö. The location was chosen as it is undisturbed, having rather large area of asphalt and non-reflective structures like buildings etc. The measurement sphere was mounted in week 27 in 2022, and the measurement preparations and measurements were made in week 28. The reference source that was used and calibrated is a JBL speaker model ASB7118, with possibilities to give significant outputs down to 20 Hz (together with a LAB.GRUPPEN FP 7000 amplifier). The speaker system was calibrated giving both stepped sine output and random noise output. To enable to extract modal damping by means of “modal analysis” the speaker system together with a significant number of microphones were tested at RISE in the receiving room of the impact sound insulation lab. The obtained information of the equipment makes it possible to extract the damping of each natural frequency in a room. These measurement results were used in the evaluation of the simulations of the absolute impact sound levels in the receiving room (WP 3 below).

Figure 1. The measurements of the reference sources at Kosta runway.

The aim of WP 3 Simulation of low-frequency impact sound insulation was to develop methods for simulating impact sound insulation and to experimentally verify methods. The background for the simulation approach was:

1. The ISO tapping machine used in impact sound insulation measurements has shown to be difficult to simulate.
2. By adopting an "infinite shaft" below the floor that is not giving any reflections, the reflected sound and associated difficulties may be omitted.
3. Simulations are made for a known harmonic excitation on the floor and the resulting a radiated sound at a distance under the ceiling below.
4. The simulation results are frequency response functions (FRFs) for the known excitation and resulting radiated sound effect for the floor as a function of excitation frequency.
5. The point mobility of the floor together with the FRFs is a descriptor for sound insulation.
6. Having a reference floor for which the sound insulation has been simulated and verified by measurements, the sound insulation performance of any new floor version or other floor may be simulated with this method.

However, since the method is not calculating the absolute sound pressure levels in the receiving room, relative comparison is made with the known reference floor. By doing so the simulations together with the relative difference gives the sound insulation of a new floor that have not been measured. The difficulties with sound absorption and simulations of the tapping machine are avoided, which make simulations simpler and more feasible.

The experimental part of WP 3 and the plan to jointly test floors in Turku in Finland was hampered by the COVID19 pandemic and associated restrictions. The lab floor design also meant that the floor plates needed to be divided into two parts to able be taken into the acoustics lab in Turku. Therefore, it was decided that LNU and RISE create their own measurement set-up in Sweden, at RISE acoustic lab in Borås. To keep the simulations simple and to obtain good accuracy, a clear setup with a continuous slab of CLT was needed. There is a limited number of CLT-manufacturers that could deliver a slab of the needed size and they had long delivery times. It took roughly 10 months (from late summer 2021 until spring early summer 2022) from contact of the CLT manufacturer until they (Stora Enso) delivered the CLT slab. The measurements and tests took place in Borås in August and September 2022. The aim was to have a well-defined measurement setup and boundary conditions to minimize the number of possible causes for deviations between measurements and simulations. After some efforts to achieve four sided simply supported boundary conditions (it is difficult to get contact all way around the floor edges), it was decided to have a set up with point supports on the corners instead. To be able to verify the mode shapes and the natural frequencies of the floor, accelerometers were mounted under the floor in an even grid pattern of 5 x 5. The room below was rigged with 24 microphones, mounted on stands at levels from floor to ceiling. The microphones measured the relative sound insulation between the two main measurement setups, with good quality, and the modal damping of the room modes can be extracted from the obtained data. The test setups consisted of one bare CLT slab and the same floor with a heavy floating screed above an impact sound insulation layer on top the CLT slab. Excitations were made with different sources such as electromagnetic shaker, modal (force measurement) hammer, the ISO rubber ball and a special ISO tapping machine with just one tapping piston which was set up to measure the impact force. The measurements went well and provided a lot of good data.

The simulation part of WP3 consisted of modelling the floor and establish the simulation script for analytical sound radiation from a surface and simulating the sound radiation of the measured floor. The modes of the natural frequencies were simulated in the finite element software Nastran. The FRFs were calculated with Matlab scripts with the theory of modal based frequency response function, together with sound radiation from a surface into a squared infinite duct. However, it was seen that the relative calculations, especially in the higher frequencies were not sufficiently accurate. The floor model has not yet been calibrated, with the use of test data, which is a cause of the deviations in the preliminary results. In the lowest frequencies, especially at the first resonances the accuracy is higher (see Figure 3). Further investigations are needed in order improve the simulations. This part has been lacking, due to project funding and time running out. The measurement data are of high quality, and they constitute a firm ground for further development of simulation methods. COVID19 took away the synergy effects of making the tests in Finland. Additionally, the full measurements and setup in Sweden took more time and expenses than was planned for in the project.

Figure 2. Left photo show the receiving room (at RISE building acoustic laboratory in Borås, for impact sound measurements of floors), where the test CLT floor is rigged with 5 x 5 accelerometers on its ceiling. Some of the microphones are also seen in the photo. The photos on the right show the above side of the floor, where the excitations and force measurements were made. The upper right shows the bare CLT- slab and the lower right shows the floor with a heavy floating screed above an impact sound insulation layer on top the CLT slab.

The data from measurements with the reference speaker in the acoustic lab will be used for estimating absolute sound levels of the sound transmission through the floor and the damping of modes in the receiving room. With this information it possible to give each mode its correct damping value which makes it possible to calculate the absolute sound levels in the receiving room of the impact sound lab in Borås. This data is considered to save much time for future further research.

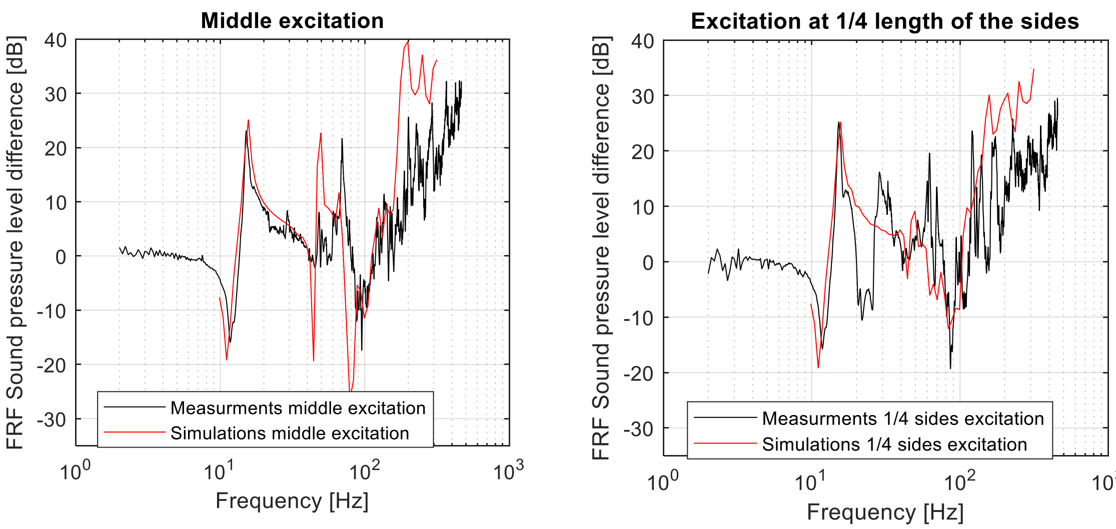

Figure 3. Comparison between the measurements in Borås between the two main set ups (bare CLT floor and CLT with additional screed and impact insulation layer) and the corresponding measurements. It is seen that in the lowest frequencies it is rather accurate, however as the frequency increases the deviations increases. The area up to 100 Hz is however of main interest.

The purpose of WP 4 Psychoacoustics of floors was to find a single number quantity (SNQ) that gives a better description of satisfaction of impact sound and measurements of impact sound in timber buildings. The descriptor used today in Finland and Sweden among other countries (Ln,w + CI,50) is not giving satisfactory quality i.e. correlation between perceived disturbance / satisfaction and measurements of impact sound insulation. This is important since the numbers are used in requirements, and a low accuracy drives higher safety margins, which costs money. This inaccuracy and low adaptation of the methods to the sound types (lower frequencies) that occurs in timber buildings motivates this research. Detailed measurements of sound insulation, the impact sound and listening test of recorded sound is here used to find a best correlation between psychoacoustic tests and SNQs. The aim is to take away the uncertainties of the corresponding in-situ studies that have been made. A summary of what was made: Fifteen variations / set-ups of wooden floors were built in laboratory and sound insulation was measured.

- Five natural impact sounds were recorded on the floors and played to participants.
- There were 52 participants in the listening tests.
- They rated the noise annoyance of recorded natural sounds using scale 0 to10.
- Annoyance could be predicted if the impact sound insulation was properly expressed.

The tests are thoroughly described in the reports / manuscript drafts produced on the subject. The subject is interesting since, for instance, the measurements of the different floor setups provide interesting design information for the building industry about performance of different floorings and ceilings on CLT and timber rib slab floors [3]. The psychoacoustic work is presented in scientific paper [4] and selected parts are for instance presented in the Forum Acusticum 2023 conference [5]. Measurement data have been published in Mendeley.

2 Publications from the project

[1] Olsson, Jörgen, Andreas Linderholt, Kirsi Jarnerö, and Valtteri Hongisto. "Incremental use of FFT as a solution for low BT-product reverberation time measurements". *Applied Acoustics* 203 (2023): 109191.

[2] Conference paper submitted to the conference proceedings of the Forum Acusticum conference 2023, to be held 11th to the 15th of September 2023:Olsson, Jörgen, Andreas Linderholt, Kirsi Jarnerö, and Valtteri Hongisto. "Incremental use of FFT as a solution to measure short reverberation times in low one-third octave bands". *Conference proceedings of the Forum Acusticum conference 2023* (2023).

[3] Finnish report Laboratory measurement results of sound insulation of intermediate floors:Hongisto, V., Alakoivu, R., Virtanen, J., Hakala, J., Laukka, J. & Keränen, J. (2022). Välipohjien ääneneristävyyden laboratoriomittaustuloksia. Turun ammattikorkeakoulun raportteja XXX, Turun ammattikorkeakoulu, Turku. ISBN (not defined)

[4] Journal paper submitted to the *Building and Environment* journal (Submitted 2023under review):V. Hongisto, J. Laukka, R. Alakoivu, J. Virtanen, J. Hakala, A. Linderholt, K. Jarnerö, Olsson, J. and J. Keränen. Suitability of standardized single-number ratings of impact sound insulation for wooden floors – Psychoacoustic experiment

[5] Conference paper submitted to the conference proceedings of the Forum Acusticum conference 2023, to be held 11th to the 15th of September 2023: V. Hongisto, R. Alakoivu, J. Keränen. J.

Hakala, A. Linderholt, K. Jarnerö, J. Olsson, and J. Laukka. "Frequencies under 100 Hz are not necessary in impact sound tests of wooden floors – Psychoacoustic experiment studying annoyance". Conference proceedings of the Forum Acusticum conference 2023 (2023).

3 Description of how the grant has contributed to competence building that will facilitate and strengthen long term collaboration between Finland and Sweden

The project started the in late spring of 2020, just after the start of the Corona pandemic. The bilateral work hampered a bit due to the Corona pandemic. It made collaboration, visits, and exchange harder in real life, but the development and use of digital tools and a new mindset regarding meetings contributed to and made intensive collaboration possible.

In October 2020 there was a two-day meeting in Växjö, Sweden. It was a start meeting to get to know each other and each other's research, planning of testing and prototypes, and exchange of ideas. A visit to Finland was planned from the start and collaborative testing to be performed in the new facilities at TUAS. Due to the pandemic the tests were performed in Sweden and Finland separately. The project final meeting was a two-day meeting in Turku, Finland in April 2023. The meeting included visit to TUAS laboratory facilities, discussion of project results, finishing of project and exploring possibilities for continued and future collaboration.

Complementary research areas have given new insights and broadened the research horizon for both countries and all three organizations. The collaboration has developed trust and mutual recognition of each other as individuals and of each other's research and development work, which has resulted in good relationships and a desire for continued collaboration.

At the meeting in April, another colleague from RISE participated. That person plans to seek collaboration with TUAS regarding psychoacoustics. The meeting gave rise to ideas about possible collaboration in R&D, but above all the intention to support each other in the common interests and involvement in the standardization work in the field of acoustics.

4 Description of research areas being started or strengthened at the departments in Finland and Sweden

Complementary research areas have given new insights and broadened and deepened the knowledge base and horizon for both countries and all three organizations. The project has improved the possibility to measure sound absorption / reverberation in the low frequency range, which has been very difficult to do with up to now current methods. One method also has potential to be used for evaluating acoustic damping in low frequencies, but also in other applications (and other fields which have similar signal processing challenges), such as structural damping.

From the Swedish side, the collaboration has deepened the knowledge regarding psychoacoustics i.e., the human response to sound, especially in the field of performing psychoacoustic tests, which is important for RISE research regarding timber buildings and impact sound insulation. It has brought in new perspectives into the research field regarding perceived annoyance of impact sound and:

- analysis and calculation of numerical values for impact sound insulation and frequency range needed to achieve high correlation with perceived annoyance for evaluated values.
- excitation methods of impact sound with tapping machine versus impact ball.

Results that are somewhat in contradiction with earlier and ongoing research in Sweden regarding single number value evaluation, which hopefully will generate interesting further research for deeper understanding. Regarding the use of impact ball, the results are very interesting since there is a lack of data with this measurement method.

TUAS had not collaborated with Swedish universities before this project. The collaboration has as whole strengthened the building acoustic research in Finland, since there is a lack of researchers in this field. TUAS has significantly strengthened the competence in sound insulation measurements of wooden floors, and psycho-acoustic research related to the impact sound insulation of wooden floors. The project initiated both these research fields at TUAS.

The Tampere University was involved in the initial discussions and planning of tests (Jesse Lietzen) and could benefit from the project to formulate research questions and implementation of doctoral studies. Prof. Karjalainen has also an independent public research project on a novel CLT solution on which TUAS has contributed during the project.

The project has contributed to build up and strengthen the research environments at all three organizations:

- The CLT slab that was bought to perform tests at RISE has strengthen the sound testing facilities. It is possible to use in future research projects regarding sound insulation in timber floors and for product development together with suppliers of flooring materials.
- The new tool/piece of equipment at LNU, a dome with 5 m radius on which microphones are mounted was used to calibrate the sound source in the project. The equipment and the microphones make it possible to continuous calibration of the used sound source, but also in measurements when spherical radiation of sound need to be measured. The calibrated sound source, loudspeaker, is ready to be used for measurements in small rooms when extraction of modal data directly from loudspeaker excitation is needed.
- At TUAS the CLT slabs used in their laboratory tests has also strengthened the laboratory resources and possibilities for future research applications and projects regarding sound insulation in timber floors and for product development together with suppliers of flooring materials.

The extensive testing has generated a lot of good data that can be reused and built on to further investigate and clarify the source to perceived annoyance of impact sound in timber buildings, but also excitation and measurement methods e.g. measurement quality when using the two different excitation sources, the tapping machine and the impact ball.

Over all the results from the project are important to further improve methods for measurements and simulations of impact sound, which is a top priority for the timber building industry. The perception of impact sound is a key factor for the customers of the industry and therefore crucial issue for the industry.

5 Description of how the grant has contributed to strengthening the forest sector in Finland and in Sweden.

Acoustics in wooden buildings is together with fire and moisture are the three top challenges for wooden structures. In the field of acoustics, the impact sound insulation is the top concern for the suppliers of wooden housing. An increased knowledge about impact sound insulation in wooden structures and measurement methods enables the development of better wooden floors. The move from building in concrete to increased building with wood is positive for the forest sector.

The measurements and evaluation methods are main problems in acoustics when building with wooden frame. It is possible to build silent timber buildings that people are happy with, but the uncertainty in knowledge and measurement methods are not making it clear. This project contributes clearly to improved accuracy in measurements and knowledge about perception important for timber building. The knowledge from the project can also be useful for the building acoustic consultants.

The industry, both those involved directly and indirectly, can benefit from the improved infrastructure and competence at the research implementers in their product development after the project. The industry has increasingly ordered acoustic test services from TUAS for product development purposes.

During the project TUAS has gained knowledge about wooden floors and established contacts with national wood building industry and suppliers of wooden structures. The data published in the test report, which contains the sound insulation of 30 wooden floors, benefits the wooden construction sector nationally, but also globally. The test data give valuable information about the effects on impact sound insulation from different types of floorings and ceilings on CLT floors and timber rib slab floors.

6 Description of communication with relevant stakeholders and end users

The results have in Sweden been communicated through the competence group for sound and vibration at RISE, which is a forum to discuss, priorities and initiate research within acoustics in timber buildings. The group consists of researchers and stakeholders from industry, both consultants and housing companies, but also the trade organization for the wood industry, The Swedish Federation of Wood and Furniture Industry (TMF). Results have also been presented at the TMF wood housing group, consisting of technical managers from the housing companies.

The studied floor constructions at TUAS were designed after intensive collaboration with industrial companies (VVR Wood, CLT Finland, Saint-Gobain Finland). The results have been shared among the Finnish acoustic consultation industry via Finnish acoustics seminars (Akustiikkapäivät. Rakennusfysiikka, Puupäivä), organized by Finnish stakeholders (Finnish Acoustics Assoc., Finnish Assoc. Civil Engineers, Wood info assoc.).

The papers that are published and in progress (coming) are good. However, for benefitting industry, regarding the Incremental FFT, some work would be needed with standardization implementation.

7 Financial accounting.

Financial reporting only for the RISE organization.

In Table 1 below the end financial accounting is presented together with the updated budget for 2023 and the outcome until end of June 2023.

Table 1. Financial accounting

Finacial accounting	Original budget Total	RISE costs Until end of 2022	New budget 2023	RISE costs Until end of June 2022	Project Total
Salary cost incl. Social service	971080	1211960	250446	270749	1482709
Material	50000	91655	0	0	91655
Equipment	200000	0	0	0	0
Travel	100000	24174	15000	19184	43358
Other costs		98015	10000	500	98515
Overhead	672650	242392	50089	54150	296542
Sum	**1993730**	**1668195**	**325535**	**344583**	**2012778**

Comment to the financial accounting:

The project budget was exceeded in the closing stages to complete the article and upcoming presentation at a conference in September, as well as to compile information for the project's experimental data and scripts for analyses. The excess amount will not debit the funder's budget but is a cost at RISE.

Copy of the budget comment from the interim reporting end of 2022:

Due to the pandemic, the travel budget has not been used in the extent as was planned. The budget for investments is apparently not used, but the costs have ended up under other costs and the amount 141 570 SEK has been used for equipment. In the item for other costs, there are also costs relating to hired help in the laboratory to prepare and carry out tests as well as transport costs for the CLT slab that was used in the tests. Salary costs have increased and are larger than estimated in the original budget. As described in the reporting above, research and testing do not always take the path you thought they would take, so new plans had to be made. Writing papers and responding to comments from reviewers takes also more time than you might initially think. Table 1: New budget proposal for RISE in SEK.