Empa
Materials Science and Technology

FEM Case Studies in Building and Room Acoustics

Sven Vallely
sven.vallely@empa.ch

Stefan Schoenwald
stefan.schoenwald@empa.ch

Laboratory for Acoustics / Noise Control
Empa, Switzerland

SGA/SSA Autumn Conference 2023

Introduction

- Finite Element Method (FEM) for acoustic problems
  - ✓ Arbitrary geometries
  - ✓ Arbitrary boundary conditions
  - × Computationally expensive

- FEM is becoming more and more viable
  - Ever increasing computing power (e.g. CPUS, GPUS, RAM, SSDs)
  - More importantly, new numerical methods

- This presentation will cover 3 case studies of FEM used to solve building and/or room acoustic problems.

Empa

Case Studies

Part I: Impact Sound Pressure Levels

Part II: Transmission Loss

Part III: Digital Twin of a Sound Transmission Suite

1. Introduction
   - Aim
   - Motivation
   - Model
2. Outcomes
   - What Worked
   - Model Simplifications
3. Summary

Part I

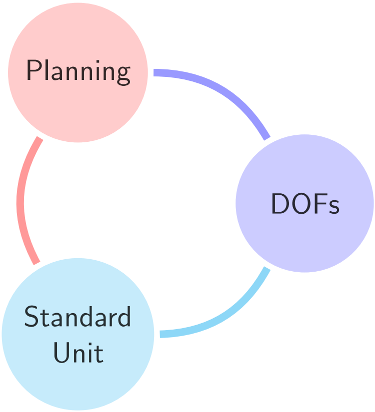
Impact Sound Pressure Levels

Sven Vallely
Stefan Schoenwald

Aim

To develop an impact sound pressure level model for cross-laminated timber floors.

Motivation



Cross-Laminated Timber (CLT)

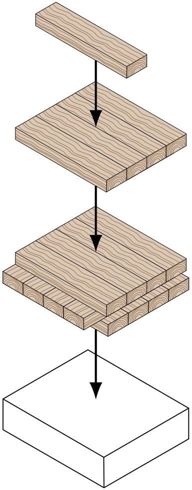
- Engineered wood product
- Many benefits, but difficult to model for acoustics

Additional design DOFs

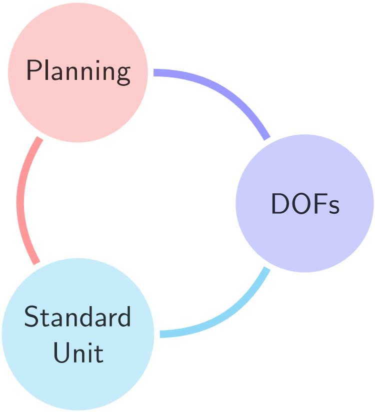
- Materials
- Thicknesses
- Orientation
- Stacking sequences

Planning Tool

- Design Freedom vs Design Knowledge



Motivation



Cross-Laminated Timber (CLT)

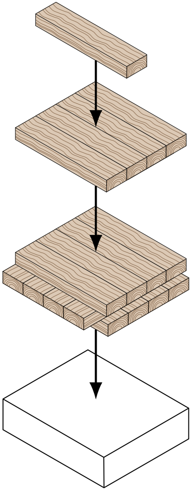
- Engineered wood product
- Many benefits, but difficult to model for acoustics

Additional design DOFs

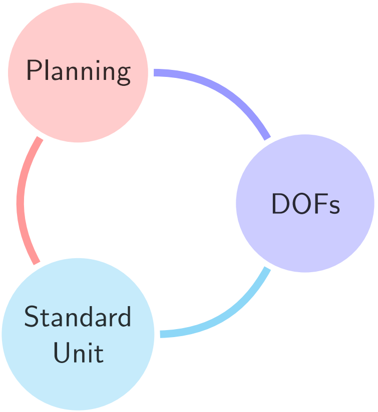
- Materials
- Thicknesses
- Orientation
- Stacking sequences

Planning Tool

- Design Freedom vs Design Knowledge



Motivation



Cross-Laminated Timber (CLT)

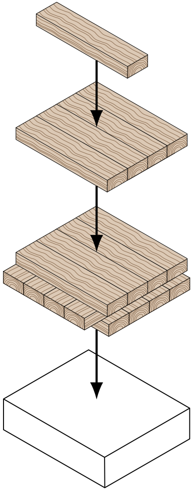
- Engineered wood product
- Many benefits, but difficult to model for acoustics

Additional design DOFs

- Materials
- Thicknesses
- Orientation
- Stacking sequences

Planning Tool

- Design Freedom vs Design Knowledge



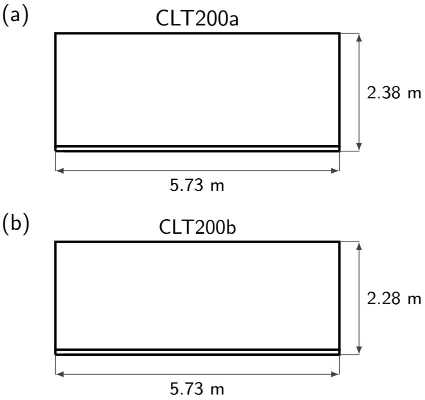
Empa

Model

The Floor Demonstrator

Floor Elements

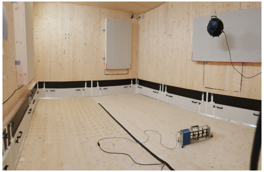
- 2 × CLT 200 mm 5-ply plates 4.56 m



Floor Testing Facility

Exterior

Interior, upper storey



Model

The Numerical Model

1. Structural Modal

- Orthotropic linear elastic plate
- Free boundary conditions
- No damping

2. Structural Harmonic

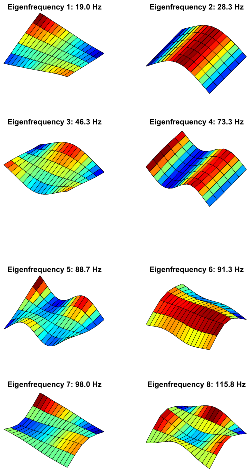
- Orthotropic linear elastic plate
- Free boundary conditions
- Structural material damping
- Harmonic point excitation

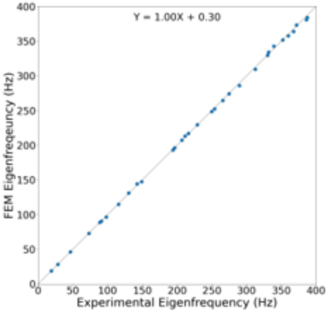
3. Vibro-acoustic Harmonic

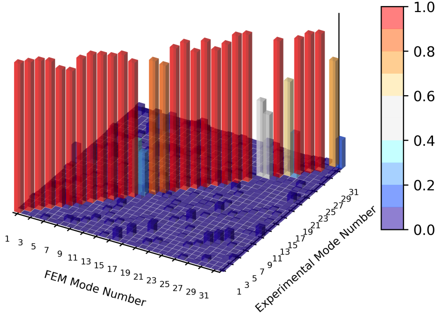
- Orthotropic linear elastic floor assembly
- Elastic boundary conditions
- Structural damping, material and boundaries
- ISO tapping machine excitation
- Semi-analytical radiated sound power calculation

What Worked

Structural Modal Model

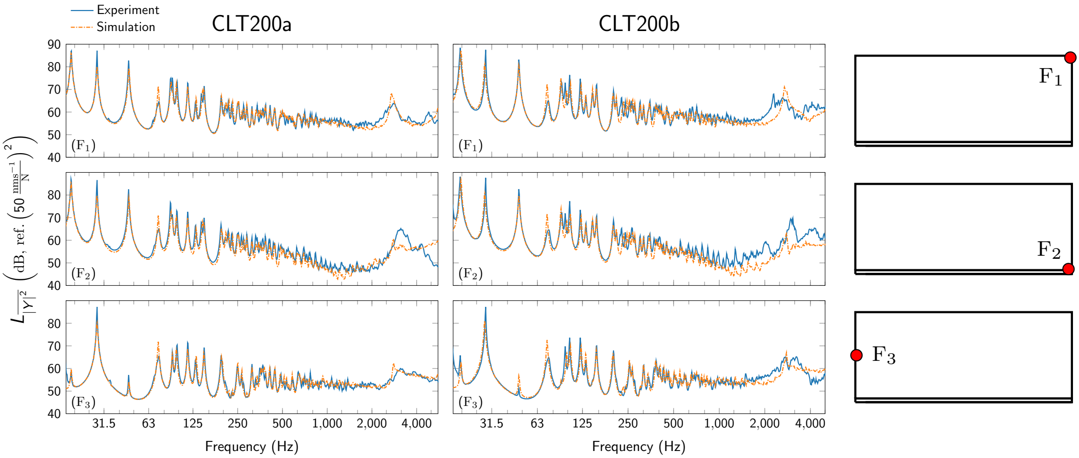






What Worked

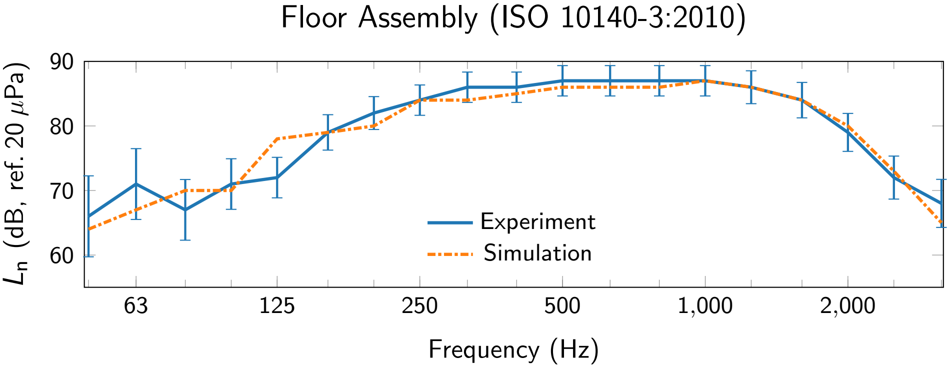
Structural Harmonic Model



Empa

What Worked

Vibro-acoustic Model

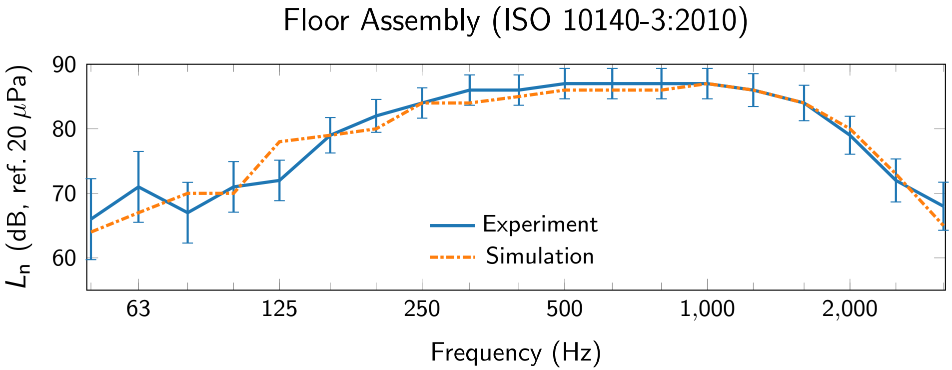


Empa

What Worked

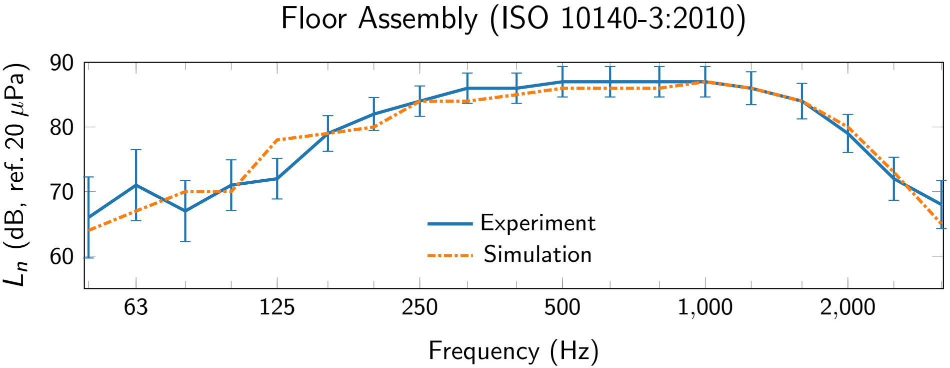
Vibro-acoustic Model

Data	$L_{n,w}$ (dB)	$L_{n,w} + C_I$ (dB)	$L_{n,w} + C_{I,50\text{-}2500}$ (dB)
Experiment	86 ± 2	81 ± 2	81 ± 2
Simulation	86	80	81

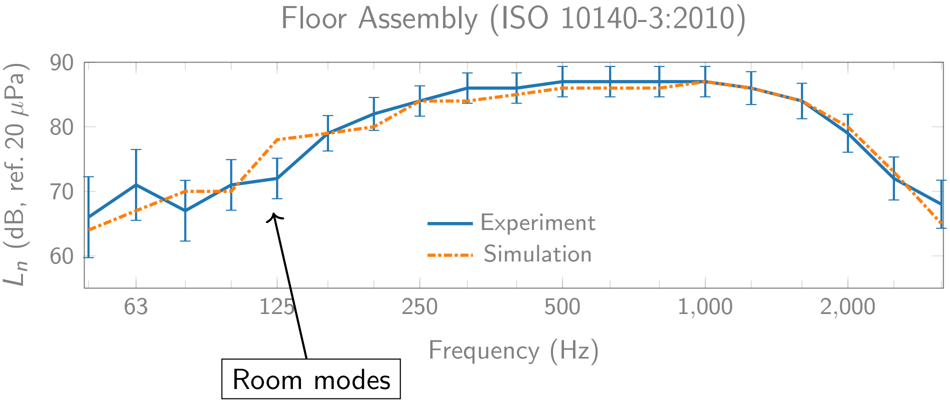


Empa

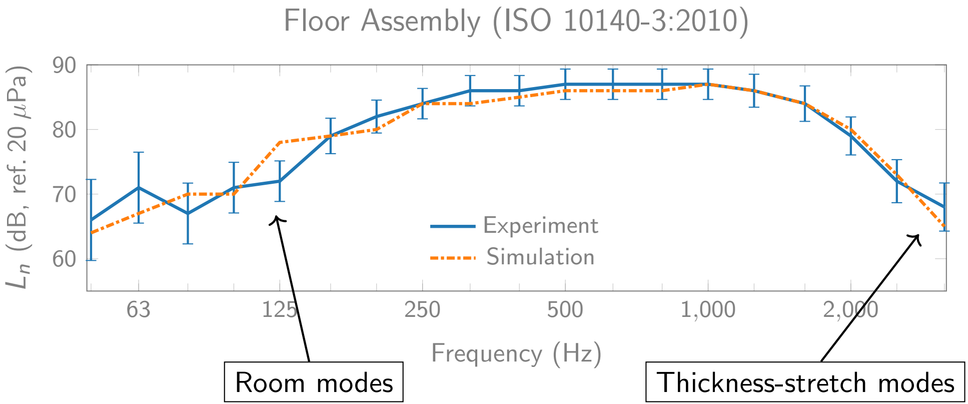
Model Simplifications



Model Simplifications



Model Simplifications



Summary and Conclusions

- Very good overall agreement with measurement for all three models
- A 'bottom-up' modelling approach worked well
- Important to understand the underlying physics of the model:
  - Simplifications made for increased efficiency
- Such models can than be used to explore chosen design spaces in a systematic and cost effective manner

Summary and Conclusions

- Very good overall agreement with measurement for all three models
- A 'bottom-up' modelling approach worked well
- Important to understand the underlying physics of the model:
  - Simplifications made for increased efficiency
- Such models can than be used to explore chosen design spaces in a systematic and cost effective manner

Summary and Conclusions

- Very good overall agreement with measurement for all three models
- A 'bottom-up' modelling approach worked well
- Important to understand the underlying physics of the model:
  - Simplifications made for increased efficiency
- Such models can than be used to explore chosen design spaces in a systematic and cost effective manner

Summary and Conclusions

- Very good overall agreement with measurement for all three models
- A 'bottom-up' modelling approach worked well
- Important to understand the underlying physics of the model:
  - Simplifications made for increased efficiency
- Such models can than be used to explore chosen design spaces in a systematic and cost effective manner

Part II

Transmission Loss

Jakub Fortuna
Stefan Schoenwald
Sven Vallely

Aim

To create an efficient model to analyse the transmission loss of partitions.

Motivation

1. Virtual testing
   - Check modification effects
   - Systematically explore design spaces

2. Explore efficient numerical modelling techniques
   - Diffuse sound field excitation
   - PML vs Infinite boundary conditions
   - Sensible default settings

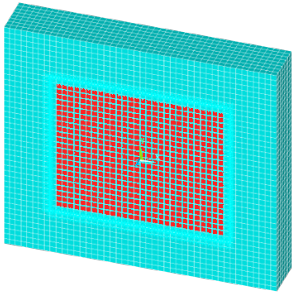
Empa

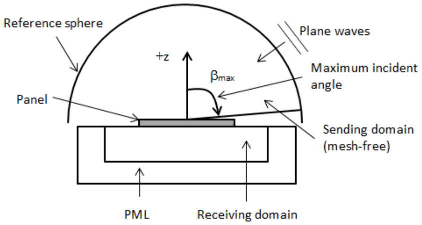
Model

The Numerical Model

Ideal Diffuse Field – Ideal Anechoic Conditions

- Shell elements for panels
- Air domain
- Infinite boundary conditions
- Mesh-free diffuse field excitation
  - Monte Carlo approach
  - Superposition of waves with random:
    - Incident angles
    - Phases
    - Equal amplitudes
- Analysis range: 50 Hz to 1000 Hz





Ansys Mechanical APDL, Release 2022R2, Help System, Acoustic Analysis Guide, ANSYS, Inc.

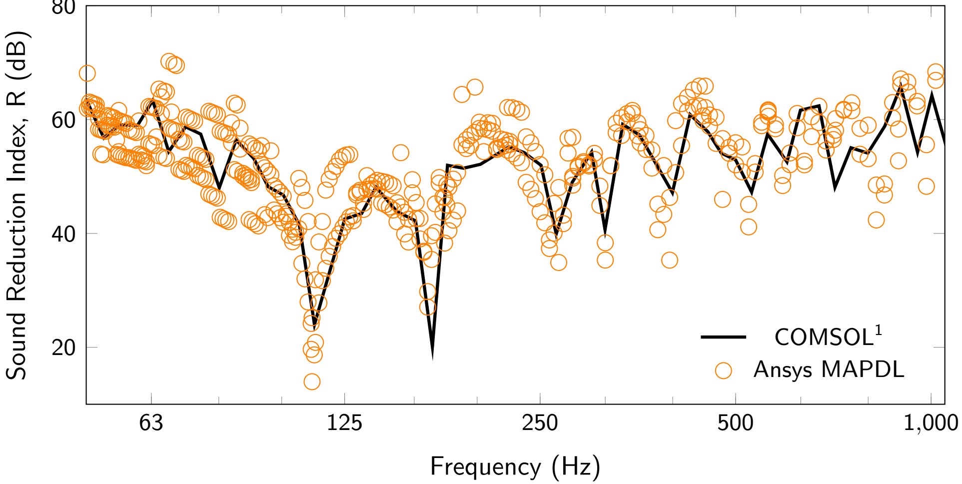
Empa

What Worked

Model Verification – Concrete Wall

4.37 m × 2.84 m × 0.203 m

[1] COMSOL Multiphysics. Sound Transmission Loss Through a Concrete Wall, Application ID: 73371, COMSOL AB, Stockholm, Sweden. 2023



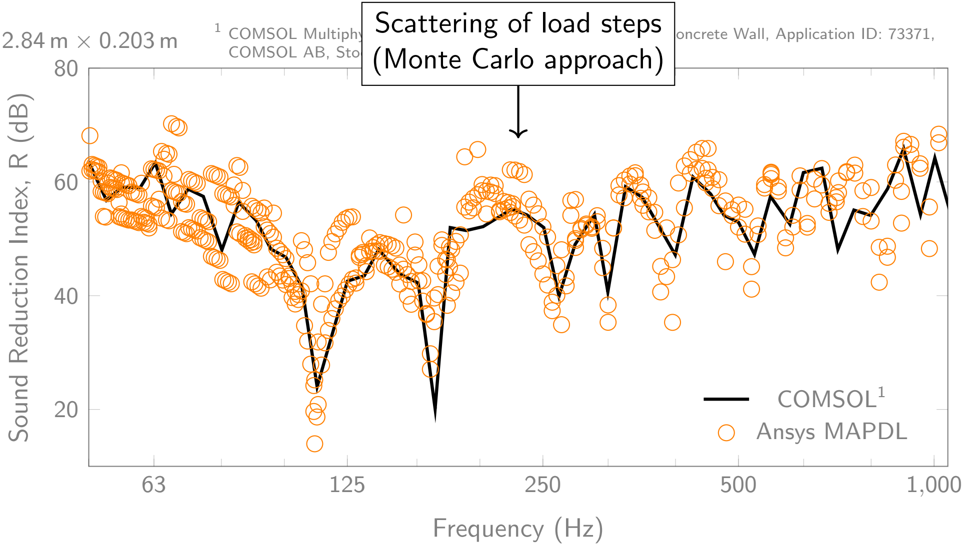
Empa

What Worked

Model Verification – Concrete Wall

4.37 m × 2.84 m × 0.203 m

[1] COMSOL Multiphy… …oncrete Wall, Application ID: 73371, COMSOL AB, Sto…



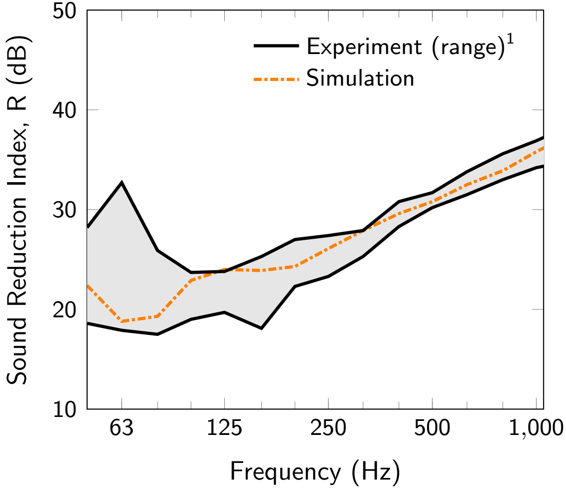
Empa

What Worked

Model Validation – Steel Panel

ISO 10140-2:2021

1.5 m × 1.25 m × 0.002 m



[1] Arne Dijkmans, Lieven De Geetere. "European Round Robin test for the Airborne Sound insulation of a Steel Panel." *Proceedings of Forum Acusticum 2023*. Turin, Italy.

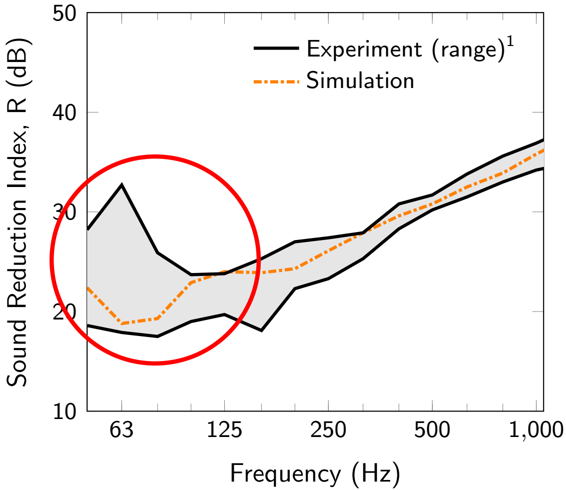
Empa

What Worked

Model Validation – Steel Panel

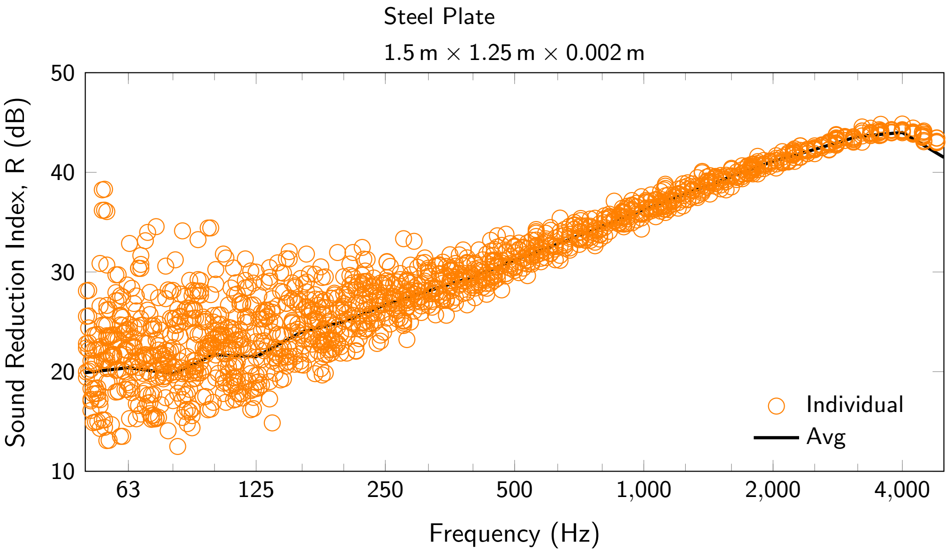
ISO 10140-2:2021

1.5 m × 1.25 m × 0.002 m



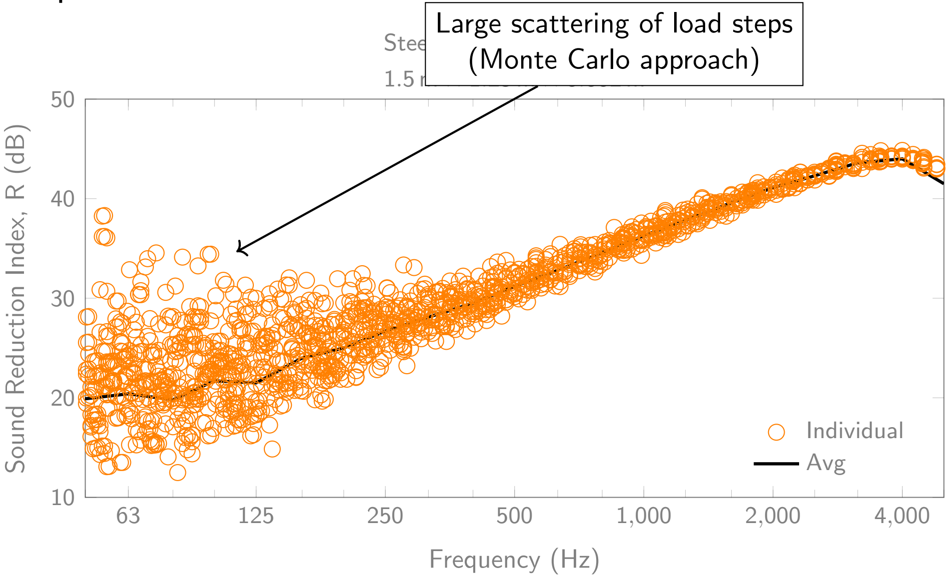
[1] Arne Dijkmans, Lieven De Geetere. "European Round Robin test for the Airborne Sound insulation of a Steel Panel." *Proceedings of Forum Acusticum 2023*. Turin, Italy.

Model Simplifications



Empa

Model Simplifications



Summary and Conclusions

- Model has good overall agreement with benchmarks
- There are simplifications and methods that allow the problem to become tractable with modern computing resources
- Large scattering is seen at low frequencies:
  - May need to account for coupling of partitions and rooms
- Overall: Appears to be a viable method for calculating sound reduction indices

Summary and Conclusions

- Model has good overall agreement with benchmarks
- There are simplifications and methods that allow the problem to become tractable with modern computing resources
- Large scattering is seen at low frequencies:
  - May need to account for coupling of partitions and rooms
- Overall: Appears to be a viable method for calculating sound reduction indices

Summary and Conclusions

- Model has good overall agreement with benchmarks
- There are simplifications and methods that allow the problem to become tractable with modern computing resources
- Large scattering is seen at low frequencies:
  - May need to account for coupling of partitions and rooms
- Overall: Appears to be a viable method for calculating sound reduction indices

Summary and Conclusions

- Model has good overall agreement with benchmarks
- There are simplifications and methods that allow the problem to become tractable with modern computing resources
- Large scattering is seen at low frequencies:
  - May need to account for coupling of partitions and rooms
- Overall: Appears to be a viable method for calculating sound reduction indices

Summary and Conclusions

- Model has good overall agreement with benchmarks
- There are simplifications and methods that allow the problem to become tractable with modern computing resources
- Large scattering is seen at low frequencies:
  - May need to account for coupling of partitions and rooms
- Overall: Appears to be a viable method for calculating sound reduction indices

Part III

Digital Twin of a Sound Transmission Suite

Arnon Vandenberghe
Stefan Schoenwald
Lukas Moy

Aim

Feasibility study: Digital twin of a sound transmission suite.

Motivation

1. Is it possible to assess modifications at our sound transmission suite with a FEM digital twin?

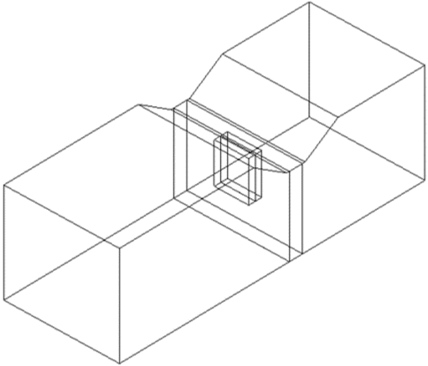
2. Basis for analysis of measurement uncertainty/reproducibility of results for an extended frequency range at low frequencies ($< 125\,\mathrm{Hz}$).

Model

The Empa Sound Transmission Suite

The Suite

- Two structurally separated rooms
  - Room 1: $101\,\mathrm{m}^3$
  - Room 2: $73\,\mathrm{m}^3$
  - Diffuse sound field: $>125\,\mathrm{Hz}$



Model

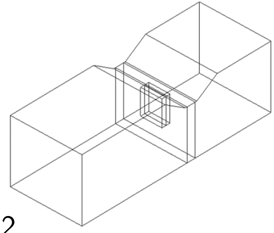
The Numerical Model

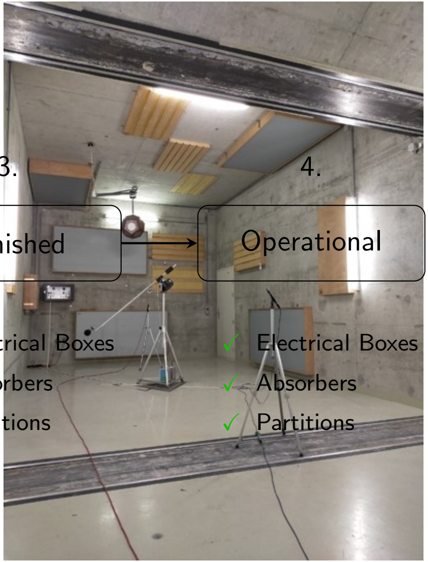
1.	2.	3.	4.
Empty →	Fitted →	Furnished →	Operational
× Electrical Boxes	✓ Electrical Boxes	✓ Electrical Boxes	✓ Electrical Boxes
× Absorbers	× Absorbers	✓ Absorbers	✓ Absorbers
× Partitions	× Partitions	× Partitions	✓ Partitions

Empa

Model

The Numerical Model





1.	2.	3.	4.
Empty →	Fitted →	Furnished →	Operational
× Electrical Boxes	✓ Electrical Boxes	✓ Electrical Boxes	✓ Electrical Boxes
× Absorbers	× Absorbers	✓ Absorbers	✓ Absorbers
× Partitions	× Partitions	× Partitions	✓ Partitions

What Worked

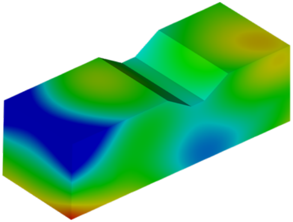
Model Details

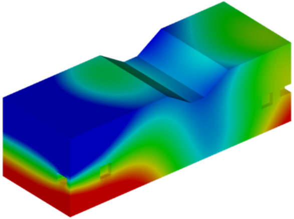
1. **Empty** → 2. **Fitted** → 3. **Furnished**

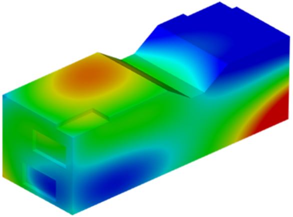
1. Empty
- × Electrical Boxes
- × Absorbers
- × Partitions

2. Fitted
- ✓ Electrical Boxes
- × No Absorbers
- × Partitions

3. Furnished
- ✓ Electrical Boxes
- ✓ Absorbers
- × Partitions



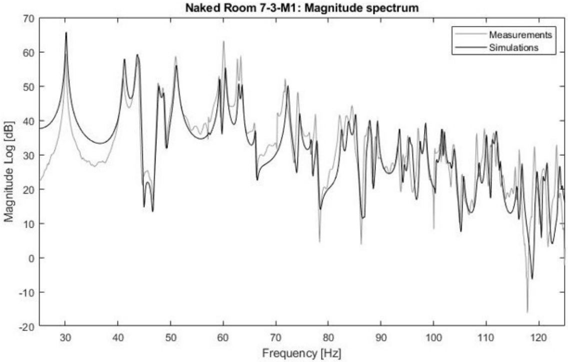


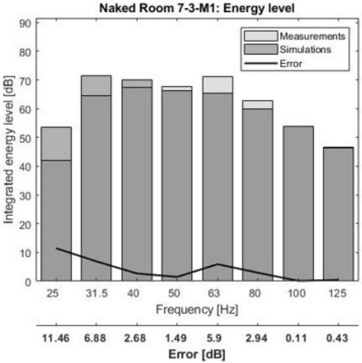


What Worked

Fitted Rooms – FRF

Element-wise absorption (walls, doors, etc.)

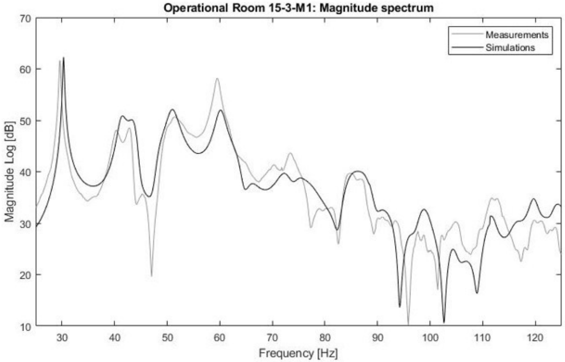


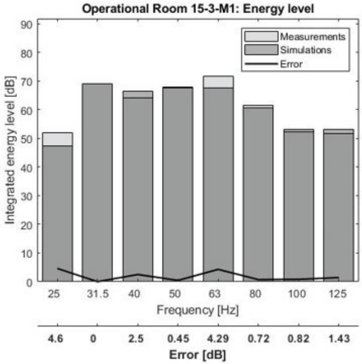


What Worked

Furnished Rooms – FRF

Average distributed absorption (single value for room)

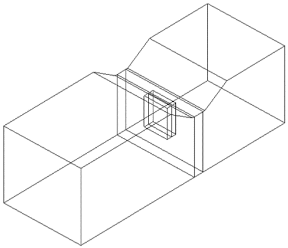




What Worked

Operational Rooms – FRF

Average distributed absorption (single value for room)



Model Simplifications

- Model fidelity
  - Sound source
    - Monopole sound source assumed
  - Boundary Conditions
    - Consider surface impedance (i.e. leakage effects, e.g. doors, seals, etc.)
- Available input data
  - Impedances
  - Sound source directivity

Summary and Conclusion

- The model has an overall good agreement with measurements
- Attention to geometrical details generally paid off
- Demonstrates possibility of augmentation of measurement results in the low-frequency range
- As usual: Trade-off between effort and accuracy

Final Summary and Conclusion

- All models require experimental validations.
- Possible to make better models, but requires more effort – beware of diminishing returns.
- Modelling can augment and speed-up the experimental process, but not replace it.

Acknowledgements

The authors gratefully acknowledge the financial support of the following research projects by

- The Swiss Federal Office for Environment (FOEN) under their:
  - Environmental Technology Promotion programme (UTF).
  - Aktionsplan Holz programme (APH).
- Empa internal funding.