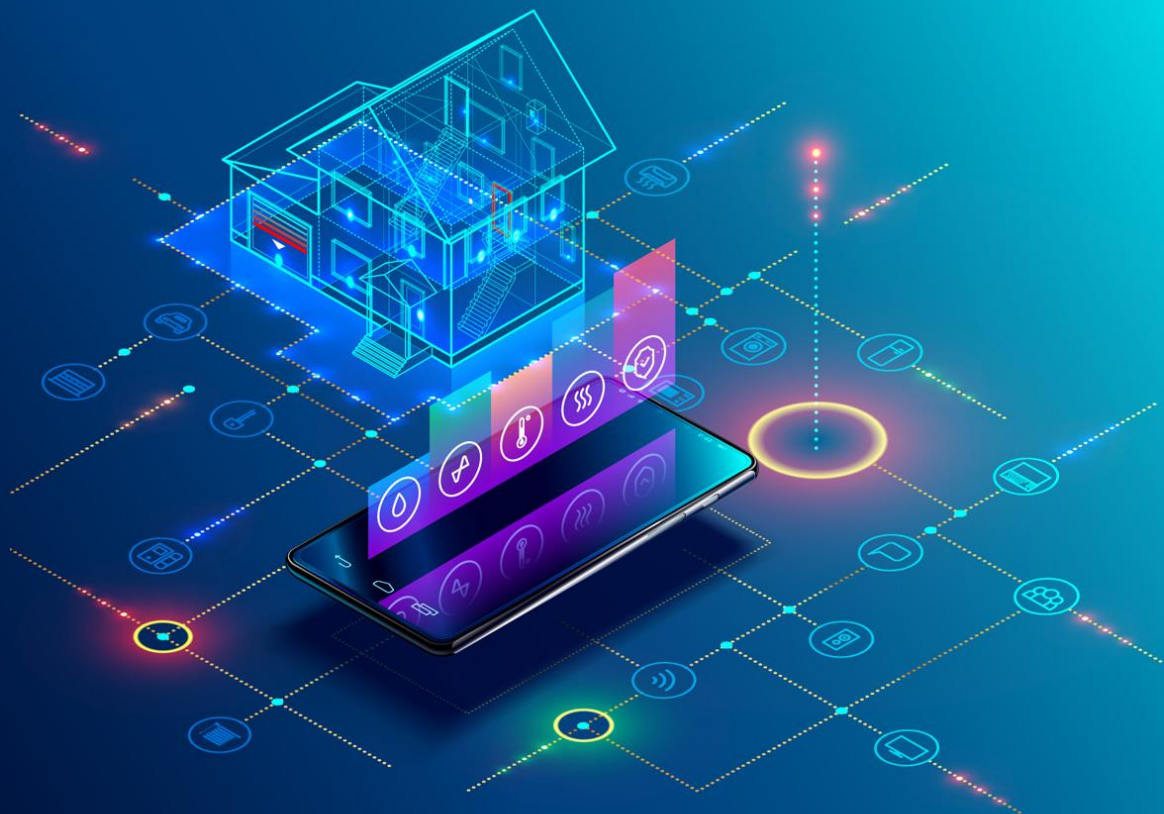**BIM** SPEED

# Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

Deliverable D4.3

Deliverable Report: D4.3, issue date on 17 November 2021

BIM-SPEED
Harmonised Building Information Speedway for Energy-Efficient Renovation

# Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

## Deliverable D4.3

## Colophon

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 2 - 84

# Change log

| Description | Author | Date |
|---|---|---|
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BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 3 - 84

# Publishable executive summary

*BIMSPEED is funded under the EU program H2020. BIM-SPEED aims to enable all stakeholders to adopt BIM to reduce the time of deep renovation projects by at least 30% by providing them with: 1) an affordable BIM cloud platform,2) a set of inter-operable BIM tools, and 3) standardized procedures for As-Built data acquisition, modelling, simulation, implementation, and maintenance of renovation solutions.*

*Within this framework, the importance of Indoor Environmental quality (IEQ) - Thermal comfort, Acoustic Comfort, and Indoor Air Quality (IAQ) - is relevant since the first function of a building is to provide a comfortable and healthy living environment. However, most of the existing buildings were built before the introduction of regulations and certification schemes that include the IEQ. For this reason, a practical framework to measure, assess and improve the IEQ in renovation projects has been developed. The framework provides tools to make use of measured, simulated and BIM-sourced data to allow detailed IEQ analysis to: i) assess current IEQ in existing buildings; ii) detect building's pathologies that cause IEQ issues iii) evaluate the impact of different renovation scenarios; iv) verify the efficacy of renovation works.*

*To this aim, different solutions have been developed and integrated with the BIM-SPEED platform:*

- *A web-service for IEQ KPIs calculation according to current standards that is compatible with simulated and with measured data.*
- *The Comfort Eye, that is a non-intrusive, IoT and smart sensing system for the monitoring of thermal comfort, IAQ and building envelope thermal performances.*
- *An acoustic calculator for acoustic comfort assessment.*
- *An acoustic leakages detector based on beamforming measurements.*

*This report presents the tools developed for the IEQ framework and results from their application in the project demonstration cases. The first part of the document describes the BIM based acoustic comfort assessment with measured and simulated data and the acoustic leakage calculator. The second part describes BIM based thermal comfort assessment with measured and simulated data and the thermal leakage calculator and BIM based indoor air quality assessment with measured data. The Tirth part describes the interoperability of the tool with the BIMSPEED platform and the last part the application in a real demonstration case.*

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 4 - 84

# List of acronyms and abbreviations

API: Application Programming Interface

BACN: Building Automation and Control Networks

BEM: Building Energy Model

BIM: Building Information Modelling

HVAC: Heating Ventilation Air Conditioning

IEQ: Indoor Environmental Quality

IFC: Industry Foundation Classes

IoT: Internet of Things

IT: Information technology

MQTT: Message Queuing Telemetry Transport

IFC: Industry Foundation Classes

DoA: Description of Action

BS: BIM-SPEED

ECM: Energy Conservation Measure

EEB: Energy Efficient Buildings

EPBD: Energy Performance Buildings Directive

EPC: Energy Performance Contract

ESCO: Energy Services Company

GIS: Geospatial Information System

IAQ: Indoor Air Quality

IPMVP: International Performance Measurement and Verification Protocol

IPR: Intellectual Property Right

KPI: Key Performance Indicator

MEP: Mechanical Electrical Plumbing

MVD: Model View Defition

M&V: Measurement & Verification

nZEB: nearly-Zero Energy Buildings

PMV: Predicted Mean Vote

ROI: Region Of Interest

DAS: Dealy-and-Sum

CB: Conventional Beamforming

PM : Particulate Matter

IR: Infrared

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 5 - 84

# Definitions

Acoustic beamforming: measurement technique, based on array of microphones, used to obtain maps/images of acoustic emission of the object of interest and to locate acoustic leakages.

Strategic noise mapping: map of the average outdoor noise level provided by local administrations for different urban areas.

IEQ: indoor environmental quality including thermal comfort, indoor air quality and acoustic comfort

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 6 - 84

# Contents

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 7 - 84

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 8 - 84

# Table of Figures

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 9 - 84

BIM-SPEED D4.3 - Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 10 - 84

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 11 - 84

# Table of tables

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 12 - 84

# 1. Introduction

## 1.1 INTRODUCTION CONTENT AND PURPOSE

The IEQ is an important aspect in the field of buildings' renovation because of its impact on human comfort, well-being, productivity, learning capability and health. IEQ derives from the combination of different factors influencing the human comfort sensation: thermo hygrometry, acoustic, illumination and concentration of pollutant components. All those aspects should be considered at the same level of importance considering that humans spend roughly 90% of their time indoors, especially after Covid-19 spreading. In addition, a recent study demonstrated that indoor environmental factors, such as temperature, humidity, ventilation, and filtering systems could have a significant influence on the infection. Several studies showed a correlation between the concentration of air pollutants, especially PM2.5 and PM10, and COVID-19 virus transmission [1][2]. Considering that 75% of European building stock was built before 1990 and with a climate context that has changed the last decade, it is reasonable that the majority of buildings is not able to keep the required comfort conditions because of the poor performance of the envelope and heating/cooling systems [3][4]. For this reason, current buildings' renovation approaches and trends are including the IEQ in the renovation assessment with an increased role of importance [5]-[7]. Even if the importance of IEQ has been largely demonstrated, actual measurement tools are not adequate because of the need of measuring several environmental quantities with a high temporal and spatial resolution. To improve buildings' IEQ level, multisensorial solutions should be adopted to assess the actual IEQ problems, to feed the building renovation design and to verify the achievement of the IEQ improvement after the renovation. Sensing solutions should integrate the measurement of different quantities, as air temperature, relative humidity, mean radiant temperature, $CO_2$, PMs, without neglecting the acoustic comfort. Concerning those quantities, the increased spread of small, low-cost and IoT sensing technologies is favouring the continuous monitoring, also in occupied environments, and allowing the monitoring during the whole renovation stages (before, during and after). However, the measurement of those quantities can be affected by uncertainly. For example, thermal comfort, specifically the mean radiant temperature, could be difficult for continuous and real-time applications. In fact, the mean radiant temperature is not homogeneous in the room and depends on the indoor walls' temperature[9][10]. ISO 7726 provides two methods for measuring the mean radiant temperature: i) the globe thermometer that is basically a temperature sensor located at the centre of a matt black sphere; ii) the angle factors approach, based on the walls' temperature measurements. The globe thermometer is widely used for spot measurements. It is intrusive, provides data only related to the position where it is located and one measurement point could not be enough to determine the real room's comfort. Thus, is not the preferable solution for continuous IEQ measurements. The second approach,

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 13 - 84

based on the angle factors, could provide a higher resolution once that the problem of measuring the walls' thermal maps is solved.

This report presents the BIM-based tools developed for IEQ performance assessment and improvement in buildings renovation. Interoperability with BIM (Building Information Model) has been developed to automatically retrieve building's data (e.g., floor area, geometry, material emissivity, occupancy etc.), needed for metrics calculation and performance assessment. Although, in the design planning phase, designers often use stand-alone software such as EnergyPlus, Climate Consultant , BIM based versions such as Bentley AECOsim Energy Simulator , Autodesk Insight 360, and Safaira for building simulation and analysis in operation in space comfort and energy consumption, a major shortcoming of a stand-alone version or a BIM based version of the simulation evaluation software is that it is impossible to simulate the evaluation of the operational phase results on the basis of actual conditions based on the specific space environment [11].  BIM and IoT integration research are still in nascent stages, and data interoperability, interaction, and cloud computing are obvious issues and limitations. To overcome this limitation, this research proposes an innovative system based on BIM and IoT technology. The designed prototype explores the integration of BIM platforms with sensor data. An integrated workflow was developed to compile, standardize, integrate, and to obtain an accurate analysis and facilitate monitoring data exchange using BIM information. After establishing the evaluation index of comfort, the developed methods are used to present the monitored data and analyzed comfort levels on the user interface. This will enhance user effectiveness and accuracy in the ability to grasp the changes in indoor environment comfort. By means of more accurate planning and forecasting of space use and user behavior patterns, user satisfaction with environmental comfort can be improved and for example excessive energy usage required for cooling and heating equipment can be reduced [12]-[13].

A BIM -based IoT system, Comfort Eye is developed to measure the required data for the thermal comfort and indoor air quality. It is composed by two nodes, the IR ceiling node for the thermographic image of all the surfaces and the desk node for the ambient parameter. The Comfort Eye is used for a long-term monitoring in continuously and in real-time, allows to have information about comfort and thermal maps of the indoor surfaces can be used to track the thermal performance of the building envelope. The large set of information available from the measured data can be used to identify IEQ problems and their origin.

Concerning acoustic comfort, a BIM-based analysis of the existing building is developed to assess the impact of renovation options on the building façades and the resulting indoor acoustic comfort improvement. The calculator requires as input the assessment of typical outdoor noise level of the surroundings and the sound insulation performance of the façade to provide an estimation of indoor noise level. Moreover, the decision for best renovation option is supported by a proposed technique for the identification of existing leakages in sound insulation of the façade.

This report focuses on the implementation of BIM for IEQ analysis and the interoperability of the tools with the BIM-SPEED Platform (Figure 1).  During the monitoring phase, in pre renovation,

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 14 - 84

starting from BIM information, and monitored data it is possible to obtain KPIs for thermal comfort, IAQ and acoustic comfort. The developed tools and methodology also allow to identify the origins and causes of discomfort and thus provide support for developing the various renewal options. The interoperability with the BIMSPEED platform allows to evaluate the KPIs with simulated data also of the different renewal strategies to be able to provide renewal support and select the best strategy The outcome will thus support the decision-making for renovation strategies.
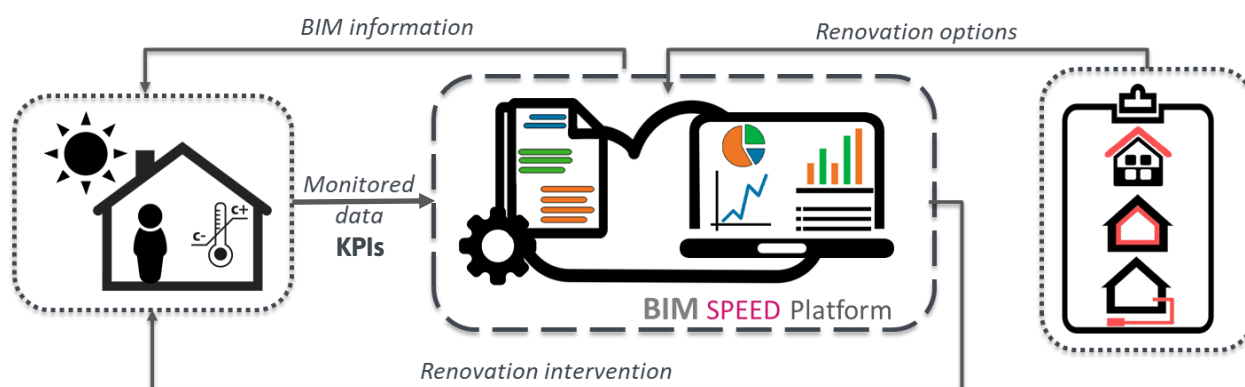


Figure 1 Dataflow Tools, BIM information and BIM SPEED Platform

This work will enhance the IEQ performance evaluation algorithms and modules based on the s-o-t-a methods developed by UNIVPM in recent or actual EU H2020 projects (NewTREND, P2Endure)

## 1.2 DESCRIPTION OF CONTENT AND PURPOSE

The document describes a practical framework for IEQ assessment, the tools and the methodology developed, the interoperability with the BIM SPEED platform and the applicability in a real demonstration case.

Section 2 is dedicated to the framework used to assess the indoor acoustic performance on both room and building scale. The methodology makes use of BIM model and the outdoor noise level to provide the acoustic class of a single room or of the whole building. Theoretical basis and standards used to predict the indoor sound pressure level and the method to assign the acoustic class are explained. The tool can be used to also predict the post renovation acoustic comfort performance. The last part of this section describes a proposed methodology to identify acoustic leakages on a room façade based on acoustic mapping with microphone arrays. This measurement technique provides useful information for picking the best renovation scenario. This tool merges together measured data and BIM data to perform simulations of the building envelope acoustic performance and to provide acoustic comfort classification

Section 3 describes the calculation model to assess the performance indicator for the IEQ: thermal comfort and indoor air quality. The methodology provides long term indicators and KPI to be used for comfort assessment according to EN 16798 assessment methodology that is based on indicators and their boundaries for building's classification. According to ISO 7730 and ISO 7726 "a human being's thermal sensation is mainly related to the thermal balance of his or her body as a whole. The IAQ

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 15 - 84

assessment methodology, that provides the $CO_2$ KPI, is defined by EN 16798, and where relevant and needed, IAQ monitoring is enhanced with the monitoring of PM. This model is applied using simulated data and measured data with the IoT system (Comfort Eye). The IoT system is integrated with BIM that provides the information necessary to process the measured data and to obtain the KPIs.

The system allows to acquire continuously thermographic images and to perform a long-term monitoring Continuous measurement of building's thermal performances is relevant to guarantee the first function of a building: providing a comfortable and healthy living environment with minimum energy consumption. This section describes also a model applied to the thermographic images to identify the main sources of discomfort or inefficiencies of building's envelope.

To improve the analysis and support the renovation a sensitivity analysis is applied. It is used to identify the most critical parameter that create discomfort conditions or the deviation from the required comfort standards. Thus, the retrofit solution should be selected to reduce their impact, improving the building performances and the capacity of the building to reach the optimal comfort conditions and keep it constant.

Section 4 describes the interoperability of the tools with the BIM SPEED platform. The tools and the KPIs output regarding the acoustic, thermal comfort and indoor air quality are integrates in the BIM SPEED platform. The system allows to perform a detailed pre renovation analysis, to evaluates IEQ and identify the origin and the main causes of discomfort. Using simulated data, and using information from the pre renovation analysis, a simulation of different renovation scenarios is performed to support the renovation and identify the best renovation option. The system supports the decision-making process during the renovation. The post renovation analysis is performed to validate the actual improvement of the renovation. All the KPIs are displayed in the BIM SPEED platform.

Section 5 describes the tools applied to a real demonstration case, the buildings in Warmond. Regarding the thermal comfort and indoor air quality, using the Comfort Eye, two tests were carried out in the pre-renewal phase for the summer season. A test for the calculation of thermal comfort KPIs with the relative sensitivity analysis and a test for the calculation of indoor air quality ($CO_2$ and PM) have been made. The tool for calculating the U-value has not been applied because the requirements of the standards are not satisfied. One of the fundamental requirements to apply the model is the difference of ten degrees between inside and outside and, having available only data from the summer season this requirement was not fulfilled. Furthermore, regarding the simulation of different renovation scenarios the BEM model is needed. It is necessary to obtain simulated data, and it is not available for Warmond demo case.

Regarding the acoustic comfort at first, a characterisation of typical outdoor noise levels has been performed with the aim to quantify the acoustic load that is responsible of indoor discomfort. In addition the measurement of Sound Reduction Index (Rw) of the façade of  two apartments has been estimated according to the standard and finally, acoustic leakages  have been identified by means of acoustic beamforming mapping.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 16 - 84

# 2. BIM BASED ACOUSTIC COMFORT ASSESSMENT

This section describes a practical framework for indoor acoustic performance assessment. This tool merges together measured data and BIM data to perform simulations of the building envelope acoustic performance and to provide acoustic comfort classification. The data flow is sketched in Figure 2 where inputs for the acoustic comfort calculator are evidenced. The BIM provides geometry and material information through the raw IFC, while outdoor noise levels are provided by the BIMSPEED platform. The platform can store the exterior sound pressure level directly measured at 2 meters from the building façade as prescribed by the standard series EN ISO 12354 (by using an acoustic level monitoring system) or retrieved from the strategic acoustic map of the building district.
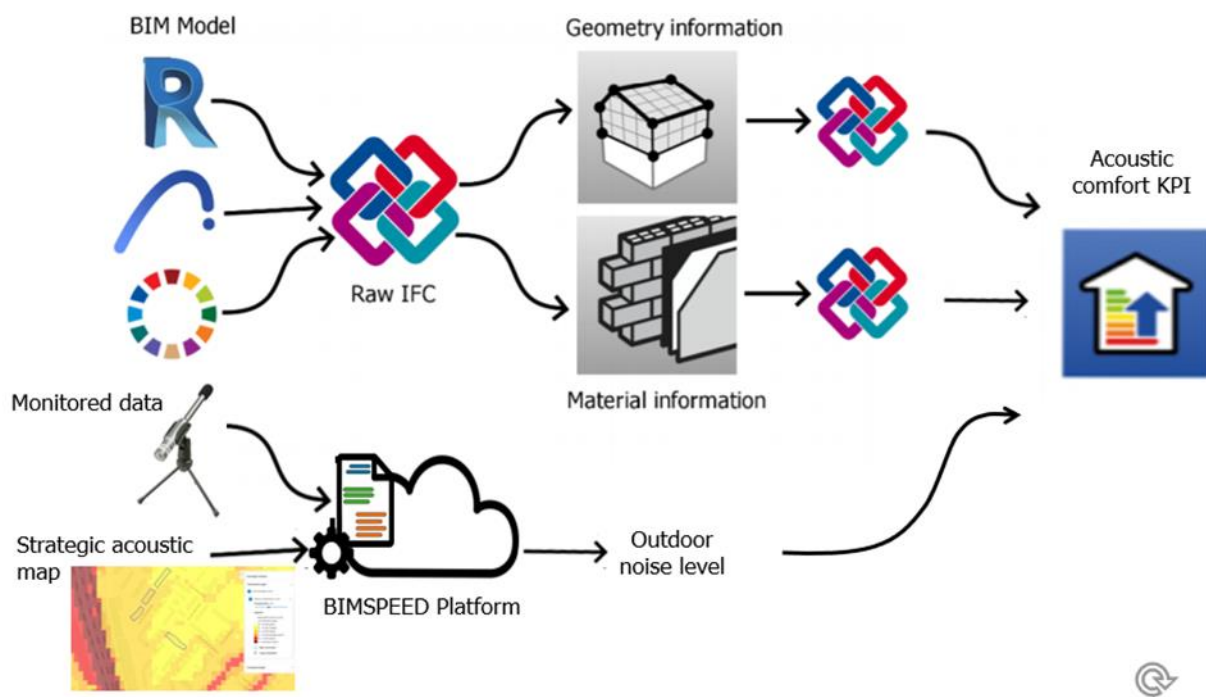


Figure 2 Acoustic calculator tool dataflow

Combining this information, the acoustic calculator tool returns an estimation of indoor acoustic comfort assigning a Class (from A to E) to each room depending on its use. The result is compared with the standards prescribed by European regulation. If minimum acoustic comfort requirement is not met, different renovation scenarios can be outlined. The impact of different renovation options can be assessed using the same tool. The identification of acoustic leakages present on a façade is also required to identify the most effective renovation scenario. A measurement system, based on beamforming techniques, is proposed in this sense. This system makes it possible to map the zones related to lower sound insulation (i.e. acoustic leakages) in presence of a uniform acoustic load on the façade under investigation (see Figure 3), in analogy with thermography for the identification of thermal bridges. The realization of acoustic maps requires an array of microphones to record pressure data from the

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 17 - 84

object of interest (similarly to the pixel array of a camera). The pressure recordings, combined with geometric data (i.e. microphone location with respect to the region to be mapped) and speed of sound, are used by an algorithm (i.e. beamforming) to produce the map of acoustic emission.
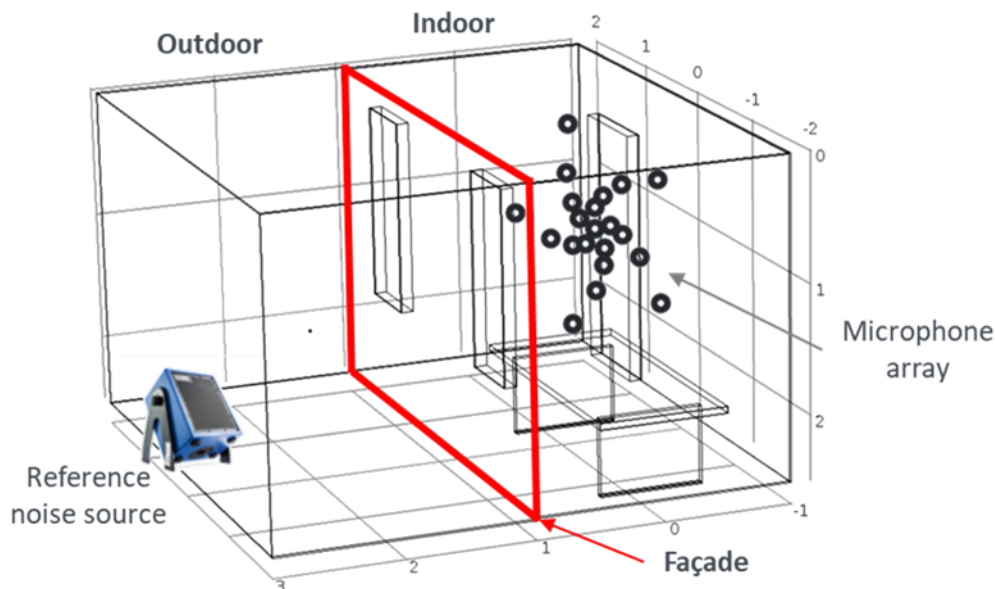


Figure 3 Acoustic mapping measurement system (black dots: microphone array exploited for the beamforming measurement; red red square: mapping surface, i.e. the façade, where the acoustic pressure has to be calculated)

This deliverable also includes the analysis outcomes of a selected real demonstration case, specifically the Warmond demo case (section 5.3)

## 2.1 ACOUSTIC COMFORT CALCULATOR TO EVALUATE THE PRE AND POST RENOVATION PERFOMANCES

The acoustic comfort calculator is a tool based on the estimation of the indoor sound pressure level according to the standard series EN ISO 12354 and it allows to assess the acoustic performance of the building and to assist the decision-making in retrofitting design, ranking different renovation options. The acoustic performance of the building is identified by an "objective KPI" called the acoustic KPI. This indicator is calculated from the sound pressure level estimated inside the rooms of the building from the knowledge of the external noise intruding inside, lowered from the acoustic abatement of the building envelope. The external noise level is generally known if a strategic noise mapping of the area where the building is located is available. Otherwise, a direct measurement of the external noise level is required. Even though is preferable to use the strategic noise mapping, when available, the uncertainty on the estimation of the indoor sound pressure level from the external noise level provided by the map is very high. It has been demonstrated [15] that the main cause of uncertainty in the indoor sound pressure level calculation is the estimation of the external noise which presents a sensitivity index of more than 80%. The use of strategic noise mapping provides indoor level predictions with an uncertainty of ±

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 18 - 84

6 dB since it samples large areas where the noise can present oscillations with respect to mean value. Therefore, a direct assessment of the external noise levels measured in front of the façade of the building under investigation is beneficial to improve the confidence on the acoustic KPI estimation.

The general procedure for the acoustic KPI calculation is based on the following steps:

(1) Direct measurement of the external noise level (i.e. the outdoor A-weighted equivalent noise level L1,2m [dB(A)]) at 2 m from the room façade of interest. When available, the outdoor A-weighted equivalent noise level can be alternatively estimated from the strategic noise map of the area where the building is located.

(2) Calculation of the standardized sound level difference of room façade based on the knowledge of the façade stratigraphy and of the façade elements available from the BIM.

(3) Evaluation of the indoor LA,eq [dB(A)].

(4) Assignment of the room acoustic class.

(5) Building-scale analysis for the building KPI assignment.

Steps from 2 to 5 are described in the following sections.

### 2.1.1 CALCULATION OF THE ROOM FAÇADE STANDARDIZED SOUND LEVEL DIFFERENCE

The acoustic insulation performance of a building façade, i.e. its ability of abating the noise coming from the exterior, is expressed through the sound level difference of the façade, $D_{2m,n,T}$ according to the standard EN ISO 12354 – 3. This parameter is defined as the difference between the outdoor sound pressure level at 2 m in front of the façade and the sound pressure level in the receiving room, corresponding to a reference value of the reverberation time. The standardized level difference of a façade depends on the façade apparent weighted sound reduction index ($R_{w'}$, related to the elements constituting the façade, like walls, windows, doors and small elements, as ventilation openings), the influence of the outside shape of the façade (like balconies), and the room dimensions. It is expressed by the following formulation:

$$D_{2m,nT,w} = R_w{}' + \Delta L_{fs} + 10 log \frac{V}{6T_0 S} \; [dB] \tag{1}$$

where V is the volume of the receiving room, $T_0$ is the room reference reverberation time (generally 0.5 s for dwellings), S is the total area of the façade facing the inside and $\Delta L_{fs}$ is the level difference due to façade shape. Corrections for the façade shapes are given in the standard EN ISO 12354 – 3. The apparent weighted sound reduction is calculated from the sound reduction index values of all the façade components (opaque and transparent and small elements):

$$R'_w = -10 log \left( \sum_{i=1}^{N} \frac{S_i}{S} 10^{\frac{-R_{w,i}}{10}} + \sum_{i=1}^{M} \frac{A_0}{S} 10^{\frac{-D_{n,e,w,i}}{10}} \right) - K \tag{2}$$

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 19 - 84

where $R_{w,i}$ and $S_i$ are the sound reduction index and the area of each element, S is the total area of the façade facing the inside, N is the total number of element of the façade, $A_0$ is the reference equivalent sound absorption area (10 m2), $D_{n,e,w,i}$ is the weighted normalised sound level difference of each small element, M is the total number of small elements and K is the correction due to the contribution of flanking sound transmission. The weighted normalised sound level difference of a small element can be estimated by the following equation:

$$D_{n,e,w} = -10log\left(\frac{S_{open}}{A_0}\right) \tag{3}$$

where $S_{open}$ is the area of the small element and $A_0$ the reference area of 10 m$^2$.

For the calculation of $R_{w,i}$ empirical formulations can be used depending on the type of façade element considered:

$$R_{w,wall} = 37.5log(m') - 42$$
$$R_{w,window} = 12log(m') + 17 \tag{4}$$
$$R_{w,door} = 20log(m')$$

where m' is the mass per unit area of the element.

All the data used as input for the equations from (1) to (4) are retrieved from the BIM of the building.

### 2.1.2 EVALUATION OF THE INDOOR LAeq

Once having evaluated the room façade standardized sound level difference, the equivalent continuous sound pressure level ($L_{A,eq}$ measured in dB(A)) inside each room of the building can be calculated. According to Annex E of EN ISO 12354-3, the indoor sound pressure level is evaluated as following:

$$L_{A,eq} = L_{1,2m} - D_{2m,nT,w} + 10log\left(\frac{T}{T_0}\right) \tag{5}$$

where $L_{1,2m}$ is the average sound pressure level at 2 m in front of the room façade, $T_0$ is the reference reverberation time (0.5 s) and T is the reverberation time in the receiving room (generally 0.5 s for dwellings). When the outdoor average sound pressure level cannot be measured at 2 m from the room façade, the values given by the strategic noise mapping of the area where the building is located can be used instead.

### 2.1.3 ASSIGNMENT OF THE ROOM ACOUSTIC CLASS

Having estimated the equivalent continuous sound pressure level ($L_{A,eq}$) for each room bordering to the external environment, an acoustic class is assigned to the room itself. Acoustic class depends on the space use (offices, bedrooms, living rooms, classrooms, etc.). Depending within which limits the calculated $L_{A,eq}$ is set, a class (from A to E) will be assigned to the room. A score is then given to each class, as reported again in Table 1.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 20 - 84

Table 1 Acoustic class limits and scores

| Type of space | Class A – Score 5 | Class B – Score 4 | Class C – Score 3 | Class D – Score 2 | Class E – Score 1 |
|---|---|---|---|---|---|
| Bedroom | $L_{A,eq}$ <30 | 30<$L_{A,eq}$ <32.5 | 32.5<$L_{A,eq}$ <35 | 35<$L_{A,eq}$ <40 | $L_{A,eq}$ >40 |
| Living room/kitchen | $L_{A,eq}$ <35 | 35<$L_{A,eq}$ <37.5 | 37.5<$L_{A,eq}$ <40 | 40<$L_{A,eq}$ <45 | $L_{A,eq}$ >45 |
| Hotel bedroom | $L_{A,eq}$ <35 | 35<$L_{A,eq}$ <37.5 | 37.5<$L_{A,eq}$ <40 | 40<$L_{A,eq}$ <45 | $L_{A,eq}$ >45 |
| Classroom | $L_{A,eq}$ <35 | 35<$L_{A,eq}$ <37.5 | 37.5<$L_{A,eq}$ <40 | 40<$L_{A,eq}$ <45 | $L_{A,eq}$ >45 |
| Nursery school | $L_{A,eq}$ <40 | 40<$L_{A,eq}$ <42.5 | 42.5<$L_{A,eq}$ <45 | 45<$L_{A,eq}$ <50 | $L_{A,eq}$ >50 |
| Office | $L_{A,eq}$ <35 | 35<$L_{A,eq}$ <37.5 | 37.5<$L_{A,eq}$ <40 | 40<$L_{A,eq}$ <45 | $L_{A,eq}$ >45 |
| Conference room | $L_{A,eq}$ <35 | 35<$L_{A,eq}$ <37.5 | 37.5<$L_{A,eq}$ <40 | 40<$L_{A,eq}$ <45 | $L_{A,eq}$ >45 |
| Hospital | $L_{A,eq}$ <35 | 35<$L_{A,eq}$ <37.5 | 37.5<$L_{A,eq}$ <40 | 40<$L_{A,eq}$ <45 | $L_{A,eq}$ >45 |
| Retail shop | $L_{A,eq}$ <45 | 45<$L_{A,eq}$ <47.5 | 47.5<$L_{A,eq}$ <50 | 50<$L_{A,eq}$ <55 | $L_{A,eq}$ >55 |

#### 2.1.4 BUILDING-SCALE ANALYSIS FOR THE BUILDING KPI ASSIGNMENT

From the score assigned to each room according to the related acoustic class it is calculated the KPI of the entire building, which is a score from 5 (optimum value) to 1 (worse value), by using the following formulation:

$$KPI = \frac{\sum_{i=1}^{N} A_i \times RA_i}{A_{tot}} \tag{6}$$

where $A_i$ is the reference floor area of the i-th room bordering to the external environment, $RA_i$ is the score assigned to i-th room and $A_{tot}$ is the total reference floor area of all the rooms bordering to the external environment. The KPI is measured as a percentage from 0 to 100 % corresponding to a score from 1 to 5, and to a class from E to A, respectively.

## 2.2 ACOUSTIC LEAKAGE IDENTIFICATION

It is well-established practice to express the acoustic insulation of a façade as a single overall value. This approach accounts for all contributions of all the parts to the total insulation, therefore, it is a synthetic and global characterization. However, this approach does not provide any information about the sound transmission of each element of the façade, e.g., walls, windows, doors, ventilation equipment. Hence, a more detailed approach is required for the identification of weak elements of the façade, in other words, those having higher level of sound transmission. These elements, which are the cause of acoustic leakages, may be difficult to identify, therefore, an appropriate measurement technique is needed for their identification.

Acoustic mapping techniques based on microphone arrays are powerful tools for acoustic leakage identification. The aim of these techniques is to use a set of microphones with a known arrangement in space (usually on a plane) to record pressure data and provide an "acoustic image" of the scene. The acoustic image shows high levels only in correspondence of noise sources, similarly to light sources in a grey scale image obtained with a common camera. To better understand the idea behind acoustic leakage identification with acoustic mapping methods, it is useful to do the

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 21 - 84

analogy with thermal insulation and thermal bridges. A thermal bridge is a zone in the façade which has sensibly lower value of thermal resistance with respect to the surrounding zones. In the same way, the acoustic leakage occurs in zones with lower acoustic insulation with respect to the surrounding zones of the façade. A single point measurement, with a thermometer or microphone, does not provide information detailed enough to identify these "bridges". In fact, a map of values is needed to accomplish this task since the bridge/leakage is identified as difference of temperature or sound pressure level between two zones. This is the reason why the identification of thermal bridges requires the thermography, and the identification of acoustic leakages requires acoustic maps. The microphone array is the hardware devoted to the acquisition of acoustic pressure data, while the map is obtained from an algorithm which needs several inputs, the most important are microphone array positions, region of interest (ROI) geometry, where to map the acoustic leakages, and environmental parameters as the speed of sound (Figure 4).
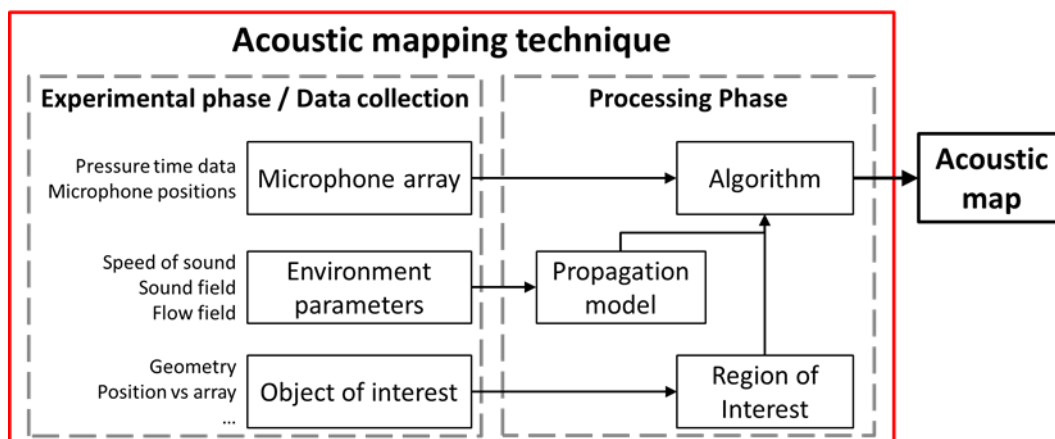


Figure 4 Scheme of the process for acoustic source mapping

The most widespread acoustic mapping technique is the acoustic beamforming [17]. The simplest beamforming algorithm is named "Delay-and-Sum" (DAS), which is also useful to understand basic principles of acoustic imaging. Consider linear array of $M$ microphones at $x_m$ locations and two sources, A and B, in different positions (Figure 5). A selective sensitivity to a specific direction $d$ is achieved by means of proper time delays $\Delta t_m$, applied to each microphone time signal $p_m$. Time-delayed signal are summed together to return the beamformer output. When the beamformer is steered in direction of A or B, source signals are aligned in time before the sum, while signals coming from other directions are not aligned before summation and, therefore, they will not add up coherently. Focusing the DAS beamformer in several directions, the whole ROI is scanned, and a map is obtained.

Figure 6 shows an example of map for 1D ROI. A maximum in the beamforming output occurs in correspondence of a source. The time domain DAS beamformer output $b(d, t)$ is calculated as:

$$b(\boldsymbol{d}, t) = \sum_{m=1}^{M} p_m\big(t - \Delta t_m(\boldsymbol{d})\big),$$

where, given the speed of sound $c$, time delays are dependent on microphone positions $\mathbf{x}_m$ and focusing direction $\mathbf{d}$:

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 22 - 84

$$\Delta t_m = \frac{\boldsymbol{d} \cdot \boldsymbol{x}_m}{c} \, .$$

In several applications, it is convenient a frequency domain approach, hence the DAS beamformer output $B(\boldsymbol{d}, \omega)$ in frequency domain can be written as:

$$b(\boldsymbol{d}, \omega) = \sum_{m=1}^{M} P_m(\omega) e^{-i\omega \Delta t_m(\boldsymbol{d})} \, ,$$

where, $P_m$ is the single line of complex spectrum of microphone signal at the frequency of interest $\omega$.
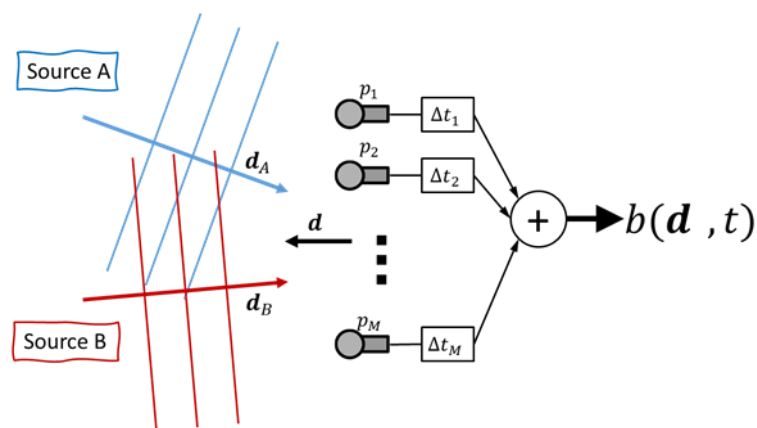


Figure 5 Delay and sum beamforming in time domain
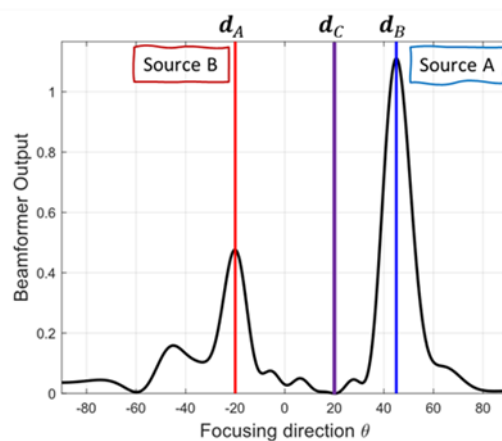


Figure 6 Typical beamformer output (1D example)

Let's consider the beamformer response to a single source, the performance of a beamformer is described by a set of parameters (Figure 7):

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 23 - 84

- **Mainlobe**: global maximum of beamformer output,
- **Mainlobe Width:** it determines the ability to distinguish neighboured sources,
- **Sidelobe:** local maxima of beamformer output,
- **Maximum Sidelobe Level**: it determines the ability to suppress sources coming from directions different from the focusing one. Sidelobes are also called "ghost images".

These characteristics depends on microphone number and positions, array diameter $D$ and wavelength of analysis $\lambda$, and are defined by the array spatial response, named also "Point Spread Function".
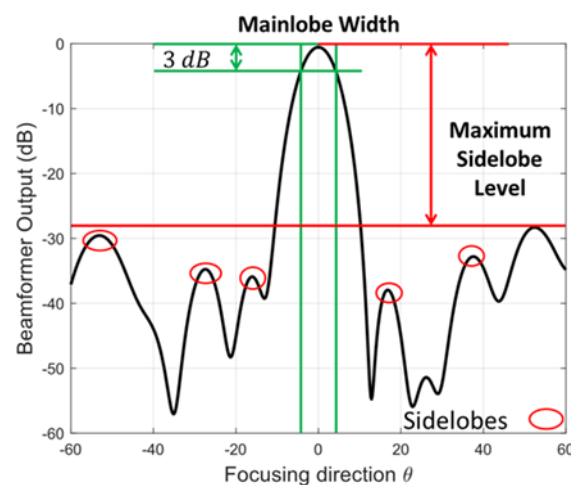


Figure 7 Beamformer characteristics (1D example)

The typical configuration of measurement setup involves a planar microphone array in front of the object of interest (Figure 8)
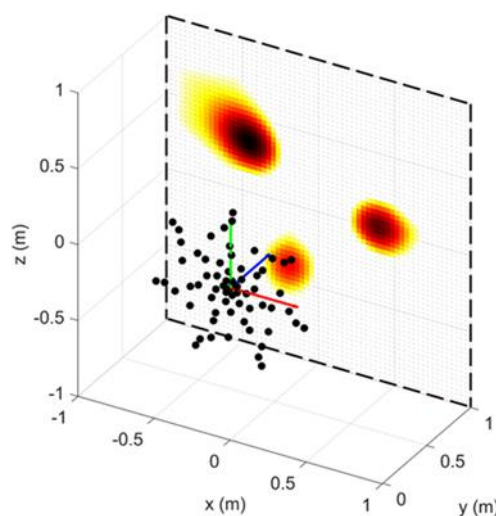


Figure 8 Typical configuration for acoustic mapping

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

The acoustic map is calculated on a plane close to the object of interest. However, the formulation of DAS beamformer, previously described, assumes plane waves, hence, sources at infinite distance. In common applications, the focalization of the beamformer must consider the propagation of spherical waves since the sources to map are at finite distance. The planar ROI to map is discretized with a certain number of monopole sources to scan with a beamformer to obtain the whole map (Figure 9)
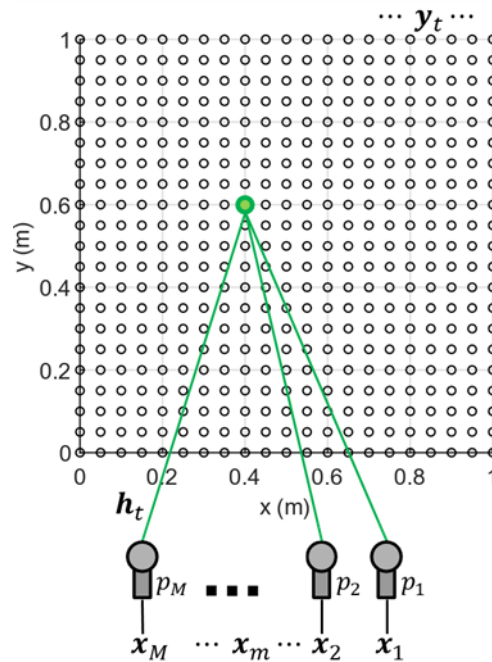


Figure 9 Scanning grid for finite distance focusing of beamformers

The most widespread beamforming formulation in frequency domain is named Conventional Beamforming (CB) [17] and is adopted to map stationary acoustic sources at finite distance. The CB output is:

$$B(\mathbf{y}_t, \omega) = \mathbf{h}_t^H \, \mathbf{P} \, \mathbf{h}_t \, .$$

where $\cdot^H$ denotes the complex transpose operator. The beamformer output $B$ returns the estimated source power at target point $\mathbf{y}_t$ for a frequency $\omega$. The column vector $\mathbf{h}_t$ is named "steering vector" because it steers the beamforming focalisation towards a point source located in $\mathbf{y}_t$. Each element of the steering vector $h_{m,t}$ is determined as function of the propagator and each element of the acoustic propagator $g_{m,t}$ models the transfer, in terms of amplitude and phase, between any potential source in the ROI and each microphone in the array:

$$g_{m,t} = \frac{e^{-i\frac{\omega}{c}R_{m,t}}}{4\pi R_{m,t}} \quad , \quad h_{m,t} = f\left(g_{m,t}\right),$$

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 25 - 84

where, the terms $R_{m,t}$ are the distances between the focus target points and microphones. Different functions to convert propagator in steering vectors give to beamformer different characteristics (e.g., correct source level or correct source locations on the map) as described in [18]. Input data from microphones is injected in the beamformer in the form of Cross-Spectral-Matrix (CSM) $\boldsymbol{P}$. Time recordings from microphone are transformed in frequency domain by means of FFT (Fast Fourier Transform) and then cross-spectra between each pair of microphones are calculated. Moreover, in case of stationary noise sources, CSM can be averaged over several time snapshots in order to have a better estimation of cross-spectra and reduce the background noise. Metrological analysis of beamforming is provided in [18].

Two main choices must be taken to produce acoustic maps: microphone array geometry and mapping algorithm. The combination of these two traces the perimeter of possible applications and defines the performance achievable in a particular application. Different array-algorithm combinations are possible for the same application. The type of object to map typically defines the array layout. Planar geometries are the most common to map objects placed in front of the array. However, three-dimensional layouts are necessary to produce maps in enclosed environments when the array is surrounded by the acoustic sources of interest. In fact, this kind of array geometry, such as spherical arrays, are capable to distinguish sources from any direction in space, therefore, a map on a surface enclosing the array is possible (e.g., walls of a room or a vehicle cabin). Conversely, microphones located on a plane cannot distinguish a source "in front" from a source "behind" the array. In this application, the focus is on the noise coming from a single façade, therefore, the side of the source is known a priori. For this reason, a planar array layout is chosen, thus exploiting all the microphones to focus the array on the façade of interest. The algorithm chosen for acoustic mapping is the Conventional Beamforming since it is robust to noise and provide adequate performance in terms of dynamic range and spatial resolution. In fact, acoustic leakages are more critical at mid-high frequency (e.g. > 800 Hz), where the façade has better sound insulation and the human ear is more sensitive (modeled by A-weighting in the equivalent continuous sound pressure level, $L_{A,eq}$).

From these considerations, a Vogel spiral array ([17], V=5) of 54 cm diameter and with 20 microphones is adopted for this application. The choice of spiral arrays is made among the possible geometries (ring, cross, regular grid, random etc.) since it provides a good trade-off between mainlobe width and maximum sidelobe level. However, the reflections coming from the other walls of the room can be captured by the microphones and mixed up with the noise actually coming from the façade of interest. In order to minimize this issue, the microphone holder is made by a non-transparent material in acoustic sense. The microphones are flush mounted on this rigid support which reduces the sensitivity to the acoustic waves coming from the back side of the array (Figure 10).

The identification of acoustic leakages by means of beamforming requires an external acoustic load to make it possible to map the sound transmission through the room façade. The acoustic source is placed externally, at sufficient distance to have a uniform acoustic load on the external side of the façade. Instead, the microphone array is placed inside the room and parallel to the façade (parallelism is

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 26 - 84

not mandatory but is suggested for simplicity of calculations). The external source is driven with broadband noise (pink noise). Once the source is switched on, the microphones recording is started. In general, few seconds of acquisition (e.g., 10-20 s) are sufficient for a meaningful map. A scheme of measurement setup is depicted in Figure 10.
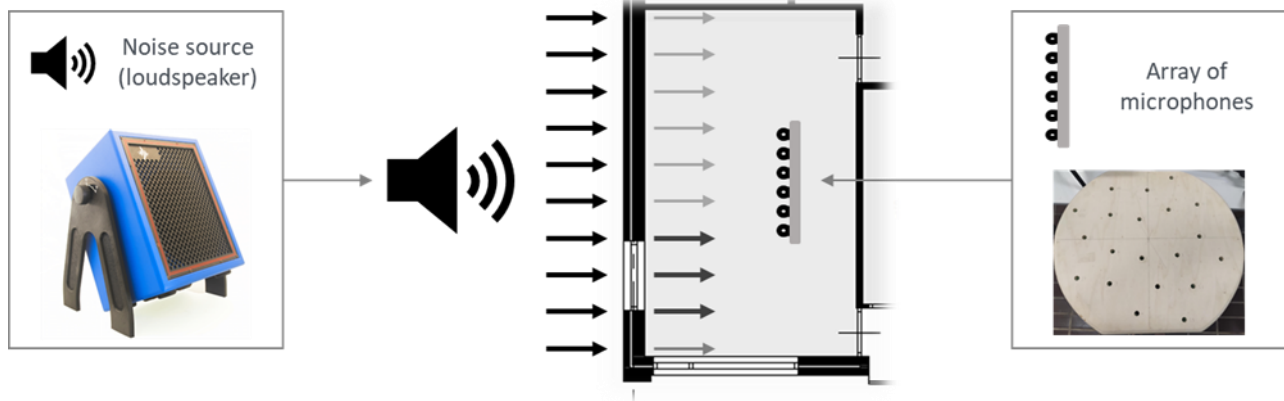


Figure 10 Scheme of measurement setup for acoustic leakage map. The loudspeaker is used to generate a uniform acoustic load on the external side of the façade with a sufficiently level higher than the background noise. On the indoor side of the façade, zones with different acoustic emission occurs depending on the different sound transmission of each element. The array inside the room records the sound transmitted by the façade and the data measured are processed via beamforming to create an acoustic map for acoustic leakages identification.

Some laboratory experiments are carried out to validate the application of CB to the identification of acoustic leakages. The array is placed inside the test room and parallel to the façade. Two kinds of preliminary tests are performed:

- Test 1: indoor vs outdoor of point source comparison (validation of the technique)

- Test 2: far-field noise source (validation of the setup to be used in real applications)

In Test 1, a small point source is placed near the façade, while in Test 2 a far-field source is used to reproduce the real test condition with the uniform acoustic load facing the exterior of the façade. A simplified representation of the test façade is depicted in Figure 11, where the black zones represent the frames of the windows, the grey zones are the glasses of the windows, while the rest is the wall of the façade. The green cross is the nominal position of the point source in Test 1. In this first test, two maps are produced. In the first, the source is placed inside the room and, in the second, it is placed outside but keeping the same location with respect to the façade and the same level. The aim of Test 1 is to compare a reference map with the source inside the room, hence in case of direct source-microphone propagation, with the map obtained in case of indirect propagation to verify if the acoustic leakages are identifiable with CB. Figure 12 shows the comparison with the point source placed outside and inside, at 3.15 kHz one-third octave band. In case of direct propagation, the map shows a clear lobe in correspondence of the source. Instead, when the source is placed outside (but keeping the same horizontal and vertical location), an acoustic leakage is revealed in correspondence of the lower seal of the window. It is worth noticing that also the levels in the maps are sensibly different, i.e. 51 dB vs 19 dB in the same area, despite the source level is the same.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 27 - 84
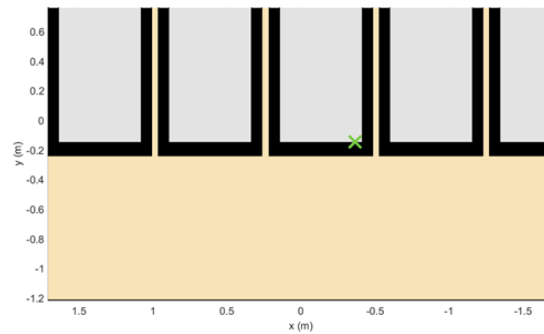
Figure 11 Scheme of test façade with the nominal source location

Test 2 is performed to validate the typical measurement process with a far-field noise source (see Figure 10 for the experimental setup). Figure 13 depicts the map obtained with the far-field source at the same band showed for the previous test (3.15 kHz one-third octave band). It is possible to see that the acoustic leakage is still evident in the lower edge of the window.
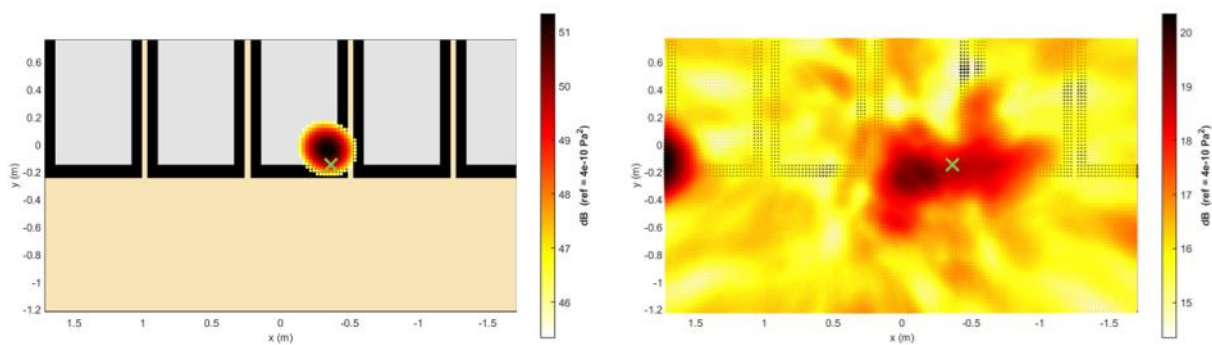


Figure 12 Test 1: point source at 3.15 kHz 1/3 octave band. Left: source inside. Right: source outside
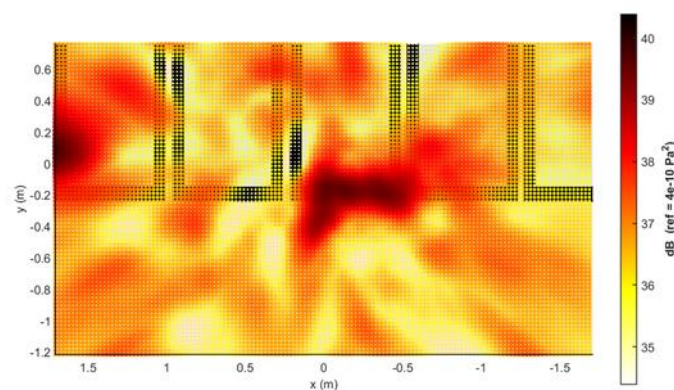


Figure 13 Test 2 with far field noise source at 3.15 kHz 1/3 octave band

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 28 - 84

The acoustic tool presented in this section allows to estimate the acoustic comfort inside the building by means of the acoustic calculator. If the resulting acoustic comfort KPI is not compliant with standardised limits, renovation strategies can be defined and their effectiveness can be estimated. In addition, the choice of the best renovation option can be supported by the acoustic leakage identification measurement system based on beamforming. This tool provides information about the building façade areas where intervention is needed for each specific case.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 29 - 84

# 3. BIM BASED THERMAL COMFORT AND INDOOR AIR QUALITY ASSESSMENT

Innovative solution, to perform pre and post renovation in buildings, is describes in this section. Together with the sensing device, a set of performance indicators has been developed to assess the overall quality in terms of thermal comfort and indoor air quality. IEQ is defined by environmental factors of thermal comfort, visual comfort, acoustic and Indoor Air Quality (IAQ), hence all the factors that exist within a building contribute to the comfort, health, and well-being of the occupants. A close relationship has been drawn between IEQ and occupants' performance [20].

This chapter describes the calculation model to assess the performance indicator for the IEQ: thermal comfort using simulated data and measured data with the Comfort Eye (ceiling and desk node) and the indoor air quality using measured data with the Comfort Eye (desk node). The first prototype of this solution is already validated in P2Endure European Project. The integration with BIM provides the information necessary to process the measured data and to obtain the KPIs.

## 3.1 KPIs CALCULATION MODEL

The proposed methodology is based on the evaluation of KPIs and benchmarks according to the buildings' classification as shown in theTable 2.

Table 2 Building's classification

| Category | Explanations |
|---|---|
| I | High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like disabled person, sick, very young children and elderly persons |
| II | Normal level of expectation and should be used for new buildings and renovations |
| III | An acceptable, moderate level of expectation and may be used for existing buildings |
| IV | Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year |

For each IEQ aspect, the assessment procedure makes use of the above building classification to assign a performance score in relation to the operating hours of the building in each category. The benchmark is done considering a threshold of maximum % of operating hours outside the targeted class.

Each KPI have a value between 0 and 100 %, 0% means that the building operates in the worst condition and 100% in the best condition.

To improve the analysis and support the renovation a sensitivity analysis is applied. It is used to identify the most critical parameter that create discomfort conditions or the deviation from the required comfort standards. Thus, the retrofit solution should be selected to reduce their impact,

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 30 - 84

improving the building performances and the capacity of the building to reach the optimal comfort conditions and keep it constant.

**IEQ: THERMAL COMFORT KPI**

The thermal criteria used within EN 16798 are based on the predefined PMV (predictive mean vote) calculations found in the ISO 7730 and ISO 7726 standards [21] [22] [23].

The PMV allows considering through a single parameter all the aspects that affect user's comfort. There are six primary factors that affect thermal comfort. These include four environmental conditions such as air temperature, mean radiant temperature, air velocity, relative humidity and two personal factors like, clothing insulation and metabolic rate:

$$PMV=f(Ta,Tr,Va,RH,Icl,M)$$

In an indoor environment, therefore in a 'calm' environment, the air velocity[m/s] can be considered constant with values < 0.2 m/s. It is possible to use a constant value as the sensitivity of the PMV is low in this air velocity regime.

Metabolic rate(M) set in function of the usual occupants' activity is defined using a table of typical metabolic rate available in EN7730. A Metabolic rate commonly used is 1.2, corresponding to normal work when sitting in an office. Domestic work is relative hard work with Metabolic values of 2.5 and 2.9.

I cl is the Insulation level of the clothing generally worn by room's occupants.  For summer season is set to 0.5 and 0.9 for winter season using table of typical clothing insulations available in EN7730.

The PMV predicts the mean value of votes of a group of occupants on a seven-point thermal sensation scale. As the predicted quality of the indoor thermal environment increases, the PMV value gets closer to 0 (neutral thermal environment). The hourly PMV values needs a limit to be set to identify a number of occupied hours outside an acceptable comfort range.

ISO 7730 define the PMV limit for each category, the I category specified as -0.2 < PMV < +0.2, the II category -0.5<PMV<+0.5, the III category as -0.7<PMV<+0.7 and the IV category -1<PMV<+1. The detailed description of the calculation method is reported in deliverable D4.1: Baseline and Use Cases for BIM-based renovation projects and KPIs for EEB renovation [24].

**IEQ: $CO_2$ KPI**

Continuous $CO_2$ monitoring can provide a comprehensive and straightforward way to assess and measure improvements in building ventilation. The IAQ assessment methodology, that provides the $CO_2$ KPI, is defined by EN 16798 [2].

Air quality must be evaluated in buildings where people are the main pollution source by measuring the average $CO_2$ concentration in the building, when building is fully occupied. This can be done either with representative samples of room air or by measuring the concentration of the exhaust air. Measurements shall be made where occupants are known to spend most of their time, preferably at head level during typical high load conditions. $CO_2$ measurements should preferably be made under winter

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 31 - 84

conditions, as normally fresh air supply is lowest during the colder months (limited use of operable windows, partly closed facade shutters due to draught risk). The hourly $CO_2$ concentration values above outdoor are assessed against a safety threshold to identify the number of hours outside an acceptable comfort range, and the room values are aggregated through a floor-area weighted average.

The $CO_2$ limit for each category, are 550 ppm for the I category, 800 ppm,1350 ppm and greater than 1350 ppm for the II, III, and IV category respectively. The detailed description of the calculation method is reported in deliverable D4.1: Baseline and Use Cases for BIM-based renovation projects and KPIs for EEB renovation. [24]

**IEQ: PM KPI**

PM is a widespread air pollutant, consisting of a mixture of solid and liquid particles suspended in the air. Commonly used indicators describing PM that are relevant to health refer to the mass concentration of particles with a diameter of less than 10 μm (PM10) and particles with a diameter of less than 2.5 μm (PM2.5) [25].

PM2.5 particles are small enough to be breathed deep into the lungs. Motor vehicles, power plant emissions and bushfires are all major sources of fine particles.

PM10 particles (often described as coarse particles) are smaller than 10 micrometers (0.01 mm) in diameter. High levels of PM10 particles in the air can irritate the eyes and throat. Common sources of PM10 particles include sea salt, pollen, and combustion activities such as motor vehicles and industrial processes. Dust from unsealed roads is a major source of PM10 particles. The PMs monitoring is significant considering the actual concerns about the high concentration revealed in some European Country .

The methodology for PM2.5 and PM10 assessment is provided by the Victoria EPA institute (Australia). EPA regulates inhalable particles. Particles of sand and large dust, which are larger than 10 micrometers, are not regulated by EPA. EPA's national and regional rules to reduce emissions of pollutants that form PM will help state and local governments meet the Agency's national air quality standards.

The categories are obtained according to the hourly and 24-hour rolling average PMs concentration as shown in the Table 3.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 32 - 84

Table 3 Category according to the hourly and 24-hour rolling average PMs concentration

| Category | 24-hr-PM2.5 [µg/m³] | 1-hr PM2.5 [µg/m³] |
|----------|---------------------|---------------------|
| Very good | 0-8.2 | 0-13.1 |
| Good | 8.3-16.4 | 13.2-26.3 |
| Fair | 16.5-25.0 | 26.4-39.9 |
| Poor | 25.1-37.4 | 40-59.9 |
| Very poor | 37.5 or greater | 59.9 or greater |

| Category | 24-hr-PM10 [µg/m³] | 1-hr PM10 [µg/m³] |
|----------|---------------------|---------------------|
| Very good | 0-16.4 | 0-26.3 |
| Good | 16.5-32.9 | 26.4-52.7 |
| Fair | 33-49.9 | 52.8-79.9 |
| Poor | 50-74.9 | 80-119.9 |
| Very poor | 75 or greater | 120 or greater |

The detailed description of the calculation method is reported in deliverable D4.1: Baseline and Use Cases for BIM-based renovation projects and KPIs for EEB renovation [24].

## 3.2 VARIABILITY AND SENSITIVITY ANALYSIS

To improve the analysis and support the renovation a sensitivity analysis is applied. It is used to identify the most critical parameters that create discomfort conditions or the deviation from the required comfort standards. Thus, the retrofit solution should be selected to reduce their impact, improving the building performances and the capacity of the building to reach the optimal comfort conditions and keep it constant.

Statistical tool is used to perform the variability and sensitivity analysis to the thermal comfort. The approach is based on Monte Carlo (MC) simulation, a powerful tool for evaluating the model output uncertainty from the perturbations of the input parameters and the sensitivity of the model to its input. The generic steps for analyzing the perturbation and sensitivity of the dependent variables caused by the variability of the independent input variables is:

1. selection of distributions of the model variables based on the assigned deviation.
2. generation of a random sample of the model variables.
3. evaluation of the model for each variable input.
4. uncertainty (in this case variability representing the variable fluctuation in the time domain) and sensitivity analyses.

The output of the analysis is provided as:

- Quantification of the scattering around the design condition: the perturbation assigned to each input variable is determined from the fluctuation around the average value to

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 33 - 84

calculate the deviation of the output. This is useful to assess how the thermal design is performing with respect to the required comfort zones.

- Quantification of the impact of each input on the final thermal performance: the sensitivity indexes, one for each input variable, are calculated and shown as percentage. The sum of all indexes is equal to 100%. Identifying the most influencing parameters is important to guide the user in the selection of the most effective retrofit solution.

### 3.2.1 VARIABILITY ANALYSIS

The aim of the variability analysis is to determine the deviation of the thermal design in time domain. Considering the fluctuation of all the parameter to calculate comfort indicators, a more accurate investigation must be done. The analysis consists in assigning to each input parameter a perturbation in function of its standard deviation, calculated on the time series gathered from the simulation as following:

$$\delta(x_i) = k\sigma_{x_i}$$

Where $\delta(x_i)$ is the variability of the input parameter xi, k is the coverage factor and $\sigma_{xi}$ is the standard deviation of the input parameter xi. The coverage factor used is 2, meaning that the 95% of the values are inside that deviation, thus the 95% of the operating conditions will fall inside the circle that represent the variability. For each input a uniform distribution equal to the mean of the time series and with the span equal to $\delta(x_i)$ is built. Then, data are randomly sampled from the distributions and provided as input for the comfort model generating a vector of 104 values of the comfort predictor (e.g., PMV for the predictive model and operative temperature for the adaptive models). The deviation of the predictor is calculated as the standard deviation of that vector.

**PREDICTIVE MODEL**

The variability analysis for the PMV model is applied assigning the perturbation to the air temperature, mean radiant temperature and relative humidity. The variability of air velocity is a fixed value. The resulting deviation on the PMV is then calculated. The Figure 14 shows the outcome of the analysis. If a building is required to perform as Category I, according to EN 16798, the design condition and its deviation (blue dot represents the design condition and blue circle the uncertainty) must remain inside the Category I zone. If the deviation goes outside the building will operate for a certain time as Category II.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 34 - 84
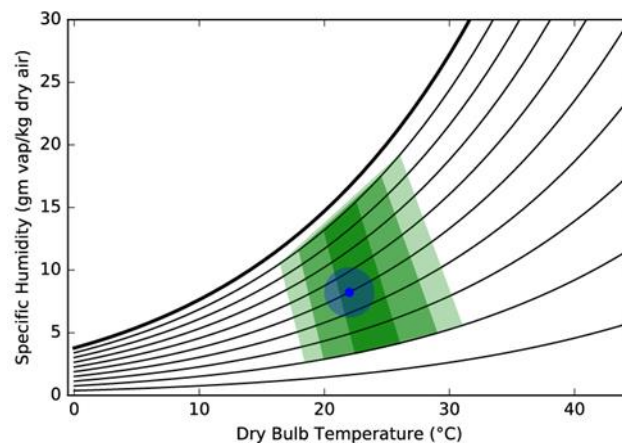
Figure 14 example of variability analysis applied to the predictive model

### 3.2.2 SENSITIVITY ANALYSIS

The sensitivity analysis gives the contribution of each input parameter to the calculated deviation of the output. The aim is to evidence the most critical parameter, that it is the origin of the discomfort, and apply the most effective solution to the retrofit design.

The general procedure consists in:

1. Calculation of the reference condition feeding the calculation model with the mean value of each time series;

2. Generation of the random uniform distribution of all parameters under investigation (as done for the variability analysis);

3. Perturbation of the model giving as input the random distribution of one parameter and keeping equal to the reference condition the others;

4. Calculation of the output variance ($V_{xi}$) due to the perturbation given in point 3;

5. Repetition of points 3-4 for all the parameters under investigation;

6. Perturbation of the model with all the parameters at the same time and calculate the total variance of the output ($V_{tot}$);

7. Calculation of the first order sensitivity indexes ($S_i$) with variance-based method:

$$S_i = \frac{V_{x_i}}{V_{Tot}}$$

The calculation is implemented considering all the input parameters uncorrelated and the sum of all the $S_i$ is equal to one. Thus, each index can be represented as a percentage of the total variance of the output. Higher the index, higher the impact on the output variation.

The comfort module performs the analysis in background and exposes the results, so the user does not have to perform any action. The calculation investigates the sensitivity of the input parameters.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 35 - 84

## 3.3 THERMAL COMFORT ASSESSMENT FROM SIMULATED DATA FOR THE EVALUATION OF REFURBISHMENT SCENARIOS

Using the methodology described in section 3. it is possible to assess the KPI also with simulated data, to simulates different renovation scenarios and evaluate their impact. The aim is to select the best renovation scenario. The BEM (Building Energy Model) simulation of a building offers an image of its behavior, reflecting the complex relation established between the outdoor environment factors, the building characteristics, the use by its occupants, and the parameters which intervene in satisfying the comfort criteria. The BIM-to-BEM process applied in BIM SPEED starts from a BIM model and using the new tools and procedures developed in Work Package 3: "Creating and calibrating Building Energy & related analytical models", allows to have a complete BEM that can be used to calculate some of the inputs needed to calculate the thermal comfort, simulating the expected data for the post renovation scenarios. BEM models can be used to calculate the following environmental parameters: Air Temperature (Ta) and Mean Radiant Temperature (Tr).

The air velocity [m/s] based on room ventilation system is set to 0.05 m/s, and the physiological variables that influence the conditions of thermal comfort are defined using EN7730 standards.

The BEM model, as developed using the CYPETHERM Eplus procedure, provides an .idf model working in EnergyPlus simulation environment and linked to a specific weather file. EnergyPlus is an energy analysis and thermal load simulation engine which calculates the energy required to maintain each zone at a specific temperature for each hour of the day. People, lights, equipment, outside air infiltration and ventilation all constitute internal gains for the thermal zone that are described as a peak level with a schedule for each hour.

By running the CYPETHERM Eplus program, it is possible to obtained data referring to the parameters which influence the comfort level. It is possible to set the following outputs with hourly timesteps:

- Site Outdoor Air Drybulb [°C]
- Site Outdoor Air Relative Humidity [%]
- Zone Mean Air Temperature [°C]
- Zone Operative Temperature [°C]
- Zone Aire Relative Humidity [%]

The outputs are characterised by different levels of accuracy depending on the level of accuracy of the data used to develop the BEM and to validate the model. In general, a BEM validated with energy bills and with a set of measured data should provide a reliable model of the actual state of the building. The baseline model will be used as a starting point to develop the interventions, modifying a few parameters and assessing the new scenarios also under the thermal comfort point of view.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 36 - 84

## 3.4 IEQ ASSESSMENT FROM MEASUREMENT DATA TO EVALUATE THE PRE AND POST RENOVATION PERFOMANCES

The necessary data for the IEQ assessment are acquired using the Comfort Eye, a sensor developed by Università Politecnica delle Marche (UNIVPM).

The Comfort Eye is an IoT sensor composed by two nodes: the ceiling node and the desk node (Figure 15).

The measurement system has been proposed for real-time, low-cost, and easy to install IEQ monitoring.

The core innovation of the Comfort Eye is the ceiling node to measure the indoor thermal surface temperatures. It is a 3D thermal scanner, a 2-axes rotating IR sensor to provide thermal maps of indoor surface temperatures.

The IR scanning system is installed on the ceiling of the room and to provide the full vertical scanning of a wall a tilt movement of the sensor is available with a 0-180° span, also allowing the possibility to measure the floor and ceiling temperatures. The continuous 360° pan movement allows the scan of all the surfaces. The thermographic images are corrected considering the emissivity and geometry of the wall.

A geometrical correction is also required to correctly reconstruct thermal maps. The scanning process produces one thermal map for each wall that is the result of the concatenation of multiple acquisitions. Given the sensor's Field of View (FOV), the installation point, and the room geometry, the reconstruction of the wall thermal map is performed to remove the overlapping pixels derived from the vertical concatenation and to remove pixels related to the neighbour walls.

A desk node is used to acquire environmental quantities used for thermal comfort and Indoor Air Quality (IAQ) assessment. An integrated sensor allows the measurement of the air temperature (Ta) and relative humidity (RH) parameters, and $CO_2$ (Sensirion SCD30)

The desk node also integrates a PM sensor, Sensirion SPS30. The desk node is in a position that should be representative of the room environmental conditions, avoiding exposures to direct solar radiation, air droughts and zones characterized by stagnant air.

An efficient IAQ monitoring system should detect any change in the air quality, give feedback about the measured values of $CO_2$ to the users, and trigger the necessary mechanisms, if available, such as automatic/ natural ventilation and fresh air, to improve performance and protect heath.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 37 - 84

The desk node communicates to the users in real time the measured values of $CO_2$ in a simple and intuitive way, through different colours of the LEDs, green, yellow, and red (green for good air quality and red for bad air quality).
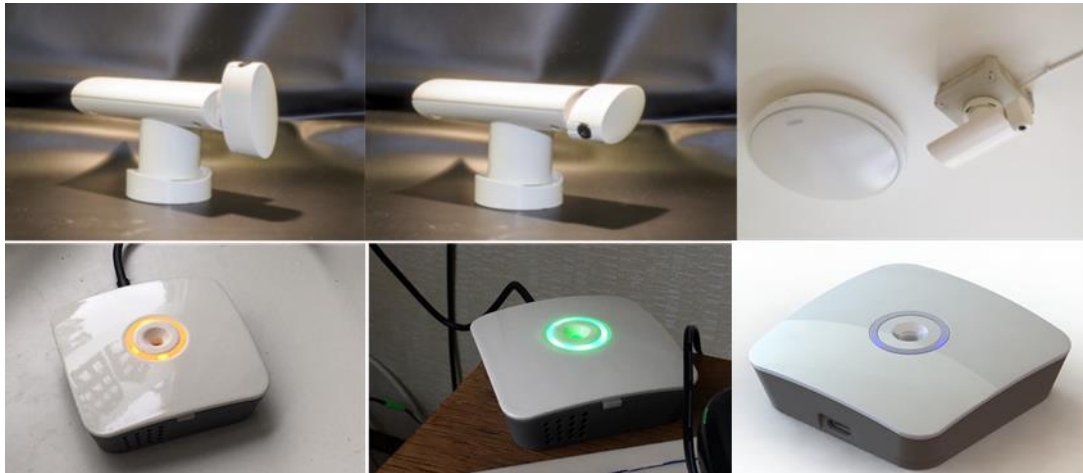


Figure 15 Comfort Eye, ceiling and desk node

**GENERAL ARCHITECTURE**

All the sensors installed are connected through the local Wi-Fi network to the remote server where data are processed to be stored in a MySQL database. The system supports Message Queuing Telemetry Transport (MQTT) protocol that it is based on the publish/subscribe model. As show in Figure 16 each node is programmed to be a pub/sub.

The first step is the configuration of the devices, the ceiling node, and the desk node. Using a mobile application, the configuration data are sent to the sensors and the connection with the local Wi-Fi network is verified.

Once the connection is established, the desk node sends the raw data to the server and processed by a subscriber. For the ceiling node the scan table is configured considering the geometrical data taken from the Building Information Modelling (BIM). Once the tilt and pan angles have been defined and published to the sensors, the data acquisition starts. The raw data are sent to the server and processed by a subscriber.

The processed data are stored on a MySQL database. The whole monitoring process takes place continuously and in real-time.

The data stored in the database are available for being consumed. A dashboard for thermal performance assessment and data exploration was developed. The dashboard is a web-app accessible through any browser. The data processing core is served by a RESTful API service running on the server and called with standard GET/POST methods. Figure 16 shows the general architecture developed for continuous building monitoring.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 38 - 84
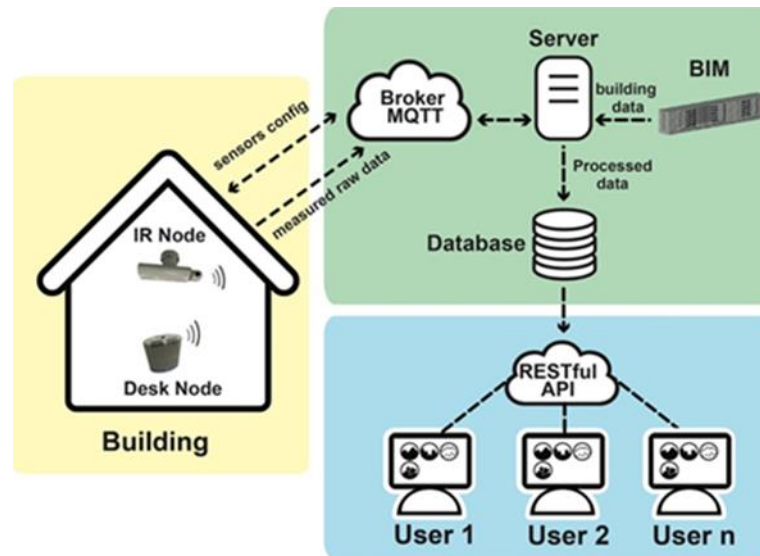
Figure 16 General architecture of Comfort Eye

**BIM INTEGRATION**

Building's data are required to configure the IR scanning process, to perform geometrical maps corrections, to apply the view factors method for the mean radiant temperature (ISO7726) and to calculate IEQ KPI. To reduce the manual operation, the integration with the BIM was developed. Considering the geometry of one room as shows in the Figure 17, the geometrical data used are:

- W length of the room
- L, width of the room
- x, that is the emissivity of the wall
- H, height of the room
- h_ce, sensor distance from the ceiling
- sensor distance from the walls



Figure 17 Room geometry

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 39 - 84
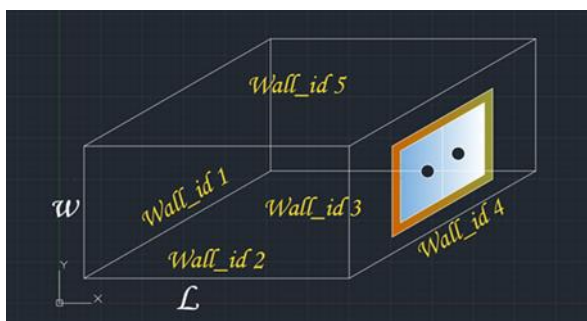
The BIM model of a building includes most of the required data, but not those related to the Comfort Eye installation. For this reason, the Comfort Eye BIM object using AutoCAD was developed (Figure 18).
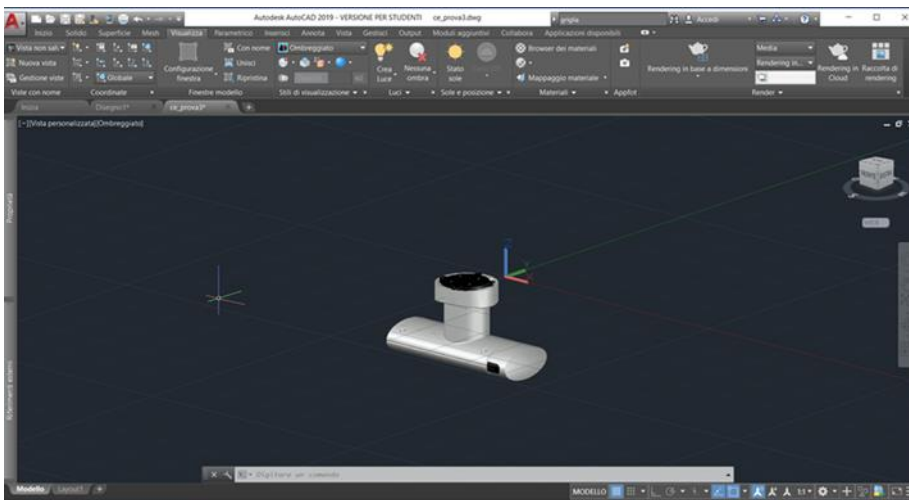


Figure 18 DWG file of sensor using AutoCAD

Starting from the Revit (rvt) file of the building, the object can be imported into the BIM and added in each room where the sensor is installed. In the Figure 19 is reported the Comfort Eye in a room of Warmond Demo Case.
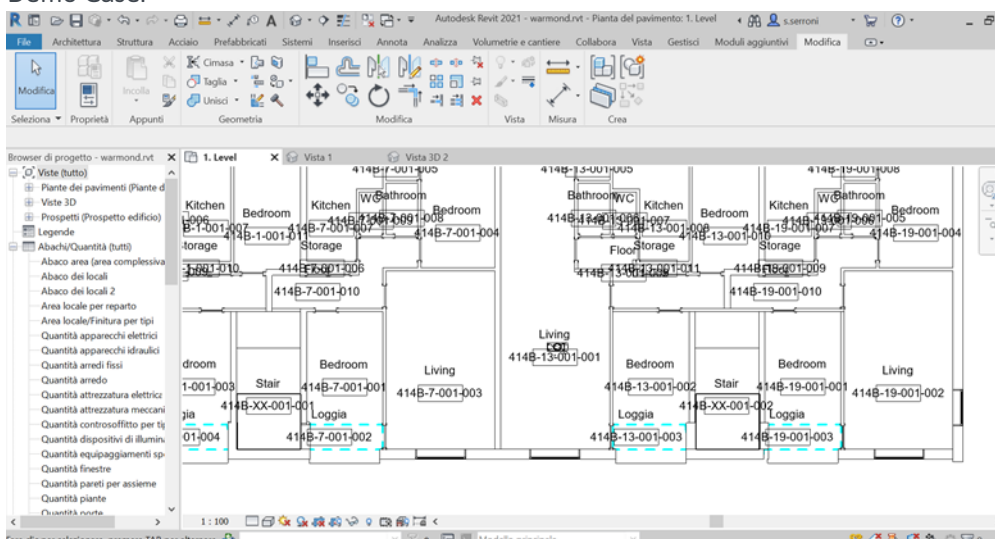


Figure 19 family with Comfort Eye of room of Warmond demo case

To export the 3D view of the building, must be created an abacus of the analytical rooms using usBIM viewer+.

The last step is to export the ifc file with all new parameters added. The ifc file will be an input of Python function to obtain all the parameters needed to do begin the thermal comfort processing. The software automatically retrieves the data and store them in the MySQL database that is used to for the automatic configuration of the Comfort Eye.

BIM-SPEED  D4.3 - Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 40 - 84

## 3.5  THERMAL TRANSMITTANCE CALCULATOR

The thermographic images of the Ceiling node are used to analyse the thermal comfort, calculating the mean radiant temperature and the thermal efficiency of the external envelope of buildings.The Comfort Eye, due to the continuous, real-time, and long-term monitoring has the advantage of detecting the surface heat changes during time. Thermal insulation of the envelope is the key factor to achieve the thermal comfort of the occupants and the reduction of heat losses. The thermal properties of buildings are determined by the thermal transmittance (U-value ($W/m^2 K$)), which describes the insulating capacity of a wall, and it is the parameter used for determining the heating and cooling energy demands. Measured thermal characteristics (U-values) present continuous degradation during buildings' lifetime with respect to defined specifications. Measurements were performed according to ISO 9869 procedures:

- The surface under examination must be shielded from rain, snow, and solar radiation.
- Data acquisition intervals should be less than 30 minutes
- The minimal measurement period should be 72 hours for stable boundary temperatures.
- The minimal indoor and outdoor air temperature difference should be 10 °C.

To estimate the U-value, the surface temperature extracted from the thermographic images [27], air temperature measured by the desk node, and data of weather station for outdoor temperature are use. The role of the desk node is important to have indoor air temperature measurements. The U-value is determined by:

$$U = \sum_{j=1}^{N}(q_{rad} + q_{conv})/\sum_{j=1}^{N}(T_i - T_e)_j$$

where $q_{rad}$ and $q_{conv}$ are heat transfer rates by convection and radiation ($W/m^2$), $T_i$ and $T_e$ are the indoor and outdoor air temperature, respectively, while index j counts the individual measurement.

The IoT IR sensor provides the surface temperature distribution of the whole area, it is possible to estimate the total heat flux rate of the building element. The main problem is the determination of the surface heat transfer coefficients, convective and radiative. In steady state condition, the heat transfer through the walls by conduction ($q_{cond}$) is equalled to the sum of the heat transfer by radiation and convection

$$q_{cond} = q_{conv} + q_{rad}$$

$$q_{conv} = h_c \; x \; (T_i - T_{si})$$

$$q_{rad} = h_r \; x \; (T_i - T_{si})$$

where $h_c$ and $h_r$ are the convective and radiative heat transfer coefficients ($W/(m^2K)$), and $T_{si}$ is the surface temperature (K).

For relatively low temperatures (i.e., -10°C to 50°C), the radiative heat transfer coefficient has a constant value, as demonstrated by Acikgoz et al. [28]. It is calculated using:

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 41 - 84

$$h_r = \varepsilon \times \sigma \times (T_i^4 - T_{si}^4)/(T_i - T_{si})$$

where, $\varepsilon$ is the surface emissivity, and $\sigma$ is Stefan-Boltzmann constant. There are different methods for determining the convective heat transfer coefficient: analytical, numerical, experimental methods. Analytical methods give minimum values of the convective coefficient. Numerical methods require substantial computational means. Experimental methods are the main source for calculating the surface heat transfer coefficient. Empirical formulae are obtained from an extensive range of situations, and the temperature is usually measured at location close to the wall. The surface heat transfer coefficient is determined by experimental data using the least square curve fitting. For natural convection, coefficient $h_c$ can be expressed using for all surfaces [29].

$$h_c = C \times \Delta T^n$$

where C and n are constant, and $\Delta T = T_i - T_{si}$. The various choices for constants C and n for the natural convection with the name of the authors who calculated the empirical expression are shown in

Table 4. In ISO 9869[30], and ISO 6946[31] the heat transfer coefficient is assumed to be 3.00 W/ $(m^2 K)$ and 2.5 W/ $(m^2 k)$, respectively, for vertical surfaces.

Table 4 convective of heat transfer coefficient of different authors

| Authors | $h_c$(W/(m$^2$K)) |
|---|---|
| Awbi et al.[19] | $1.49 \times \Delta T^{0.345}$ |
| Khalifa et al.[20] | $2.07 \times \Delta T^{0.230}$ |
| Michejev [21] | $1.55 \times \Delta T^{0.330}$ |
| King [22] | $1.51 \times \Delta T^{0.330}$ |
| Nusselt [23] | $2.56 \times \Delta T^{0.250}$ |
| Heilman[24] | $1.67 \times \Delta T^{0.250}$ |
| Wilkers et al[25] | $3.04 \times \Delta T^{0.120}$ |
| ASHRAE[26] | $1.31 \times \Delta T^{0.330}$ |
| ISO 9869[5] | 3.00 |
| ISO 6946[3] | 2.5 |
| Bejan[27] & Chu[28] | Equation (6) |
| Almadari & Hammond[29] | Equation(7) |

For laminar flow, the equations from Bejan [32] and Chu [33] need to be used.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 42 - 84

$$h_c = \begin{cases} 1.34 \times (\dfrac{|\Delta T|}{H})^{0.25} & |\Delta T| \times H^3 > 9.5 \\[2mm] 1.33 \times |\Delta T|^{1/2} - \dfrac{0.474}{H} & |\Delta T| \times H^3 < 9.5 \end{cases}$$

where H is the wall height(m).

For laminar and turbulent flow, Almadari and Hammond [34] suggest the following equation:

$$h_c = \left[ (1.51 \times \left( \frac{|\Delta T|}{H} \right)^{0.25})^6 + (1.33 \times |\Delta T|^{\frac{1}{3}})^6 \right]^{1/6}$$

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 43 - 84

# 4. INTEROPERABILITY OF THE ANALYTICAL TOOLS WITH THE BIM SPEED PLATFORM

## 4.1 DATA RETRIEVE FROM THE BIM FOR ACOUSTIC COMFORT (INPUT FOR THE TOOLS)

### 4.1.1 INPUTS NEEDED TO PERFORM THE CALCULATIONS OF THE ACOUSTIC TOOL

The acoustic comfort tool provides a measure of indoor acoustic comfort due to noise coming from outside. This evaluation is done considering the indoor noise levels room by room, based on the criteria of the amount of external noise lowered by the acoustic attenuation of the building envelope.

Different calculation methods can be followed, as explained in deliverable 4.1- Baseline and Use Cases for BIM-based renovation projects and KPIs for EEB renovation of the BIM-SPEED project. The list of required inputs to perform the calculations is summarized in Table 5. It may be noticed that only the information associated with the rooms adjacent to the external environment is used. They are grouped considering the level of detail they provide, in relation to different elements of the building.

Table 5 Inputs needed to perform the calculation

| Associated element | Input |
|---|---|
| Building information | • District land use |
| Room information | • End use<br>• Volume<br>• Floor area<br>• Shape (i.e., open/ closed fence)<br>• Floor level<br>• External equivalent noise pressure level<br>• Balcony width<br>• Balcony material |
| Elements in façade information | • Element type (window, door, small element)<br>• Surface |
| Walls information | • Layer thickness<br>• Layer density |

### 4.1.2 BIM GUIDELINES FOR THE GENERATION OF ETL IFC4ACOUTIC PARSER INPUT MODELS

To obtain the inputs needed for the Acoustic tool, a specific ETL (Extract, Transform and Load), called IFC4Acoustic parser, has been developed by CARTIF to connect the Acoustic tool to the BIM-SPEED platform. This ETL performs an automatic parse between the BIM model and the Acoustics tool,

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 44 - 84

using an IFC file as input (IFC4: ADD2-TC1 schema version) and generating an output in JSON that will be used by the Acoustic tool and will connect through an API.

For the generation of the IFC to be used as input for this ETL, the following modelling recommendations must be considered should be noticed:

- All rooms of the building must be included in the IFC with the class **IfcSpace**. The rooms are classified according to their use in the ETL, which needs to be specified in the Property Name of each IfcSpace, as which corresponding to one of the following definitions: Bedroom, Living room, Kitchen, Hotel bedroom, Classroom, Nursey school, Conference room, Hospital, Retail shop. Calculations and limits differ depending on this parameter.

- Data on the external equivalent sound pressure level must be included in the IFC. The **IfcSoundPressureLevelMeasure** class must be added in the BIM model for each external wall of the building to obtain this parameter in the IFC file.

- **Walls must be correctly classified**, to be able to distinguish between external and internal elements.

- It is necessary to include a term that refers to party walls in the Name of the wall element, to be able to discard those walls that are not in contact with the outside but are in contact with other building with a party wall. In these cases, the **Party Wall** name must be added to the walls Name.

- The layers of the walls must be defined for each wall. The IFC must include information on the density of the materials for each of the wall layers. There is a parameter called **MassDensity** for this purpose, in the information related to the material of the layer. In case the value of this parameter is not available in the IFC, the calculations of the Acoustic tool cannot be carried out.

- The IFC model does not need to contain the **Second Level Space Boundaries**, since the surface of elements of interest is automatically calculated by the ETL from the geometrical information contained in the in the room faces and, in the walls, touching those rooms. These geometrical calculations have been performed because the surface of the room in contact with the external walls cannot be directly retrieved in a correct way from an IFC, even if the model has generated the Second Level Space Boundaries.

### 4.1.3 ETL IFC4Acoustic parser

The ETCL IFC4Acoustic parser automatically retrieves information from the IFC file, following a previously defined structure, to be able to feed the API provided by UNIVPM. It has been developed using the Python language and makes use of the IfcOpenShell[1] library to extract data from the BIM file. In this context of information exchange, the use of a Model View Definition (MVD), as described in D5.2- *BIM connectors for interoperability between different BIM tools and with the BIM-SPEED platform of the BIM-SPEED project*: "*MVD has been used in the BIM-SPEED tools to extract specific information of the IFC model in order to foster the interoperability*". This means that this ETL is developed to be able to obtain data from different

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[1] http://ifcopenshell.org/

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 45 - 84

IFC files, as it is defined according the IFC classes and Property Sets. More information about the MVD can be found in D5.2 (section 5.2.3).

The JSON which contains the building's data extracted from BIM follows the structure presented below in Figure 20

```json
{
    "RoomFacade": {
        "Rooms": {
            "Room use": [··,··,··],
            "Room volume": [··,··,··],
            "Room floor area": [··,··,··],
            "Room shape": [··,··,··],
            "Room floor": [··,··,··],
        "District_Land use category": ··,
        "District_Total number of buildings": ··,
        "Building_ID": [··,··,··],
        "Building_Total number of room facades of each building": ··,
        "RoomFacade_ID": [··,··,··],
        "Room_ID": [··,··,··],
        "RF_Surface": [··,··,··],
        "RF_Strategic Noise Mapping value": [··,··,··],
        "RF_Balcony material": [··,··,··],
        "RF_Balcony width": [··,··,··],
        "External equivalent sound pressure level": [··,··,··],
    "ElementFacade": {
        "Wall": {
            "Number of wall id": 5,
            "Wall id": [··,··,··],
            "Wall layer thickness": [··,··,··],
            "Wall layer density": [··,··,··],
        },
        "Element Building_ID": [··,··,··],
        "Element RoomFacade_ID": [··,··,··],
        "Element type": [··,··,··],
        "Element surface": [··,··,··],
        "Element id": [··,··,··],
    }
}
```

Figure 20 JSON structure. Note: RF=Room Façade.

Most of the parameters shown in Figure 20 can be directly extracted from the IFC file. However, some of them cannot be directly mapped or do not provide the final value to be used for the calculation, and some considerations have been done:

- **Room use**: the space property Name is treated to categorize the rooms, and assign them to the appropriate group (i.e., Bedroom=1, Living room | Kitchen=2, Classroom=4, etc.). In the tests carried out with the tool for the case study of the Vitoria demo, only type 1 or 2 rooms are considered.
- **Room shape**: it cannot be directly retrieved from the IFC model because it would be very complex to analyse whether the facades have any areas with balconies associated with that facade, or the facade is not on the same plane, etc., then it is set by default to 1 (façade in the same plane without balcony). It should be noted that this version of the ETL is in prototype version, therefore the default values have been considered for the model that has been validated, in this case a Spanish demo that will be explained in more detail in the demonstration section.
- **Room floor**: this parameter can be extracted using the storey level and considering that the numbering starts in 1 for the ground floor.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 46 - 84

- **District land use category**: it is set by default to 2 for the demonstration of Spanish demo (the options considered are Countryside=1, Residential Area =2 or Urban Area =3).
- **Room façade surface**: this parameter refers to the wall surfaces of the rooms that are in contact with the outside. It is not provided directly in the model but is calculated using geometric properties of the elements that can help define the surface. To perform these calculations, spaces are considered, on the one hand, on the other, walls that meet the requirements (external, not party-wall type). The intersection surfaces are calculated, to know the total surface of the room that is in contact with the outside.
- **Balcony information (material/width):** these parameters cannot be retrieved directly from the IFC model because these are connected to the previous parameter (Rooms shape) which cannot be obtained, then are set by default (-99).
- **Element id**: it is assigned according to the Element type parameter: type of element considered (wall=1, window=2, door=3, small element=4). The Wall id is defined according to the type of wall and the parsing is done automatically by the ETL. Window id is defined statically according to its properties (window type, included in Analytic construction properties), so in this case is introduced manually according to the existing windows of the tested Spanish demo. The small element id is always considered as a ventilation opening, then is set by default (-99).

Once the JSON is created following the structure presented above, information is sent to the API developed by UNIVMP, by using an http post request. In next section, Figure 21 shows the workflow of the connection with the BIM-SPEED platform and data storage.

### 4.1.4 ETL IFC4Acoustic parser as a service of the BIM-SPEED platform

To obtain the necessary data as input for the ETL IFC4Acoustic parser and for the data storage of the results obtained after the acoustic calculations in the BIM-SPEED platform, a specific service (a BIM connector as defined in the deliverable 5.2 of the BIM-SPEED project) has been created that connects the ETL with the platform.

The ETL IFC4Acoustic parser is currently in a prototype phase. The integration of the ETL IFC4Acoustic parser as a service with the BIM-SPEED platform has been done by developing an associated BIM connector in the form of a web service as a service of the BIM SPEED platform. The validation status of the tool is TRL6 and has been demonstrated in the context of the BIM-SPEED project using one of the BIM-SPEED Spanish demo cases, as shown in the demonstration cases section of this deliverable.

The conceptual diagram and general workflow of the IFC4Acoustic parser service is shown in Figure 21.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 47 - 84
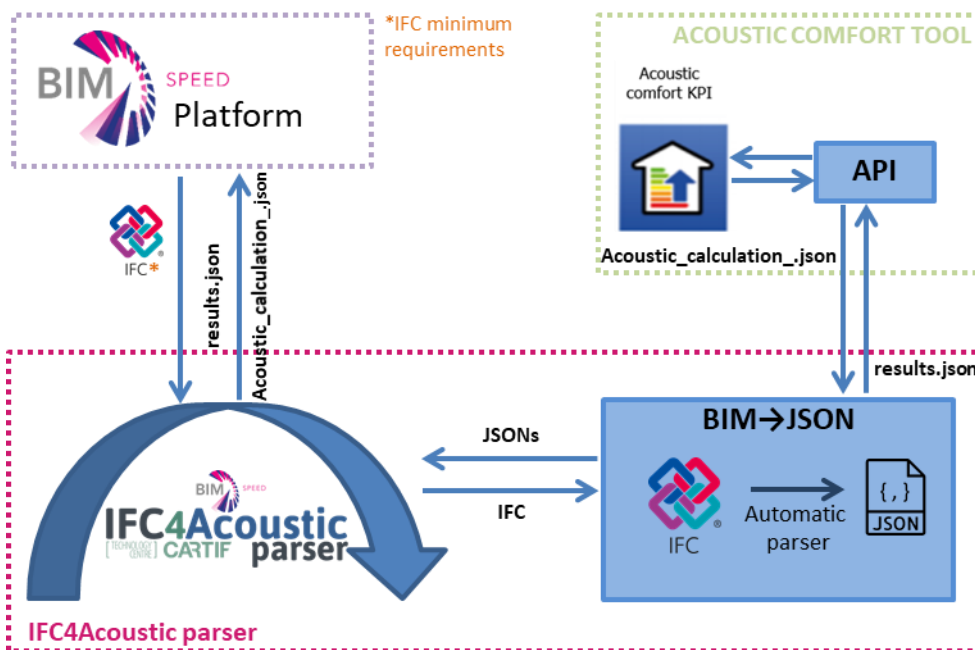
Figure 21 IFC4Acoustic parser service conceptual diagram.

### 4.1.5 EXPLOITATION RESULTS

The ETL IFC4Acoustic parser shown in this deliverable is a result of developments carried out in the BIM-SPEED project and is currently in a prototype phase. The validation status of the ETL is TRL6 and has been demonstrated using one BIM-SPEED case, as show in this deliverable in the demonstration section. The ETL IFC4Acoustic parser is currently hosted in a shared applications server on the CARTIF premises (a server where the application is running) in this URL: https://bim-speed.cartif.com/acoustic/ . The IFC4Acoustic parser is available directly on the BIM-SPEED platform as a service for the consortium, Project Officer (PO) and Project Technical Advisor. The commercial exploitation of the software is not explored at the time of writing this report due the actual developments are focused on a research and development phase and will be considered at the end of the BIM-SPEED project.

## 4.2 IEQ API (INPUT FOR THE TOOLS)

### 4.2.1 Comfort Eye API

Comfort Eye provides a REST API to connect the platform and download data. Five main functions are defined in this API, divided in the following groups:

- thermalData: provides timeseries of thermal quantities with UNIX timestamp: air temperature, relative humidity, surface temp wall1, surface temp wall2, surface temp wall4, surface temp wall5, surface temp wall3 (floor), surface temp ceiling, mean radiant temperature, timestamp
- tclKPI: provides KPIs of thermal comfort according to EN16798, percentage of time in Category I, II, III and IV
- ieqData: provides timeseries of indoor environmental quality quantities with UNIX timestamp: $CO_2$, LUX, PM2.5, PM10, timestamp

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 48 - 84

- calKPI: provides KPIs of indoor air quality according to EN16798, percentage of time for Category I, II, III and IV
- thermalMaps: provides thermal maps of indoor walls

The previous main functions use several parameters defined as General properties, which are the ones shared by all these functions and other Function-specific properties that will be explained following. As well examples of the use of the API and the definition of the endpoints will be described.

**General Properties:**

- _nodename_: unique name of each comfort eye that identifies building and room
- _start_date_: initial day of the period to be investigated (YYYY-MM-DD)
- _end_date_: final day of the period to be investigated (YYYY-MM-DD)
- _time_start_: initial time of the room occupied daily time (hh:mm:ss)
- _time_end_: final time of the room occupied daily time (hh:mm:ss)

**Function-specific properties:**

/**calKPI**/<nodename>/<start_date>/<end_date>/<time_start>/<time_end>/<ty_data>/<aggregation>

_ty_data_: feature to be investigated. Available entries: CO2, LUX, PM2_5, PM10_0

_aggregation_: time aggregation. Entries: hourly, raw (only for ieqData and thermalData functions)

/**calKPI**/<nodename>/<start_date>/<end_date>/<time_start>/<time_end>/<ty_data>/<aggregation>

_ty_data_: feature to be investigated. Available entries: CO2, LUX, PM2_5, PM10_0

_aggregation_: time aggregation. Entries: hourly, raw (only for ieqData and thermalData functions)

/**tclKPI**/<nodename>/<start_date>/<end_date>/<time_start>/<time_end>/<state>/<v_air>/<met>/<clo>/<pos>

_state_: usual state of the room's occupants. Available entries: _seated, standing_

_v_air_: air velocity [m/s] based on room ventilation system. Input type number with decimals. No mechanical ventilation v_air = 0.05

_met_: metabolic rate set in function of the usual occupants' activity. Input type number with 1 decimal, e.g. 1.1 met (typical office/school activity). Table of typical metabolic rate available in EN7730

_clo_: insulation level of the clothing generally worn by room's occupants. Input type number with 1 decimal, e.g. 0.5 for summer season, 0.9 winter season. Table of typical clothing insulations available in EN7730

_pos_: position occupants in the room. Available entries: _int_= internal position, _cen_= central position, _ext_= external position (near the window)

/**thermalData**/<nodename>/<start_date>/<end_date>/<time_start>/<time_end>/<state>/<pos>/<aggregation>

_state_: usual state of the room's occupants. Available entries: seated, standing

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 49 - 84

*pos*: position of occupants in the room. Available entries: *int*= internal position, *cen*= central position, *ext*= external position (near the window)

*aggregation*: time aggregation od the time series. Available entries: hourly = hourly data averaging, raw = time series with original sensor acquisition time (about 5 minutes)

/**ieqData**/<nodename>/<start_date>/<end_date>/<time_start>/<time_end>/*<aggregation>*

*aggregation*: time aggregation od the time series. Available entries: hourly = hourly data averaging, raw = time series with original sensor acquisition time (about 5 minutes)

/**visualizerCE**/<nodename>/<date>/<time>

*date*: selected day for data retrieval (YYYY-MM-DD)

*time*: time of the thermal scan to be retrieved (hh:mm:ss). Each scanning has a duration of 5 minutes, given the input time, a time frame of 30 minutes starting from that time is scanned for data retrieving.

**Example URLs for using the Comfort Eye API**

**Raw thermal data:**

http://193.205.129.218:5000/thermalData/warceca01/2021-07-20/2021-08-30/09:00:00/17:00:00/seated/ext/raw

**KPI thermal comfort:**

http://193.205.129.218:5000/tclKPI/warceca01/2021-07-20/2021-08-30/09:00:00/17:00:00/seated/0.05/1.1/0.5/ext

**Raw IEQ data:**

http://193.205.129.218:5000/ieqData/warca01/2021-07-20/2021-08-30/09:00:00/17:00:00/hourly

**KPI IAQ:**

http://193.205.129.218:5000/calKPI/warca01/2021-07-20/2021-08-30/09:00:00/17:00:00/CO2/hourly

**Thermal Maps:**

http://193.205.129.218:5000/visualizerCE/warce01/2021-07-25/12:00:00

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 50 - 84

## 4.3 DATA STORAGE IN THE PLATFORM (OUTPUT OF THE TOOLS)

This section describes a technical scenario for the overall dashboard generation and integration inside the BIM-SPEED project. The following scheme (Figure 22) proposes a technical flow to be created to set BIM-SPEED dashboards up:
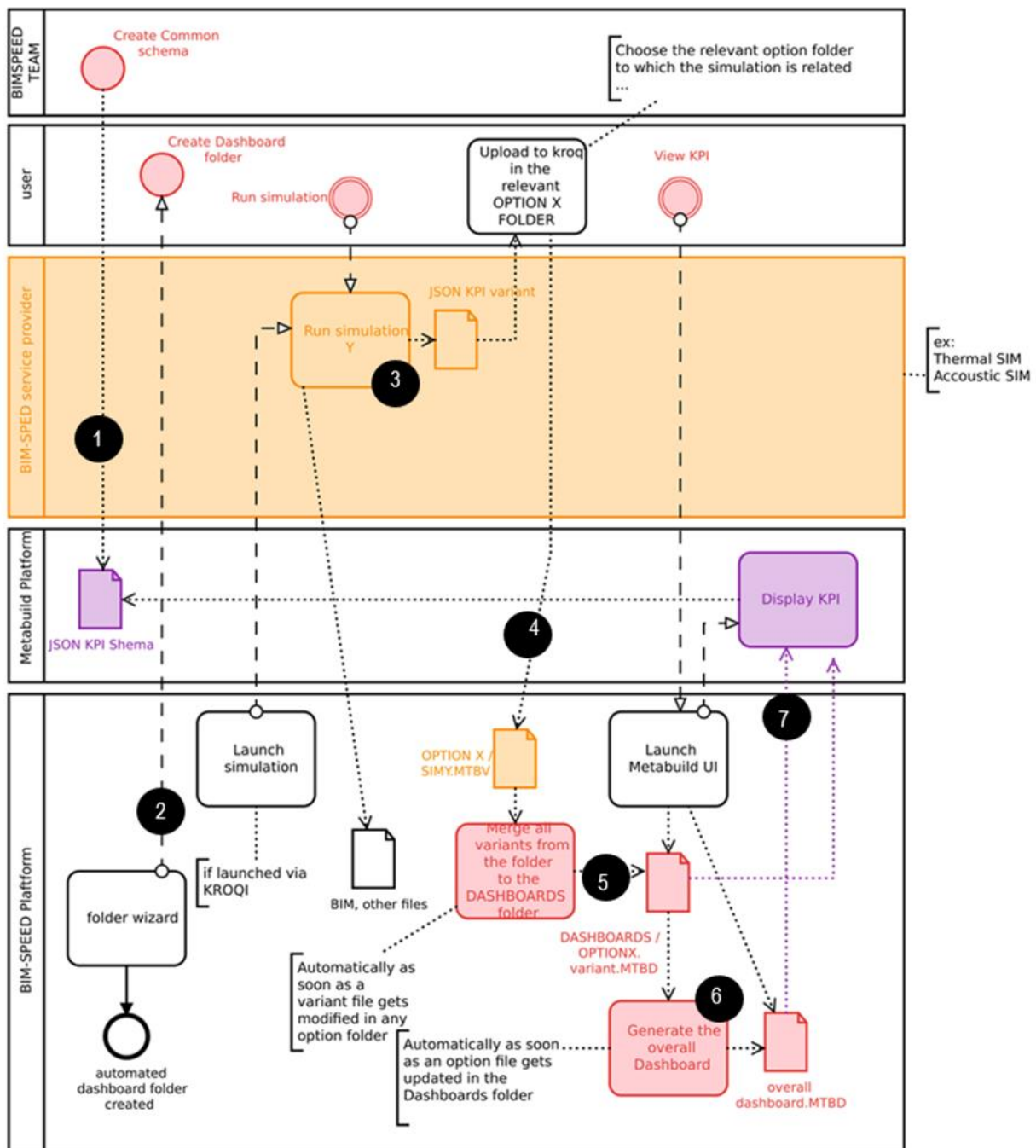


Figure 22 BIM-SPEED dashboard schema

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 51 - 84

In the context of BIM-SPEED there are several actors to be considered in the process flow of generating renovation dashboards. In this BPMN diagram the actors are represented by different swim lanes:

- The **User** is the final user of the integrated solution: the AEC stakeholder using BIM-SPEED ecosystem
- the **BIM-SPEED service provider** this one of the BIM-SPEED partners providing a technical service or tool for renovation at a specific step of the renovation project
- **Metabuild platform** represents the Metabuild backend containing the BIM-SPEED dashboard service
- Finally, the **BIM-SPEED platform** is the place where documents are managed, and BIM-SPEED services can be registered and triggered by BIM-SPEED users.

The following points are commenting the numbers placed in the figure above.

1. The BIM-SPEED team needs to **define the dashboards technical schemas** inside the Metabuild platform. It possible for every service provider to create its own KPI model, in this work IEQ KPIs, in the form of a JSON file can be generated via a dedicated Interface on the Metabuild platform. This file needs to be uploaded on the BIM SPEED platform where data storage happens. This file is later transferred to the Metabuild platform via the BIM SPEED platform together with the other input json files.

   For dealing both with different variants of a building and with different analysis tools we have two different JSONs:

   "**kpi-schema.schema**" – This is the schema to define the KPIs (or results) that are transferred from the specific tool (Comfort Eye and Acoustic tool) to the dashboard.

   - The properties of each KPI are defined (e.g., name, unit, category, optimum min or max, etc.).
   - The value/result of a KPI is NOT transferred in this file.
   - Some fields are mandatory, and some are optional. This is described in the scheme.

   "**external-variant.schema**" – This is the schema to describe one renovation scenario and to give the KPI-results from one tool.

   - Describes a building variant displayable on the Metabuild dashboards and pareto frontier chart
   - The value/result of the KPIs are transferred here
   - Custom fields can be set to describe details of the variant (e.g., "renovation package: 1"). They will be displayed on the dashboards as well.
   - Some fields are mandatory, and some are optional. This is described in the scheme.

2. using the BIM-SPEED platform folder wizard service, the project's users can **create an automated Renovation option folder** that will be used to put any formatted simulations variances according to the schema defined at step 1

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 52 - 84

3. Later, a user is using one simulation tool from BIM-SPEED consortium to prepare a renovation option. This simulation tool needs to generate a **variant file for the renovation option**, which is compliant with the schema which was defined as step 1.

4. the simulation responsible person then needs to **upload the result variant file of the simulation under the relevant renovation option folder** inside the BIM-SPEED **Renovation option folder.**

5. The dashboard folder is automated by nature, as soon as the variant file gets dropped or updated in a **Renovation option folder**, the process gets triggered which **concatenates all the options variants from the Renovation option folder into an option-dashboard file which is put in the Dashboards folder**

6. there is another automation taking place at this step: anytime an aggregated dashboard from a **Renovation option folder** gets dropped inside **Dashboards folder** the process aggregates all the option dashboard files into overall integrated dashboard file.

7. later, browsing the **Dashboards folder**, the user can trigger the Metabuild dashboard service on any option dashboard or overall dashboard file (.MTBD) that can be found inside the dashboard folder to do view results via the Metabuild service.

### 4.3.1 DASHBOARD FOLDERS STRUCTURES

Here is very related folder structure for the BIM-SPEED dashboards.
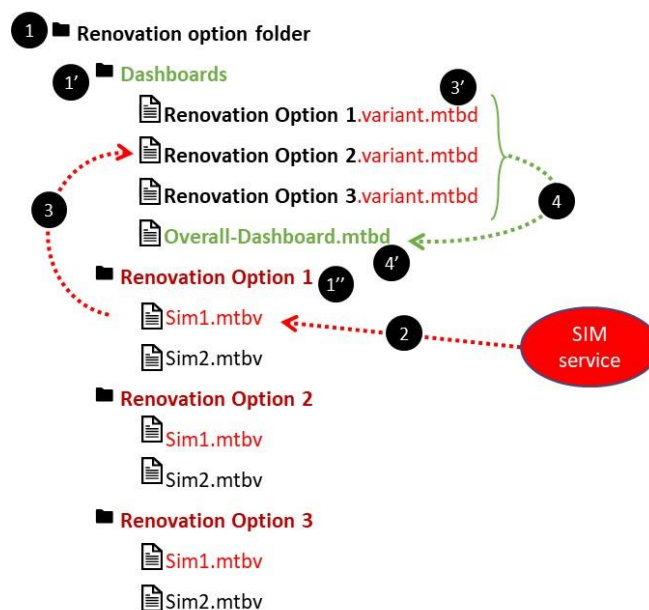


1. The BIM-SPEED folder wizard service will make it possible for users to create a **Renovation option folder.** This automated folder contains a **Dashboards folder** (see 1') which will receive all the aggregated dashboard files from various renovation options scenarios. It can contain as many renovation option folders (see 1'') as required by the project team requiring to simulate various renovation options. The wizard may create some sample renovation

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 53 - 84

folder, but the project's users can manually create as many "renovation option" folders as they want under the **Renovation option folder**.

2.  During the renovation design process, a simulation service will be run that generates, for the purpose of various options evaluations, simulation results in the format of the predefined Metabuild dashboarding schema. The renovation responsible person must drop the simulations result file (variant file) the relevant **Renovation option folder**.

3.  As soon as a file gets dropped inside a **Renovation option folder**, all variant files contained by this folder will be computed to be aggregated into a renovation option file which will be put in the **Dashboards folder**. The convention is that this dashboard file takes a name of the form: ***<<name of the option folder>>. variantmtbd*** (see 3').

4.  as soon as the **Dashboards folder** gets updated we with a renovation option file containing the "*variant.mtbd*" pattern in its name, all the renovation-option-dashboard files get compiled and aggregated into an **Overall-Dashboard.mtbd** which is set in the **Dashboards folder** (see 4').

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 54 - 84

# 5. DEMONSTRATION ON A SELECTION OF REAL DEMONSTRATION CASES

## 5.1 WARMOND DEMOCASE

The Comfort Eye was installed in Warmond demo case in July 2021, located in the Netehrlands. The monitoring was carried out for the assessment of Thermal Comfort (summer season), Indoor air quality and Acoustic Comfort in pre renovation. In Figure 23 is possible to observe the buildings tested.



Figure 23 Building tested

In Figure 24 is possible to observe the selected apartments
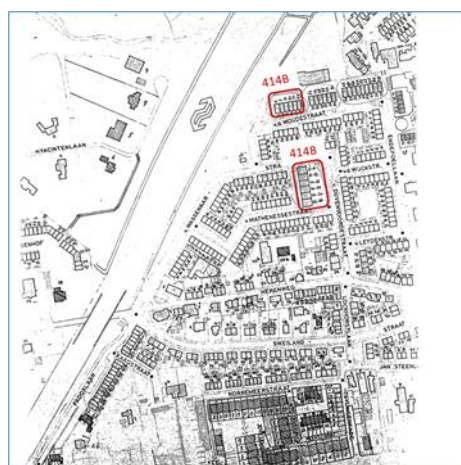


Figure 24 Selected apartments

The tests carried out for each selected apartment are as follow

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 55 - 84

**ACOUSTIC:**

- TEST # 1 Measurement of indoor and outdoor sound pressure level
- TEST # 2 Measurement of Sound Reduction Index (Rw)
- TEST # 3 Localization of sound insulation leakages

**IEQ: THERMAL AND INDOOR AIR QUALITY:**

- TEST # 1 Measurement of Thermal Comfort (KPI)
- TEST # 2 Measurement of Indoor air quality ($CO_2$, PM2.5, PM10)
- TEST # 3 Localization of thermal insulation leakages

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 56 - 84

## 5.2 RESULTS IEQ: Thermal and indoor air quality

Monitoring started in July 2021, the Comfort Eye is still installed and is still acquiring data. The data acquired up to 07/2021-08/2021 (summer season) have been analysed for the assessment of thermal comfort and IAQ building performance in pre renovation state.

### 5.2.1 TEST # 1 Measurement of Thermal Comfort KPI – 414B room 1

The results for the summer season are shown in Figure 25 and Figure 26 respectively. Concerning thermal comfort, the PMV model was applied using a metabolic rate of 1.2 met (typical office/school activity) and a clothing insulation of 0.5 clo.



Figure 25 KPI and sensitivity analysis of room 1 414B



Figure 26 Thermal comfort room 1 414B

The building(room1-414B) operates for the summer season in Category IV, III, II with a KPI of 0% as demonstrated by the blue dot location with respect to thermal comfort zones calculated

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 57 - 84

according to the EN 16789 (Figure 26). This turns out to provide an indication of uncomfortable condition in pre renovation. The sensitivity analysis suggests that the most important factor is the mean radiant temperature and the air temperature.

5.2.2    TEST1 # Measurement of Thermal Comfort KPI- 414B room 34

The results for the summer season are shown in Figure 27 and Figure 28 respectively. Concerning thermal comfort, the PMV model was applied using a metabolic rate of 1.2 met (typical office/school activity) and a clothing insulation of 0.5 clo
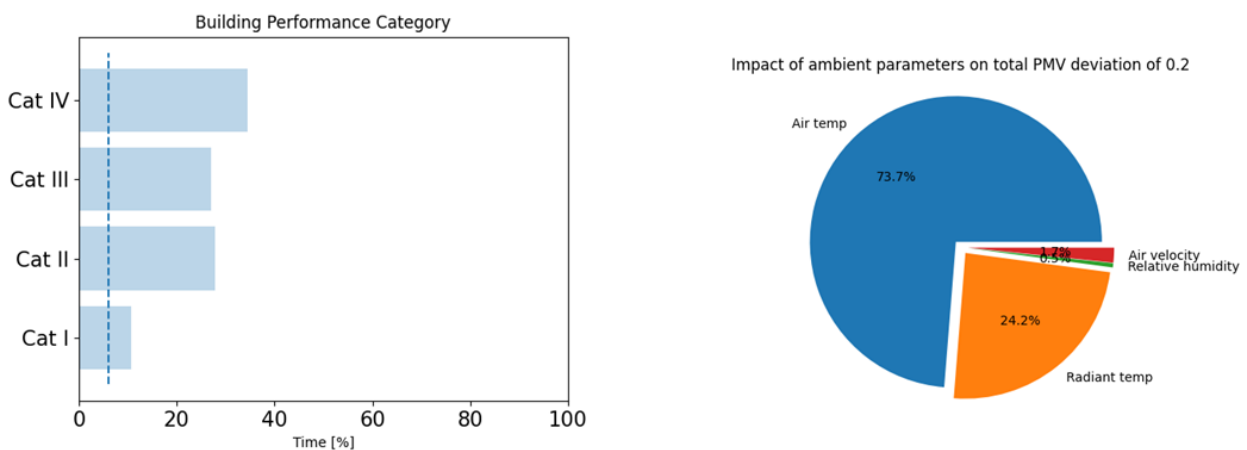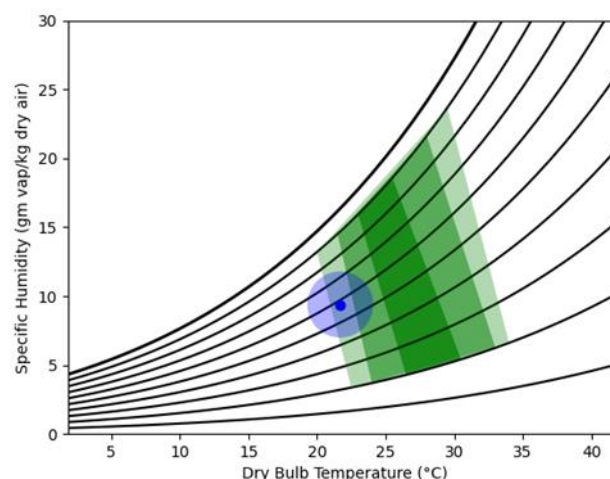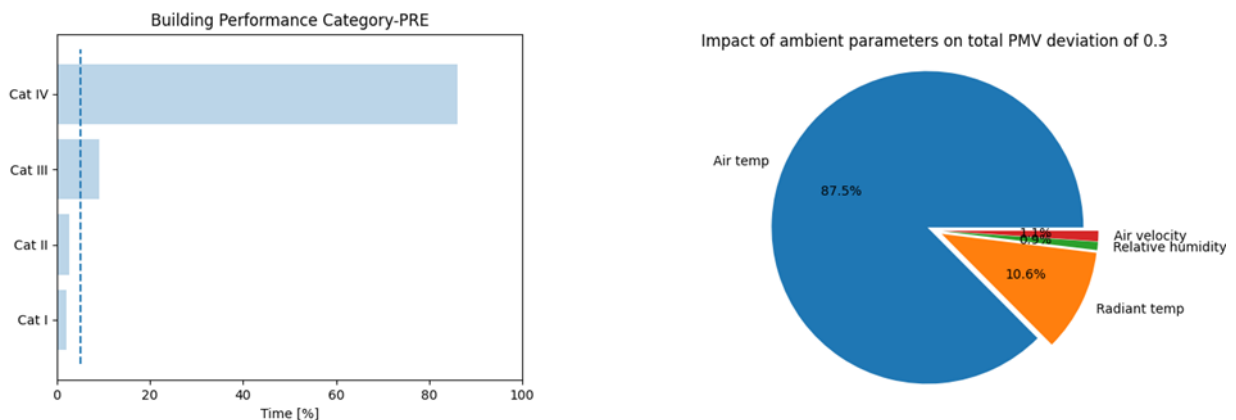


Figure 27 KPI and sensitivity analysis room5 414B
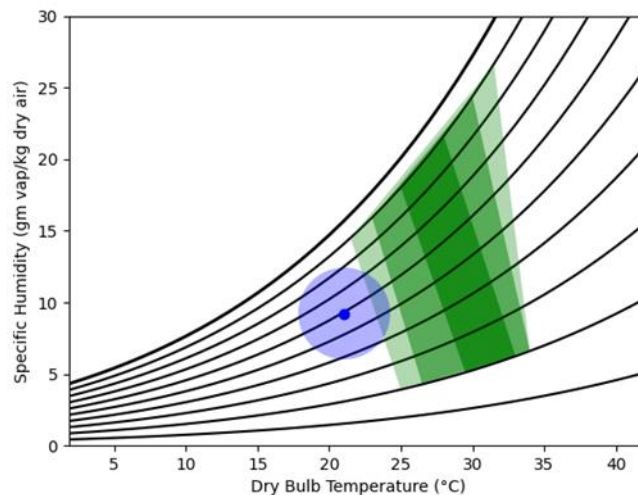


Figure 28 Thermal Comfort room5 414B

The building (room5-414B) operates for the summer season in Category IV with a KPI of 0% as demonstrated by the blue dot location with respect to thermal comfort zones calculated according to the EN 16789 (Figure 28). This turns out to provide an indication of uncomfortable

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 58 - 84

condition in pre renovation. The sensitivity analysis suggests that the most important factor is the mean radiant temperature and the air temperature.

### 5.2.3 TEST #2 Measurement of Indoor air quality ($CO_2$, PM2.5, PM10) room 1

The monitoring turned out to provide a good level of IAQ with $CO_2$ concentrations always within the Category I, and PM always within the category very good, leading to a KPI equal to 100% (Figure 29). It is important to evaluate IAQ also in winter, considering that there will be no natural ventilation due to the opening of the windows.
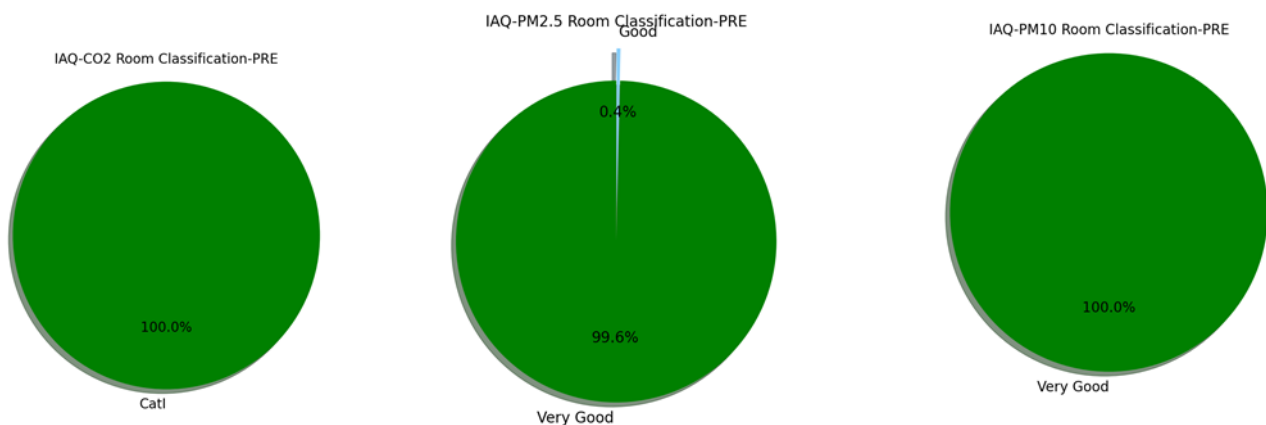


Figure 29 IAQ room1

### 5.2.4 TEST # 2 Measurement of Indoor air quality ($CO_2$, PM2.5, PM10) room 34

The monitoring turned out to provide a good level of $CO_2$ with a concentration always within the Category I leading to a KPI equal to 100%. Considering the PM2.5 and PM10, the building presented about 30% and 35% below the 'good' conditions respectively with a KPI of 0%. (Figure 30). It is important to evaluate IAQ also in winter, considering that there will be no natural ventilation due to the opening of the windows.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects
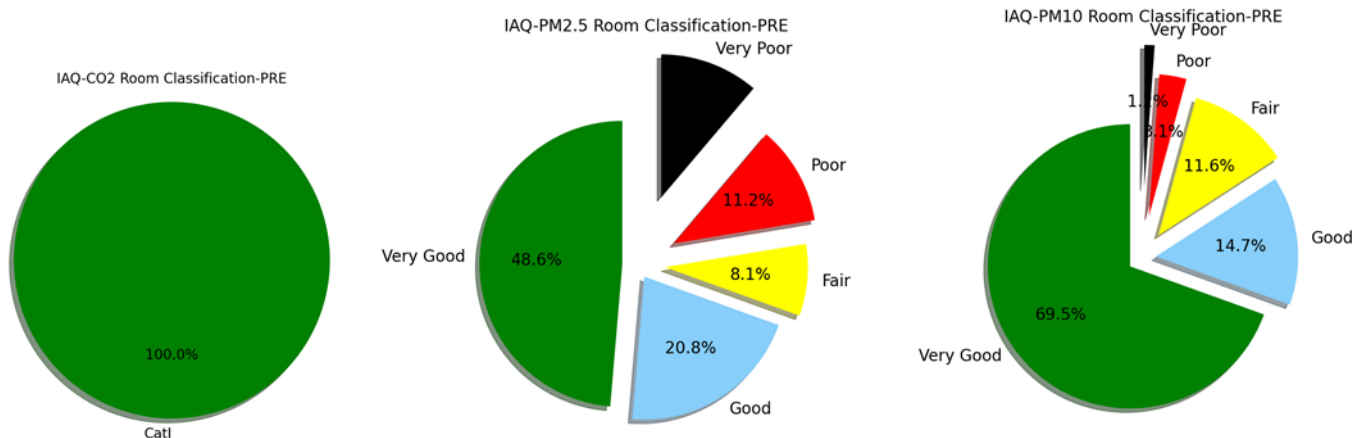
page 59 - 84

Figure 30 IAQ Room 34

## 5.3  RESULTS: Acoustic tests

### 5.3.1  TEST #1 Measurement of outdoor and indoor sound pressure level

The characterization of outdoor noise level is important since it represents the load that is responsible of the acoustic discomfort inside the dwellings. A monitoring of outdoor Sound Pressure Level (SPL) was performed with the aim to estimate typical levels in the zone of the demo cases during the day. The characterization of external noise is made in terms of two categories of sounds: continuous background noise and isolated single sound events. The continuous background noise is the base level typically present in the zone (e.g., industrial plant noise), while sporadic events are related to peak levels, which are concentrated in time (e.g., passage of road vehicles or trains, roadworks etc.). The peak levels are measured with Instantaneous A-weighted SPL $L_A$ (1 s), while the continuous noise level is measured with A-weighted Equivalent SPL $L_{Aeq}$ over 30 s. The latter represents the level of an ideal continuous and constant sound which has the same energy of the measured 30 s of sounds. In the following figures, the final value of a $L_{Aeq}$ curve is the integration over the whole period. Two monitoring microphones were installed in 414B WOUDESTRAAT, as depicted in Figure 31. A near-field microphone is placed 2 meters far from the façade of the building in front of the apartment 1 (ground floor), while a far-field microphone is installed in free-field, to characterize the noise level avoiding the masking caused by obstacles. The far field monitoring is also meaningful for apartment 5. Far-field measurements are compared with the strategic noise mapping of the town depicted in Figure 33. Strategic noise mapping does not provide an exact value for each exposed room façade, since it should be measured at 2 m from the façade for the model adopted, but only a representative value of the entire area. Therefore, the actual noise level can be different from a façade to another. For this reason, an uncertainty equal to ± 5 dB(A) is considered for the strategic noise mapping. Figure 34 shows the outdoor level measured in 414B WOUDESTRAAT with the far-field microphone in a quiet condition, i.e., in the early morning without traffic, train noise etc., hence, it represents an optimistic estimation of outdoor background noise. In this condition, the level is constantly around 40 dB(A), while the strategic noise mapping suggests a level of 56-60

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 60 - 84

dBA for this area. More typical daily conditions are depicted in Figure 35, Figure 36, Figure 38 and Figure 39, where different sporadic noise sources occur, such as moderate traffic, train passage and road sanitation. In such conditions, the strategic noise mapping is more representative of measured noise levels. Figure 39 shows an example of noise caused by a technician that is operating close to the apartments (about 10 meters). It is noticeable that the sounds are loud since the source is near the monitoring microphone, but they have short time duration. The peaks are related to closing the doors after taking the tool kits from the van.

Some of these outdoor noises occur on regular time basis, such as traffic noise, train passage, road sanitation and so on, while other types of noise occur in non-predictable moments. The monitoring presented here is not intended to comprehensive of all possible cases, but it is representative of typical daily conditions for the demo case.

As regards indoor levels, Figure 32 depicts the measurement setup with the outdoor nearfield microphone at 2 m from the façade and 5 microphones inside the room, randomly distributed (at least 0.7 m from the walls). Figure 40 shows the background noise level inside the apartment 1, which is at the first floor compared with near-field microphone. It is worth noticing that, in this case, the indoor level is not meaningfully affected by outdoor noise. This means that the contribution from outdoor noise is below the background level of indoor noise. This aspect must be considered in the evaluation of the estimated indoor level, hence the acoustic comfort.
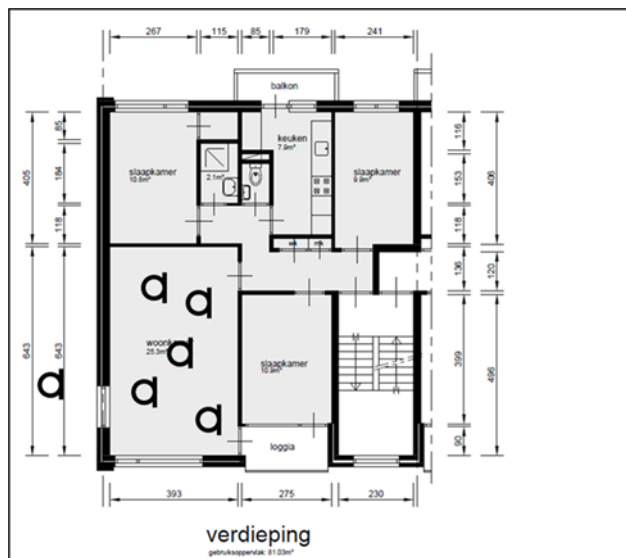
The other demo case is in 414B DUVENVOORDSTRAAT. In this case, the strategic noise mapping suggests a range of 51-56 dB(A) for this area. The monitoring of the outdoor noise in typical daily condition confirms this value, as depicted in Figure 41. In this case, the building is very close to a park for children. The monitoring in apartment 36, showed in Figure 42, reveals a great influence of the children noise inside the apartment.

In conclusion, the monitoring of outdoor noise confirmed that the strategic noise mapping is representative of average daily noise level. However, it must be considered that sporadic noise may produce higher peak levels for a short time, while in some time windows the external noise level could be lower. In addition, it must be stated that the noise mapping is representative of the zone, but it is not the exact acoustic load for a specific façade. Lastly, the outdoor noise can be neglected when it causes an indoor level below the indoor background noise.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 61 - 84

Figure 31 Exterior noise measurement locations for 414B WOUDESTRAAT demo case.



Figure 32 Scheme of measurement setup for indoor vs outdoor level monitoring



Figure 33 Strategic noise mapping in dBA. In blue the demo buildings

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 62 - 84

Figure 34 Outdoor $L_{Aeq}$ (in red) and $L_A$ (in brown) measured in 414B WOUDESTRAAT with far-field microphone. Grey range is the level provided by strategic noise mapping. The baseline background level measured in early morning without significant sources of sporadic noise. This can be considered an estimation of the optimistic (lowest) background level.



Figure 35 Outdoor $L_{Aeq}$ (in red) and $L_A$ (in brown) measured in 414B WOUDESTRAAT with far-field microphone. Grey range is the level provided by strategic noise mapping. This measurement is taken in a moderate traffic condition and represents an example of typical daily condition of continuous outdoor noise.



Figure 36 Outdoor $L_{Aeq}$ (in red) and $L_A$ (in brown) measured in 414B WOUDESTRAAT with far-field microphone. Grey range is the level provided by strategic noise mapping. This measurement is taken in a moderate traffic condition and a passage of a train on the railway This case represents an example of outdoor sporadic noise in presence of typical level of continuous noise which is one of the most likely case during daytime.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects
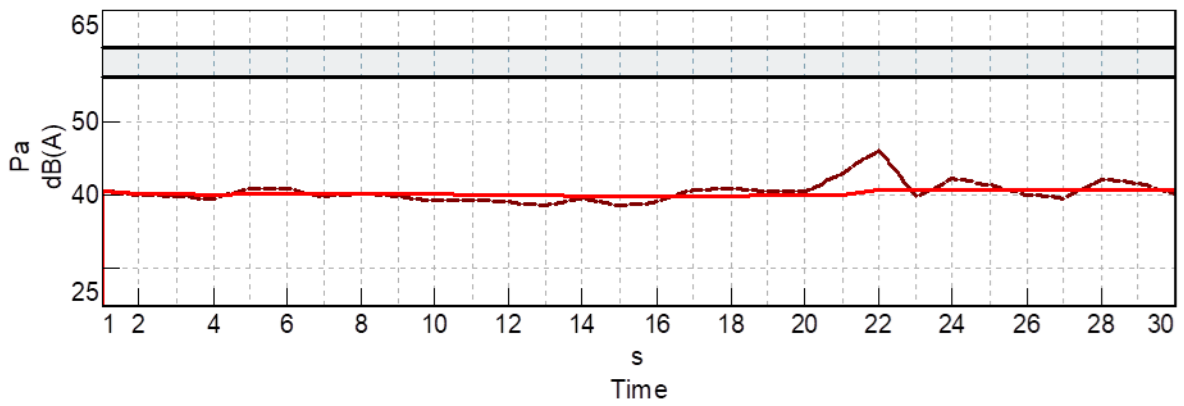
page 63 - 84

Figure 37 Outdoor $L_{Aeq}$ (in red) and $L_A$ (in brown) measured in 414B WOUDESTRAAT with far-field microphone. Grey range is the level provided by strategic noise mapping. This measurement is taken during the passage of two consecutive trains on the railway. This represents an example of annoying sporadic outdoor noise since the train passage is a regularly occurring event during daytime.
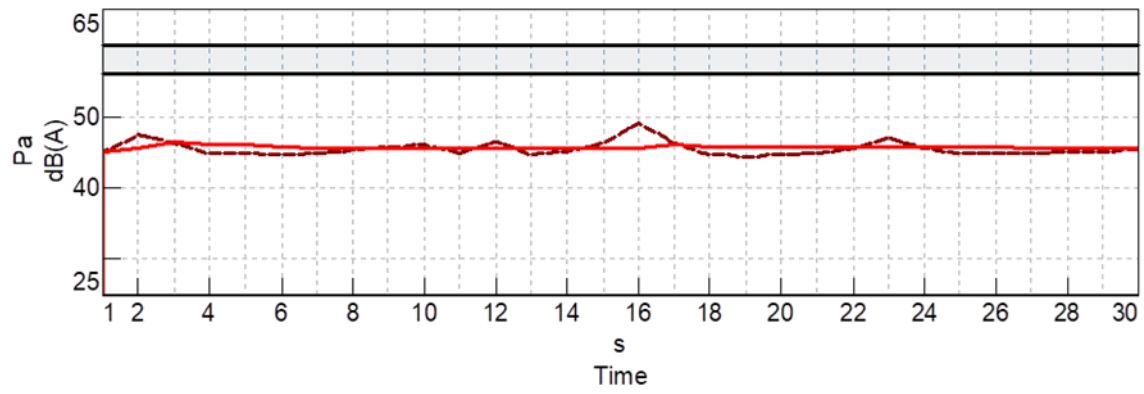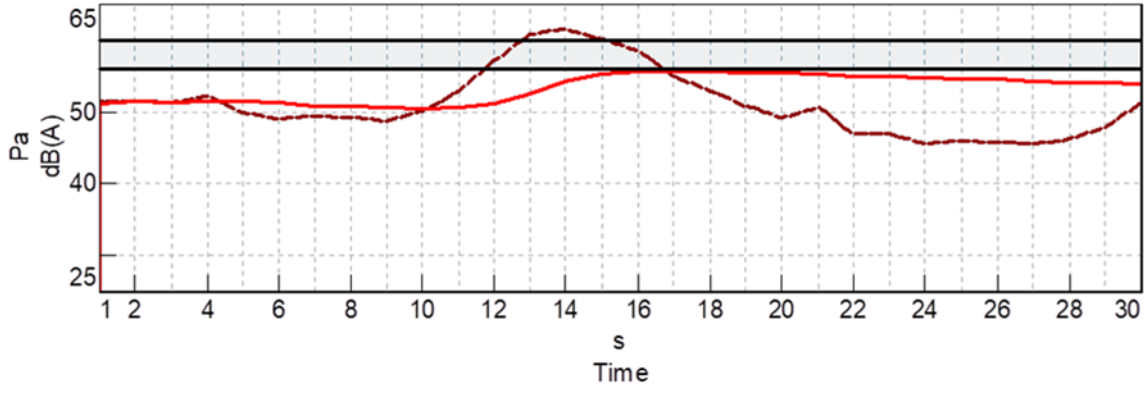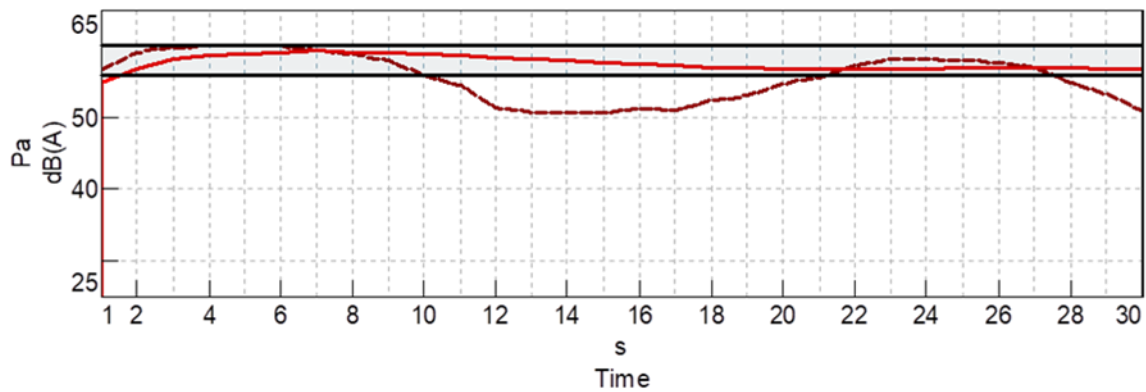


Figure 38 Outdoor $L_{Aeq}$ (in red) and $L_A$ (in brown) measured in 414B WOUDESTRAAT with far-field microphone. Grey range is the level provided by strategic noise mapping. This measurement is taken during the passage of road sanitation (about hundred meters far from the apartments) which represents an example of typical daily condition of continuous outdoor noise. This kind of noise generally occur on weekly basis.



Figure 39 Outdoor $L_{Aeq}$ (in red) and $L_A$ (in brown) measured in 414B WOUDESTRAAT. Grey range is the level provided by strategic noise mapping. This measurement is taken during the operations of a technician taking tools from the van (about 10 meters from the apartments). This is an example of high-level sporadic noise not occurring with a regular time basis.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 64 - 84
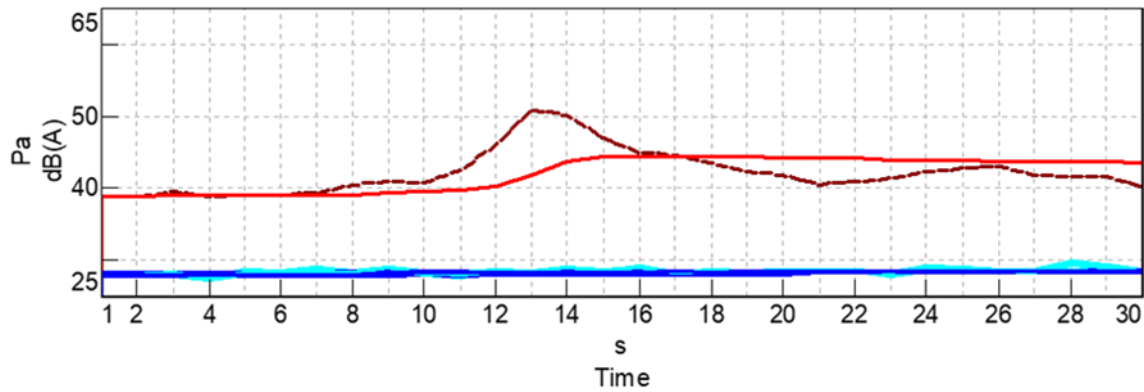
Figure 40 Outdoor versus indoor level measured in apartment 1. Outdoor $L_{Aeq}$ (in red) and indoor $L_{Aeq}$ (in blue). Outdoor $L_A$ (in brown) and indoor $L_A$ (in cyan). Outdoor level is measured with near-field microphone in low noise condition with a car passing on the road near the apartment.
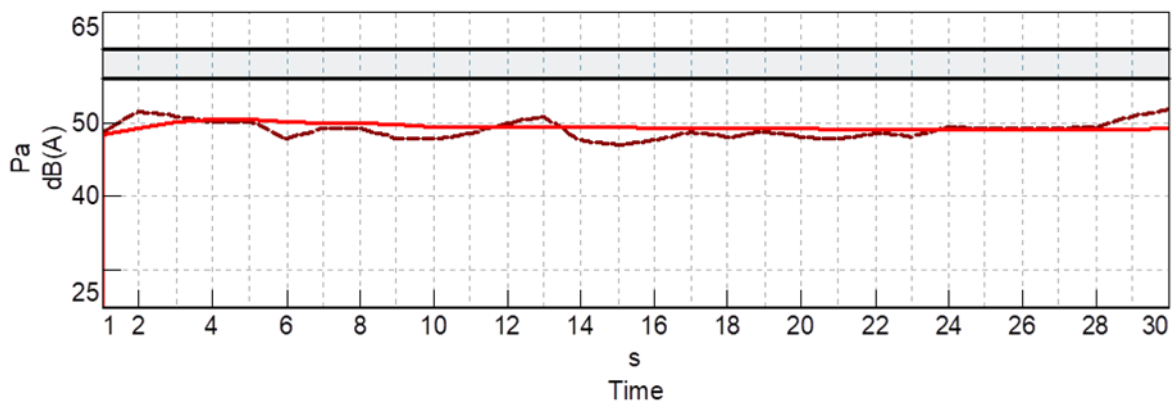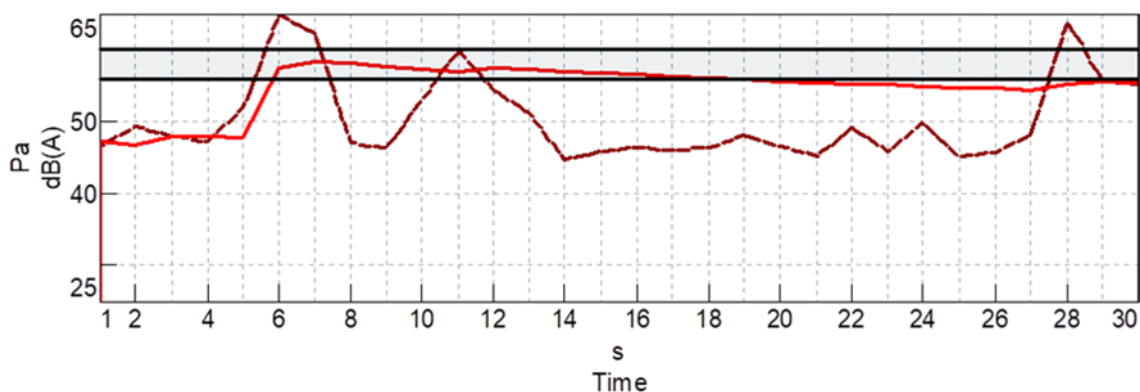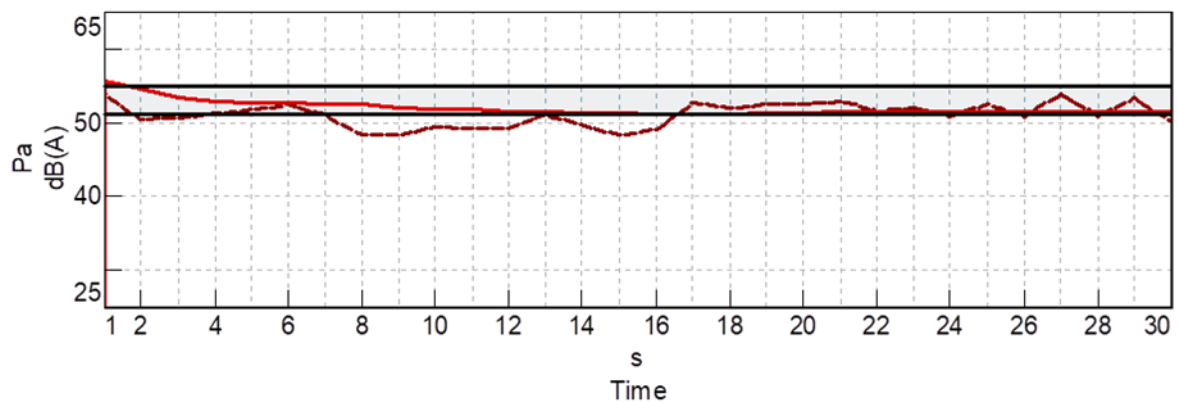


Figure 41 Outdoor $L_{Aeq}$ (in red) and $L_A$ (in brown) measured in 414B DUVENVOORDSTRAAT. Grey range is the level provided by strategic noise mapping. This measurement is taken with near-field microphone in a typical daily condition.
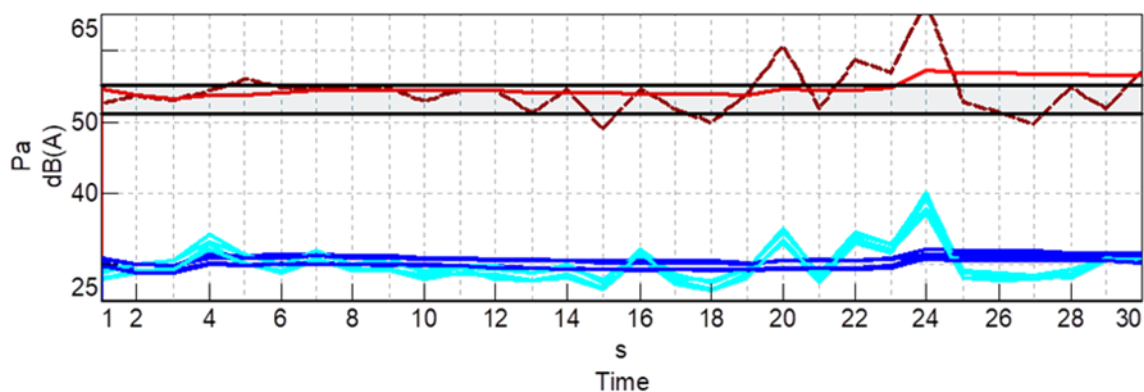


Figure 42 Outdoor versus indoor level measured in apartment 36. Outdoor $L_{Aeq}$ (in red) and indoor $L_{Aeq}$ (in blue). Outdoor $L_A$ (in brown) and indoor $L_A$ (in cyan). Outdoor level is measured with near-field microphone while children were shouting and playing basketball. This represents a noise source frequently occurring in daytime.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 65 - 84

### 5.3.2 TEST #2 Measurement of Sound Reduction Index (Rw)

The measurements of Sound Reduction Index (Rw) were conducted according to standard UNI EN ISO 16283-3. The measurement setup is depicted in Figure 43, which is the same adopted for level monitoring except for the loudspeaker placed in front of the façade, at sufficient distance to assume a uniform acoustic load. The speaker is driven with pink noise (up to about 5 kHz) and it must induce an indoor level sufficiently higher than indoor background noise. Equation (5) makes it possible to calculate the standardized level difference of the façade $D_{2m,nT,w}$, using the external level at 2 m from the façade and the indoor level. The latter is calculated as the average among all five internal microphones. The test case is the façade 2 of apartment 1 in 414B WOUDESTRAAT (refer to the map in Figure 44). Figure 45 shows measurements for this case. The internal level is more than 10 dBA above the indoor background level showed in Figure 40, therefore, the loudspeaker can be considered the main contribution to indoor level. The estimated $D_{2m,nT,w}$ is 41.0 dB assuming a reverberation time of 0.7 s. The Sound Reduction Index can be calculated from the standardized level difference using Equation (1). The term $\Delta L_{fs}$ is null since the façade has no balcony. The measured Sound Reduction Index Rw of this façade is 37.5 dB. Apartment 32 in 414B DUVENVOORDSTRAAT, is analogous to the previous case, i.e. same façade elements, apartment at first floor and no balcony is present. Figure 46 shows an outdoor versus indoor condition similar to the one measured for apartment 1. In this case, the Rw calculated from measurements is 33.9 dB. The difference between the measured Rw of the two apartments is in line with the uncertainty of the measurement technique, variability in façade realization and measurement conditions.

Further details on acoustic performance of apartment 1 are provided. For façade 2 of this apartment, the simulated Rw is 30.7 dB (refer to acoustic simulation report for this value), while the strategic noise mapping provides 58 dB(A) for the zone of this dwelling. The combination of these two puts the living room of apartment 1 in Class A, hence $L_{Aeq}$ < 35 dB(A) (see Table 1). The measurements do the same considering different cases of external level and sound insulation. Equation (1) can be used to propagate different outdoor levels inside the apartment through the façade using the measured value of the standardized level difference of the façade $D_{2m,nT,w}$. Table 6 shows some indoor estimated values, with respect to external noise levels showed in the analysis of the previous section. In all conditions, the indoor level is compliant with Class A. In the previous section, the indoor background level in the living room of apartment 1 is estimated as 28 dB(A), therefore, predicted indoor levels below this threshold can be neglected.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 66 - 84

Table 6 Prediction of indoor levels caused by measured external noise levels using measured standardized level difference $D_{2m,nT,w}$.

| External source | Outdoor level [dB(A)] | Indoor level $L_{Aeq}$ [dB(A)] | Predicted Class |
|---|---|---|---|
| Strategic noise mapping | 58.0 | 18.5 | A |
| Early morning (optimistic) | 40.0 | 0.5 | A |
| Train + moderate traffic | 54.0 | 15.9 | A |
| Train passage (peak) | 60.0 | 20.5 | A |
| Operating technician (peak) | 65.0 | 25.5 | A |
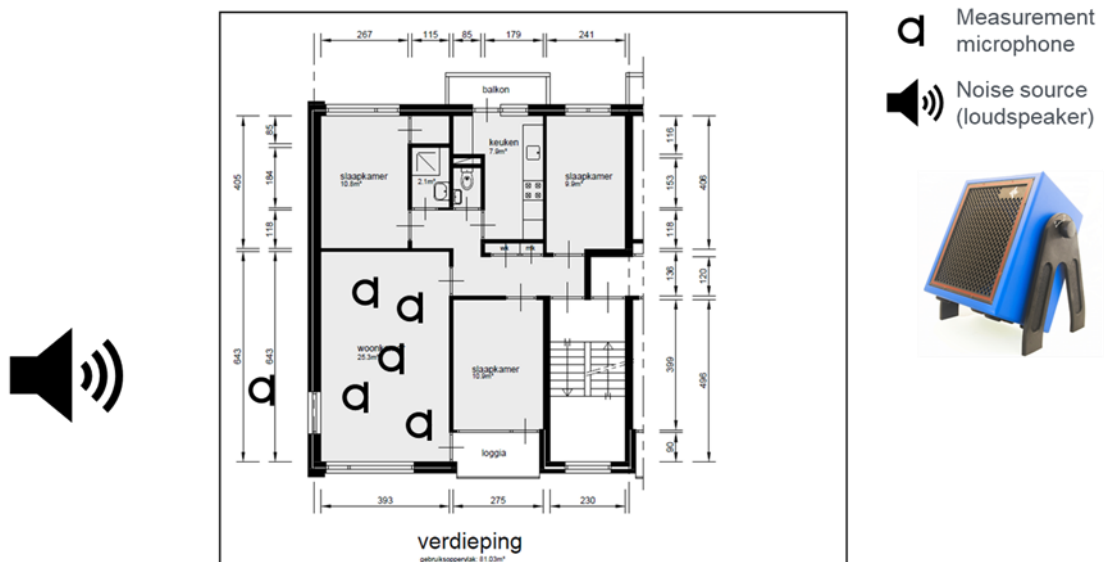


Figure 43 Scheme of measurement setup for Sound Reduction Index (Rw)

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 67 - 84

Figure 44 Numbering of room and façade for apartment 1

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 68 - 84

Figure 45 Outdoor versus indoor level measurement in apartment 1. Outdoor $L_{Aeq}$ (in red) and indoor $L_{Aeq}$ (in blue). Outdoor $L_A$(in brown) and indoor $L_A$(in cyan)
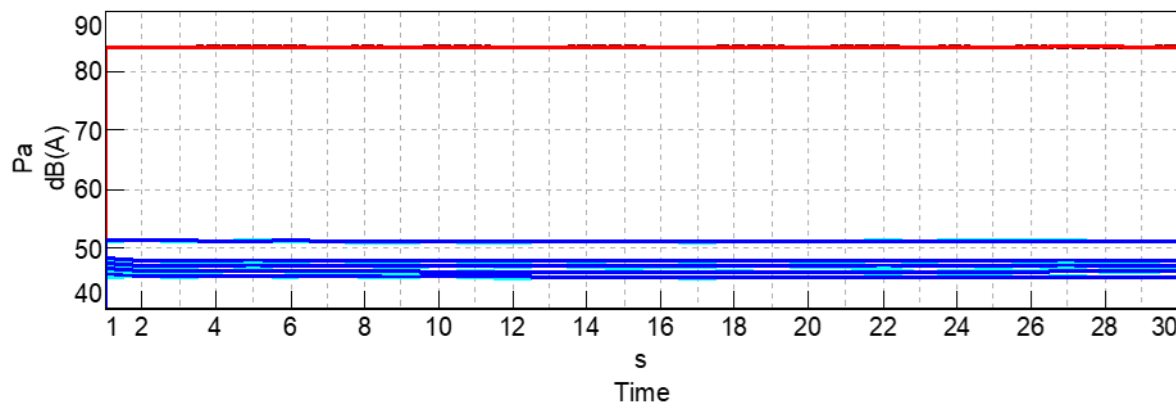


Figure 46 Outdoor versus indoor level measurement in apartment 32. Outdoor $L_{Aeq}$ (in red) and indoor $L_{Aeq}$ (in blue). Outdoor $L_A$(in brown) and indoor $L_A$(in cyan).

### 5.3.3 TEST # 3 Localization of sound insulation leakages

The apartment 32 (414B DUVENVOORDSTRAAT) was the object of test for localization of sound insulation leakages. The acoustic indoor measurement was performed with the same microphone array with 20 microphones used for preliminary tests. In this case, the array was placed at 3 meters from the façade. The external source was the same loudspeaker used for Sound Reduction Index measurements. Figure 47 shows a picture of the measurement setup. The array act as an "a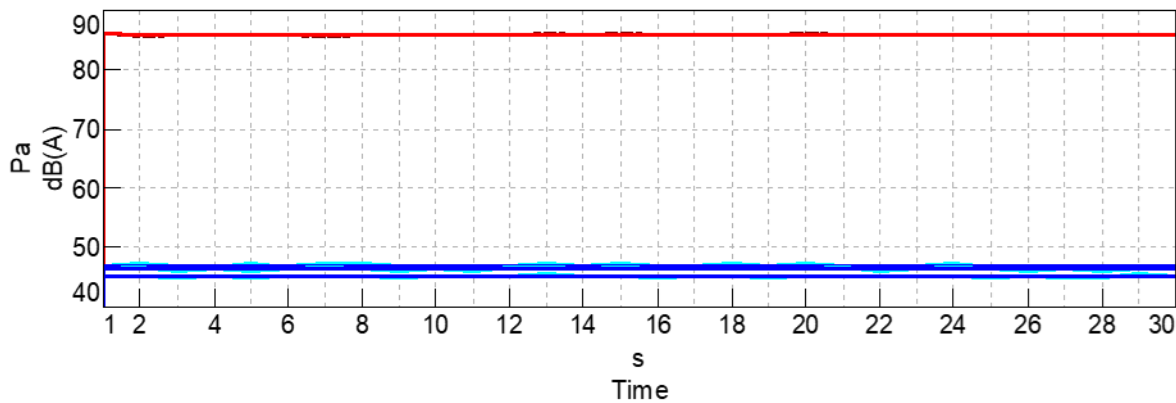coustic camera" that looks at the sound emission of the internal side of the façade. The size of the array is not suitable for sound source localization below 800 Hz, therefore, this is the lower limit used for the acoustic map. The higher limit is at 5 kHz that is given by the sound source emission. Figure 48 shows the map of the full range just mentioned.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 69 - 84
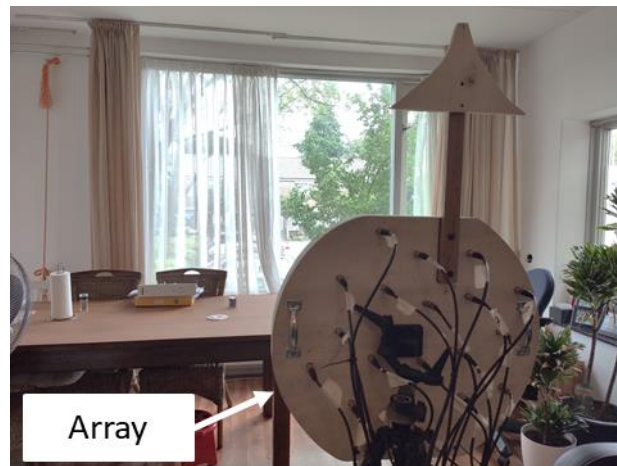
Figure 47 Photo of measurement setup for identification of acoustic leakages with microphone array.
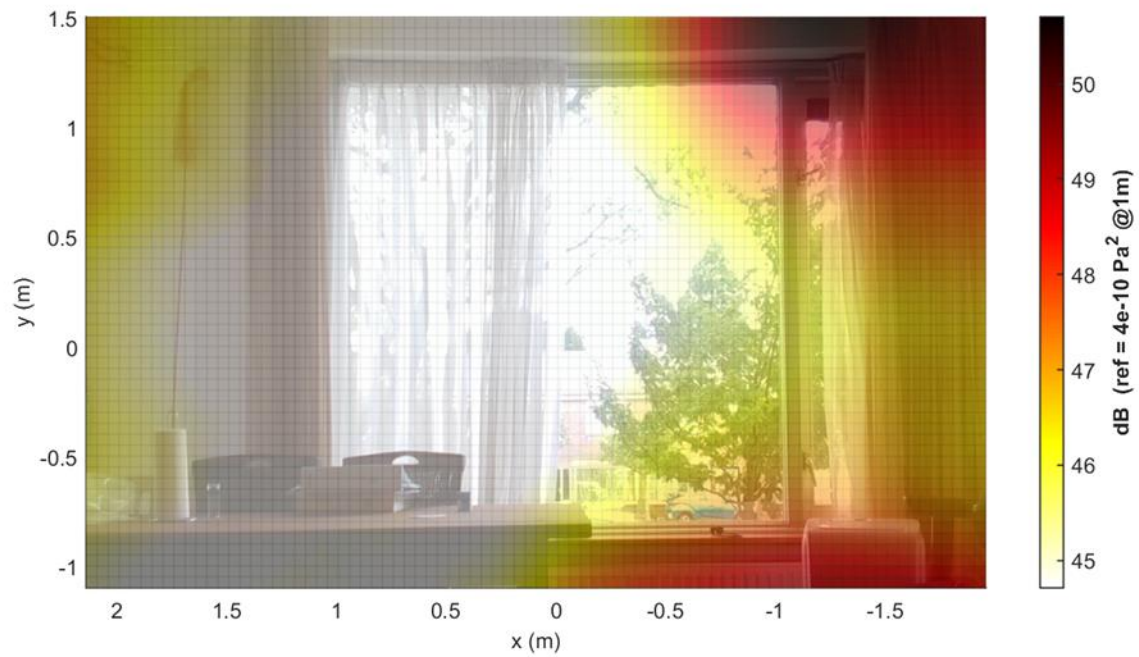


Figure 48 Acoustic map for sound insulation leakages identification (800 – 5000 Hz)

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 70 - 84
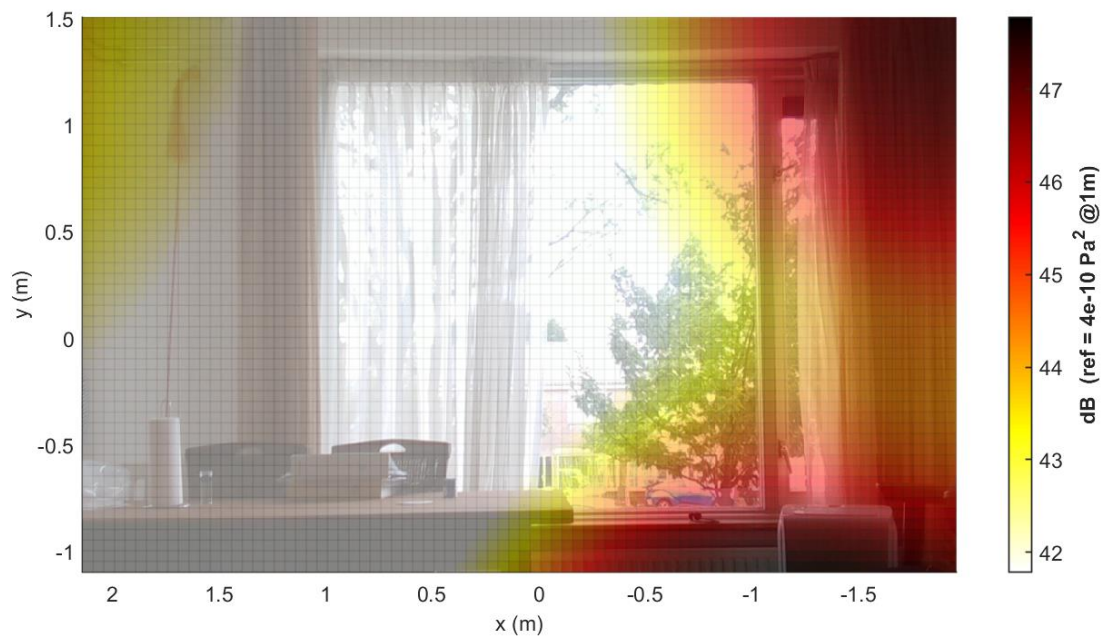
Figure 49 Acoustic map for sound insulation leakages identification (800 – 1500 Hz)



Figure 50 Acoustic map for sound insulation leakages identification (1500 – 5000 Hz)

By splitting the acoustic map in two frequency ranges (800-1500 Hz and 1500-5000 Hz) it is possible to retrieve more information from the same measurement. In fact, given for low

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 71 - 84

frequency it is more difficult to have a fine resolution of the acoustic map. The reason is twofold. On the one hand, the array provides a worse spatial resolution and, on the other hand, the transmission of acoustic waves through the façade may put in vibration larger areas with respect to high frequency. On the contrary, the better spatial resolution achievable with acoustic map and the higher level of insulation of façade elements for high frequency ease the leakage localization task. Therefore, it is suggested to start the identification of acoustic leakages at higher frequency. Figure 50 shows an evident leakage can be identified in the top right corner of the map. This means that the leakage should be searched in the edge of the window or in the top corner of the wall. As regards the low frequency range, the map shows sources in three of four corners of the map (Figure 49). In this case, leakages identified for hi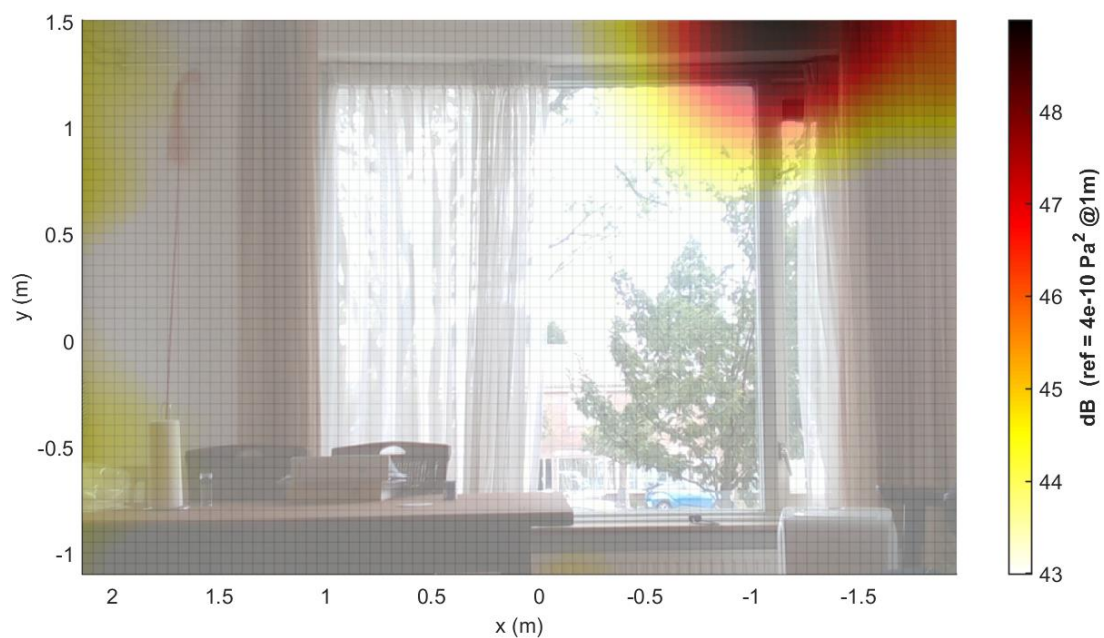gh frequency can help the interpretation of low frequency map. Otherwise, further investigation is necessary such as observe the façade from different position, hence producing different maps from different array positions. This helps in discriminating artifacts from actual sources, i.e. leakages.

## 5.4 KPI CALCULATION BY MEANS OF THE ACOUSTIC SIMULATOR TOOL

The acoustic simulator tool described in Section 2.1.1 has been exploited to calculate the acoustic class of the building located at 414B Woudestraat (refer to Figure 23 and Figure 24).

The inputs for the calculation are the following:

1. the external A-weighted equivalent noise level retrieved from the strategic noise map of the building district, given in Figure 33.
2. The building data such as room dimensions (Figure 51), room use (Figure 52), geometry and material of the façade components, walls (Figure 53) and windows (Figure 54), small element dimension, outside shape of the façade. All those data are retrieved from the BIM of the building. The Figure 51 to Figure 54 demonstrate a clear visualisation of the process within a BIM model.
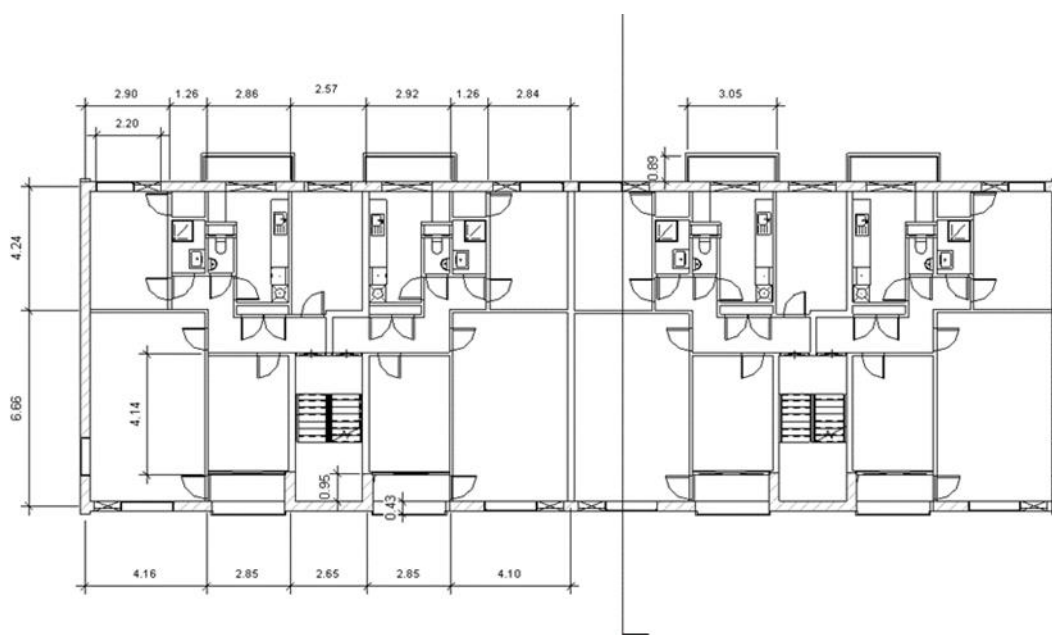


Figure 51 Room dimensions

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 72 - 84

Figure 52 Room use
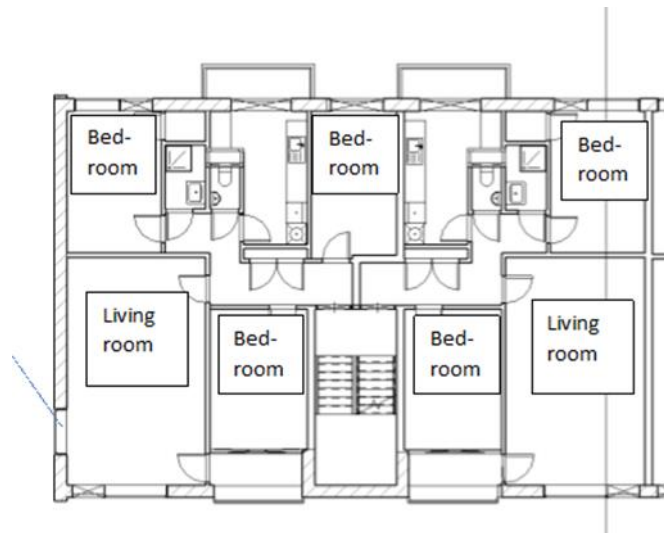


| Wall properties | Wall dimensions |
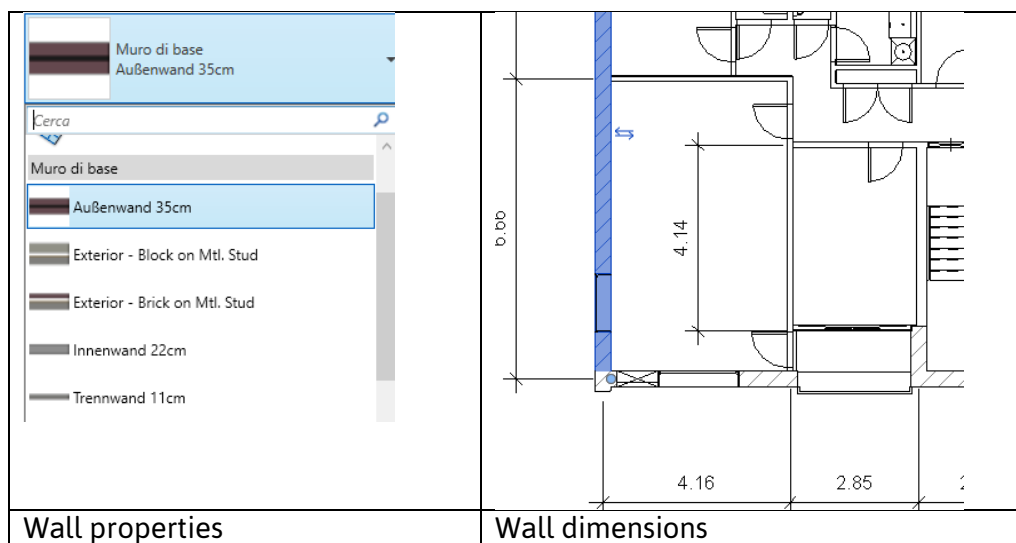
Figure 53 Wall properties (density and thickness of all layers

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 73 - 84
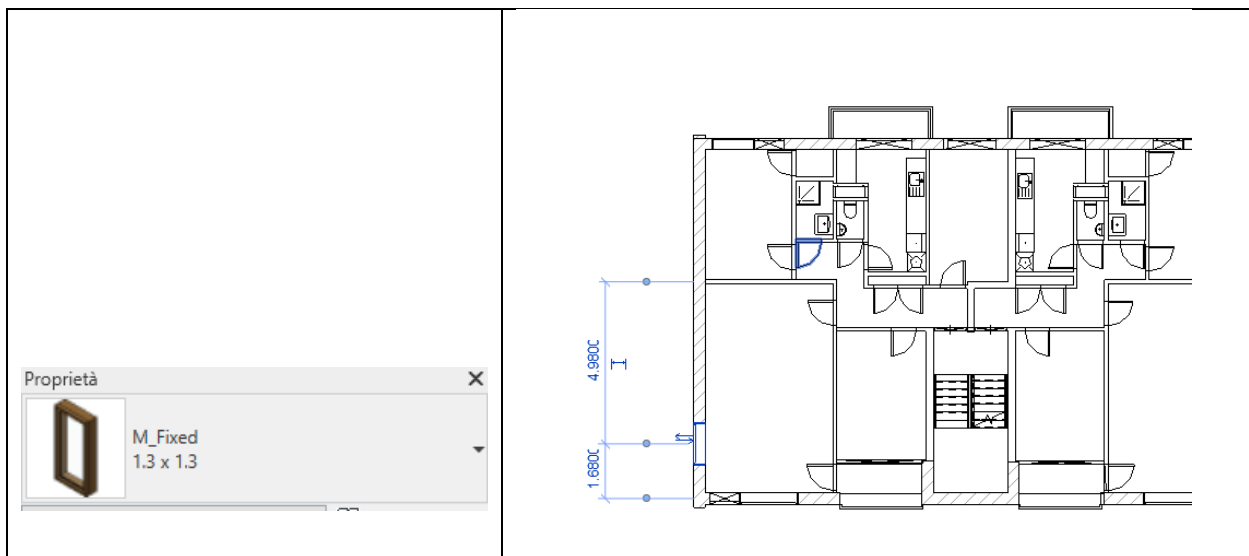
Figure 54 Windows dimensions and materials

The tool will calculate the following outputs:

- The weighted sound reduction $R_w$ for each room façade
- The sound level difference of each room façade $D_w$
- The reverberation time (T60) of each room bordering to the external environment
- The equivalent continuous sound pressure level ($L_{A,eq}$) inside each room bordering to the external environment
- The class of each room façade
- The class of each room bordering to the external environment
- The building KPI
- The building class.

The outputs calculated for the building located at 414B Woudestraat for the rooms 1 to 7 are reported in Table 7. The room and room façade numbering for two different floors of the building are shown in Figure 55. The weighted sound reduction Rw calculated using equation 2 for each room façade is ranging from 28 (for room with large windows) to 59 dB(A) (for rooms without windows). Those values are indexes of good acoustic performance of the building façade. This is confirmed by the equivalent continuous sound pressure level inside each room bordering to the external environment, estimated by equation 5, which ranges from 30 to 35 dB(A). If comparing those levels to the limits prescribed by the standards (see Table 1) each room can be ranked in class A and the same goes for the building. The building KPI is therefore 100%.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 74 - 84

Table 7 Acoustic calculator outputs

| Building ID | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|---|---|
| Room Facade ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Floor | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Room ID | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Wall number | 1 | 1 | - | - | 1 | 1 | - | - |
| Window number | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 1 |
| Door number | - | - | - | - | - | - | - | - |
| Small element number | - | - | - | - | - | - | - | - |
| Road Type | - | - | - | - | - | - | - | - |
| Industry Type | - | - | - | - | - | - | - | - |
| Railway Type | - | - | - | - | - | - | - | - |
| Strategic Noise Mapping | - | - | - | - | - | - | - | - |
| Other External Noise Type | - | - | - | - | - | - | - | - |
| Rw | 37.5 | 30.7 | 27.8 | 27.8 | 30.7 | 30.7 | 27.8 | 27.8 |
| Dw | 37.4 | 32.7 | 28.7 | 28.7 | 32.7 | 32.7 | 28.7 | 28.7 |
| T60 | 0.7 | 0.7 | 0.5 | 0.5 | 0.7 | 0.7 | 0.5 | 0.5 |
| External Noise | 58.0 | 58.0 | 58.0 | 58.0 | 58.0 | 58.0 | 58.0 | 58.0 |
| Internal Noise | 35 | 35 | 30 | 30 | 35 | 35 | 30 | 30 |
| Room Facade Class | A | A | A | A | A | A | A | A |
| Room Class | A | A | A | A | A | A | A | A |
| Building KPI | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Building Class | A | A | A | A | A | A | A | A |

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects
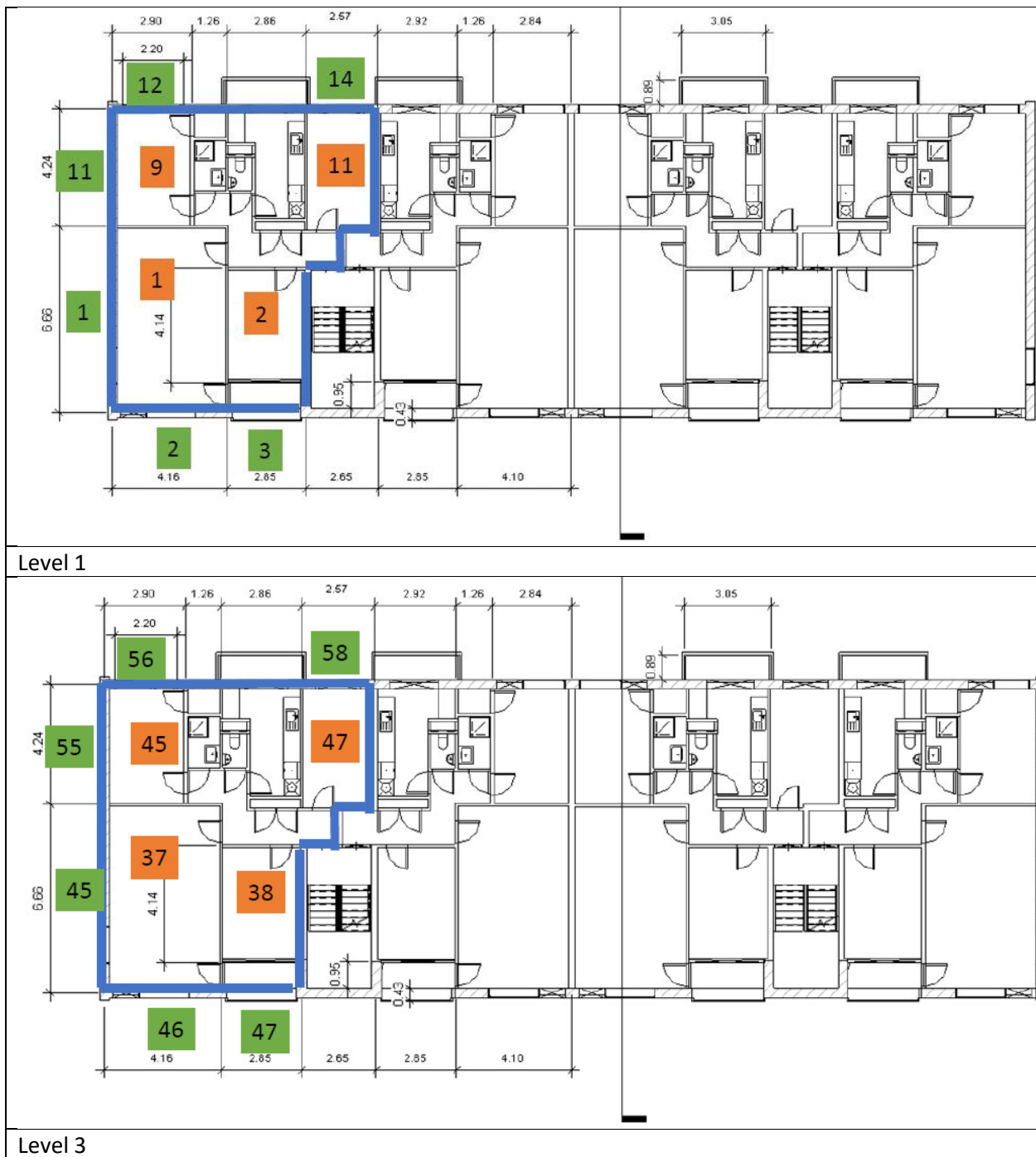
page 75 - 84

**Level 1**



**Level 3**

Figure 55 Room and room façade numbering (top, level 1 and bottom, level 3). Numbers in green represent the room facades, numbers in orange represent the rooms

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 76 - 84

## 5.5 VITORIA DEMO CASE

The validation status of the Acoustic comfort tool, using the IFC4Acoustic parser service, is TRL6 and has been demonstrated in the context of the BIM-SPEED project using one BIM-SPEED case: ARCAYA5 demo in Vitoria-Gasteiz, Spain. This validation has been done in two steps defined below.

### 5.5.1 Data retrieve from the BIM (Input for the tools)

Connection to the BIM-SPEED platform to launch the ETL IFC4Acoustic parser, and connection the ETL IFC4Acoustic parser with the Acoustic's API to send the results obtained from the IFC data parsing to JSON needed to be used as inputs to the Acoustic tool.

The IFC file of the building to be used to launch the service has been enhanced with the BIMtoBEPS tool developed by CARTIF to obtain the thermal parameters of the wall layers that were not included (see Figure 56). As defined in the BIM guidelines included in this document, density is mandatory for the IFC file, and it was not included because the model was exported from REVIT software and the thermal parameters of the wall layers are not available for export to IFC.
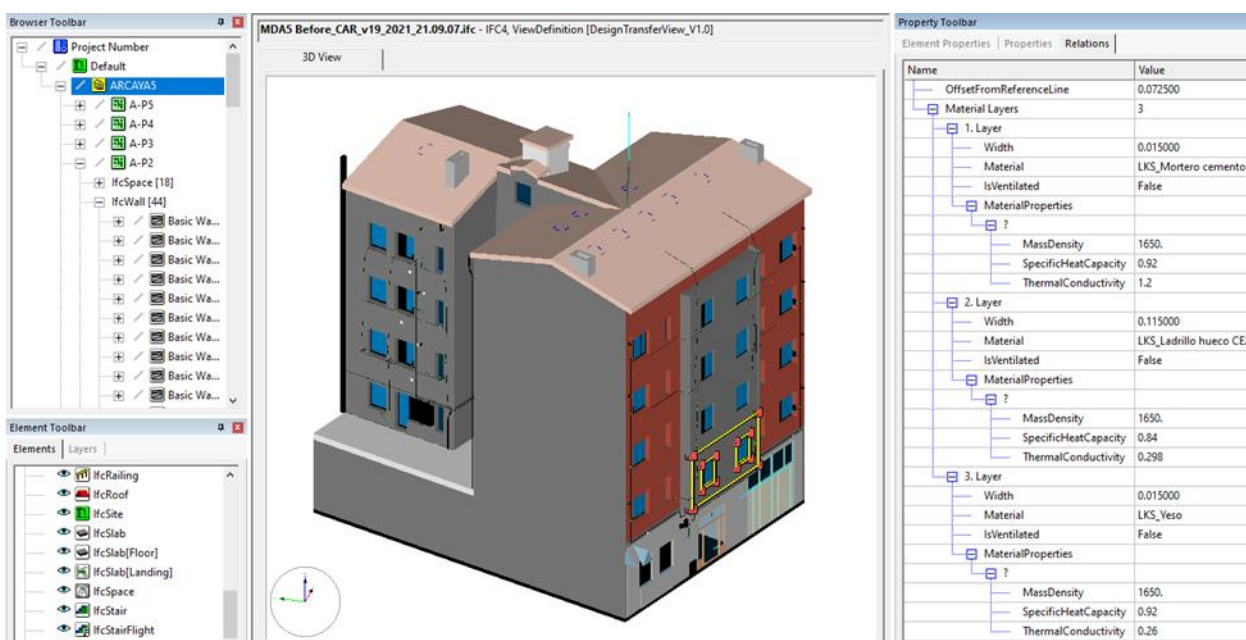


Figure 56 Visualization of the enhanced IFC of the ARCAYA5 building showing the thermal parameters added by the BIMtoBEPS tool.

The first step is to launch the service directly by selecting from the platform the IFC on which the calculations are to be performed, as show in Figure 57,Figure 58.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects
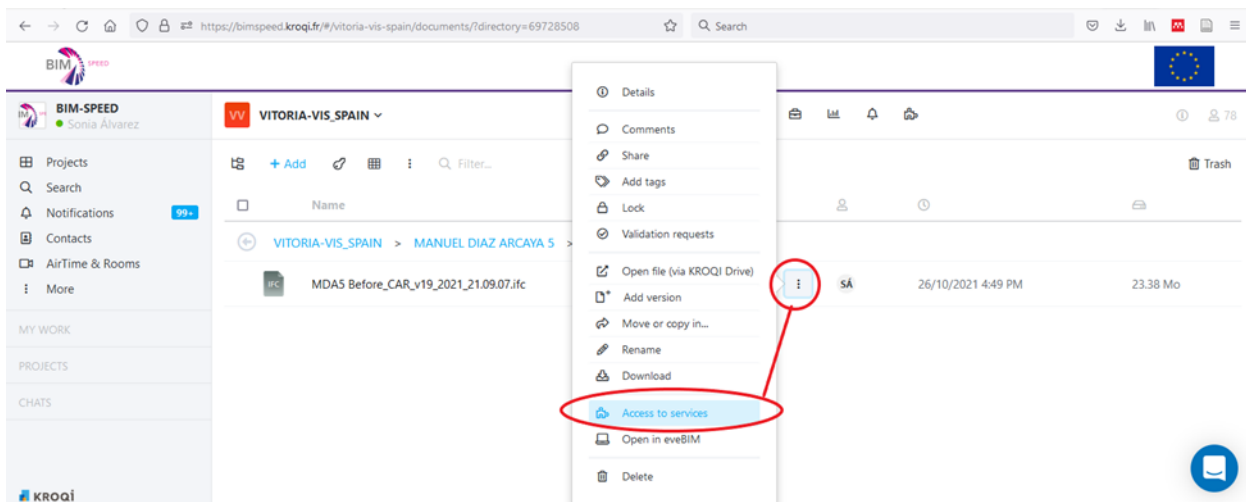
page 77 - 84

Figure 57 Select the IFC and access the services available for use with type of file, within the BIM-SPEED platform
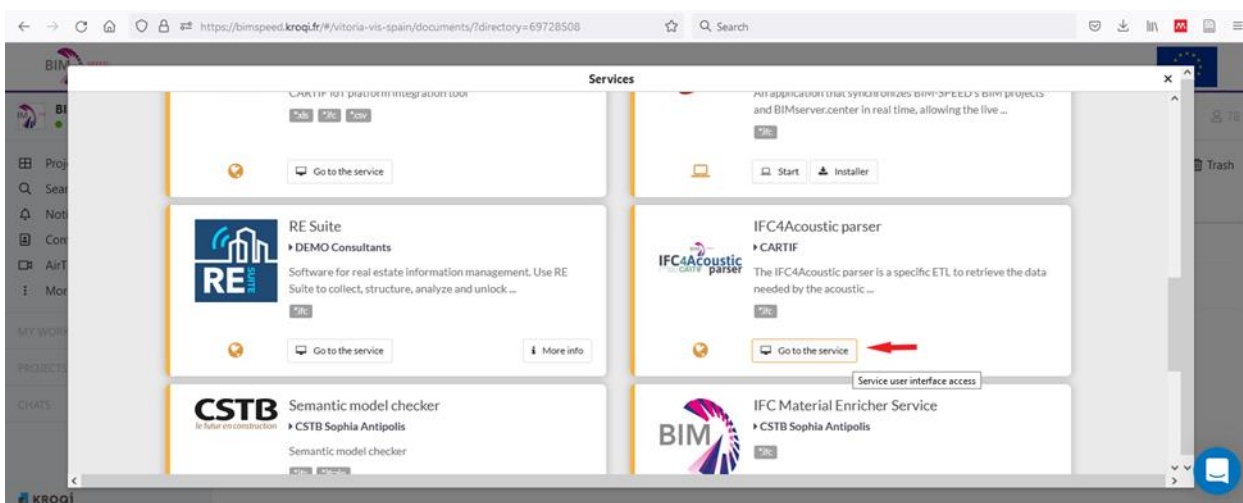


Figure 58 Services available to launch with an IFC file.

After launch the IFC4Acoustic parser service, the IFC selected is loaded directly in the tool, as shown in Figure 59. Once the process has been launched and the tool is ready to continue working on the back-end, a warning appears on the screen to warn that the browser window can now be closed, as shown in Figure 60.

From now on the parsing between the IFC and the JSON that the acoustic tool needs as input, is being done in the back-end. Once the parsing is finished, the ETL will send the JSON file with the results obtained from the parsing directly to the Acoustic tool using its API.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 78 - 84

Figure 59 IFC4Acoustic parser service interface.



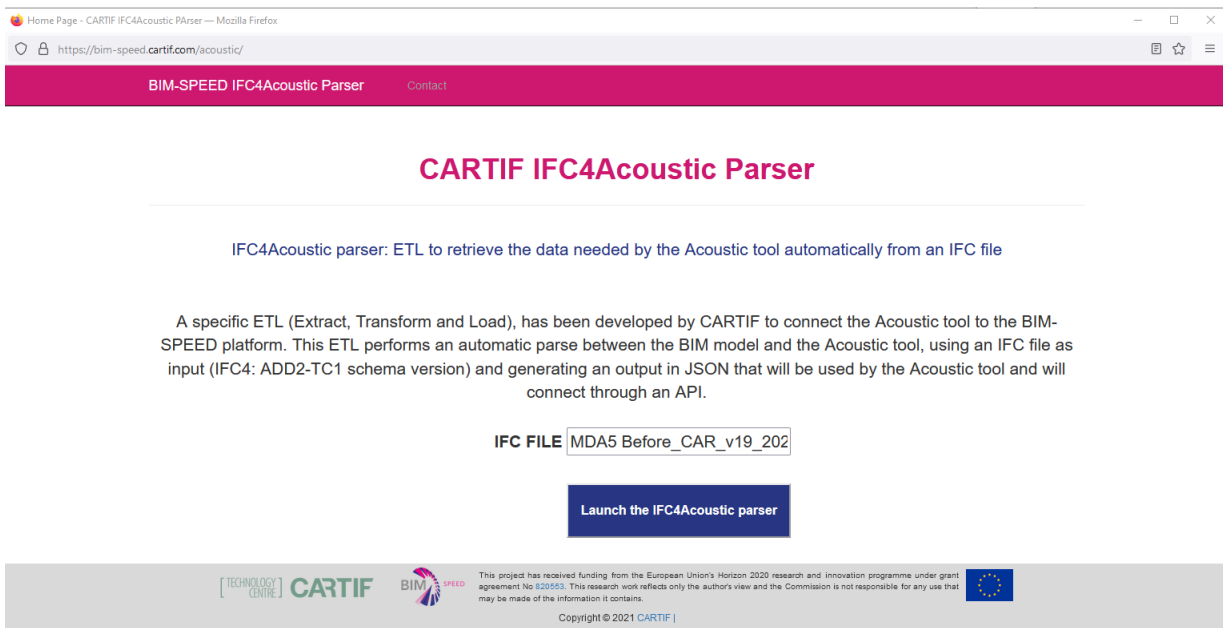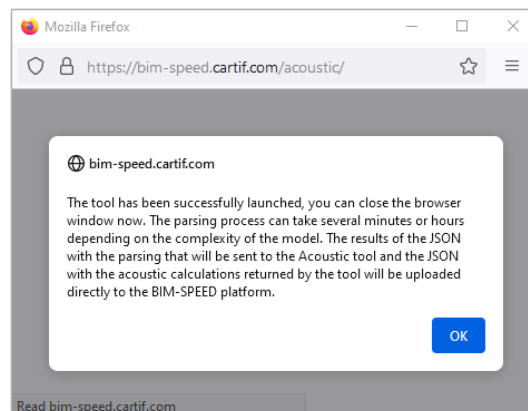Figure 60 Warning launched by the web service.

5.5.2 Data storage in the platform (Output of the tools)

Connection of the Acoustic tool with the BIM-SPEED platform to return the results obtained from the acoustic calculations. This connection is made through the Acoustic's API, which returns the JSON with the acoustics calculations to the ETL IFC4Acoustic parser and the implemented service stores them in the BIM-SPEED platform. The service stores 2 files, the JSON obtained from the parsing with the IFC (named **name_results_ID.json**) and the acoustic calculations results (named **acoustic_calculation_ID.json**). This ID is automatically defined by the service and is associated with the IFC file used.

For this demo, the generation of the results took 1h32min, the files loaded in the BIM-SPEED platform are shown in Figure 61.

BIM-SPEED  **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 79 - 84

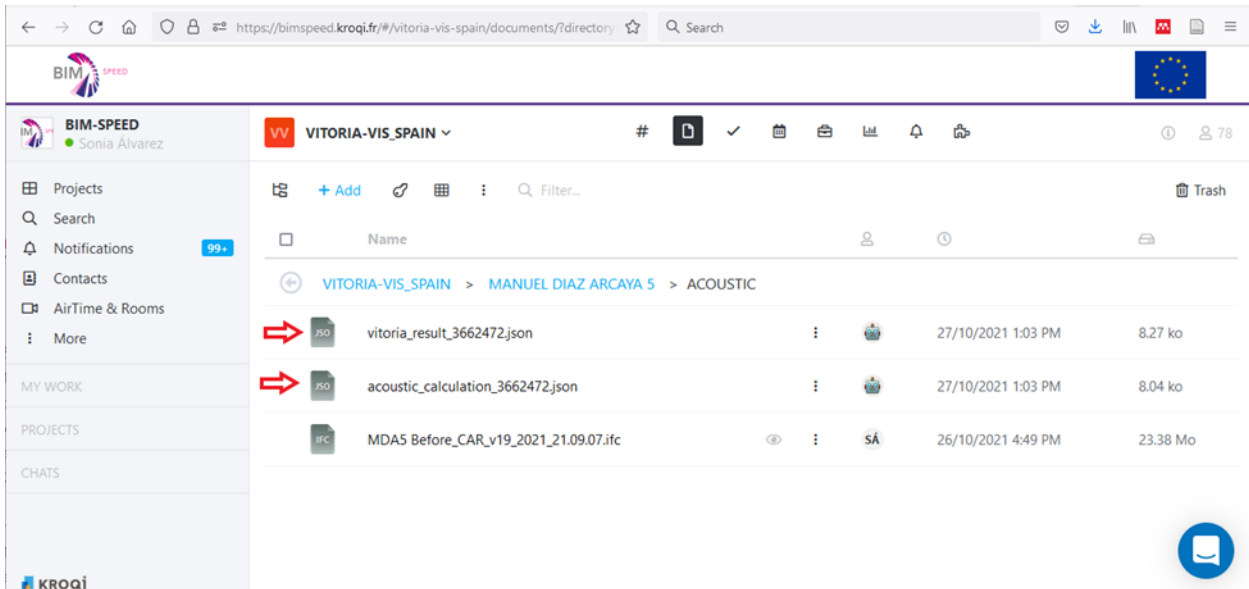Figure 61 JSON results loaded automatically by the developed service.

The acoustic calculation (Figure 62) shows that the building has in this moment a "*High level of building acoustic comfort: retrofit interventions on building envelope are not required*", and the district has "High level of district acoustic comfort: retrofit interventions on buildings are not required."
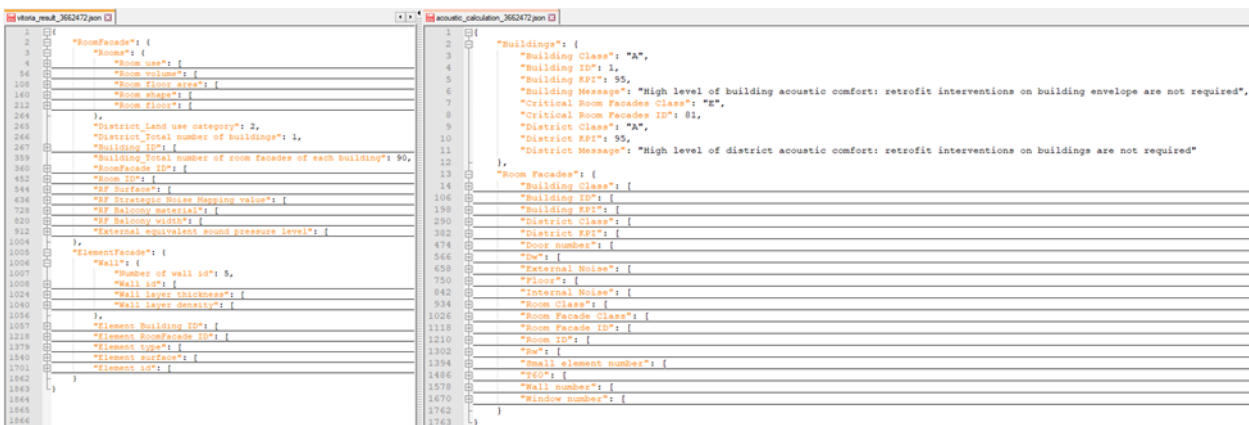


Figure 62 (Left) Results obtained from the BIM to JSON parser. (Right) Acoustic calculation results obtained for the ARCAYA5 building.

Although the tool has taken more than 1h to return the results, due to the complexity of the building, its application considerably reduces the time it takes to obtain the results using the traditional methods. This time reduction is due to the fact that it does not require manual intervention by the user. Accuracy is also improved, as calculations are performed with precise geometric operations and calculations, avoiding human error.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 80 - 84

# 6. CONCLUSION

A BIM- based system, Comfort Eye and acoustic monitoring system have been developed for the evaluation of thermal and acoustic comfort and indoor air quality. In addition to the measurement system, the methodology for defining IEQ KPI has also been developed, which can be calculated with both measured and simulated data. The goal of monitoring is to provide effective information to support the renovation process. This objective is achieved by doing a pre and post renovation analysis and simulating the various renewal strategies.

For a correct KPI evaluation and data processing, BIM information are required in Input. The system output will be provided to the BIMSPEED platform. The dashboard will then provide support to the entire design team during the various phases of the renovation.

The Comfort Eye carries out long-term monitoring continuously and in real time for the thermal comfort and indoor air quality assessment and, thanks to this IoT system it is possible to track the thermal performance of the building envelope over time. A mathematical model has been developed for calculating the thermal transmittance to be applied to the acquired data. An acoustic calculator was developed and validated to evaluate the acoustic performance of the building. Moreover, a technique for the identification of leakages in acoustic insulation is proposed and applied.

The large set of information available from the measured and simulated data can be used to identify IEQ problems, their origin, and the best renovation option. The integration with the BIM aims to develop innovative methods and tools to speed up the process of renovation of residential buildings. The underlying technology on which the project is based is BIM, a digital representation of a building, standardized and interoperable. The activity carried out was aimed at integrating IEQ calculation modules with BIM, so that the data provided by them were available and can be analyzed internally of the digital model.

This methodology was validated by applying it in a real demonstration case, Warmond. The installation was carried out in July 2021, the report shows the result of the pre renovation analysis for the summer season. This system allows to perform the IEQ assessment in the most impact season e simulating the various renewal strategies.

BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 81 - 84

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page 83 - 84

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BIM-SPEED **D4.3 -** Practical framework for BIM-based acoustic, thermal comfort, and indoor air quality assessment in renovation projects

page 84 - 84