Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Corso di Dottorato in Ingegneria Industriale

Sviluppo di una procedura di misura del comfort acustico degli edifici basata su soft-sensing

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XVII edition - new series

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Alla mia famiglia, al mio
fidanzato e a Hero…ciascuno, a modo suo, sempre presente.

Acknowledgements

I wish to thank the person who made this work feasible and has been a guide for me, Professor Gian Marco Revel. Thanks for the motivation and the opportunity of growing provided during these years. A special thanks is for my colleagues, starting from my co-tutor, Dott. Marco Arnesano, always available for helping and supporting me, and also Federica, Andrea, Lorenzo, Filippo, Rachele, Gianmarco and Federico. They are not only colleagues, but friends. Finally, I cannot forget my family, my boyfriend and my friends, which have lived this experience by my side, with a lot of patience, supporting me every day in giving more.

Livia

Abstract

Occupants' well-being is one of the main aspects to be considered in buildings design and refurbishment. In fact, the indoor environment impacts significantly on health and work productivity. Comfort is a very broad concept since it regards multiple aspects, such as indoor air quality, acoustic, thermal and visual comfort. In this contest, acoustic comfort is a complex topic because of its dependence on both physical and physiological variables. Despite being an important concept in engineering, acoustic comfort is vaguely defined and explored in literature. In fact, although the construction industry is facing the issue of requalifying existing buildings to increase performance, acoustic comfort is not yet one of the main drivers due to the lack of holistic reference procedures.

The research presents the development and the application of a methodology for measuring acoustic comfort of buildings, using a soft-sensing approach. The proposed soft-sensor provides a measurement system, which takes into account experimental, simulated, assumed and subjective data, through which the buildings indoor acoustic quality, in relation to the outdoor surrounding noise level, can be evaluated. The metric is represented by Key Performance Indicators (*KPIs*), which express the buildings acoustic comfort, either quantitatively and qualitatively, and make possible the comparison among acoustic comfort of different existing buildings. The evaluation system based on *KPIs* can be applied in buildings renovations for evaluating the acoustic quality of buildings before and after the retrofitting design, supporting the stakeholders in the evaluation stage. In particular, in this work, two *KPIs* have been developed: the first one is identified as "objective *KPI*" and provides information regarding the acoustic comfort of the building, with normalized value for simplified quantification of acoustic performance. The second one is identified as "subjective *KPI*" and aims at validating the objective one, since it is based on the assessment of the occupants' rating.

Several case studies are used to demonstrate the exploitability of the developed soft-sensing method, using in-field measurements combined with calculation models and subjective data. Sensitivity and uncertainty analyses are performed to establish how the accuracy of the KPIs measurement impacts on the decision-making process. The application of the methodology has shown promising results in the identification of the best retrofit strategy.

The soft-sensor system for buildings' acoustic comfort measurement has been integrated within the European project New TREND (Horizon 2020) and applied on one demo-case in order to demonstrate its usability and reliability.

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CHAPTER 1
INTRODUCTION

1.1 Framing of the scientific issue

The major purpose of a building is to provide a healthy and comfortable environment for occupants, since people spend about the 90% of the day indoors [1], [2], [3]. In Europe, more than 70% of the existing building stock has been constructed before the 70s, when there was a growing need to build low-cost dwellings up in urban areas and building codes and standards were very limited [4]. The fast urbanization and the lack of strict regulations were the main causes of the poor energy performance and indoor quality of the buildings [5]. Therefore, the majority of existing buildings require renovation actions to improve and guarantee structural resistance, energy efficiency and high-quality of internal spaces, including, for instance, noise protection [5].

Growing concerns on the environmental, social, and economic sustainability of buildings caused a substantial focus of research on the effects that indoor environmental quality has on human comfort, performance, and health [6]. The indoor environment results from the interaction of the site, the climate, the building system and occupants [7]. A key factor in achieving healthy environments in buildings is the provision of a high level of Indoor Environmental Quality (IEQ) [7] - [11]. IEQ is considered as an indicator of the level of comfort which includes elements such as thermal, acoustic and visual comfort and indoor air quality [12]. In both existing and new buildings, there is now an increased focus on the energy efficiency subsequent to the Energy Performance Buildings Directive (2010/31/EU) (EU, 2010). However, achieving energy efficiency does not automatically ensure better IEQ, particularly, in existing buildings [13]. Building owners often do not consider improving IEQ as a means of keeping the running costs lower and rather invest only in immediate maintenance and operation. The lack of understanding of IEQ could have adverse effects on the occupant's health in the long term [14]. In addition, IEQ could directly affect the productivity of the occupants and induce higher costs on employers [15]. Moreover, other than being driven by individually quantifiable physical factors, occupants' response to IEQ is generated by a combination of stimuli where physiological and psychological dimensions must also be taken into account.

Regulations which indicate measurement methods and set values of indoor environmental parameters for improving the comfort and energy efficiency of buildings, was elaborated [16] and new ones are yet under development. The REHVA position paper to the European Commission on the proposal to revise the EPBD (EU, 2010) extensively promotes the application of methods to improve the indoor environment quality along with the energy efficiency (REHVA, 2017). The EN15251 standard [16] is a result of the EPBD and specifies the criteria for achieving better indoor environmental conditions. Usually, measurement of IEQ involves the use of high price equipment which combines a series of sensors able to measure indoor environmental parameters and then to analyse a large amount of information in a short time [17], [18].

Recent studies have provided evidence that the acoustic comfort is one of the most influential factors on human perception and behaviour, which significantly contributes towards the regulation of their physical and psychological well-being [19]. Noise is a pollutant which cannot be avoid in daily life and often is one of the lead causes of dissatisfaction and discomfort within the living environment [20]. The World Health Organization (WHO) [21] has defined the noise as “unwanted, unexpected and unpleasant sound” that penetrates external walls, party walls and separating floor structure, and cause of concern of the inhabitants and users of the buildings. In addition, the WHO identified a considerable number of effects of excessive noise levels into living environments, including annoyance, sleep-disturbance and irritability, and also long-term health effects such as cardiovascular disease, heart illness, hypertension and psychiatric problems. Despite being an important concept in engineering, acoustic comfort is vaguely defined and explored in literature [22]. Acoustic comfort of a building is ensured if occupants are not annoyed from noise, cannot hear unwanted sounds that interfere with their communication and disturb to sleep, and in general not suffer from noise impact [23]. Buildings are subjected to noise pollution: traffic, external and internal installations, anthropic noise coming from neighboring units, due to incorrect layout (arrangement of space) or low insulation between adjacent spaces, often make the indoor environments unhealthy and cause of stress and other pathologies from acknowledged as "sick building syndrome". The acoustic quality of a building is represented by its ability to "block" the noise coming from outside and from inside of the building itself, or rather by the quality of its passive building acoustic requirements.

Despite being recognised as an important parameter, research indicates that acoustic comfort is not considered high priority in building design and rehabilitation, leading to several post occupancy productivity and well-being related issues [24]. Although, it is becoming popular and more and more buildings are being analysed for acoustical comfort there is a long way to go in this area [25]. Green building guidelines have started including acoustic comfort as one of the criteria but the overall priority for this is low. Leadership in Energy and Environmental Design (LEED), which is one of the most popular green building guidelines has included acoustic credits as an option but lots more need to be done to make it a mandatory element of green building guidelines [26]. Even the EN15251 [27] recommends the maximum permissible sound levels [dB(A)] for occupied buildings with non-continuous noises. Anyway, the standard is only based on noise from service equipment and not outside noise. In addition, it provides measurement criteria to be used to check whether the performance of the building meet the design requirement, for thermal environment, for indoor air quality and lighting, but not for acoustics. This because EN15251 is a standard primarily used for energy simulation, then only few or none practical guidelines on how accurately and efficiently measure IEQ performance, along with acoustics, are included [28].

Many studies dealt the issue to measuring acoustic quality within living environment, using different measurement approaches, both subjective and objective. Concerning the subjective methods, surveying through questionnaires is often the simplest and least-expensive method for evaluating IEQ concerns in a building [29]. For example, Annex H of EN15251 [27], suggests using the direct subjective reaction of the occupants for overall evaluation of the indoor environment, including the acoustic perception. Several studies, as [30] analyzed acoustic satisfaction in office environment through satisfaction-scale questions, on the basis of noise level and speech privacy. The subjective analysis correlates

the distribution of noise level or speech privacy votes with a particular aspect of the office environment, like office type (private office, open office environment, etc.), and gender.

A common complaint in work spaces is the lack of speech privacy in open plan and private offices. Standard methods exist to quantify speech privacy by measurement and calculation. Performing these methods, although accurate, requires the precision of expensive hardware and the experience of professional acousticians [31].

The work presented in [32] focuses on the evaluation of acoustical quality in high school classrooms, performing several field measurements, including:

- Sound insulation, according to [33];
- Reverberation time, according to [34];
- Clarity, according to [34];
- Speech Transmission Index, according to [34], [35];
- Background noise according to [33].

In this study, field investigations were carried out to investigate the acceptable range of every individual environmental factor as well as the cumulative effects of multiple factors on indoor environmental quality. In the survey, the parameters of thermal, luminous, and acoustic environments were measured and subjects' satisfaction levels with regard to the indoor environment were determined using questionnaires.

In [12], in-field measurements of the noise level [dB(A)] were performed. Socio-cultural buildings have been investigated from an acoustic point of view because the noise disturbed activity and weakened the ability to concentrate of the occupants. In particular, the sources of noise pollution were located outside of buildings. For that reason, the acoustic pressure levels were measured with Bruel & Kjaer Hand-held Analyser Type 2250 in classrooms, providing, during measurement, doors and windows closed and none noise sources at indoor. Then, an acoustic comfort index was calculated starting from measured value of sound level.

Catalina and Iordach [36] developed an IEQ index model to predict variables such as operative temperature, indoor sound pressure level, indoor average illuminance, and specific energy consumption. The A-weighted sound pressure level were measured using various equipment. The occupants' satisfaction with the indoor environment was investigated by a questionnaire in office buildings, educational buildings, and libraries. Based on the analysis of the relationship between occupant's satisfaction and the different measured indoor environmental parameters, a predictive model for evaluating overall satisfaction with the indoor environment was developed.

In [37], a methodology for indoor environmental quality classification is presented. Without an appropriate classification methodology, comparison among performances of different existing buildings is impossible. In particular, in the study, acoustic comfort was evaluated by means of prediction models capable of assessing the noise levels affection the indoor environment once the wall features and outdoor noise level characterizing the acoustic zone of the building site are known.

Many researches proposed methods for evaluating IEQ in buildings using a scoring system [37], [38], which includes also the acoustic comfort rating. Anyway, while some of them offer guidance on subjective and objective measurement method, the specific of how to implement these methods are left up to user [28]. There are limited guidelines on how to use the scoring models, along with a lack of consensus on measuring protocols. Moreover, there

is a lack of agreement on the results interpretation and if and how buildings can be compared based on model results [28].

Basing on the literature review, it emerges that there is a lack of a clearly defined and detailed holistic procedure, based on a scoring/rating system, for measuring the acoustic quality of buildings. For that reason, in the presented research, a complete procedure for measuring the acoustic comfort of buildings has been developed, which includes an appropriate classification procedure for the comparison among acoustic comfort of different existing buildings, based on Key Performance Indicators. In particular, the acoustic comfort is assessed on the basis of the equivalent sound pressure levels within the living environments, deriving by the external noise surrounding a building. On this context, the building envelope performance plays an active role in the protection against external noise and in the acoustic comfort conditions maintaining.

1.2 Objective of the research project

This PhD thesis treats the development and application of a procedure for measuring the acoustic comfort in buildings. The work has been developed within the H2020 EU project NewTREND[1] (New integrated Methodology and Tools for Retrofit design towards a next generation of ENergy efficient and sustainable buildings and Districts) that has the scope of developing a collaborative design platform for energy retrofitting of buildings at district level, establishing energy performance and user comfort as key components of refurbishments. The developed soft-sensor system has been included within the integrated collaborative design platform of the NewTREND project for retrofit assessment.

Acoustic comfort of buildings is not represented by a unique physical quantity, that can be directly measured, but rather, depends on the combination of different physical variables, as well as subjective parameters. Therefore, it cannot be measured by means of a "direct" measurement instrument. It can be assessed indirectly through the direct measurement of some variables, the assumptions of others difficult to measure, in particular in automated process, and, also, the simulation of other data, who themselves take into account measured, simulated, assumed and in-situ collected data. In addition, the acoustic comfort is also a subjective parameter, which depends on human perception and sensitivity.

Given the lack of a holistic procedure to measure the acoustic comfort [39], [40], an efficient soft-sensing approach for acoustic comfort measurement has been developed, which combine experimental measurements, mathematical models, which take into account real measurements, simulated or assumed data, and subjective data, providing outputs for acoustic comfort assessment.

[1] http://newtrend-project.eu/home-it/

1.3 Sound insulation indicators against external noise

Most of the buildings in Europe are located in densely populated urban areas, with business activities or even near high traffic roads that has been shown to be the main pollutants that influence the quality life and the well-being within the buildings [41] - [43]. It has been estimated that about 80 million people are exposed to unacceptable noise levels and that almost 170 million people live in area where noise causes sleep disturbance, adverse health effects and serious annoyance [43] - [45]. Together with the pursuit of government actions aimed at reducing the environmental noise levels (sound barriers, infrastructures renovation projects, industrial noise mitigation, etc.), the main approach to protect buildings' users from the transfer of the outside noise into an indoor environment is designing high sound insulation building envelopes [46], given its significant contribution to reduce external noise level, both in case of new and existing buildings [47] - [49].

In Europe, regulatory requirements and classification schemes for façade sound insulation present a high degree of diversity, regarding not only the limit values but also the different descriptors used. Limit values of the parameters describing the acoustic requirements are divided into several acoustic classes, which reflect different levels of acoustic comfort [50], [51]. The façade sound insulation requirement can be represented through 27 different descriptors. They are divided into two main categories related to the performance of the building (façade sound insulation) and the indoor sound level, or rather directly or indirectly related to the external noise [52] - [54]. Some countries (D, F, LT, NL) consider the minimum façade sound insulation as a function of outdoor noise level, based on outdoor noise mapping. Anyway, the noise mapping not necessarily is representative of the noise exposure of each single facade of the building [52]. Hence, in general, the determination of the required façade sound insulation does not consider adequately and sufficiently the real noise exposure at different positions at the building. This can lead to non-optimized building envelope design [52] and also to not satisfactory indoor acoustic conditions for occupants [55], even if acoustic requirements respect the limits imposed by the standards. It may happen that an acoustic class does not correspond to the perceived acoustic quality [56]. A demonstration case is provided by the descriptor adopted in Italy for the façade sound insulation, $D_{2m,nT,w}$, according to Italian decree DPCM 5 December 1997 [57], for which the respect of the minimum value is requested by the national regulation for the protection against external noise. The majority of building envelope renovation interventions are based on the achievement of the limit value defined by the European standards and does not consider the external noise levels of the area where the building is located. However, the acoustic quality of buildings' internal environments depends largely on the urban context. It would not be cogent to evaluate a building's acoustic quality based on its façade sound insulation value without considering its interrelationships with its urban surroundings [58]. Actually, it could happen that the outdoor noise in front of the building is so excessive that higher façade sound insulation value has to be reached, even if it respects the limit imposed by the national standard. Thus, during renovation projects, together with the necessity to verify the compliance of the noise limits, it is important to link the outdoor noise level (in front of a specific room façade) and the internal one, through the façade sound insulation performance [47], assigning an acoustic class representing the perceived indoor acoustic quality. This can avoid waste of money due to inadequate retrofit designs causing no improvements. Hence,

in order to ensure a better acoustic protection, noise limits within the living environment should be defined, expressed in terms of L_{Aeq} or L_{Amax}, in such a way as to avoid the interference with the people' daily activities, which is inducted by the outdoor noise. Therefore, it is necessary adding to the external noise control concepts, highly expensive and difficult to be monitored, a new philosophy concerning the protection within the living environments defining the acceptable noise levels which, if are exceeded, may induce annoyance and discomfort conditions, and from that thresholds, design adequate building systems [59].

Usually information concerning buildings acoustic performance are transferred through decibels quantities (e.g. noise insulation indices), thus not expert people are forced to understand the meaning of these expressions [60]. Therefore, users are rarely involved in the decision-making process. In addition, often happens that people have difficulties in choosing dwelling to live because of the lack of information on how to select buildings that provide an appropriate noise protection. As a matter of fact, acoustic technicians so far seem to be unable to provide data concerning the acoustic quality of buildings in a simple and clear manner. The introduction of metrics as acoustic classification schemes and performance indicators has been a core aspect of building assessment systems and has allowed the simplification and the readability of information about the acoustic quality. An indicator that represents a quantifiable value to determine in which measure the strategic and operative goal is reached, is called Key Performance Indicator, *KPI* [61]. It works as design and decision support tool, providing the designer with quick and clear feedback on the performance achieved and also, it can be compared to identify the best retrofitting option [62].

In the presented research, two acoustic *KPIs* have been developed, with the purpose to provide a metric through which express the acoustic comfort measure of buildings. They can be used by the stakeholders involved in the retrofitting process to take informed and aware decisions.

1.4 NewTREND project overview

NewTREND is a European Project of the Horizon 2020 program, included in the topic entitled "EeB-05-2015: Innovative design tools for refurbishment of buildings at district level". The project has started in date 01-09-2015 and it was successfully closed on the 31st August 2018. The consortium is composed by thirteen partners, between universities, research institutes and companies, including the UNIVPM, *Università Politecnica delle Marche* (Italy).

The scope of the project was to develop an integrated methodology for energy retrofitting of buildings at district level, establishing energy performance and user comfort as key components of refurbishments. To enable the effective application of the methodology, a toolkit has been developed to support each phase from concept design to implementation and operation, fostering collaboration among stakeholders, involving building inhabitants and users. The methodology was supported by an online collaborative platform to integrated design, which plays the role of exchanging information and facilitating dialogue between the different stakeholders involved in the retrofit process. During its development, the NewTREND methodology for acoustic comfort measurement has been tested in practice,

using the methodology at its full length. This thesis gives a detailed description of the developed methodology and summarizes the main results, presenting two significant pilot studies, although many other investigations have been conducted during the research development.

CHAPTER 2
MATERIALS

The soft-sensor system for the "objective" measurement of the acoustic comfort allows acoustic analyses starting from the measurement or the simulation of indoor sound pressure levels within the living environments, due to the external noise surrounding the building under investigation.

In-field measurements of equivalent continuous indoor sound pressure level [dB (A)] can be carried out using traditional or low-cost acoustic sensors (see 2.1), according to the desired accuracy and budget availability. The measurement setup and procedure are explained in chapter 4.

Alternatively, indoor A-weighted sound pressure level can be calculated according to analytical model provided by standard [63], starting from the measured or estimated outdoor sound pressure level, by using the sound level difference of the room façade, expressed in a single number rating [63]. In the following paragraphs, required calculation models are briefly described.

2.1 Sound measurements and acoustic sensors

Typically, the sound is measured using instruments working as a "proxy" for human ears, and techniques of analysis which take part of the function performed by brain in interpreting the information recorded. Microphones are the most common sound sensors and they convert acoustic energy in calibrated electrical signals, which can be recorded for future analyses or processed in real-time. Sometimes, acoustic analyses are performed for a single point in the space and contain a unique information, since it depends on the relative positions of the measurement point and the source of noise contributing to the acoustic field at that point. If a moving microphone is used for measuring at a number of discrete points, spatially averaged "image" of the sound field is obtained. Often, the need to quantify the acoustic field is to determine compliance with regulatory requirements or to compare the sound field features with those intended through a process of design.

Roughly, in order to measure the way in which the human hearing system responds to the intensity of sound, the sound pressure signal has to be converted in decibels [dB]. In that way, measuring *sound pressure level* (L_p) does not takes into account the sensitivity of the hearing system to low and high frequency. This is typically accommodated by adjusting the linear response of the microphone using an A-weighting. This yields an *A-weighted sound pressure level* (L_A [dB(A)]), which is similar to unweighted levels if the sound field contains the majority of its energy in the mid frequencies, and lower than unweighted levels if there are dominant high or low frequency components. The measurements which reflect human perception of sound is roughly reflected by this combination and use of a decibel scale.

Typically, when performing measurements, it is uncommon to focus on instantaneous sound pressure levels, since is more interesting quantifying the characteristics of a sound field over a period of time. The *equivalent continuous sound pressure level* (L_{eq} [dB(A)] or [dB], specified along with the period of time over which the measurement was taken) is the

simplest measures that accommodates the time-varying nature of different sound sources. Therefore, the measured time-varying sound pressure level is replaced with a single continuous sound pressure level that, if present at the measurement point, would contain an equivalent amount of acoustic energy. The capability to quantify sound through the L_{eq}, allows to specify maximum background noise levels for the environments to design.

Noise can be defined as an unwanted, unpleasant or unexpected sound. In physics, the sound is a perturbation, of an oscillatory character (mechanical vibration, aerodynamic turbulence, etc.), generated by a sound source which, propagating in an elastic means (air, water, solid, etc.) causes a variation of pressure that the human ear can detect [64]. In other words, sound is a mechanical energy transport shape, without matter transport, through waves that propagate in an elastic means at a certain speed, which strongly depends on the propagation means (in air, speed is about 344 m/s at 20°C of temperature). Without an elastic means, sound propagation does not occur. In the air sound wave can be caused by a vibration surface such as the cone of a loudspeaker, a vibrating fluid, such as a resonating air column in an organ pipe, or by the turbulent mixing of the air masses, as in the exhaust of a jet. In all cases the sound wave, which can be considered a pressure "disturbance", propagates outwards from the source into the surrounding means.

According to the above description, many sensors provide measures of the sound pressure levels and other acoustic quantities within the environment. Procedures for measuring that quantities can take a lot of time and, moreover, instruments can be really expensive. Typically, acoustic sensors can be distinguished between two different typologies: "classic" sensors and the low-cost ones. The first typology generally consists in Class 1 Sound Level Meters, that is a noise measurement instrument that meets the requirements of IEC 61672-1:2002 [65] to Class 1 performance. This standard specifies two levels of performance, Class 1 and Class 2, with Class 1 being effectively more accurate. The same standard provides a set of performance criteria that an instrument must meet with an associated tolerance. The functions that an instrument must provide are not defined in this standard and so there are many different Class 1 Sound Level Meters that will give different functions whilst providing the same overall performance. A simple sound level meter that meets the standard may only provide Sound Pressure measurements whereas a much more sophisticated instrument may provide for the measurement of Sound Pressure, L_{eq} and Peak Sound Pressure. When specifying a Sound Level Meter, a good starting point is to decide what quantity, and in which contest the measurement has to be performed and then find an instrument that provides those features. However, the recent research is striving to move forward with new sensors and new integration methodologies, so midsized and lower cost sensors are becoming more and more interesting for developers, sellers and even researchers. In the last years, with the development of the Internet of Things (IoT), low cost sensors and smartphones are playing a key role. As a matter of fact, innovative applications for the assessment of acoustic comfort are based on IoT technology or on smart devices that can monitor the environmental sound. Nowadays, almost all smartphones are equipped with a several sensors, including those measuring sound. As a consequence of this fact, recent studies have focused their attention on typology, technology and accuracy of microphones embedded in commercial systems, such as smartphones. In [66], an experimental test conducted on 100 smartphones in a reverberation room is presented. The goal was to assess the capability of noise monitoring applications to be utilized as an alternative low-cost solution to traditional noise monitoring using a sound level meter. According to results, iOS application has better performances in

respect to those written for Android. A similar consideration is reported in [67]. In [68], an example of Wireless Sensor Networks (WSNs) equipped with microphones is reported. It could be considered as a low-cost solution for real-time audio data acquisition, offering applications in terms of environmental monitoring. Some studies have been carried out in order to evaluate the stress level of the occupants of a building generated by annoyance sources or environmental noise. In these cases, microphones, embedded in mobile phones, provide the opportunity to continuously and non-invasively monitor the stress in real-life situations [69]. Among all the studies on the various and new technologies implemented to monitor acoustic comfort, a great part is dedicated to those on measurement accuracy and uncertainty. About this, results of researches are conflicting. Some studies suggest smartphones as innovative devices for the assessment of environmental noise [70]. According to others, these kinds of measurements are not comparable to those obtained by standard methods. Just for instance, in [71], sound level meters, a dosimeter and a smart device are tested and compared. Results show that the smart device considerably differ from SLMs and dosimeter measurements.

For that reason, in the present research, traditional instruments (¼'' condenser free-field measurement microphones) have been used to measure acoustic quantities.

2.2 Evaluation of building envelope sound insulation against external noise

Given the impact that unwanted sound has on the acoustic comfort of a room, it is necessary to take measures to protect an environment from noise. In the case of noise surrounding a building, several strategies exist to yield significant reductions in incident sound pressure levels. The most efficient strategy is an appropriate design of building envelope, in order to let itself to fulfil its functions and goals. Sound insulation of the façade is the measure of how effectively the external sound is limited when passing through a building element (wall façade, windows frame, etc.). As a matter of fact, one of the primary scopes is to preserve the indoor environment from the external one, including the protection against the external noise sources [72]. Generally, the key features present in sound insulating construction are mass and continuity, since their combination reflect a significant amount of the incident sound and limit the vibration of the structure in response to the incident wave. The heavier the construction, the more effective this strategy is, and the greater the level of sound insulation provided. If multiple leaf construction is used, the mass can be traded off against isolation. This strategy can yield high levels of sound insulation using relatively lightweight construction.

Technical standards [63] provide calculation models which allow evaluating the apparent sound reduction index starting from the sound reduction index values of all the components (opaque and transparent) (see 2.2.1). However, the more the wall is different from the laboratory condition, the more difficult result applying and solve the empirical mathematical models.

The sound, in order to spread in the environment and be perceived, requires an elastic means. When the sound energy spreads within the buildings, that means, is represented by

the air and also by the structural elements of the building (wall, floor, etc.). The sound transmission occurs through two different propagation mechanisms:

- Airborne transmission;
- Structure-borne transmission (direct and flanking transmission).

In the first case, the principal transmission means is represented by the air and the noise spreads without encountering solid impediments. Airborne sound transmission is a series of air particles compressions and rarefactions, travelling in a longitudinal wave form. Audible sound has wavelengths between 17 meters and 17 millimeters, and a wave frequency varying between 20 and 20000 Hertz. Sound travels at a speed of 334 m/s through air but is influenced by humidity and air pressure conditions and will travel a further distance downwind. Sound will pass through any small gaps or openings and will reflect or rebound off any hard surfaces without significant loss or reduction in the sound intensity. Amplification of sound can occur due to funneling effects and wave interference.

Concerning the structure-borne transmission, the propagation occurs through the solid structure of the building (walls, floors, ceilings, pipes, pillars, etc.) by means of elastic vibrations. It happens when sound arises from the actual impact of an object on a building element. The impact causes vibration, generation sound waves. Direct sound transmission occurs where a building element is excited by an airborne or a structure-borne sound source on one side and radiates directly the sound from the other side.

Indirect or flanking transmission occurs when the sound travels by alternative pathways through separating or flanking walls or floors or along service pipes or conduits that circulate through a building. Alternative pathways for sound transmission should always be carefully considered as there is little point in raising the sound insulation in one part significantly beyond the level of the insulation value in an adjacent part. The flanking transmissions evaluation is difficult to quantify, because it is complicated summarized the phenomenon of the structural coupling with the other partitions and also because the flanking transmissions contribution can vary in function of the accuracy of the performed construction works. Fig. 1 illustrates the various routes sound can take through a building structure.

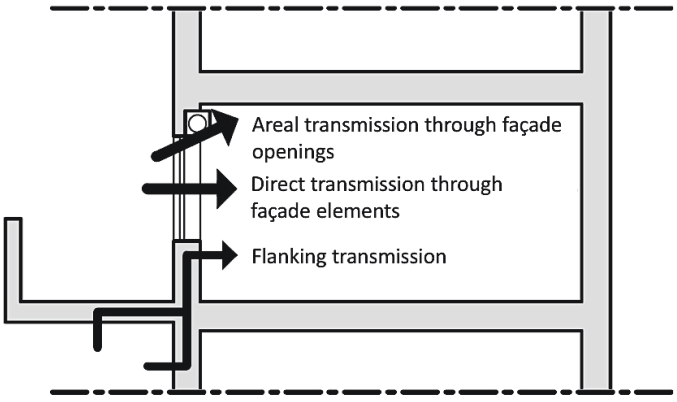


Fig. 1 Sound transmission paths through building façade

2.2.1 Calculation of standardized sound level difference of façade

"Façade" is understood to mean the whole outer surface of a room. The façade consists of different elements, e.g. wall, window, door, ventilation equipment; the sound transmission through the façade is due to the sound transmission by each of these elements. It is assumed that the transmission for each element is independent from the transmission of the other elements. However, the assumption that the transmission for a diffuse incident sound field has been proven to be representative for these varying types of exterior sound fields. Therefore, the apparent sound reduction index of the façade for diffuse incident sound is calculated, from which all other quantities are deduced. The apparent sound reduction index, R', of the façade for diffuse incident sound is calculated by adding the sound power directly transmitted by each of the elements and the sound power transmitted by flanking transmission, as shown by Eq. 1 [63]:

$$R' = \left(-10\log\left(\sum_{i=1}^{n} \tau_{e,i} + \sum_{f=1}^{m} \tau_f \right) \right) \quad [\mathrm{dB}] \qquad \text{Eq. 1}$$

Where $\tau_{e,i}$ is the sound power ratio of radiated sound power by a façade element *i* due to direct transmission od incident sound on this element, relative to incident power on the total façade; τ_f is the sound power ratio of radiated sound power by a façade r flanking element *f* in the receiving room due to flanking transmission, relative to incident power on the total façade; *n* is the number of façade elements for direct transmission; *m* is the number of flanking façade elements. All elements of the façade shall be included in the calculation. The sound power ratio is calculated according to the following, where the distinction between a small technical and other element is in accordance with ISO 10140-1 [73]. Small technical elements are calculated using Eq. 2:

$$\tau_{e,i} = \frac{A_0}{S} 10^{-D_{n,e,i}/10} \quad [\mathrm{dB}] \qquad \text{Eq. 2}$$

Where A_0 is the reference equivalent sound absorption area, for dwellings given as 10 m^2, $D_{n,e,i}$ is the element normalized sound level difference of small element *i, S* is the total area of the façade as seen from the inside (i.e. the sum of the area of all elements) [m^2]. These façade elements like air inlets show a large variety in construction details, which make it impossible to present generalized data. For unsilenced air inlets, like openings or louvres, a global indication is given by treating the element as an opening with negligible sound reduction. This results in an element normalized level difference shown by Eq. 3:

$$\mathrm{D}_{n,e} = -10\log\left(\frac{S_{open}}{A_0}\right) \quad [\mathrm{dB}] \qquad \text{Eq. 3}$$

Where A_0 = 10 m^2 and S_{open} is the area of the opening [m^2].

Other elements (wall, window, door) are calculated using formula:

$$\tau_{e,i} = \frac{S_i}{S} 10^{-R_i/10} \quad [\text{dB}] \qquad \text{Eq. 4}$$

Where R_i is the sound reduction index of element *I* [dB], S_i is the area of element *i* [m^2], *S* is the total area of the façade as seen from the inside (i.e. the sum of the area of all elements) [m^2].

The sound power ratio τ_f for flanking transmission by element *f* follows from the sum of the flanking transmission factors for all flanking transmission paths to that element. These flanking transmission factors can be determined in accordance with EN ISO 12354-1 [74]. The contribution of flanking transmission is normally negligible. However, if rigid elements, such as concrete or brick, are connected to other rigid elements within the receiving room, such as floors, flanking transmission can contribute to the overall sound transmission. In these cases, flanking transmission can be incorporated in a global way by reducing the sound reduction index for this type of rigid, heavy façade elements; subtracting 2 dB is normally acceptable (see Eq. 7).

The prediction of the acoustic insulation provided by the elements of the façade can be expressed through the sound level difference of the façade, $D_{2m,n,T}$ [75], [77], which is a parameter representative of the building behavior (or, more exactly, of the analyzed environment) respect to the noises coming from the outside of the building structure. In particular, it represents the capability of the façade, of a specific indoor environment, to reduce noise from outside. The standardized level difference of a façade depends on the sound reduction index of the facades as see from the inside, the influence of the outside shape of the façade, like balconied, and the room dimensions. In particular, the receiving room volume influences $D_{2m,nT}$, (it increases at the volume increasing); instead, the volume, does not influence the value of the apparent sound reduction index, R'. In addition, $D_{2m,nT}$ is highly influenced by the presence of façade elements such as windows, doors or small openings (see Fig. 1). It follows from Eq. 5, provided by the European standard EN ISO 12354 - 3 [63].

$$\mathrm{D_{2m,nT}} = R' + \Delta \mathrm{L_{fs}} + \left(10\log\left(C_{sab}\frac{\mathrm{V}}{\mathrm{T_0 S}}\right)\right) \quad [\text{dB}] \qquad \text{Eq. 5}$$

Where $R^{'}$ is the apparent sound reduction index of the façade [dB], *V* is the volume of the receiving room [m^3], T_0 is the reference reverberation time (for dwellings it is given as 0,5 s) [s], *S* is the total area of the façade as seen from the inside [m^2], C_{sab} is the Sabine constant, equal to 0,16 [s/m] and ΔL_{fs} is the level difference due to façade shape [dB]. The corrective term ΔL_{fs}, which quantifies the influence of the façade features, depends on the façade shape, the absorption coefficient of the eventual reflected surface above the considered façade and the acoustic waves incidence (see Fig. 2). ΔL_{fs} is evaluated according to EN ISO 12354-3 [63]. It is defined as the difference in sound pressure level of the incoming sound field and the sound on the façade surface plus 6 dB. The façade shape is identified by a vertical cross-section through the balcony. The weighted the sound absorption coefficient indicates absorption, according to EN ISO 11654 [78], as 0.3; 0.6; 0.9. Intermediate values can be obtained by interpolation between these values. The height of the line of sight from the source

at the façade plane characterizes the direction of the incoming sound. Examples of the level difference due to the façade shape are presented in Fig. 3, from [63]. The value depends on the shape of the façade, the absorption of the underside of any balcony and on the general direction of the incoming sound. The shielding or partial shielding of the façade plane by balconies or other objects contribute to provide a positive effect. Extra reflections and a sound field that could be considered to be reverberant when a balcony forms a partial enclosure around the façade plane provide negative effects.

The model can be used to calculate the sound level difference of the façade in frequency bands, based on acoustic data for the building elements in frequency bands (one-third-octave bands or octave bands). Moreover, it can be used to calculate directly the single number rating for the building performance, based on the single number ratings of the elements involved. The weighted standardized level difference of the façade is calculated according to the analytical formula (Eq. 6):

$$D_{2m,nT,w} = R'_w + \Delta L_{fs} + 10\log\frac{V}{6T_0S} \quad [dB] \qquad \text{Eq. 6}$$

Where R'_w is the apparent weighted sound reduction index of the façade elements[dB], expressed through a single index.

The accuracy of this calculation method depends on the accuracy of the input data, i.e. type and geometry of involved elements, rooms and building structure.

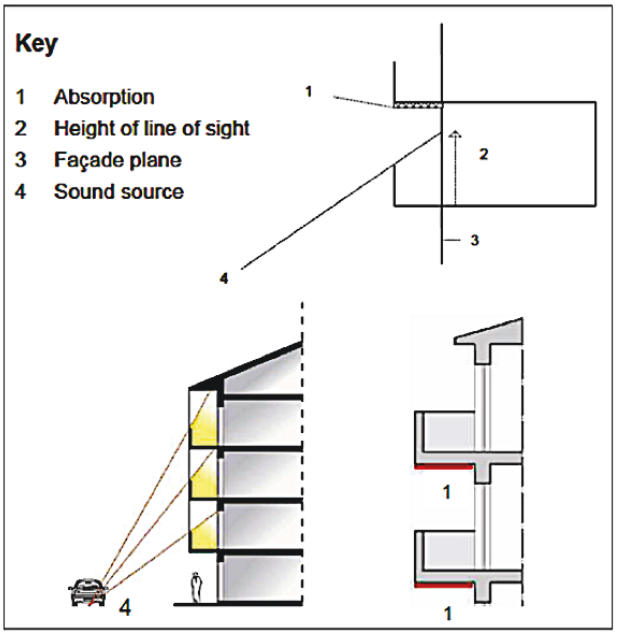
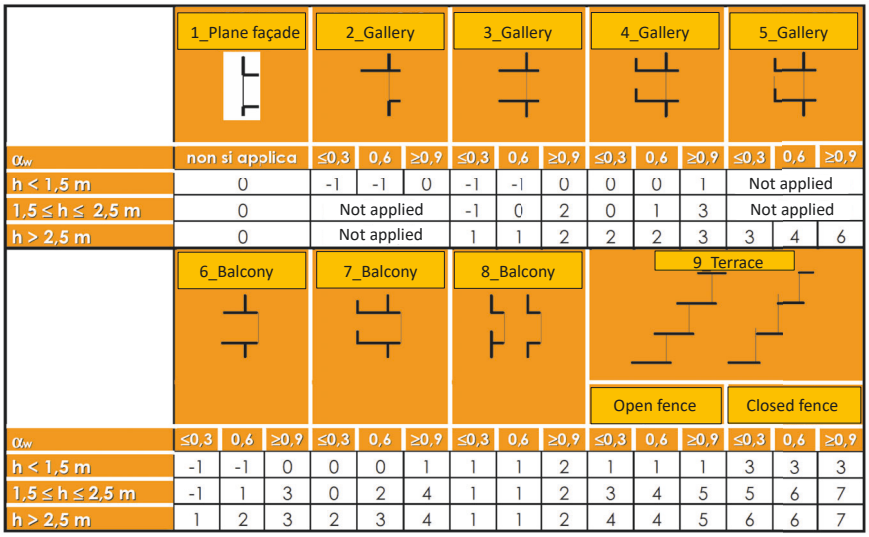


Fig. 2 Illustration of relevant parameters for the façade shape level difference



α_w	non si applica	≤0,3	0,6	≥0,9	≤0,3	0,6	≥0,9	≤0,3	0,6	≥0,9	≤0,3	0,6	≥0,9
h < 1,5 m	0	-1	-1	0	-1	-1	0	0	0	1	Not applied		
1,5 ≤ h ≤ 2,5 m	0	Not applied			-1	0	2	0	1	3	Not applied		
h > 2,5 m	0	Not applied			1	1	2	2	2	3	3	4	6

α_w	≤0,3	0,6	≥0,9	≤0,3	0,6	≥0,9	≤0,3	0,6	≥0,9	≤0,3	0,6	≥0,9	≤0,3	0,6	≥0,9
h < 1,5 m	-1	-1	0	0	0	1	1	1	2	1	1	1	3	3	3
1,5 ≤ h ≤ 2,5 m	-1	1	3	0	2	4	1	1	2	3	4	5	5	6	7
h > 2,5 m	1	2	3	2	3	4	1	1	2	4	4	5	6	6	7

Fig. 3 Façade shape level difference

According to Eq. 5 and Eq. 6, sound transmission through building façade is established by calculating the apparent sound reduction index of the façade. This is used to determine the noise difference between the outside and inside. The apparent sound reduction index requires knowledge of sound reduction index values of all the components (opaque and transparent). When the and it is calculated according to the following relation (Eq. 7) provided by the EN ISO 12354-part 3 [63].

$$R' = -10\log\left[\sum_{i=1}^{n}\frac{S_i}{S}10^{\frac{-R_i}{10}} + \sum_{i=1}^{n}\frac{A_0}{S}10^{\frac{-D_{n,e,i}}{10}}\right] - K \text{ [dB]} \qquad \text{Eq. 7}$$

Where A_0 is the reference equivalent sound absorption area (10 m^2), $D_{n,e,i}$ is the normalized sound level difference of small element [dB], R_i is the sound reduction index of element [dB], S is the total area of the façade as seen from the inside [m^2], S_i is the area of the elements and of the small elements of the façade [m^2] and K is the correction due to the contribution of flanking sound transmission (explained above). The relationship (Eq. 7) does not depend on frequency and therefore it can be applied to different frequency ranges [63].

Sound reduction index of elements should be analyzed in frequency domain, in order to effectively reduce human exposure to annoyance, because external sources have different frequency emissions. Anyway, the weighted sound reduction index of elements, R_w, is used to evaluate and quickly compare many different solutions [75].

2.2.1.1 Analytical model to estimate weighted sound reduction index of elements

Sound insulation performance is a measurement of a material's ability to reduce the amount of sound transmitted from one side of a panel element to the other. A simple rule of thumb is that the thicker or denser a material, the better its sound insulating performance. This is because the heavier or stiffer a material, the more difficult it is to set up vibrations within it and the sound waves simply rebound. Heavy concrete floors and walls therefore have very good sound insulation properties, whereas thin single-glazed windows and lightweight timber walls are comparatively poor. Conversely, the more resilient or flexible the fixing used in composite and layered systems, the better the insulation performance for absorbing impact sounds.

Weighted sound reduction index of element, R_w, is used to measure the level of sound insulation provided by a construction element such as wall, window, door. The higher the R_{wi} value, the better the airborne sound insulation performance. The weighted sound reduction index of an element i, R_{wi} is a value which describes the sound insulation performance of a material as determined by laboratory standardized testing. Generally, the prediction of acoustic performance of the construction elements as a function of frequency is highly uncertain, since it is not possible to reliably consider the different properties of the materials, the geometry, the typology and the construction techniques. The provisional verifications are made on the basis of experimental data obtained in the laboratory. From the elaboration of these data various empirical formulas have been proposed for the prediction weighted sound reduction index of an element. As a consequence, in the absence of laboratory data, it is possible to obtain R_{wi} of a construction element by using:

- Reliable database from literature or datasheet;
- Empirical predictive formulas derived from statistical processing of experimental data, obtained in laboratory, which allow to predict R_{wi} starting from the mass for unit area, m' [kg/m^2] of the element. These formulas, based on the mass per unit area of the structure [kg/m^2], provide results that are not always congruent and therefore should be used with caution.

Below, mathematical formula implemented in the soft-sensor for the acoustic comfort measurement are reported:

$$R_{w,wall} = 37.5 \log(m') - 42 \ \text{[dB]} \quad \text{Eq. 8}$$

$$R_{w,window} = 12 \log(m') + 17 \ \text{[dB]} \quad \text{Eq. 9}$$

$$R_{w,door} = 20 \log(m') \ \text{[dB]} \quad \text{Eq. 10}$$

2.2.1.2 Analytical model to estimate weighted sound reduction index improvement of additional layer

The increasing of the weighted sound reduction improvement index due to external wall lining expresses the improvement due to the contribution of additional layer applied to the wall. In particular, if an additional layer on elastic support is applied on an existing wall, a resonant system in double layer is determined. This produces an improvement in the overall sound insulation of the structure and depends on the type of the basic structure to which the additional layer is applied.

In the absence of experimental data, the increasing of the weighted sound reduction improvement index can be calculated as a function of the resonant frequency of the system composed by the basic structure and the coating, according to EN ISO 12354 part 3:

$$f_0 = 160\sqrt{s'\left(\frac{1}{m_1'}+\frac{1}{m_2'}\right)}\ \text{[Hz]} \qquad \text{Eq. 11}$$

Where s' is the dynamic stiffness of the insulation layer [MN/m^3] (according to EN 29052-1 [76]), m_1' is the mass per unit area of the basic structure [kg/m^2] and m_2' is the mass per unit area of the additional layer [kg/m^2] (see Fig. 4).

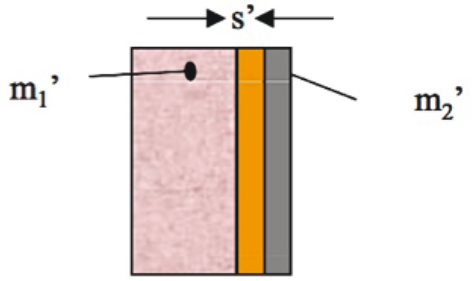


Fig. 4 Illustration of relevant parameters for the façade shape level difference

On decreasing of frequency, the acoustic performance of the overall structure improves. Same wall (m_1'), there will be a greater ΔR_w when:

- m_2' of the additional layer increases;
- s' of the insulation layer decreases.

The weighted sound reduction improvement index of the additional layer is calculated according to Eq. 12:

$$\Delta R_w = 72 - \left(\frac{R_{w,m_1'}}{2} + 20\log(f_0)\right)\ \text{[dB]} \qquad \text{Eq. 12}$$

Where $R_{w,m_1'}$ is the weighted sound reduction index of the existing wall, having mass for unit area equal to m_1', f_0 is the resonant frequency of the system [Hz].

The overall value of the weighted sound reduction index of the external wall, $R_{w,wall}$, which is applied additional layer, is Eq. 13:

$$R_{w,wall} = R_{w,m_1'} + \Delta R_w \text{ [dB]} \quad \text{Eq. 13}$$

Where $R_{w,m_1'}$ is the weighted sound reduction index of the existing wall, having mass for unit area equal to m_1', ΔR_w is the weighted sound reduction index improvement of the additional layer [dB].

2.3 Estimation of reverberation time

Reverberation time (T_{60} [s]), is the most commonly used measure to quantify the acoustic character of a space and this may be derived from the impulse response. Reverberation time in receiving room (T_{60}) is defined as the time required for the sound energy density to decay 60 dB after the source has stopped emitting It depends on the acoustic and geometric characteristics of the walls, which bound the space [77], [78]. As a general rule, larger a room have longer reverberation time, since sound must travel further before it meets the room boundaries and is reflected back into the space. Similarly, rooms with more absorption will tend to have shorter reverberation times as the amount of energy removed on each reflection is greater. This correlation is useful during rooms design, because it allows the reverberation time to be dictated by selecting materials that provide sufficient absorption so as to balance the effect of room volume [34]. Anyway, some reverberation is needed. For instance, the design of a space to support speech-based activities needs to provide a reverberation time that offers a balance between reinforcing the direct sound and masking it, and minimize extraneous sources of noise, intended as unwanted sound.

Reverberation time can be measured according to ISO 3382-2 [34]. However, it can also be simulated according to the Sabine formula, since it is correlated with the volume and absorption of the environment. EN ISO 12354-6 Standard [79] describes a calculation model to estimate the reverberation time of enclosed space in buildings. In diffuse sound field conditions, for a reverberant room with walls of a homogeneous geometrical and acoustic nature, the reverberation time can be estimated according to the average absorption coefficient of the walls, following the Sabine formula (Eq. 14):

$$T_{60} = \frac{55{,}3 * \mathrm{V}(1-\psi)}{c_0 * A} \text{ [s]} \quad \text{Eq. 14}$$

Where V is the volume of the room [m^3], $c_0$is the speed of sound in air [m/s] (the ratio (55,3/ c_0) is assumed equal to 0.16, since the speed of sound has to be taken as 345,6 m/s); ψ is the object fraction, which represents the ratio between the sum of the volume of all the elements [79] and the volume of the empty environment and A is the total equivalent absorption within the room [m^2], calculated as follows (Eq. 15):

$$A = \sum_{i=1}^{n} S_i \alpha_i \quad [m^2] \qquad \text{Eq. 15}$$

Where α_i is the absorption coefficient of each material i used within the room [-], S_i is the speed of sound in air [m/s] (the ratio (55,3/ c_0) is assumed equal to 0.16, since the speed of sound has to be taken as 345,6 m/s); ψ is the object fraction, which represents the ratio between the sum of the volume of all the elements.

The validity of this formula is strictly correlated with the geometric and acoustic characteristics of the environment. The acoustic field must be sufficiently widespread; the dimensions must be comparable; the absorption of the various elements and walls must be quite homogeneous and sufficiently low.

2.4 Estimation of outdoor noise climate

Acoustic climate means the noise levels coming from the sound emission sources considered typical of the area under investigation because they are regular throughout the 24 hours of the day (exceptional events are not considered). They produce the major contribution of the acoustic pollution of the district and they influence the acoustic of the internal space.

According to calculation method provided by the standard [63], indoor sound pressure level is calculated using the measured or estimated outdoor noise level at 2 meters in front of the façade, since the sound level difference is referred to that position.

The Directive 2002/49/EC [80] "relating to the assessment and management of environmental noise" (Environmental Noise Directive, END) aims to harmonies European member states' policies and technical approaches concerning noise exposure reduction issues. For that reason, it offers numerical models for roads, railways, industrial site, airports and harbors. Predictions of sound pressure levels through calculation models, are usually more time and cost efficient than measurements. Anyway, they may not give the noise levels corresponding to reality [81], because the analytical models are valid under specific constraints.

Since the sound level difference is referred to a position of 2 meters in front of the façade, the external sound pressure level has to be measured or calculated at that point. In evaluating exposure to noise sources, the most commonly used single index quantity is the equivalent continuous A-weighted sound pressure level, which is determined over the most representative periods of the day.

In this research, the developed soft-sensor includes analytical models to calculate road, railway traffic and industrial noise levels at two meters in front of each room façades of the building, according to END [80]. In particular, these models are:

- For road traffic noise: the French national computation method 'NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)', referred to in 'Arrêté du 5 mai 1995 relatif au bruit des infrastructures routières, Journal Officiel du 10 mai 1995, Article 6' and in the French standard 'XPS 31-133'.

- For railway noise: the Netherlands national computation method published in 'Reken- en Meetvoorschrift Railverkeerslawaai '96, Ministerie Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, 20 November 1996'. This method is referred to as 'RMR' in these guidelines.
- For industrial noise: ISO 9613-2: 'Acoustics — Abatement of sound propagation outdoors, Part 2: General method of calculation' [82]. This method is referred to as 'ISO 9613' in these guidelines.

2.5 Estimation of indoor sound pressure level

Once having defined the evaluation methods of the needed quantities, the equivalent continuous sound pressure level (L_{eq} [dB(A)]) can be calculated. According to Annex E of EN ISO 12354-3 [63], the indoor sound pressure level is evaluated following Eq. 16:

$$L_2 = L_{1,2m} - D_{2m,nT} + 10\log\left(\frac{T}{T_0}\right) \text{ [dB]} \quad \text{Eq. 16}$$

Where L_2 is the average sound pressure level in the receiving room [dB], $L_{1,2m}$ is the average sound pressure level at 2 m in front of the room façade [dB], $D_{2m,nT}$ is the standardized sound level difference of the room façade [dB], T_0 is the reference reverberation time [s] (0,5s) and T is the reverberation time in the receiving room [s].

Reverberation time can be both measured, according to the standard EN ISO 3382 part 2 [34], and calculated by means of predictive formula suggested in EN 12354 part 6 [79].

Eq. 16 is valid on the hypothesis of diffuse field in indoor environment; in the present study, that condition has been assumed, as already done in previous case studies by other researchers [41], [83]. The internal sound pressure level can be expressed through the indoor A-weighted sound pressure level [dB(A)]. The A-weighting is the most common frequency weighting used because it weights lower frequencies as less important than mid - and higher - frequencies and it approximates the frequency response of human hearing system [84]. If the standardized sound level difference is expressed in a single number rating, the internal sound pressure level is can be determined directly from the A-weighted outdoor sound pressure level at 2 m in front of each building façade, according to the above relation.

CHAPTER 3
SOFT-SENSING SYSTEM FOR ACOUSTIC COMFORT MEASUREMENT

A soft sensor is a tool where several data, derived from different sources, are combined and processed together through mathematical models. The interaction of the different typologies of quantities that can be obtained easier [85] (measured, simulated and/or subjective) can be used to predict new variables which are difficult to be measured, as the case in exam.

By using a soft sensor approach, the result can be biased by estimation errors [86], since the accuracy of the final output depends on the uncertainty related to each parameter input of the soft-sensor, beyond that the uncertainties of the calculation models. This issue will be treated in chapter 5. A review of the existing approaches regarding soft sensor evaluation is given in [87].

The realized hybrid virtual-sensor aims at providing a tool based on the soft-sensing approach that measures the acoustic comfort within buildings (see Fig. 5). The developed metric for expressing the acoustic comfort is represented by the Key Performance Indicators (*KPIs*).

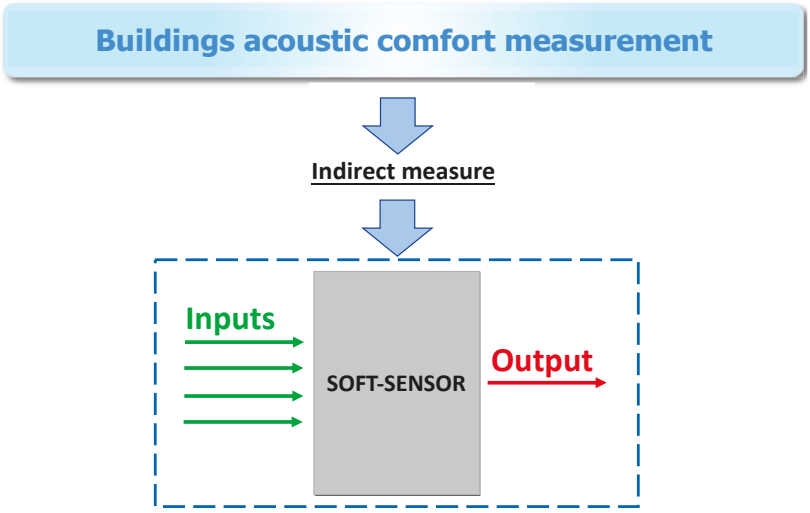


Fig. 5 Soft-sensor for acoustic comfort measurement

The soft-sensing system integrates experimental data, measured by microphones, numerical data, estimated by mathematical models based on direct surveys and assumptions, and subjective data (see Fig. 6).

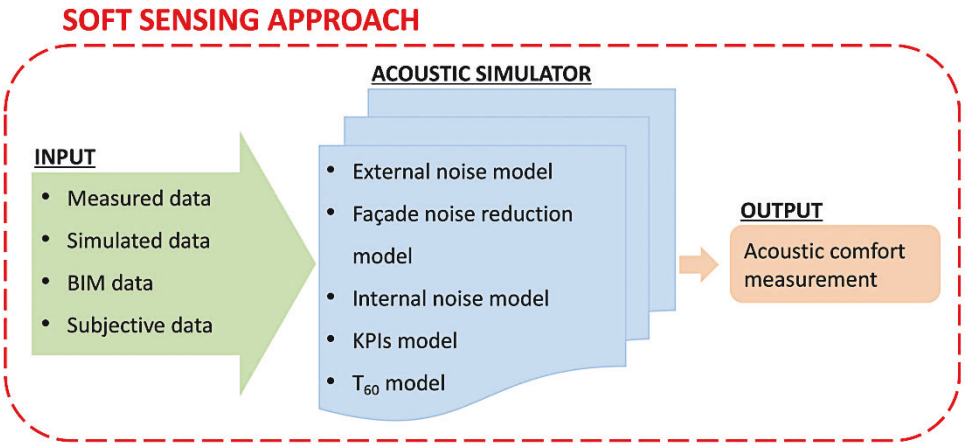


Fig. 6 Soft-sensing approach

Within the NewTREND project, the soft-sensor system with the developed *KPIs* have provided a valid tool for assisting the decision-making in buildings' retrofitting design, ranking different renovation options. The complete procedure of the *KPIs* calculation is described in detail in paragraphs *3.1* and *3.2*. In the present research, two *KPIs* have been developed, which operate in a complementary manner, with the purpose to measure acoustic comfort though an "objective" and a "subjective" assessment. The first *KPI* is based on objective assessment of acoustic quantities (i.e. indoor sound pressure levels in each room) (see paragraph 3.1). The second *KPI* is representative of the subjective occupants' rating (see paragraph 3.2) and it is used to validate the "objective *KPI*" and to support the decision-making (as explained in paragraph 5.3).

The use of *KPIs* and benchmarking is fundamental to any improvement strategy [88]. "An indicator system should provide a measure of current performance, a clear statement of what might be achieved in terms of future performance targets and a yardstick for measurement of progress along the way" [89]. Hence, a *KPI* is an indicator that represents a quantifiable value to determine in which measure the strategic and operative goal is reached [90].

3.1 Measurement method of the "objective *KPI*"

The "objective *KPI*" is based on the overall evaluation of the noise levels assessed within the rooms of the building, which result from the quantity of the external noise intruding inside, lowered from the acoustic abatement of the building envelope. The general procedure is outlined in Fig. 7. If indoor noise levels are determined through experimental measurements, the procedure starts at step 3.

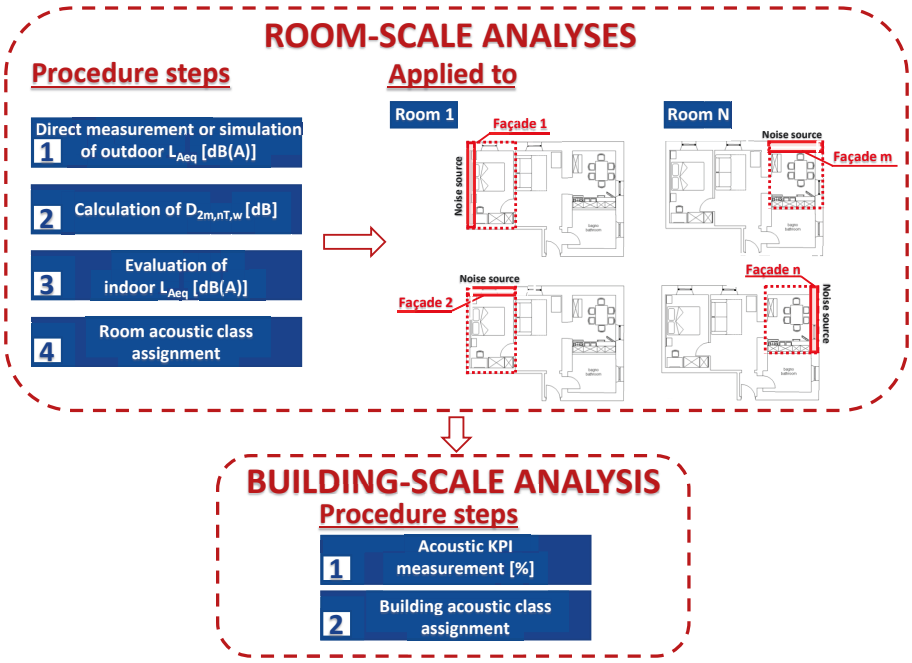


Fig. 7 KPI calculation procedure

For each room bordering to the external environment, the equivalent continuous sound pressure level ($L_{Aeq,}$, dB(A)) is determined, through indirect or direct measurement method, and an acoustic class is assigned. Acoustic class is defined by the design values of indoor A-weighted sound pressure level ($L_{Aeq,}$) for every type of space use (offices, bedrooms, living rooms, classrooms, etc.) (see Table 1). The calculated L_{Aeq} is assessed against the set limit for each acoustic class, in order to identify how far it is from the values suggested in this research, deduced by the acceptable noise limits from literature **Errore. L'origine riferimento non è stata trovata.**, [92]. As such, the World Health Organization [21] provides guideline values for community noise, setting the maximum indoor A-weighted sound pressure level to 35 dB (A) for daytime and 30 dB (A) at night inside residences with windows opened [93] in order to avoid critical effects such as annoyance, speech intelligibility and sleep disturbance [94]. Limit values vary from Country to Country and there is not a uniform regulated classification of the internal sound pressure level due to sound coming from outside.

Type of space	Class A	Class B	Class C	Class D	Class E
Bedroom	$L_{Aeq} \leq 30$	$30 < L_{Aeq} \leq 32.5$	$32.5 < L_{Aeq} \leq 35$	$35 < L_{Aeq} \leq 40$	$L_{Aeq} > 40$
Living room / kitchen	$L_{Aeq} \leq 35$	$35 < L_{Aeq} \leq 37.5$	$37.5 < L_{Aeq} \leq 40$	$40 < L_{Aeq} \leq 45$	$L_{Aeq} > 45$
Hotel bedroom	$L_{Aeq} \leq 35$	$35 < L_{Aeq} \leq 37.5$	$37.5 < L_{Aeq} \leq 40$	$40 < L_{Aeq} \leq 45$	$L_{Aeq} > 45$
Classroom	$L_{Aeq} \leq 35$	$35 < L_{Aeq} \leq 37.5$	$37.5 < L_{Aeq} \leq 40$	$40 < L_{Aeq} \leq 45$	$L_{Aeq} > 45$
Nursery school	$L_{Aeq} \leq 40$	$40 < L_{Aeq} \leq 42.5$	$42.5 < L_{Aeq} \leq 45$	$45 < L_{Aeq} \leq 50$	$L_{Aeq} > 50$
Office	$L_{Aeq} \leq 35$	$35 < L_{Aeq} \leq 37.5$	$37.5 < L_{Aeq} \leq 40$	$40 < L_{Aeq} \leq 45$	$L_{Aeq} > 45$
Conference room	$L_{Aeq} \leq 35$	$35 < L_{Aeq} \leq 37.5$	$37.5 < L_{Aeq} \leq 40$	$40 < L_{Aeq} \leq 45$	$L_{Aeq} > 45$
Hospital	$L_{Aeq} \leq 35$	$35 < L_{Aeq} \leq 37.5$	$37.5 < L_{Aeq} \leq 40$	$40 < L_{Aeq} \leq 45$	$L_{Aeq} > 45$
Retail shop	$L_{Aeq} \leq 45$	$45 < L_{Aeq} \leq 47.5$	$47.5 < L_{Aeq} \leq 50$	$50 < L_{Aeq} \leq 55$	$L_{Aeq} > 55$

Table 1 Room acoustic class limits

Acoustic classification scheme goes from class A (high level of acoustic comfort) to class E (very bad level of acoustic comfort). A score is assigned to each room, ranging from 5 (Class A) to 1 (E) (see Table 2).

Class	Score [-]
A	5
B	4
C	3
D	2
E	1

Table 2 Score assigned to each room acoustic class

Only the main rooms that are occupied for several hours that can be identified as “acoustically sensitive” (e.g. bedrooms, living rooms, offices, classrooms) are considered. Short-term occupancy and transit areas (e.g. bathrooms, corridors, small storage areas, hallways) can be excluded from the analysis. Limit values are referred to windows closed, without any shading and rolling shutter systems closed, because it is supposed that these systems are opened for the majority of the hours of the daylong. A label is assigned to each acoustic class, which represents an understandable way to express the level of acoustic comfort expected by occupants (Fig. 8).

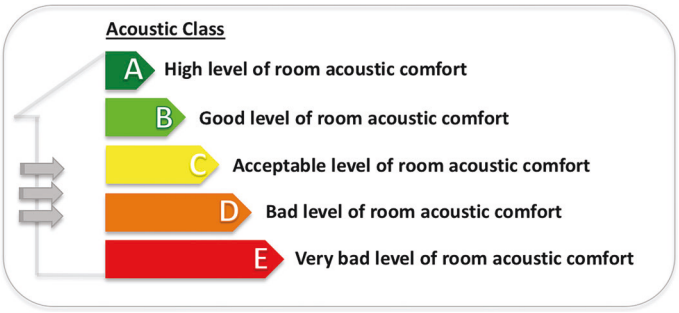


Fig. 8 Room acoustic class labels

Once that the score is assigned to each room according to the acoustic class, it is possible to calculate the *KPI* of the entire building according to Eq. 17, that is a score from 5 (optimum value) to 1 (worse value).

$$KPI = \left(\frac{\sum_{i=1}^{n} A_i * RA_i}{A_{tot}}\right) \quad [-] \qquad \text{Eq. 17}$$

Where A_i is the reference floor area of each room bordering to the external environment i [m^2], RA_i is the score assigned to each room i [-] and A_{tot} is the total reference floor area of all the rooms bordering to the external environment [m^2].

Then the *KPI* is expressed in a percentage scale from 0 % to 100 %, through a linear interpolation from 1 to 5, where the score 1 corresponds to 0 % and the score 5 to 100 %. The building acoustic classification, which ranges from A to E, is based on thresholds defined in this scale. In Table 3, acoustic class limits are defined. A label is assigned to each acoustic class, according to the one proposed in Fig. 8.

Class A	Class B	Class C	Class D	Class E
87.5%<KPI≤100%	62.5%<KPI≤87.5%	37.5%<KPI≤62.5%	12.5%<KPI≤37.5%	0%≤KPI≤12.5%

Table 3 Building acoustic class limits

The acoustic *KPI* is a quantity that represents the whole building acoustic performance, thus it can hide localized discomfort conditions (e.g. in space exposed to a very congested road). Since the methodology to calculate the *KPI* is based on room-scale analysis, it is possible to identify the critical rooms and eventually intervene only on these ones.

3.1.1 Soft-sensor configurations for objective measure of acoustic comfort

Depending on data availability, a wide amount of input parameters can enter in the soft-sensor for calculating the *KPIs*. The soft-sensor system provides three configurations to objectively assess the acoustic comfort of a building, basing on the indoor noise levels evaluation. They depend on the different input parameters and consequent resulting difference in accuracy and cost: "Advanced", "Combined" and "Premium". All three modes provide the same output, the "objective *KPI*". In addition, they require a geometrical model of the building, since some data (e.g. reference floor area of the rooms) are required for the *KPI* evaluation.

Experimental measurements of equivalent continuous sound pressure levels involve high costs or long times, even because they involve acoustic technicians ("Combined" and "Premium" modes). For that reason, the other mode allows also non-technical users to perform an acoustic comfort assessment of the building ("Advanced" mode).

In the following sub-paragraphs, the three soft-sensor configurations are described.

3.1.2 Soft-sensor for "Advanced" mode

The first soft-sensor configuration, the "Advanced" mode, uses design and calculated data as its main data sources. This mode requires high demand on data (i.e. geometric model including detailed building properties). Data can be manually collected by user during in situ inspections, through the Data Manager tool of the NewTREND project or get by BIM model. Advanced mode relies heavily on user input data to operate.

Fig. 9 highlights the main quantities required for running the "Advanced" mode. The complete list with the attributes is reported in Appendix B. In the "Advanced" mode, the indoor sound pressure level is calculated from the simulation of the external sound pressure levels and of the building envelope performances.

Although the generation and propagation of sound is a complex scientific field, numerous standards exist which give simple mathematical relationships between input parameters and output sound levels. External noise climate can be simulated through the characterization and modelling of the external noise sources (roads, railways, industries) by knowing source data such as traffic flow, type of road and rail, type of vehicles and speed, etc. plus terrain data such as ground cover, buildings, barrier, etc. The soft-sensor contains algorithms for simulating external noise in front of each room façade of the building under investigation. Alternately, external noise climate can be deduced by strategic noise mappings, which are often available by the municipality. Noise maps are the graphical representation of the predicted situation with regards to noise in a particular area with different colours representing different noise levels in decibels [dB(A)]. They are designed to assess noise exposure in a given area, resulting from particular noise sources (roads, railways, airports). These maps are normally prepared using computer modelling techniques.

Façade sound insulation is calculated by the soft-sensor algorithms (Eq. 6) detailed in paragraph 2.2.1. The soft-sensor contains algorithms also to calculate the reverberation time

of the rooms, starting from the collection of furnishing data, according to Sabine's formula. Collecting data about environmental noise sources can be often complicated; in fact, the most common software tools specialized in the prediction of environmental noise can be used only by experts' team, because they require several input parameters which can be collected only from experts on urban acoustics, dealing with the complex phenomenon of sound propagation. Involving an acoustics specialist for routine predictions can often add delays. On the contrary, the "Advance" mode is developed in order to be used also by non-specialists, since the data collection tool developed in NewTREND allows the user to collect simplified data, that are suitably explained, with information readily available (easy and quick data collection process).

The main limit of the "Advanced" mode is that the measurement of the acoustic comfort resulting from the acoustic *KPI* calculation is affect by high uncertainty, due to the assumption and estimations made and the uncertainty due to the adoption of simplified calculation models used to predict the acoustic quantities. However, the application of the soft-sensor for the "Advanced" mode in real case studies, is a low-cost system, since it is not required an acoustic specialist for performing an experimental campaign.

"Advanced" mode of the soft-sensor is intended to support the decision-making in retrofitting design, since different potential renovation scenarios can be simulated and compared between each other. Paragraph 3.3 details the soft-sensor procedure to support the decision making in renovation designs. The complete list of the attributes for required for "Advanced" configuration is to be find in Appendix B.

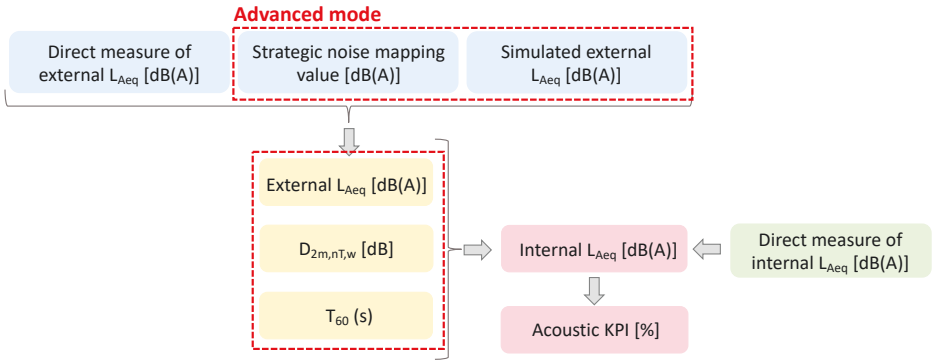


Fig. 9 Advanced mode soft-sensor system

3.1.3 Soft-sensor for "Combined" mode

"Combined" mode uses as inputs of the soft-sensor system for the acoustic comfort assessment both simulated and measured data. The mode requires the same information as the "Advanced" mode, however, the external noise in "Combined" configuration is based on real data, rather than simulated data as for the "Advanced". Hence, the soft-sensor mode

considers real measure of the external noise in addition to building's data. Therefore, an experimental test campaign is conducted with the purpose to measure the equivalent sound pressure level in front of each room façade. The façade sound insulation performance is simulated; hence the mode requires data concerning building elements features, geometries, etc. The accuracy depends heavily on user inputted data, both measured and collected.

Fig. 10 highlights the main quantities required for running the "Combined" mode. The "Combined" mode requires a specialist to carry out the external noise measurement campaign. Involving an acoustics specialist for routine predictions can often add delays, even if the external noise evaluation accuracy improved since it depends only on the measurement sensors error.

As for the "Advanced" mode, the "Combined" allows ranking and comparing different renovation options, through the identification of the best retrofitting solution. In particular, the developed acoustic *KPI* helps designers during the decision-making process and the final stakeholder to take informed-decision about the real estate investment. For this reason, uncertainty and sensitivity analyses have been performed to evaluate how the accuracy of the acoustic *KPI* measurement impacts on the decision-making process, as already done for thermal comfort in recent works [47]. The complete list with the attributes is to be find in Appendix C.

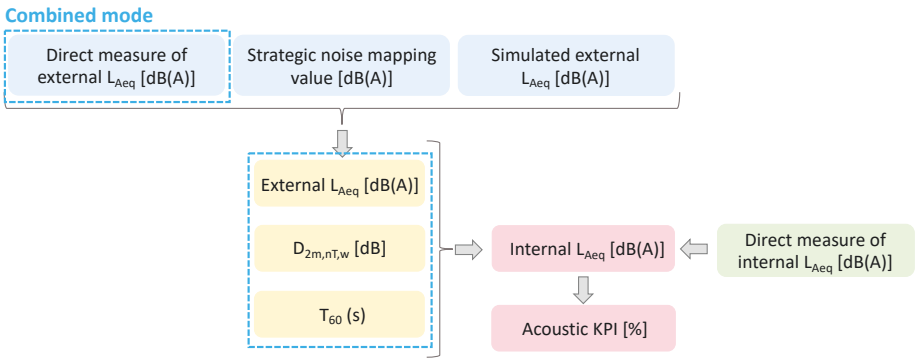


Fig. 10 Combined mode soft-sensor system

3.1.4 Soft-sensor for "Premium" mode

"Premium" mode requires on site-measured equivalent indoor sound pressure levels as its main data (see Fig. 11). The direct measure of the indoor noise levels allows to calculate directly the acoustic *KPI*, without any acoustic quantities' simulation process. Thus, "Premium" mode is intended to function as a controller of the building performance before and after retrofitting.

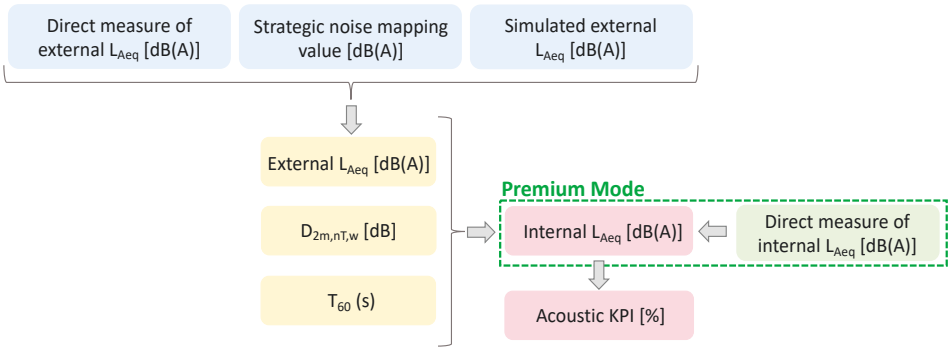


Fig. 11 Premium mode soft-sensor system

3.2 Assessment of the occupants' rating to support the decision-making process: "Socio-acoustic" *KPI*

The soft-sensor includes algorithms for the "Socio-acoustic *KPI*" evaluation, which uses subjective input data, directly collected between the building inhabitants through questionnaires. The purpose of the "subjective *KPI*" is to provide a validation of the reliability of the "objective *KPI*". Since the evaluation scale is the same, the "subjective" and "objective *KPIs*" can be compared each other. The "Socio-acoustic" *KPI* is based on the real user perception and it aims to solve the uncertainty's issue of the soft-sensor methodology, as explained in 5.3.

According to literature [95], [30], the idea of associating and comparing data of human sound perception to technical acoustic data seems essential. The choice of suitable criteria to establish statistical relationships between the average reaction of occupants of a building to noise and the physical single number quantities that can either be predicted or measured was one of the main tasks of the COST TU0901 Actions [96]. Assessing the reaction of occupants to noise in their homes is a complex task to accomplish. Such reactions are often influenced by factors other than the sound exposure. The other factors can include the occupant's expectations, satisfaction, sensitivity and attitude to noise. Hence, such factors may be expected to influence individual answers given in a questionnaire. There are some studies where researchers have tried to take such effects into account [97]. Furthermore, reactions to noise can be affected by a presence of several simultaneous sources of noise, e.g. exposure to noise from several types of traffic may increase the overall annoyance compared to exposure from one source at a time [98].

The intention of the occupants' rating assessment developed in this research is to determine the average perceived acoustic comfort of the occupants in a building and express it through a quantity that can be related to the "objective *KPI*", which is based on evaluation of physical properties of the building. Direct subjective response of building occupants has been used for overall assessment of indoor acoustic comfort pf the building, in relation to the outdoor noise, and to evaluate if the building under investigation requires renovation actions.

Subjective assessments of the acoustic environment are generally based on interviews. The questions in the interviews are formed with the aim to understand better the perception of acoustic comfort by inhabitants/users of the buildings [99].

In Annex H of EN ISO15251 [27], a method for the evaluation of the parametric subjective sensation (thermal sensation, air quality, etc.) through questionnaires, is proposed. The general idea is based on questions which are expressed according to the levels of judgement. In absence of a standard method, the development of questionnaire formulation has been based on bibliographic research in literature [27], [96], [100], [101], [102] following which the main points useful for the research purposes were identified. The questionnaire, based upon the international technical specification ISO/TS 15666 [100], is configured in sequences of items and structured on an intensity subjective scale; it is composed by five multiple-choice questions, with the purpose to evaluate the degree of acoustic comfort in the living environment, in relation to the external noise. The respondents are asked to indicate only one answer [103]. The questionnaires have to be distributed and filled by each building/apartment occupants, for each room bordering to the external environment. Questionnaires have been integrated and presented to the user through the Data Manager tool, which developed in NewTREND (see 3.4.2.1), which has the purpose to allow the data collection of objective data and also subjective data (see Fig. 18).

The questionnaires have to be filled out at representative times during the day, for example during middle morning or middle afternoon, or however during periods in which people could be more sensible.

Below, the five developed questions are expressed:

1. Thinking about the period in which you have lived/worked/frequented this area, how do you find the acoustic comfort of the room?
2. Thinking about the period in which you have lived/worked/frequented this area, do you hear noise generated from external noise sources (road traffic, railway traffic, industrial activities, etc.) when you are inside the room with closed windows?
3. How much do you think that building envelope interventions (e.g. increasing wall and windows sound insulation) are necessary in order to improve your acoustic comfort inside building?
4. Is the noise generated from external noise sources the main source of sound that interfered with your activities inside building?
5. How sensitive are you to noise in general?

Questions are divided in two categories:

a. Questions used for assessing the “Socio-acoustic” *KPI* (questions number 1, 2, 3);
b. Questions used as indicators for the design team of a specific issue (questions number 4, 5). In particular, question number 4 is used to identify if other acoustic problems cause annoyance to the inhabitants (e.g. noise from service installations or building equipment), that are out of NewTREND purpose. Concerning question number 5, in case of evident differences between the responses of the questionnaires filled by the inhabitants in the same room, the answer to this question allows evaluating if the user response should be not considered (because of the high sound sensibility of the user).

The "Socio-Acoustic" *KPI* calculation method consists in the processing of the answers of the questions number 1, 2 and 3. The evaluation procedure is described in the following steps:

1. Correlate each answer to the acoustic classification scheme of Table 2, assigning a score to each one (score equal to 5, if the answer allows to state that the condition of "acoustic comfort" within room is completely respected; 1, on the contrary);
2. Calculate, for each room, the average value of the scores obtained from the questionnaire, as explained in step 1, for each respondent.
3. Calculate, for each room, the average value of the scores obtained in step 2 of all the respondents;
4. Calculate the "Socio-acoustic" *KPI* according to the Eq. 18:

$$\text{"Socio-Acoustic" KPI} = \left(\frac{\sum_{i=1}^{n} A_i * RA_i}{A_{tot}}\right) \quad [-] \qquad \text{Eq. 18}$$

Where A_i is the reference floor area of each room bordering to the external environment i [m^2], RA_i is the average value calculated for each room i [-] and A_{tot} is the total reference floor area of all the rooms bordering to the external environment [m^2]. Then the *KPI* is expressed in a percentage scale from 0 % to 100 %, through a linear interpolation from 1 to 5, where the score 1 corresponds to 0 % and the score 5 to 100 %. In this way, the "Socio-acoustic" *KPI* follows the same classification scheme of Table 3.

In this way, the objective and subjective *KPIs* can be compared each other, in order to evaluate how the human perception leads away from the acoustic comfort measure, based on simulation or experimental measurements of the acoustic quantities. This correlation responds to the acoustic sensation of the most people inside an environment, anyway they are subject to substantial errors, because the individuals show a large difference in sensibility to noise. In Annex A, the developed questionnaire form is reported.

3.3 Soft-sensor to support the decision-making in renovations

Within the NewTREND project, the developed soft-sensor for the acoustic comfort measurement of buildings intends to support the decision-making process in retrofitting design, by comparing different renovation scenarios (Fig. 12).

The support offered by the "Socio-acoustic" *KPI* in the decisional stage of retrofitting intervention selection in explained through a real case study (see paragraph 5.4).

As already described in paragraph 3, only the "Advanced" and "Combined" modes of the soft-sensor allow simulating in design stage and comparing different potential renovation scenarios, while the "Premium" mode allows only to assess the acoustic comfort improvement of the building before and after retrofitting; hence it cannot be adopted during

the design stage. When all the input data concerning the building under investigation are collected through the Data Manager, they are used by the soft-sensor system to measure the building acoustic comfort. As first, the current state of the building is evaluated, through the "As-is" *KPI*. Afterwards, different potential renovation scenarios are simulated and the "What-if" *KPIs* are calculated and compared between each other.

The stakeholders involved in the renovation project take part in the decision-making process: technicians and acoustic experts present the different simulated scenarios to the client/owner of the building and the final decision will be based on the most convenient solution in terms of significant acoustic comfort improvement and cost saving.

The feasibility of the developed approach for supporting the decision-making process has been show through the application to real buildings (see chapter 4).

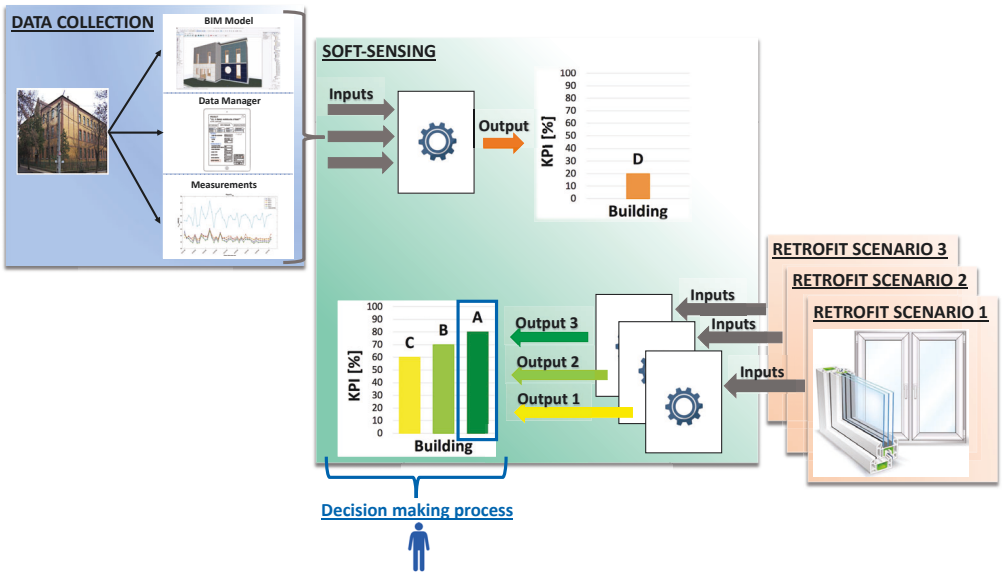


Fig. 12 Soft-sensing to support the decision-making

3.4 Integration of the soft-sensor within the NewTREND platform

The soft-sensor system has been included within the integrated collaborative design platform of the NewTREND project for retrofit assessment. Before explaining the integration steps and the developed tools able to assess the acoustic comfort through the soft-sensor, an overview of the NewTREND project and its innovation is introduced.

3.4.1 NewTREND project and innovations

As already anticipated in chapter 1, the NewTREND project has the purpose to create a new methodology, linked with software tools, that increases the uptake of renovation across the EU, exploiting the potential for buildings refurbishment at the neighbourhood level. As it stands in fact, the design and construction processes are inefficient and effective communication does not always occur between each stakeholder in the process. The problem grows exponentially for renovation projects, as the project increases in complexity due to the additional constraints related to existing structures and occupants. Also, current practices tend to separately consider design and assessment activities - frequently, assessment and analysis is out of sequence with design decision-making. These concerns have fostered innovation in the construction industry, convincing its stakeholders to push forward an innovative digital and software-intensive design paradigm: Building Information Model (BIM). BIM is now widely recognized as a cornerstone of future tools and practices in the construction industry. Despite these recent evolutions however, BIM and innovative design paradigms are currently rarely applied to refurbishment projects due to the difficulties in retrieving the necessary information to build a BIM model and to the traditional character of the sector. Furthermore, BIM is mainly used for architectural purposes and energy and comfort aspects are included only in the end of the process as a final validation of choices already made. Moreover, software tools used by architects, engineers, etc. for the realisation of a construction project do not always communicate between each other in an interoperable manner and as a result the outputs that are transferred between software tools require considerable time to present the data in a format that other stakeholders can use. Despite enhanced practices and tools, the building life cycle is still largely fragmented, and information flows suffer from discontinuities.

The NewTREND design methodology includes specific metrics to assess the retrofit design project in terms of energy efficiency, comprising the following design quality aspects:

- Energy performance;
- Thermal and acoustic comfort;
- Sustainability;
- Social impacts on users and inhabitants.

The methodology is supported by a comprehensive online platform to support collaborative design, which will play the role of exchanging information and facilitating dialogue between the different stakeholders involved in the retrofit process. The platform stores all the information useful to the design of the retrofit intervention in a cloud based interoperable data exchange server, i.e. the District Information Model (DIM) Server (implemented by NewTREND consortium partners: University Colle Dublin and University College Cork) which has the ability to import and export multiple file formats as a result of semantic web technologies this will ensure energy efficient retrofit design integrated with neighbourhood. A dedicated easy to use tool, Data Manager tool, has been developed (in collaboration with the NewTREND partners) to guide the designers in the data collection phase for the construction of the DIM model, which might be a complex task for retrofit projects where information and drawings are scattered or even not available. The

NewTREND platform is a tool for collaborative design of the renovation process allowing evaluation of different design options at both individual building and district level through dynamic simulations via a Simulation & Design Hub. The Simulation Design & Hub includes several algorithms for comfort assessment, able to support the design team in taking informed decisions assessing the impact of different design options on the building to be retrofitted considering the surrounding district. Design options are to be presented to the design team, together with available financing schemes, in a library which will be assembled several construction typologies. The following figure shows how the different NewTREND tools are linked together and exchange information.

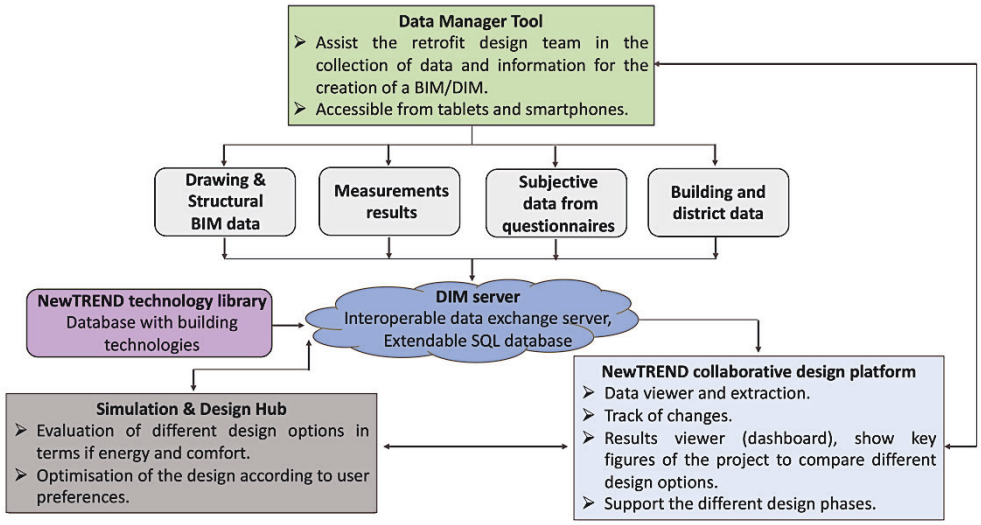


Fig. 13 Overview of the NewTREND web toolkit

In retrofit projects, occupants usually are not involved in the design process and sometimes the installed technologies and interventions are unsuitable for the occupants or incorrectly used, thus increasing the gap between designed and actual performances. Furthermore, comfort aspects, in particular the acoustic one, are rarely considered. To address this, NewTREND design methodology fosters the involvement of building users and inhabitants across the whole life cycle of the retrofit project through the development of 'Participatory Design' approaches and techniques and through user 'validation' of the selected options, in recognition of their central influence on the expected impacts of the intervention.

NewTREND offers its users the possibility to operate in three different methods of operation, namely: Advanced, Combined and Premium Modes. These modes offer the user different accuracy of the output, depending on the accuracy of input data. The different modes have been explained in chapter 3.

3.4.2 “Acoustic module” within the platform

The soft-sensor is integrated within the platform and named “acoustic module”. The acoustic module is a powerful tool to measure the acoustic comfort and to support the design team during the evaluation of the different design options on building to refurbish, considering the surrounding neighborhoods, through the assessment of adopted envelope design options. It is proposed as a sub-system of Simulation & Design Hub, which communicates with DIM Server obtaining input data in order to run simulations for acoustic comfort measurement. The module contains algorithms to evaluate the *KPIs* and therefore to provide a measure of the building acoustic comfort, as described in paragraph 3.4.2.2.

The presented workflows show the platform architecture and how the acoustic module fits into its context in case of analysis of building in current state (Fig. 14) and after renovation option selection (Fig. 15). Green boxes show tools which have a graphical user interface, while blue boxes show tools which users don’t interact with actively.

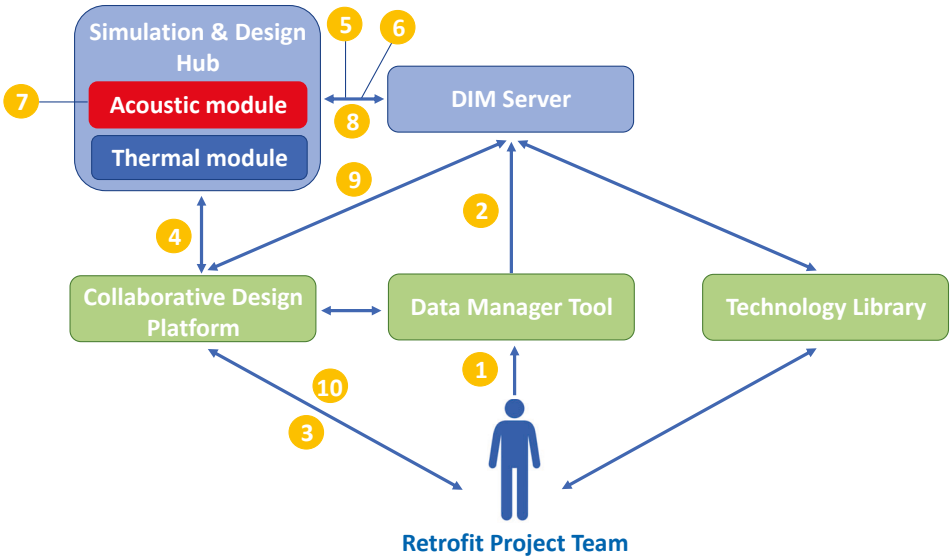


Fig. 14 Link with the modules of the NewTREND toolset – “As-is” diagram

Step 1: User collects building and district data through the Data Manager Tool.

Step 2: Building and district data collected through the Data Manager Tool are directly sent and stored into the DIM Server.

Step 3: Once collected manual data, user triggers the “As-is” acoustic simulation.

Step 4: Collaborative Design Platform instructs the Simulation Design and Hub to run the "As-is" acoustic simulation.

Step 5: Simulation Design and Hub requests simulation input from DIM Server (BIM data and manual collected data).

Step 6: DIM Server sends requested input to the Simulation Design and Hub.

Step 7: Acoustic Module runs the "As-is" simulation and processes "As-is" simulation results (Acoustic KPIs).

Step 8: Simulation Design and Hub sends "As-is" simulation results to DIM Server.

Step 9: DIM Server schedules and stores the results and sends them to Collaborative Design Platform.

Step 10: Collaborative Design Platform - Front End displays the "As-is" simulation results to the user through a GUI.

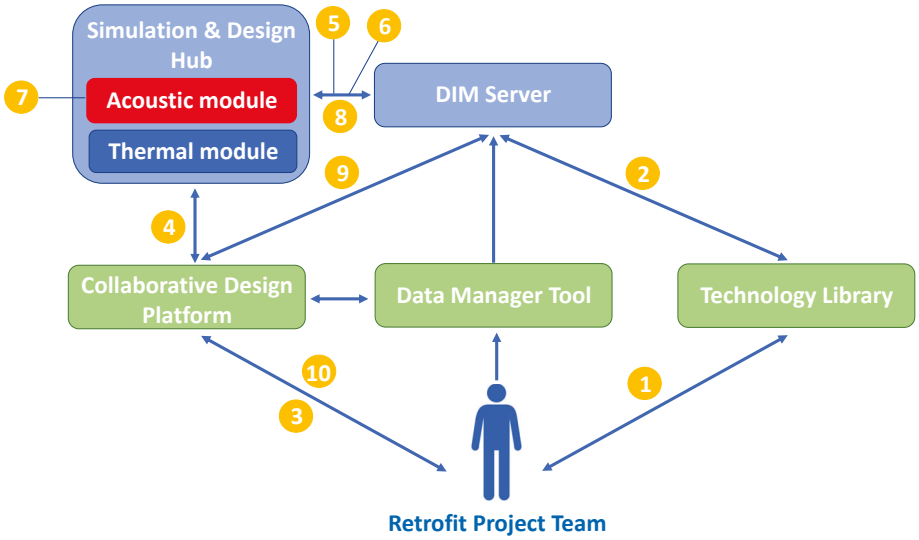


Fig. 15 Link with the modules of the NewTREND toolset – "What-if" diagram

Step 1: User selects the retrofit option through the Technology Library.

Step 2: Technology Library sends retrofit data to DIM Server, which manages and adds the new data to those one collected for the pre-retrofit simulation.

Step 3: Once selected retrofit option, user triggers the "What-if" acoustic simulation.

Step 4: Collaborative Design Platform instructs the Simulation Design and Hub to run the "What-if" acoustic simulation.

Step 5: Simulation Design and Hub requests simulation input from DIM Server (BIM data and manual collected data).

Step 6: DIM Server sends requested input to the Simulation Design and Hub.

Step 7: Acoustic Module runs the "What-if" simulation and processes "What-if" simulation results (Acoustic KPIs).

Step 8: Simulation Design and Hub sends the "What-if" simulation results to DIM Server.

Step 9: DIM Server schedules and stores the "What-if" simulation results and sends them to Collaborative Design Platform.

Step 10: Collaborative Design Platform - Front End displays the "What-if" simulation results to the user through a GUI.

3.4.2.1 Data collection process and storage to run the acoustic module

Data Manager is the web-based tool that supports the acquisition of the data required for the creation of the DIM Server able to support the acoustic comfort analyses. The new developed approach for an advanced data collection method in the preparation phase of retrofitting projects for existing buildings guides the user/designer in the data collection phase, which might be a complex task for retrofit projects where information and drawings are scattered, poor or even not available. Data Manager tool provides two approaches to collect data.

1. Detailed data collection: e.g. user enters manually the weighted sound reduction index of the construction elements.
2. Data collection through approximation: e.g. user selects typical values for given construction elements type, located in internal databases.

User collects data concerning the building façades and then he associates elements and related features (wall, windows, doors, small elements) to each façade to create an 'As-is' model of the building. Data concerning the building façade also include district data, in case of Advanced Mode configuration, and measured data in case of Combined and Premium Mode configurations. For each data, the user enters information through labels, which give the possibility to choose between different options from a drop-down list. As first, required data are referred to the façade identification and definition. Rooms involved in the acoustic

comfort analysis are only the rooms having at least one façade bordering to the external environment. Rooms could have more than one façade (see Fig. 16).

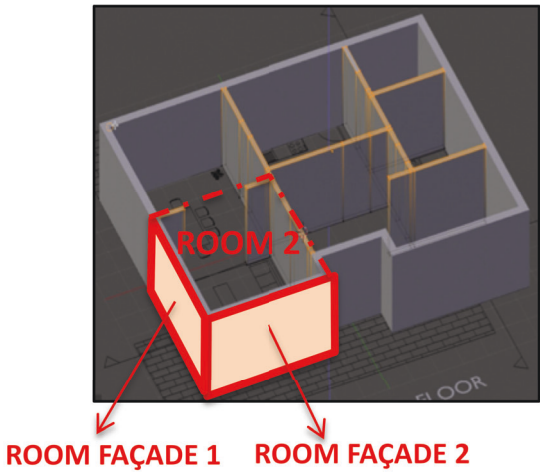


Fig. 16 Façade identification

For each façade, at least one external noise source (road, railway, industry, others) or strategic noise mapping value has to be defined. For example, if the user does not know the value of the strategic noise mapping, and the examined façade overlooks a road, he has to select the road type (e.g. urban high speed highway, urban road, local road, etc.), the road slope (e.g. flat, up, down), the road surface (e.g. porous surface, cement concrete and corrugated asphalt, etc.), the road traffic density (e.g. continuous fluid, etc.). Otherwise, if the road is not present, information referred to it are not required. If several façades have the same features, the option "As rom façade (e.g.) 1" (see Fig. 17) is allowed, in order to make the user task quicker. In addition to the external noise sources characterization, the user has to enter specific information concerning the façade, as the floor level (e.g. ground floor, first floor, second floor, etc.), the end use of the room (e.g. bedroom, living room, classroom, etc.), the shape of the façade (e.g. flat, with balcony, etc.). Also, the façade elements have to be defined, including the acoustic features (if known) or the properties of the constituent materials. If the elements properties are available to IFC files of BIM, the user does not need to fill these fields.

If the "Combined" mode is active, the designer has not to enter data related to external sound sources, but only the results obtained from measurements of the external and internal sound pressure levels. In Appendix B ("Advanced" mode) and Appendix C ("Combined" mode), the required information are fully listed.

In the same way, if the "Premium" mode is operated, only some geometrical data (detailed in Appendix D) and indoor sound pressure levels measurement values are entered in the Data Manager. In Fig. 17, a sketch of Data Manager tool is provided, and some examples of input data are showed.

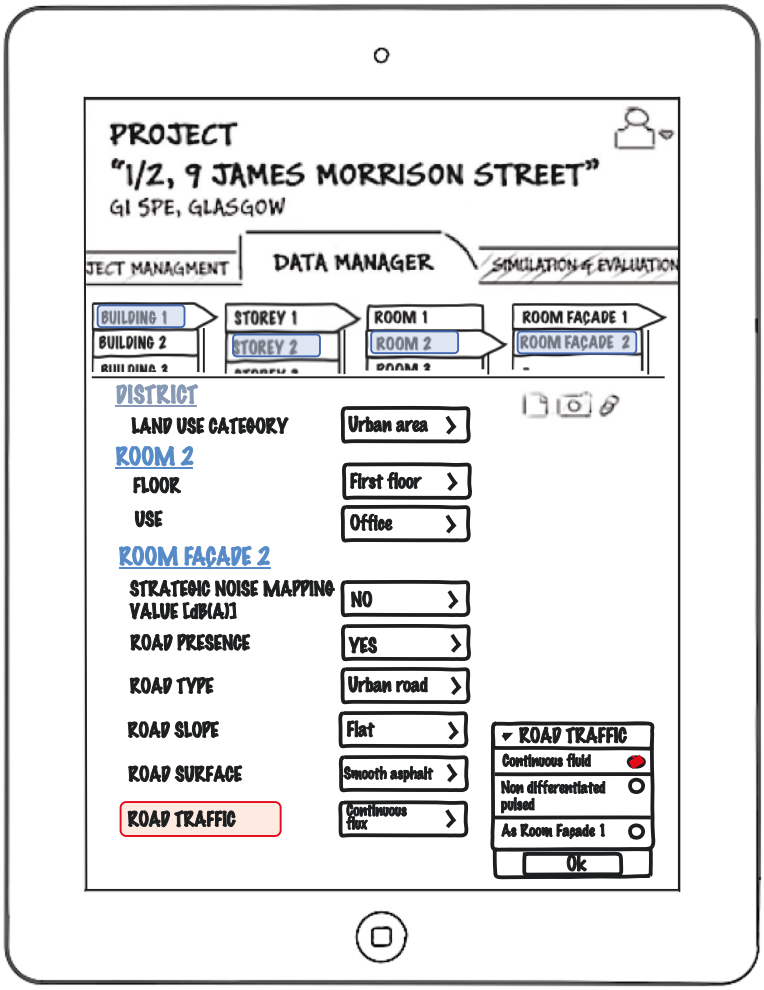


Fig. 17 Data Manager mockup for user data collection

As already mentioned in 3.2, Data Manager allows also to carry out socio-acoustic surveys through questionnaires (Fig. 18).

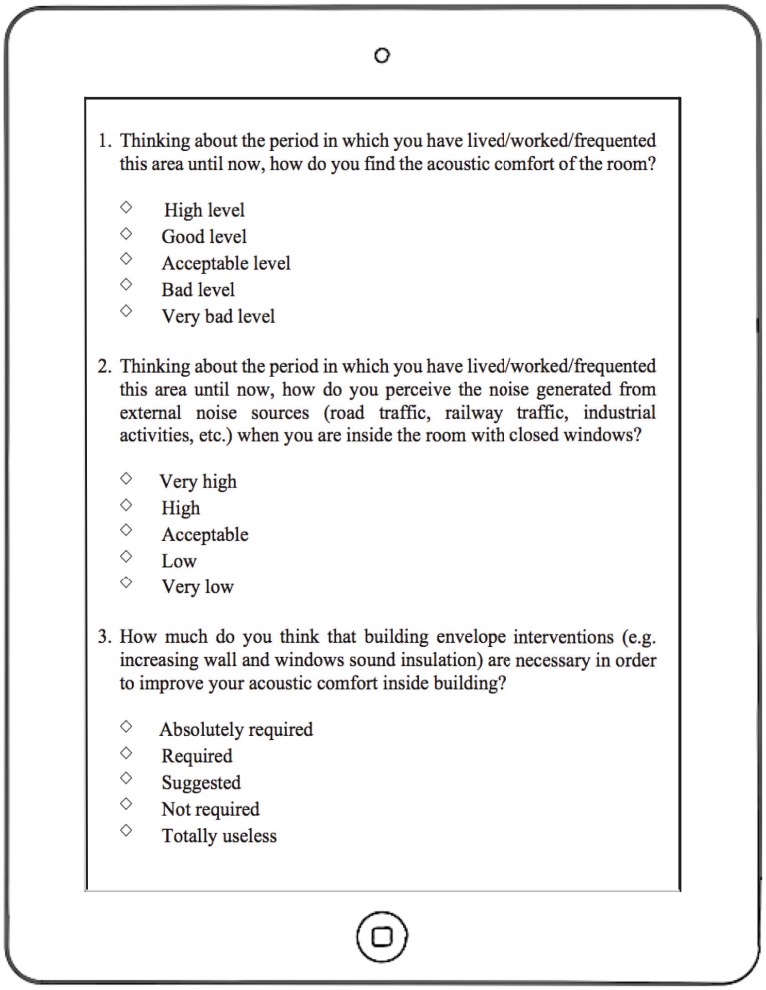


Fig. 18 Data Manager mockup for questionnaires

Collected information are managed and stored on the DIM server, where also information from BIM (spatial information/building geometry/material properties, etc.) are persisted. They are processed and located in a set of database tables. In particular, information which arrive to DIM Server are collected in CSV files since to each user selected option of the Data Manager fields corresponds to a numerical value in the CSV files. Following a partial set of Data Manager – CSV Files encoding is shown (Fig. 19):

Data Manager field	Data Manager options	CSV file encoding	Data type
BUILDING	1	1	Integer
	2	2	
	n	n	
LAND USE CATEGORY	Countryside	1	Integer
	Residential area	2	
	Urban area	3	
FLOOR	Ground floor	1	Integer
	First floor	2	
	Secondo floor	3	
	n	n	
USE	Bedroom	1	Integer
	Living room	2	
	Hotel bedroom	3	
	Classroom	4	
	Nursery school	5	
	Office	6	
	Conference room	7	
	Hospital	8	
	Retail shop	9	
STATEGIC NOISE MAPPING VALUE	"Write a value"	65	Float
	NO	0	
ROAD PRESENCE	YES	1	Integer
	NO	0	
ROAD TYPE	Extra-urban motorway	1	Integer
	Urban motorway	2	
	Extra-urban high speed highway	3	
	Urban high speed highway	4	
	Urban road	5	
	Local road	6	
ROAD SLOPE	Flat	1	Integer
	Up	2	
	Down	3	

Fig. 19 Data Manager – CSV Files encoding

Retrofitting scenarios are collected within the Technology Library. The user/designer selects the intervention from the Technology Library front-end and new information are exchanged between the Library and the DIM Server, which modifies existing elements (e.g. old window properties) and add the new ones in order to generate the "What-if" CSV file. In Appendix E, retrofit interventions database included in the Technology Library is reported.

3.4.2.2 Acoustic module: acoustic comfort simulation

The soft-sensor contains algorithms for acoustic comfort assessment. When all the input data are collected into DIM Server they are sent in the acoustic module, through CSV files. DIM Server exports two different CSV files: the first CSV file contained data about district, building, room and room façade. This CSV file does not change when post-retrofitting simulation is performed. The second CSV file contained data about building elements of each room façade (walls, windows, doors, small elements). Only the second CSV changes when post-retrofitting interventions are applied.

Acoustic module checks if every required input data is present and if at least one input data is missing or incorrect, the user is informed with an error displayed in through Collaborative Design Platform front-end.

Once required data are received, the algorithms contained within the Acoustic module perform the acoustic comfort simulation, calculating the *KPIs.*

The simulation pre ("As-is") and post-retrofit ("What-if") solution run separately: the first analysis is the "As-is" simulation, in order to evaluate the acoustic comfort of the building before any retrofit intervention. If the acoustic comfort conditions are not satisfied, renovations are required. Every retrofit change on building envelope needs new simulations. The building designer/user selects different retrofit intervention (e.g. windows exchange) and the simulation (post-retrofitting) runs again, given different outputs. The outputs of the "What-if" analyses allow the user to make informed decisions on the solutions to be installed and select the better one, in order to improve the acoustic comfort inside the building. The workflow of the algorithms shown in Fig. 20 (only the workflow of algorithms for the "Advanced" mode is reported).

Finally, results are stored into the DIM server, which sends them to the Collaborative Design Platform. Collaborative Design Platform - Front End displays the simulation results to the user, providing feedbacks which allow to make informed decisions and evaluate the impact of the retrofit choices.

Acoustic algorithms are based on robust theoretical models, already described in chapter 2 and 3. The final scope is to evaluate the *KPIs,* as indirect measure of building acoustic comfort. The algorithms have been implemented in Python language and they allow the evaluation of:

1. External equivalent sound pressure level in front of each room façade, due to external noise sources (road, railway, industry);
2. Weighted apparent sound reduction index of room façade, through the evaluation of the weighted sound reduction index of façade elements (wall, window, door, and small elements);

3. Weighted sound level difference of each room façade;
4. Reverberation time of the room;
5. Indoor equivalent sound pressure level of each room bordering to the external environment;
6. Objective and subjective *KPIs.*

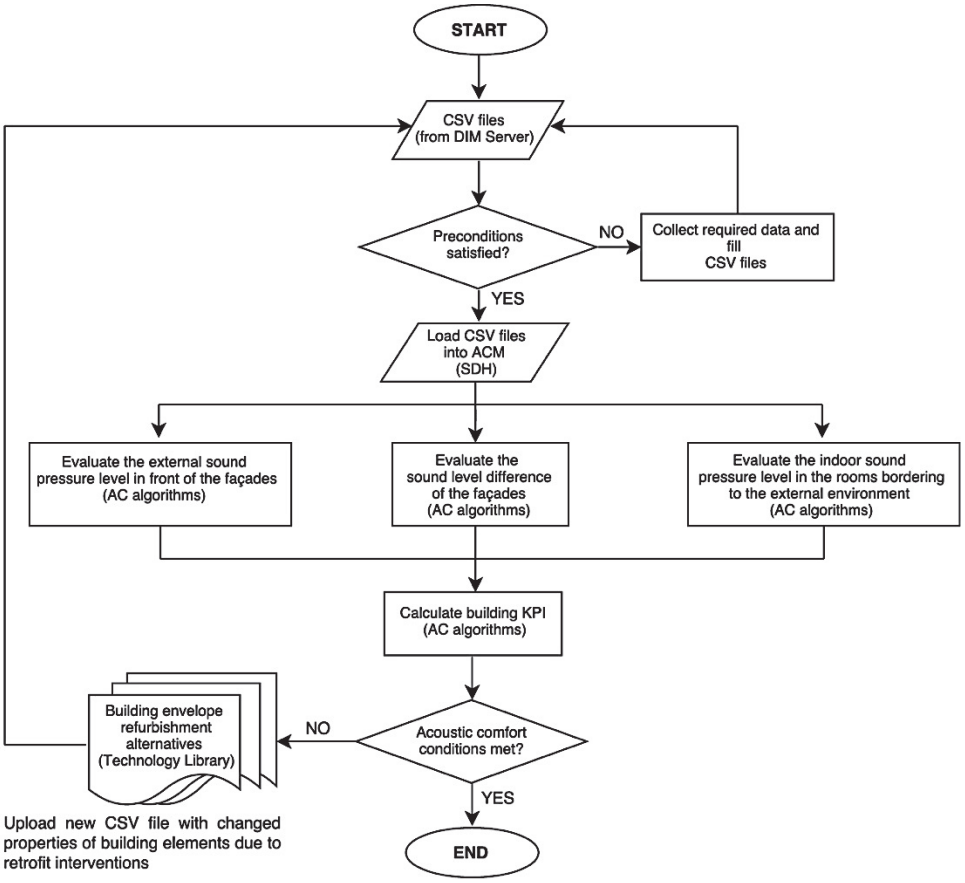


Fig. 20 Acoustic simulation Workflow

The module allows to perform analysis of single room and room façade, which compare simultaneously the change of the room class and other acoustic parameters of room and room façade due to applied retrofitting interventions (see Fig. 21, Fig. 22, Fig. 23).

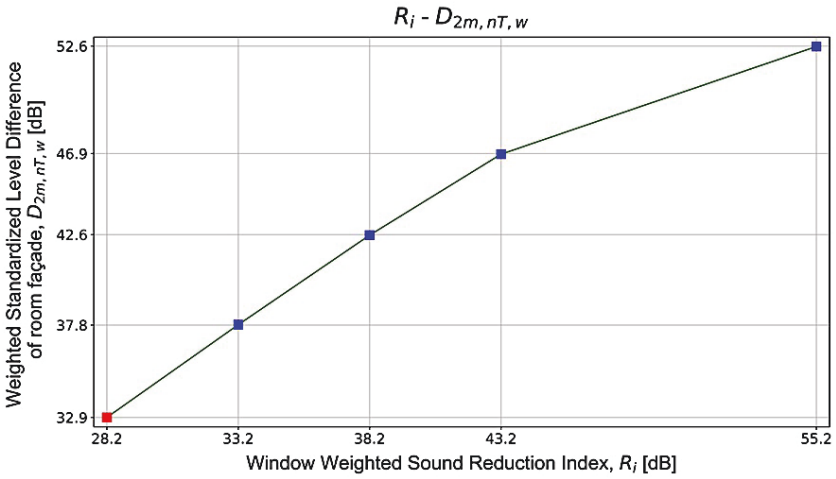


Fig. 21 Windows weighted sound reduction index and room façade insulation

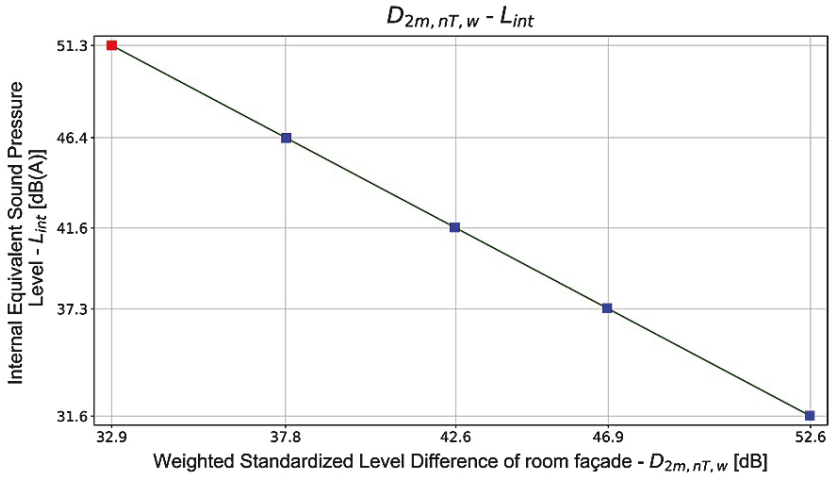


Fig. 22 Room façade insulation and internal equivalent sound pressure level

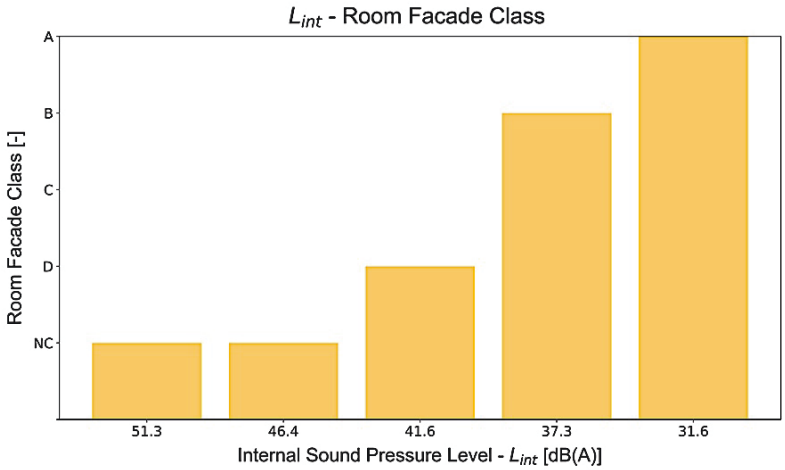


Fig. 23 Internal equivalent sound pressure level and room class

3.5 Summary of developed *KPIs*

In this section, a brief summary of the already presented *KPIs* is reported, aims to recap the soft-sensor outputs.

The developed *KPIs* for measuring buildings acoustic comfort are two: "objective *KPI*", based on objective assessment of acoustic quantities and "subjective *KPI*", representative of the subjective occupants' rating.

Concerning the "objective *KPI*", it can be assessed basing on the indoor noise levels evaluation, through different soft-sensor configurations: "Advanced", "Combined" and "Premium". All the soft-sensor configurations provide the same output, but they differ from each other for the indoor noise levels evaluation procedure, hence, the consequent accuracy.

In addition, since the soft-sensor can be used, as done within the NewTREND project, for assess building acoustic comfort in current conditions and after renovation options through the *KPIs*, the terms "As-is *KPI*" and "What-if *KPI"* have been introduced to express respectively the acoustic comfort of the building before and after retrofit intervention.

CHAPTER 4
APPLICATION OF THE SOFT-SENSOR TO REAL CASE - STUDIES

4.1 Case study 1: historical residential building in Ancona (Italy)

In order to demonstrate the reliability and the feasibility of developed approach, the soft-sensor system has been applied and validated in seven real case studies, making use measured and simulated data. In this chapter, only two significant case studies have been reported. In particular, the Combined mode has been applied as first. The external sound pressure level in front of each room façade has been measured and the façade sound insulation simulated, according to predictive methods. The "As-is" *KPI* of the building has been calculated and two different renovation scenarios were analyzed in order to compare the resulting *KPI*s.

Furthermore, even the Premium Mode has been applied, with the main purposes to assess the accurate estimation of the internal sound levels obtained through direct measurements and to compare such results with the indoor sound pressure levels obtained running the calculation model of the standard [63].

The case study is a four-storey residential building, situated in one of the most congested areas of Ancona (Italy). Since the building inhabitants were annoyed, especially in some rooms of the building, by the traffic noise, the study intends to support the development of a refurbishment project, aiming to optimize the noise protection against external noise, improving the façade insulation. In the current state of the present research, only one apartment at the ground floor was object of investigation, with the intention of extending the analyses to the other units of the building.

4.1.1 Building description

The analysed dwelling is a ground floor of a residential multi-apartment building, located in "Viale della Vittoria, 27 A", Ancona (Italy) (see Fig. 24). It was built in 1735 and some minor changes were done in the 1970. It is chosen as it is representative of a great share of Italian residential buildings built before the implementation of D.P.C.M. 5/12/97 [57] regulating the acoustic requirements of buildings, and thus without any acoustic concerns. Since the BIM model is not available for the building under investigation, specific data about the construction, as elements geometries, materials, rooms surface, volumes, etc., were collected from in situ-inspection. The apartment is composed of seven rooms, including three corner rooms with two external room façades for each one. The north side of the floor (comprising two bedrooms and the living room) overlooks a highly congested urban road (room facades are about 5 m away from the road); the other sides (which include three bedrooms and the kitchen) are exposed to private garden and internal court, where other dwellings are faced (Fig. 24 and Fig. 25). No industries, railway or airports are located close to the analysed building; thus, road traffic noise is the main noise source.

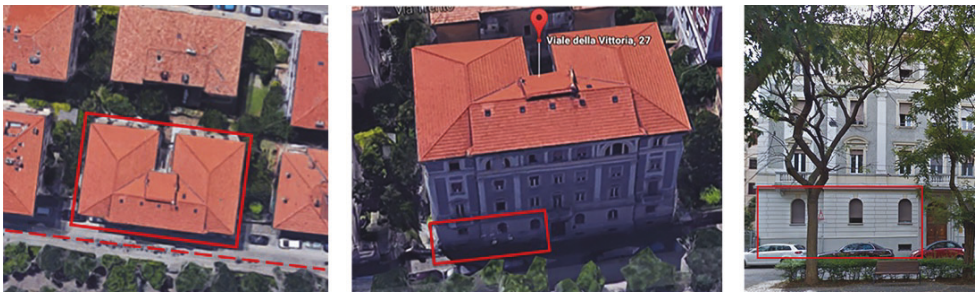


Fig. 24 Building aerial views and frontal view (north side)

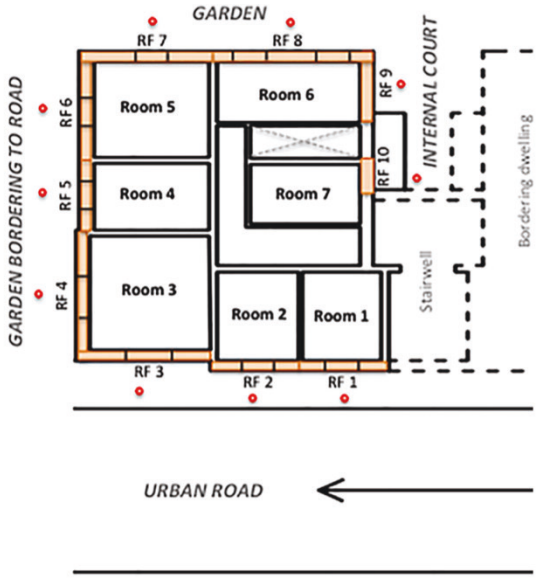


Fig. 25 Building plan and external microphones positions (red dots)

Since the investigation tackles "in-situ" evaluation of the outdoor acoustic climate, a measurement campaign of external sound pressure level in front of each room façade of the apartment was carried out. In addition, for each room façade (*RF*), the weighted standardised level difference was calculated according to Eq. 6. Thus, the noise level entering in each room, necessary for calculating the "As-is" *KPI*, was obtained from Eq. 17, where the average reverberation time of the rooms has been assumed for simplicity equal to 0,5 s, as already done in previously studies and investigations of furnished rooms [104], [105].

The investigated rooms are described in Table 4. Looking at Fig. 25, it is possible to note that one room was not considered (marked with a grey cross); it is a bathroom, hence a short-term occupancy area, uninfluential for the acoustic comfort assessment. During in-situ

inspections, construction elements were deeply investigated, in order to identify their acoustic properties. In particular, the wall structure (thickness equal to 50 cm), called “a sacco” masonry, is made of double solid bricks, inner and outer, and the gap is filled with stone chippings and mortar, and internally there is 1,5 cm of plaster. This wall typology has high acoustic insulation performance, due to the high mass for unit area. Instead, windows sound insulation is very low, because they are composed of 3 mm single glass and wood frame. They do not have any shading devices or venetian blinds placed inside and also, neither air sealing systems. The small ventilation holes, located in the living room and kitchen facades, do not have any insulating filling, but simply a protection grate. The normalized sound level difference of the small elements has been calculated according to Eq. 3, provided by the standard EN ISO 12354 – Part 3 [63], which uses the hole area. Since the sound reduction indexes of façade elements (wall and windows) were not measured for this study, they have been estimated. In particular, the wall sound reduction index was calculated according to the empirical equation for monolithic structures proposed by the standard EN ISO 12354 - Part 1 [74], making use of the mass for unit area, set equal to 950 kg/m^2, according to materials properties databases (specific weight equal to 1900 kg/m^3). The calculated value of the wall R_w is 69,7 dB. Concerning the windows, databases on glass laboratory measurements are very approximated, with few references [106]. Though, a value equal to 15 dB has been assumed [107], considering the old window typology, with non-efficient joints and high permeability.

Room	Room use	Numb. of RF	Ext. noise source [-]	Room vol. [m³]	RF surf. [m²]	Ref. floor area [m²]	Window surf. [m²]	Wall surf. [m²]	Small element surf. [m²]
1	Bedroom	1	Road	38	10	11	2	8	-
2	Bedroom	1	Road	38	10	11	2	8	-
3	Living room	1	Road	81	15	24	2	13	-
		2	Garden bordering to road		19		2	17	0.01
4	Bedroom	1	Garden bordering to road	46	11	14	2	9	-
5	Bedroom	1	Garden bordering to road	67	15	20	2	14	-
		2	Garden		15		2	13	-
6	Bedroom	1	Garden	51	18	15	3	15	-
		2	Internal court		10		0	10	-
7	Kitchen	1	Internal court	38	4	11	2	1	0.02

Table 4 Building data collection

4.1.2 “Combined” mode

Once having collected building data, external and internal noise levels of each room of the building have been evaluated, through direct measurements, for the first ones, and through simulations, for the second ones, obtaining, through the soft-sensor, an indirect measure of the acoustic comfort of the building, expressed through the “As-is” *KPI* (Eq. 17).

4.1.2.1 External noise measurement

The L_{Aeq} outside the apartment were measured at 2 meters from the building facades (or 1 meter in case of balcony) (see Fig. 27), following the global method of the standard EN ISO 16283 – Part 3 [33].

Fig. 26 Measurement setup: external microphone position

The A-weighting indicates that the value has been filtered to focus on the frequencies to which the human ear is sensitive. It has been assumed as sound excitation of the measurements the real external noise. Sound pressure levels were measured in the frequency range between 20 Hz and 10 kHz [108]. The measurement campaign was conducted in April 2017, spread over a time period of two weekdays representative of typical workdays traffic level. For each position, measurements should be performed for a 24-hour period, but this would lead to long-lasting campaign, ineffective for the study purpose. Hence, measurements were carried out during daytime (between 7:00 h and 19:00 h), given the fact that road traffic noise exposure (in particular for façades directly exposed to the road, i.e. *RF 1, RF 2,* and *RF 3*) is most significant during that time interval. In particular, since the outdoor noise due to traffic is time fluctuating, it was chosen to measure the equivalent sound pressure levels during the peak-hour of the day (when more traffic was observed). Single 20 minutes observations have shown to yield stable conditions at locations where noise level and hence traffic intensity were of practical interest. Spreading the time interval to 1 hour or more, has been considered unnecessary because, within this period, traffic conditions and resulting noise levels, do not change significantly during daytime [109]. This was confirmed through long-term measurements carried out during other experimental tests in Ancona.

Noise levels measurements were performed with ¼'' condenser free-field measurement microphones (Sensitivity ± 2 dB, ref 1V/Pa), connected to eight-channel dynamic signal acquisition modules for making high-accuracy measurements. All microphones were synchronously sampled at 56 kHz. A custom-made software was developed to measure indoor and outdoor A-weighted equivalent sound pressure levels starting from the acquisition

of the signals time histories. The measured chain was calibrated before and after the measurements with a class 0 pistonphone (250 Hz, 124 dB) (see Fig. 26).

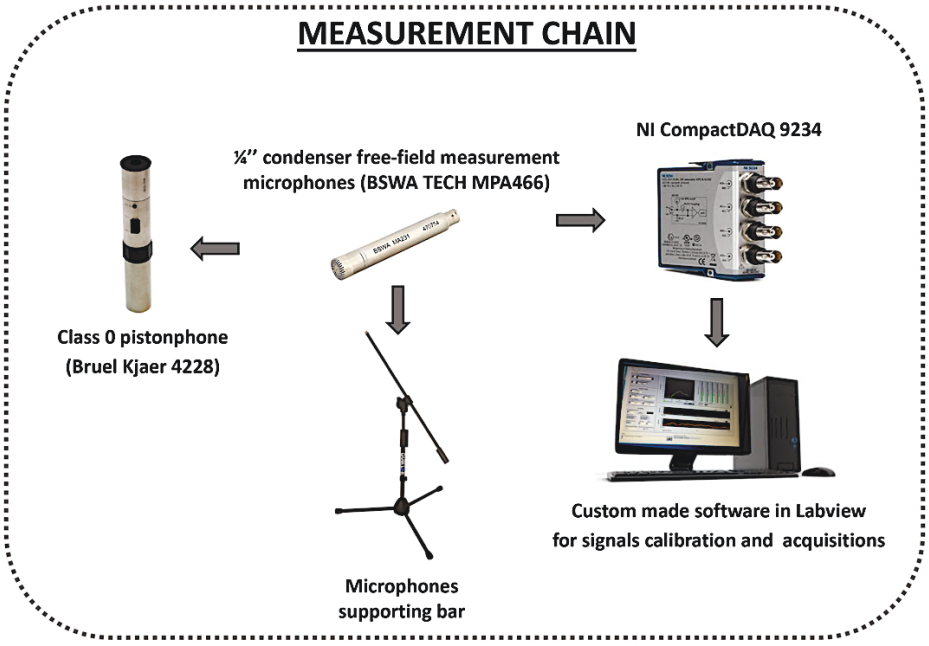


Fig. 27 Measurement chain

The measurement campaign was carried out in absence of atmospheric precipitations and with wind speed not exceeding 5 m/s. The outdoor L_{Aeq} over the measured time period (20 minutes) is calculated as a mean value of the equivalent sound pressure levels registered for each integration time step, set equal to 30 seconds (Table 5). Fig. 28 shows the trends of the measured outdoor L_{Aeq} in front of the room facades most exposed to traffic noise.

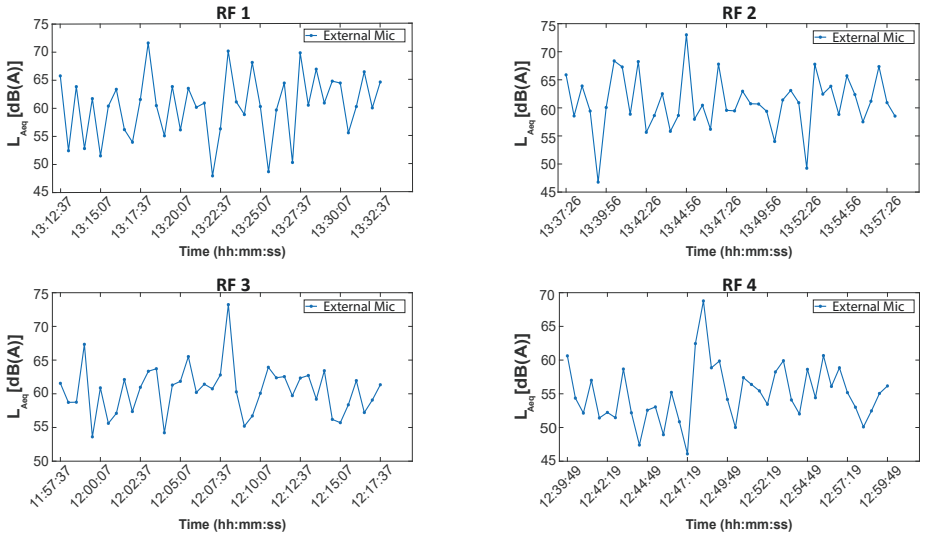


Fig. 28 Equivalent sound pressure levels in front of the room façades most exposed to traffic noise

Analysing data of Table 5, it is possible to note that the outdoor L_{Aeq} measured directly in front of the road (*RF 1, RF 2* and *RF 3*) are those showing the highest average value. The variation between them is a consequence of the difference in number, speed and typology of vehicles passing in the monitored time period. Concerning room facades of the side exposed to the garden bordering to the road (*RF 4, RF 5* and *RF 6*) present similar noise levels, which decrease gradually distancing from the road. Facades facing the internal garden (*RF 7* and *RF 8*) show lower values. In this case, the differences between the registered sound levels could depend on exceptional neighbourhood noises (e.g. dog barking, human shout), which influence the equivalent sound pressure level measurement. Facades 9 and 10 overlook an internal court and for this reason the noise values are the lowest measured. Since *RF 10* presents a balcony, the measure was performed at 1 m from the balcony [33]. Because of the microphone closeness to the frontal façade, acoustic reflections affect the acquired noise level. Building facades are exposed to four different noise sources, as shown in Fig. 25: road, garden bordering to road, garden, internal court. The highest external sound pressure level measured on each side of the building was assigned for each façade exposed to one of those noise sources (Table 5). This assumption has been done to consider that measurements were performed only for short spot durations, which consider only limited events and sometimes do not catch periods when major noise occurs (e.g. pick hours of the day when highest traffic noise is registered).

Source	RF	Outdoor L_{Aeq} measured [dB (A)]	Outdoor L_{Aeq} assigned [dB (A)]
Road	1	60	61
	2	61	
	3	61	
Garden bordering to road	4	55	55
	5	53	
	6	53	
Garden	7	47	47
	8	47	
Internal court	9	41	45
	10	45	

Table 5 Measured and assigned outdoor L_{Aeq} in front of each RF [dB(A)]

4.1.2.2 "As-is" *KPI* evaluation

Using data collected in Table 4, the $D_{2m,nT,w}$ of the façades was calculated according to Eq. 6. Afterwards, the L_{Aeq} inside each room due to the sound entering from each room façade was determined Eq. 16. To simplify and speed up the procedure, the reverberation time was assumed in this case study equal to the value of the reference reverberation time ($T = T_0 =$ 0.5 s); this statement derives from an approximation based on the reverberation time values measured generally in typical residential furnished environments [110].

Since the determination of the acoustic class (Fig. 8) has to be defined at room level (and not for each room façade), for rooms having more than one external façade (i.e. room 3, 5 and 6), the highest resulting indoor L_{Aeq} has been assumed. With the same outdoor noise levels and reverberation time, the different values of the indoor sound pressure level coming transmitted through the facades depends on room and façade intrinsic properties (i.e. façade surface, room geometry, elements type and surfaces). Table 6 shows the measured values of outdoor noise levels, the calculated values of indoor noise levels and the assigned room acoustic class.

Room	Room Use	Measured outdoor L_{Aeq} [dB (A)]	Calculated indoor L_{Aeq} [dB (A)]	Class
1	Bedroom	61	43	E
2	Bedroom	61	43	E
3	Living room	61	40	C
4	Bedroom	55	36	D
5	Bedroom	55	35	C
6	Bedroom	47	30	A
7	Kitchen	45	35	A

Table 6 Measured and calculated quantities for each room

Once evaluated the rooms acoustic class, in order to provide a measure of the acoustic comfort of the building in current state, the "As-is" *KPI* was calculated according to Eq. 17. The "As-is" *KPI* is equal to 49 %, which returns in acoustic class C ("Acceptable level of building acoustic comfort").

4.1.3 "Premium" mode

Indoor sound pressure level measurements have been performed in order use them as inputs of the soft-sensor and calculate the *KPI*. Hence, during the outdoor equivalent sound pressure levels acquisition, also the internal ones were measured. In fact, the standard EN ISO 16283- Part 3 [33] imposes to measure simultaneously outdoor and indoor sound pressure levels, with microphones located at a certain distance from vertical and horizontal partitions. In particular, besides the microphone used for measuring sound pressure levels at 2 meters distance to the external facades, 5 microphones for measuring the indoor noise levels inside the rooms, as shown in Fig. 29 and Fig. 30 (distances are expressed in meters).

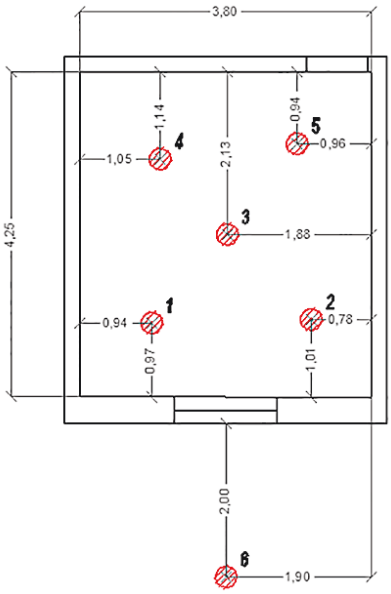


Fig. 29 Room 1 plant: distribution of indoor and outdoor microphones

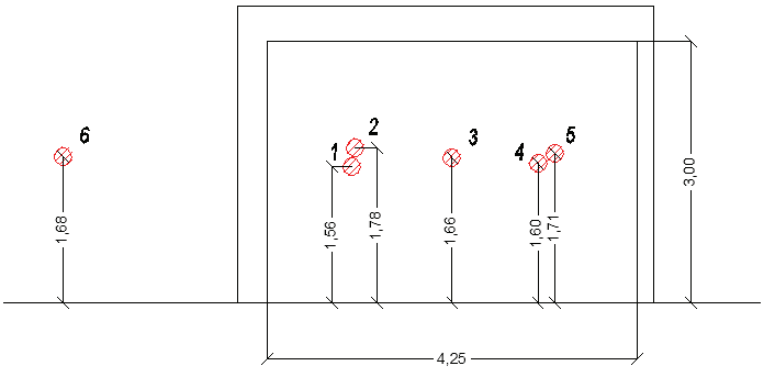


Fig. 30 Room 1 section: distribution of indoor and outdoor microphones

Noise levels measured in 5 points of each room have been averaged spatially and temporally. During the measurements campaign, building's occupants were asked to stay outside their home and the service equipment were switched off, in order to assume that the indoor sound environment was mainly due to the sound coming from outside. Background noise was more than 10 dB lower than measured noise levels, hence, results presented are reported without any correction to background noise [108].

Table 7 shows the measured values indoor noise levels and the acoustic class of each room. Therefore, the graphical comparison between the acoustic class of the rooms obtained from indirect and direct measurement of indoor sound pressure levels is shown in Fig. 31.

Room	Room use	Measured indoor L_{Aeq} [dB (A)]	Class
1	Bedroom	41	E
2	Bedroom	40	D
3	Living room	39	C
4	Bedroom	36	D
5	Bedroom	36	D
6	Bedroom	35	C
7	Kitchen	35	A

Table 7 Measured quantities for each room

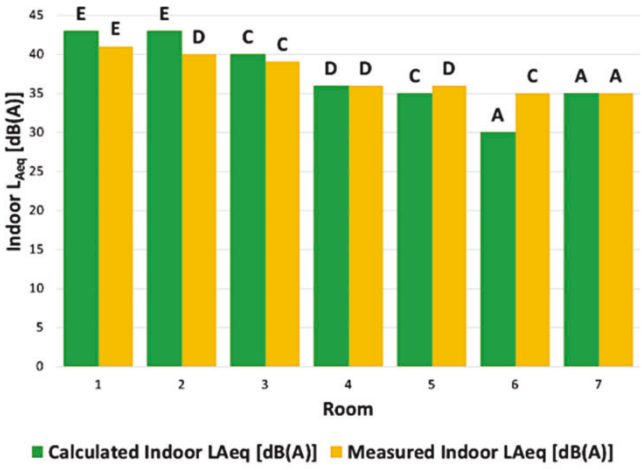


Fig. 31 Comparison between room acoustic classes obtained from indirect and direct measurement of L_{Aeq} [dB(A)]

Indoor noise levels evaluated through indirect and direct measurement differ between them for several reasons. As first, reverberation time in the calculation model used to evaluate the indoor noise level was assumed to be equal to the reference value (0,5 s). However, reverberation time in some rooms could be different from 0.5 s and this could lead to different

values indoor noise levels. A study on the sensitivity of the calculation model to reverberation time is discussed in chapter 5 and it demonstrates that the model is sensitive to that input variable. In addition, the accuracy of the adopted model of the standard EN ISO 12354 Part 3 depends on several factors: the correct estimation of input data (e.g. the assumed and estimated sound reduction index of windows and wall), the fitting of the analysed case into the models, elements and building type, shape and geometries, etc. Moreover, the highest indoor noise levels measured, for example, in rooms 5 and 6, could be due to other sounds coming from the adjacent apartments (e.g. impact sounds), which are not considered in the calculation model. All these factors contribute to increase the uncertainty associated to the estimation of indoor sound pressure levels.

Finally, the "As-is" *KPI* obtained from direct measured has been calculated and the result is 52% (Class C). The latter value can be easily compared with the "As-is" *KPI* evaluated from the calculated indoor sound pressure levels already described in 4.1.2.2, which is equal to 49 % (Class C). From these results, it can be stated that the Combined mode results suitable for the assessment of building acoustic comfort, even considering the assumptions made (windows and wall sound reduction index and reverberation time approximations) and the uncertainty due to the simplified calculation model proposed by the standard [63].

4.1.4 Application for building renovation and "What-if" *KPIs* calculation

Two retrofit solutions that enhance building envelope sound insulation have been supposed in order to evaluate different retrofitting scenarios to improve noise protection against external noise. The wall presents high sound insulation performance and the weakest part of the building is represented by the windows. Thus, retrofit interventions should be concentrated on these ones. Anyway, since thermal and energy efficiency analyses were required for other studies, even an insulation intervention of external wall was simulated. The resulting "What-if" KPIs were calculated and compared with the "As-is" *KPI* (Table 8).

- Scenario 1: Addition of external wall insulation (polystyrene insulation layer), 50 mm thickness.
- Scenario 2: Windows replacement with double insulated glazed (4+4 mm), coating, filled with argon (R_w = 42 dB).

OUTPUTS	SCENARIO 1	SCENARIO 2
"As-is" KPI [%]	49	
Pre-retrofit Class	C	
"What-if" KPI [%]	49	100
Post-retrofit Class	C	A

Table 8 "As-is" and "What-if" KPIs comparison for each scenario

The results of this study show that a crucial improvement of acoustic comfort is gained through the refurbishment of the transparent elements of the envelope. Generally, openings are the weakest part of the building envelope; hence the overall façade sound insulation is due to the windows. In particular, from Table 8, it is possible to note that applying external wall insulation is not convenient from an acoustic point of view, because the acoustic *KPI* does not improve**.** For what concern the second scenario, the replacement of windows increases significantly the acoustic comfort of the building. Replacing windows with best-performing and expensive ones (e.g. acoustic double insulated glazing, 4+8 mm, coating, filled with argon, R_w = 54 dB) is useless, because high level of acoustic comfort is obtained also with less expensive systems.

4.1.5 User subjective response: calculation of the "Socio-acoustic" *KPI*

In order to provide a validation of the reliability of calculated *KPIs* (see 4.1.2.2 and 4.1.3), the human acoustic perception has been taken into account by calculation the "Socio-acoustic" *KPI* through the procedure described in 3.2. Then, the objective and subjective *KPIs* have been compared each other. Below, the results of the subjective data and the calculation procedure of the "Socio-acoustic" *KPI* is reported in detail.

The survey was filled by 5 occupants of the building, that are 23 - 26 years of age. According to Fig. 25, the investigated rooms are 7. The questionnaire has been filled by each one for each room bordering to the external environment. Therefore, the total number of the questionnaires was 35. Results of questionnaires are illustrated in Table 9 – Table 15. To each answer, a score representative of the level of the acoustic comfort is associated, according to Table 2 and Fig. 8.

ROOM 1							
User	**Quest. 1**	**Score**	**Quest. 2**	**Score**	**Quest. 3**	**Score**	**User mean vote**
Stefano	Very bad level	1	Very high	1	Absolutely required	1	1
Nicola	Very bad level	1	Very high	1	Absolutely required	1	1
Lorenzo	Bad level	2	High	2	Required	2	2
Andrea	Bad level	2	High	1	Required	2	2.5
Davide	Acceptable level	3	Acceptable	3	Suggested	3	3
						Room mean vote	**1.9**

Table 9 Results of questionnaire for room 1

ROOM 2							
User	**Quest. 1**	**Score**	**Quest. 2**	**Score**	**Quest. 3**	**Score**	**User mean vote**
Stefano	Very bad level	1	Very high	1	Absolutely required	1	1
Nicola	Very bad level	1	Very high	1	Absolutely required	1	1
Lorenzo	Very bad level	1	High	2	Required	2	1.7
Andrea	Bad level	2	High	2	Required	2	2
Davide	Bad level	2	High	2	Suggested	3	2.3
						Room mean vote	**1.6**

Table 10 Results of questionnaire for room 2

ROOM 3							
User	**Quest. 1**	**Score**	**Quest. 2**	**Score**	**Quest. 3**	**Score**	**User mean vote**
Stefano	Bad level	2	High	2	Required	2	2
Nicola	Bad level	2	High	2	Required	2	2
Lorenzo	Bad level	2	High	2	Required	2	2
Andrea	Acceptable level	3	Acceptable	3	Suggested	3	3
Davide	Acceptable level	3	Acceptable	3	Suggested	3	3
						Room mean vote	**2.4**

Table 11 Results of questionnaire for room 3

ROOM 4							
User	**Quest. 1**	**Score**	**Quest. 2**	**Score**	**Quest. 3**	**Score**	**User mean vote**
Stefano	Bad level	2	High	2	Required	2	2
Nicola	Bad level	2	High	2	Required	2	2
Lorenzo	Bad level	2	High	2	Suggested	3	2.3
Andrea	Bad level	2	High	2	Suggested	3	2.3
Davide	Bad level	2	High	2	Suggested	3	2.3
						Room mean vote	**2.2**

Table 12 Results of questionnaire for room 4

ROOM 5							
User	**Quest. 1**	**Score**	**Quest. 2**	**Score**	**Quest. 3**	**Score**	**User mean vote**
Stefano	Bad level	2	High	2	Required	2	2
Nicola	Bad level	2	High	2	Required	2	2
Lorenzo	Acceptable level	3	Acceptable	3	Suggested	3	3
Andrea	Acceptable level	3	Acceptable	3	Suggested	3	3
Davide	Acceptable level	3	Acceptable	3	Suggested	3	3
						Room mean vote	**2.6**

Table 13 Results of questionnaire for room 5

ROOM 6							
User	**Quest. 1**	**Score**	**Quest. 2**	**Score**	**Quest. 3**	**Score**	**User mean vote**
Stefano	Acceptable level	3	Acceptable	3	Suggested	3	3
Nicola	Acceptable level	3	Acceptable	3	Suggested	3	3
Lorenzo	Good level	4	Low	4	Not required	4	4
Andrea	Good level	4	Low	4	Not required	4	4
Davide	Good level	4	Low	4	Not required	4	4
						Room mean vote	**3.6**

Table 14 Results of questionnaire for room 6

ROOM 7							
User	**Quest. 1**	**Score**	**Quest. 2**	**Score**	**Quest. 3**	**Score**	**User mean vote**
Stefano	Good level	4	Low	4	Not required	4	4
Nicola	Good level	4	Low	4	Not required	4	4
Lorenzo	High level	5	Very low	5	Not required	4	4.6
Lorenzo	High level	5	Very low	5	Not required	4	4.6
Davide	High level	5	Very low	5	Totally useless	5	5
					Room mean vote		**4.4**

Table 15 Results of questionnaire for room 7

Once collected and processed the results of the survey, according to the procedure already explained in 4.1.2.2, the last step has been performed, calculating the "Socio-acoustic" *KPI*, according to Eq. 18. Geometrical data concerning the investigated rooms are collected in Table 4. The obtained "Socio-acoustic" *KPI* is 2.7, that, through a linear interpolation, is equal to 54 %. According to Table 3, the correspondent acoustic class is C: "Acceptable level of building acoustic comfort".

Finally, the three *KPIs* obtained through the different models of the soft-sensor system for the acoustic comfort assessment have been compared each other. Obviously, since the interview has been performed for the "As-is" configuration, in order to assess the necessity of the renovation from the users' point of view, "As-is" *KPIs* obtained from the Combined and Premium Mode have been used for the comparison.

As-is *KPI* – "Combined" mode [%]	**Building class**	**As-is *KPI* – "Premium" mode [%]**	**Building class**	**"Socio-acoustic" *KPI* [%]**	**Building class**
49	C	52	C	54	C

Table 16 Objective and subjective *KPIs* comparison

The subjective investigation confirms the results obtained with both the soft-sensor systems for the acoustic comfort measurement, which use measured and simulated data. Moreover, the occupants stated that external noise is not the main source of sound that interferes with the activities inside building, since major noise disturbance is due to the near apartment (from results of question number 4).

4.2 Case study 2: Bókay School in Budapest (Hungary)

The soft-sensor approach has been applied to the Bókay Primary School, that is a NewTREND project's Demo Case.

"Advanced" and "Premium" modes have been applied and the results compared in terms of *KPIs*. An accurate data collection process has been performed, making use of the Data Manager Tool of NewTREND platform. Since the BIM model was available for the project demonstrator, geometrical data (surfaces and dimensions) concerning rooms and elements (wall, windows), spatial information, material properties, etc. have been gained through the IFC files of the BIM model and sent directly to the soft-sensor, without any user action, thanks to the integration of the acoustic simulator into the NewTREND platform. In addition, a measurement campaign has been carried out, in collaboration with ABUD consultancy firm, (which is part of the NewTREND consortium) with the purpose to measure the indoor sound pressure levels within the rooms for the Premium mode acoustic comfort analysis.

Finally, a renovation intervention has been supposed and the relative improvement in terms of acoustic comfort has been simulated. The intervention simulated in the design stage has been applied in the building and a new measurement campaign has been performed, with the purpose the measure directly the improvement of the indoor sound pressure level. both showing the improvement of the acoustic comfort.

4.2.1 Building description

The school is situated in an urban area and it faces to a one-lane road, where average/low speed is achieved. No industries, railway or airports are located close to the analysed building; road traffic noise is the main noise source which annoys the students. High levels of noise can cause several negative health effects especially for younger children; for that reason, retrofitting interventions needs. The building has high operational costs and mostly the high heating energy demand is responsible for it. Therefore, the reduction of heating energy demand is required. This is planned to be achieved with the insulation of facades and the replacement of current, out-dated doors and windows.

Originally the primary school building was a two-storey building; in the 1980s a 3rd floor was built upon it with a steeper pitched roof structure (Fig. 32). The building has brick walls. The original exterior wall structure (ground floor + 1st floor walls) is a 70 cm thick traditional solid wall structure with small-sized brick wall. The extension (2nd floor) has narrower exterior walls, equal to 50 cm. None façade-insulation interventions have been applied until now. At the North - East and North - West street facades looking the street and at the façade of the interior courtyard, the windows were replaced partially few years ago. Double-glazing plastic windows replaced the outdated traditional wooden windows. In the inner side facades there are still outdated windows. Replacing them is essential as they are not only in poor condition but also dangerous for the user well-being. It is also advised from an energetic aspect. For that reason, the retrofit project of the school provides that the old wooden windows will be replaced by plastic windows with 3-layered glazing, with Argon gas between the layers.

Fig. 32 Bókay Primary School frontal views

Since the data collection stage and the measurement campaign are highly time-cost spending, only three representative classrooms (highlighted in blue, Fig. 33) were object of the acoustic comfort analysis. Once the improvement in these classrooms due to the intervention has evaluated through the soft-sensor, the retrofit interventions will be carried out in the remaining part of the school.

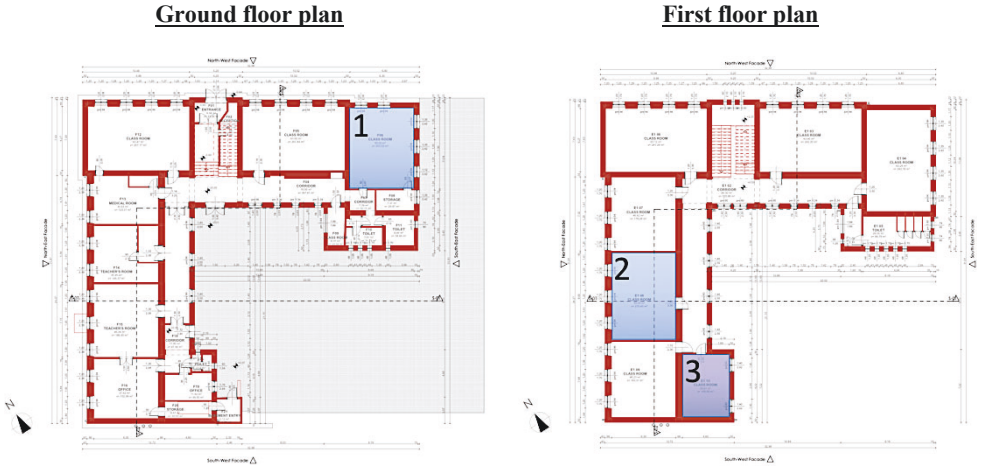


Fig. 33 Bókay Primary School plans

4.2.2 "Advanced" mode

The soft-sensor for the "Advanced" mode allows to measure the acoustic comfort using simulated input data. In particular, the external noise climate and the façade sound insulation performance have been simulated, starting from a data collection process. Required information have been collected manually, through the Data Manager Tool of the NewTREND platform (see 3.4.2.1).

The data collection for the "Advanced" mode is based on the gathering of each data required for the external noise source characterization and modelling, of all the physical features necessary for the building envelope insulation simulation and of the general building information required by the analytical models. A monitoring campaign has been performed during the different time bands of several days a week, with the purpose to investigate the light and heavy vehicles mean flux and the mean driving speed. Then, these data have been used as inputs on the soft-sensor to calculate the external sound pressure levels. Even additional data of the façades and the facades' elements identification have been done manually through the acoustic data entry. Input data required for the Advanced mode are listed in Appendix B. In Table 17, pre-retrofit scenario's features were summarized. Since in room 1 and 2 the outdated wooden windows have been replaced few years ago with double-glazed plastic windows, the critical room, where the acoustic comfort conditions are inadequate, is represented by the classroom 3, characterized by old windows.

Room	Room floor	Windows typology	Wall typology
1	Ground floor	Double-glazing plastic windows	70 cm brick wall structure
2	First floor	Double-glazing plastic windows	70 cm brick wall structure
3	First floor	**Single-glazing plastic windows**	70 cm brick wall structure

Table 17 Pre-retrofit scenario's features

When all the required data were collected, the soft-sensor for the "Advance" mode has been applied. Table 18 and Table 19 show the results of the soft-sensor for the acoustic comfort assessment for the Advanced Mode. Indoor sound pressure levels in each room have been calculated according to Eq. 16. Differently for what concerns case study 1, in which the reverberation time has been assumed equal to 0,5 s, in this analysis the quantity has been measured directly, for the purpose explained below (in 4.2.4). For that reason, in order to get more accurate results, the reverberation times measured values have been used as input of the indoor sound pressure level calculation model. The evaluated *KPI* is representative only of the three analyzed rooms.

Room	Calculated outdoor L_{Aeq} [dB (A)]	Calculated indoor L_{Aeq} [dB (A)]	Class
1	63	39	C
2	60	40	C
3	50	43	D

Table 18 Advanced mode pre-retrofit room acoustic class assignment

Building KPI [%]	Building class	Building message	L_{int} critical room [dB(A)]	Critical room class	Critical room message
56	C	Acceptable level of building acoustic comfort	43	D	Bad level of room acoustic comfort

Table 19 Advanced mode – pre-retrofit *KPI* calculation

As already said, the post-retrofit scenario consists in the replacement of the old windows of classroom 3, with 3-layered glazing plastic windows with Argon gas between the layers (R_w=39 dB) (Table 20).

Room	Room floor	Windows typology	Wall typology
1	Ground floor	Double-glazing plastic windows	70 cm brick wall structure
2	First floor	Double-glazing plastic windows	70 cm brick wall structure
3	First floor	**3-layered plastic windows**	70 cm brick wall structure

Table 20 Post-retrofit scenario's features

A new acoustic comfort assessment post-retrofitting has been carried out, calculating the *KPI* (Table 21).

Building KPI [%]	Building class	Building message	L_{int} critical room [dB(A)]	Critical room class	Critical room message
61	C	Acceptable level of building acoustic comfort	32	A	Hight level of room acoustic comfort

Table 21 Advanced mode – post-retrofit *KPI* calculation

The renovation intervention has led to an improvement of the indoor sound pressure level, and consequently, of the room acoustic class (from D to A) but not to a *KPI* improvement such as to change the building class. If the retrofitting would be applied in all the classrooms, in particular those one having outdated wooden windows, the building KPI would increase still further such as to jump in a better acoustic class. To better show this result, for the classroom 3, a partial *KPI* has been calculated, before and after retrofitting, as representative of all the buildings' classroom.

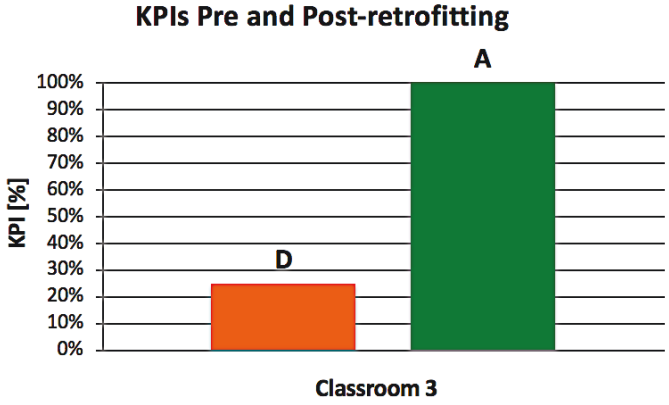


Fig. 34 Advance mode - Comparison between pre and post-retrofitting *KPIs*

Thanks to the replacement of the windows, the partial *KPI* change from 25% (pre-retrofit) to 100% (post-retrofit). Hence, the retrofit solution appears suitable and it is reasonable to extend the intervention to the totality of the outdated windows of the building.

4.2.3 "Premium" mode

School has reached the post-retrofitting stage in May 2018, when the school was closed for summer holidays. This permitted execution of the acoustic measurements, since the school was empty, and it has been possible to measure only the indoor noise due to the

external noise sources. Acoustic measurements were performed only in the same three representative rooms of the building. The indoor sound pressure levels have been measured at different time of the day and different position in each classroom, then it is averaged over the time and the space. As first, the measurement campaign has been performed before the windows replacement in room 3, obtaining the following results:

Room	Measured indoor L_{Aeq} [dB (A)]	Class
1	40	C
2	38	C
3	41	D

Table 22 Premium mode pre-retrofit room acoustic class assignment

Building KPI [%]	Building class	Building message	L_{int} critical room [dB(A)]	Critical room class	Critical room message
45	C	Acceptable level of building acoustic comfort	41	D	Bad level of room acoustic comfort

Table 23 Premium mode – pre-retrofit *KPI* calculation

After the windows replacement, measurements have been carried out only in room 3, since the other two classrooms were not change.

Building KPI [%]	Building class	Building message	L_{int} critical room [dB(A)]	Critical room class	Critical room message
61	C	Acceptable level of building acoustic comfort	30	A	Hight level of room acoustic comfort

Table 24 Premium mode – post-retrofit *KPI* calculation

The indoor sound pressure level measured in room 3 is reduced considerably, thanks to the major acoustic insulation of the building envelope due to the high performing 3-layred plastic windows. The scale-leap is from D (Bad level of room acoustic comfort) to A (High level of room acoustic comfort). Since nothing has been changed in the other classrooms (no improvements on the facades nor the windows), the *KPI* value is increased, but not enough

to improve the building acoustic class. Anyway, “Premium” mode has shown the same qualitative results of the “Advanced” mode, even if some discrepancies appear due to the input quantities estimations and assumptions.

4.2.4 Reverberation time measurement

In order to assess if the high internal sound pressure levels of the analyzed rooms depend also to other acoustic problems, a further investigation concerning the reverberation time has been performed. The reverberation time within the three classrooms has been measured, using the interrupted noise method, as described in ISO 3382-2 [34] in order to use these values in the acoustic comfort simulation for the “Advanced” mode. The measured reverberation time values at the middle frequencies (500 Hz) inside the classrooms are summarized in the following table:

Room	Reverberation time [s]
1	1.5
2	0.9
3	1

Table 25 Measured reverberation time

From results emerges that the measured values are higher than the recommended ones for reverberation time inside classrooms (ideally, a reverberation time in the range of 0.4-0.6 seconds should be guarantee for classrooms) [111]. Hence, further interventions aiming at improving the acoustic comfort in classrooms are those ones able to reduce the reverberation time. A correct reverberation time value inside a classroom improve learning efficiency for pupils and work conditions for teachers and reduce noise levels, thus the comfort of everyone increases. The best strategy is to move some of the absorption from the ceiling to the walls and keep the middle of the ceiling hard to reflect the lectures’ voice toward the back of the classroom. Half absorptive and half reflective ceiling can be built with a standard ceiling grid, by placing acoustical ceiling tiles around the perimeter of the ceiling and gypsum board panels in the center of the grid. The ceiling can be shaped over the teachers’ location at the front of the room, to reflect more sound to the back of the room. In addition, absorptive materials on the walls should be placed (e.g. fabric-covered glass fiber panels). Usually, classrooms are filled with hard surfaces: desk and plastic chairs, hard flooring. For that reason, the noise levels can be reduced by soften up hard surface. For example, the sound absorption will be improved by upgrading to upholstered chairs. In addition, curtains or blinds at the windows will help to absorb the sound within the classroom, helping also to protect against the sound coming from outside. Hard flooring is usually very used in classrooms, and it is very poor at absorbing noise and it is a major contributing factor to high background noise levels within classrooms. For that reason, adding thin carpeting to the floors (e.g. cushion-backed carpet tiles) reduce reverberation time, improving the general acoustic comfort of the classroom.

CHAPTER 5
SENSITIVITY AND UNCERTAINTY ANALYSES

As already stated in this research, the acoustic comfort is an indirect measure, which depends on several parameters. The uncertainty level of the acoustic comfort measure depends on the combination of the uncertainties of each input variables.

The sensitivity analysis (SA) has the purpose to evaluate the most critical variables, providing a measure of how much is the contribution of each input parameter to the calculated deviation of the output. For that reason, in this research, a SA aims to analyze the deviation of the adopted indoor sound pressure level evaluation model, identifying the final reliability. In addition, identifying the most influencing parameters is important to highlight which one of them has to be considered carefully before applying the soft-sensor methodology for the acoustic comfort measurement.

Since the indoor sound pressure level can be calculated according to different input data configurations, separated analyses have been carried out. Depending on the availability of budget and time to spend for measurements and of existing input data, different are the ways used to evaluate the indoor sound pressure levels, from which ones the acoustic *KPI* is then calculated. For that reason, three different configurations have been presented (see Fig. 37, Fig. 39, Fig. 41) and, for each one, a sensitivity analysis has been carried out. In particular, data which can change in each configuration are those one related to the external noise evaluation, that can be carried out:

- Trough simulation of outdoor noise in front of each room façade, knowing and assuming external noise sources features (flux of light and heavy vehicles, velocity flux, etc.): Advanced Mode;
- Through acoustic data provided by the municipality, i.e. strategic noise mapping: Advanced Mode;
- Through direct measurement of external noise in front of each room façade: Combined Mode.

Therefore, the SA analyses performed in this research have dual functions:

1. To calculate the indoor sound pressure level deviation of each soft-sensor configuration;
2. To evaluate quantitatively how the uncertainty of the output is distributed between different sources of variation in the calculation model inputs [112].
3. To identify the best input data configuration, which minimize the uncertainty of critical input variables, providing the lowest deviation of the indoor sound pressure level.

Finally, using the best identified configuration, an uncertainty analysis of the soft-sensing methodology has been performed, by spreading the uncertainty related to each input parameter into the *KPI* calculation model. The uncertainty of the *KPI* depends on the accuracy of the internal sound pressure levels, measured directly or indirectly, in each room of the building bordering to the external environment. Then, the accuracy of the *KPI* impacts

on the building acoustic class assignment, which guides the designer during the selection of the best retrofitting solution.

5.1 Sensitivity analysis by Monte Carlo method

The sensitivity analysis has the purpose to study how the uncertainty of the mathematical model's output can be apportioned, qualitatively or quantitatively, to different sources of variation in the model's inputs. Uncertainties are related to the input data entering in the indoor sound pressure level calculation model, as explained in 0. Input perturbation are performed using the Monte Carlo method, according to [119], [113].

The basic principle of the Monte Carlo theory is to perturb the calculation model by assigning a distribution to the inputs variables and then evaluating the sensitivity of the model to its inputs and the output variation. Input perturbations are performed using the Monte Carlo simulation, as shown in Fig. 35. The output variation due to each perturbed input variable, or combination of more of them, is evaluated, starting from a reference condition. Then, in order to define the critical parameters, the influence of all variables is studied, by means of sensitivity indices [112]. The potential of the sensitivity analysis with the Monte Carlo method is to perturb all the parameters at the same time, considering all the possible combinations.

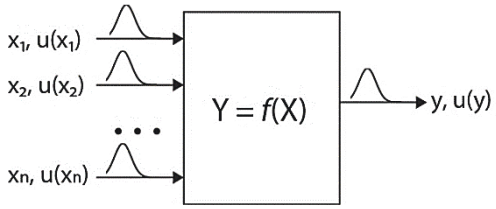


Fig. 35 Generic scheme of the Monte Carlo approach

The Monte Carlo simulation requires assumptions on the distribution function of the observed variables and the explanation of the relationships among the variables involved. The principal elements of the technique can be described as follow (Fig. 35):

- *Parameters*: input defined by the decision-maker, hence controllable.
- *Input variables*: input variables which depends on events not under decision-makers' control.
- *Output variable*: variable representative of the simulation result; in that specific case, it is the indoor sound pressure level.
- *Model*: mathematical equation (functions of input variables) which define the relation of the output with the input parameters and variables.

The method is based on the fact that a direct analytical solution of the problem, that allows to directly specify the link of the output to be obtained with the input data, can be too expensive or even impossible. Hence, the problem is solved numerically, by producing a

sufficiently high number, N, of possible combinations of the values that input variables can assume and then calculating their output on the basis of the model equations. To build up each of the N combinations is randomly generated a value for each input variable, according to the specified probability distribution and respecting the correlations between variables. By repeating the process N times (with N sufficiently "large" to allow statistically reliable results, e.g. $N = 10^4$), it is possible to obtain N independent values of the output variable, which therefore represent a sample of the possible values assumed by the output.

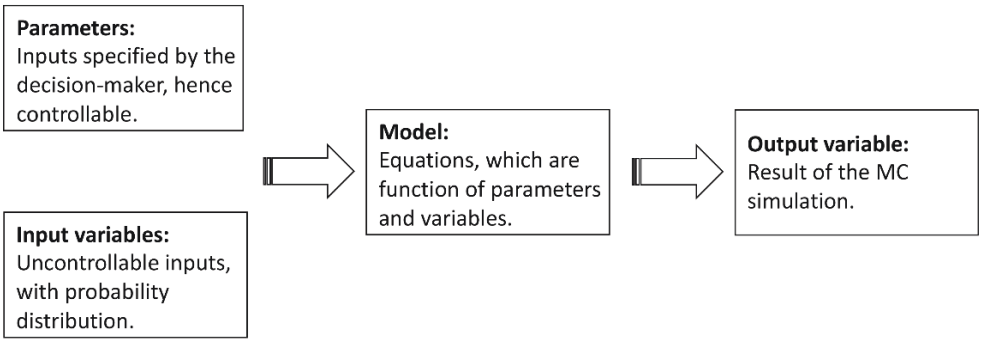


Fig. 36 Elements of Monte Carlo simulation

The generic procedure for analyzing perturbation and sensitivity of the input variables are:

a. *Identification of input parameters and variables*: interested data, i.e. the critical elements on which the indoor sound pressure level depends, are identified. Although one of the points of force of the MC simulation is allowing the inclusion in the model of a large number of parameters to represent the complexity of reality, the most appropriate trade-off between accuracy and implementation simplicity should be sought. Therefore, it is appropriate to select only the variables that are really relevant for the analysis.
b. *Model definition*: the mathematical equations that allow to determine the output variable (i.e. indoor sound pressure level) are expressed, as a function of the input variables. Also, in that case, the right balance between representativeness and simplicity of the model is required. Steps a and b represent the most critical aspects of the procedure, because the quality of the result depend on them.
c. *Probability distribution assignment*: the probability distribution of each input variable is specified, based on the assigned deviation. The distribution can be assigned based on quantitative data or it can be assigned in a subjective way by the decision maker, possibly through the consultation of experts with appropriate methods.
d. *Simulation setting*: at this point it has to be defined the plan of the tests, setting the number of iterations to be performed, establishing the appropriate way to reproduce numerically in the calculator the statistical functions of the input variables, implementing the algorithms for generating pseudo-random numbers, etc. It becomes therefore possible to carry out the planned simulations and obtain the sample of the values assumed by the output variable. The output variable is a random variable; through the Monte Carlo

simulation, an analytical formulation is not obtained, but a sample of values whose frequency makes it possible to derive an approximate indication of the probability distribution of this variable. Furthermore, by increasing the number of simulations, a larger sample and therefore greater precision and accuracy is obtained. In other words, as the number of iterations increases, there is a convergence of the output towards the values that would be analytically "exact" [114], [115].

The procedure applied in this research is consisted in:

1. Calculation of the reference condition feeding the calculation model;
2. Definition of a distribution for each input;
3. Generation of the random distribution of all parameters under investigation: data are randomly sampled form the distributions and provided as input for the indoor sound pressure level model, generating a random sample of possible combinations, at least, 10^4 values, of the input variables, which yield to a stable convergence of data;
4. Perturbation of the model giving as input the random distribution of one parameter and keeping equal to the reference condition the others.
   To each input parameter, a perturbation in function of its standard deviation has been assigned, calculated as following:

$$\delta(x_i) = k\sigma_{x_i} \quad \text{Eq. 19}$$

   Where $\delta(x_i)$ is the variability of the input parameter x_i, k is the coverage factor and σ_{x_i} is the standard deviation of the input parameter x_i. Considering a coverage factor equal to 2, which guarantees that the 95 % of the indoor sound pressure level values are in this range, it is possible to obtain the output uncertainty.
5. Calculation of the output variance (V_{x_i}) due to the perturbation given in point 3;
6. Repetition of points 4-5 for all the parameters under investigation;
7. Perturbation of the model with all the parameters at the same time and calculate the total variance of the output (V_{tot});
8. Calculation of the first order sensitivity indexes (S_i) with variance-based method [119]:

$$S_i = \frac{V_{x_i}}{V_{tot}} \quad \text{Eq. 20}$$

   Where the variance values of the output are gained through the Monte Carlo simulation. The sensitivity index of each given input parameter x_i is the fractional contribution to the total variance of the output [112]. In the performed analysis, the calculation is implemented considering all the input parameters uncorrelated and the sum of all the indices equal to one. Thus, each index can be represented as a percentage of the total variance of the indoor sound pressure level. Higher the index, higher the impact on the output variation.
   The total or combined variance is perceived as the sum of the estimated variances related to the output obtained from each x_i perturbation [113], [115]. The uncertainty of the model is calculated as the standard deviation of the vector generated at point 3. The standard deviation of the input variables calculated with the sensitivity analysis represents the uncertainty of the final output due to the uncertainty of the input parameters of the

models. Considering a coverage factor (k) equal to 2, which guarantees that the 95 % of the values are in this range, is possible to obtain the estimated uncertainty.

5.2 Sensitivity analysis of the soft-sensor

The soft-sensor system for measuring the acoustic comfort includes a MC library to treat inputs data and analyze the output. The output of the analysis is provided as the quantification of the impact of each input on the indoor sound pressure level.

Sensitivity analyses have been carried out for the case study explained in 4.1. Anyway, the results, even if applied to other buildings, would be qualitatively the same (as proved through other performed analyses concerning other case studies). As already explained in chapter 3, the soft-sensor allows to assess the acoustic comfort starting from the measurement or the prediction of the internal noise. Since the direct measurement of indoor sound pressure level is affected only by the sensors' uncertainty, it is reasonable to state that the greatest source of uncertainty is attributable to the prediction of the noise levels, which depends on different input data. The variable data are related to the external noise evaluation. From the SA it is possible to deduce the optimal input data configuration able to minimize the uncertainty in the prediction of indoor noise level.

Following, the results of the application of the SA on three different input data configurations for indoor noise level evaluation are shown.

The first input data configuration is shown in Fig. 37 and it is characterized by input data required for the simulation of the outdoor noise in front of each room façade, based on the assumptions concerning the road features (flux of light and heavy vehicles, velocity flux, etc.). As stated in chapter 4, the assumptions (e.g. reverberation time equal to 0,5 s) and estimations (e.g. sound reduction index of elements, light and heavy vehicles flux, vehicles velocity, etc.) made, affect the accuracy of the internal sound pressure levels calculation. Input parameters investigated by the sensitivity analysis are (Fig. 37):

- Sound reduction index of wall (dB);
- Sound reduction index of window (dB);
- Road distance (m);
- Vehicles velocity (km/h);
- Light vehicles flux (veh/time);
- Heavy vehicles flux (veh/ time);
- Reverberation time (s).

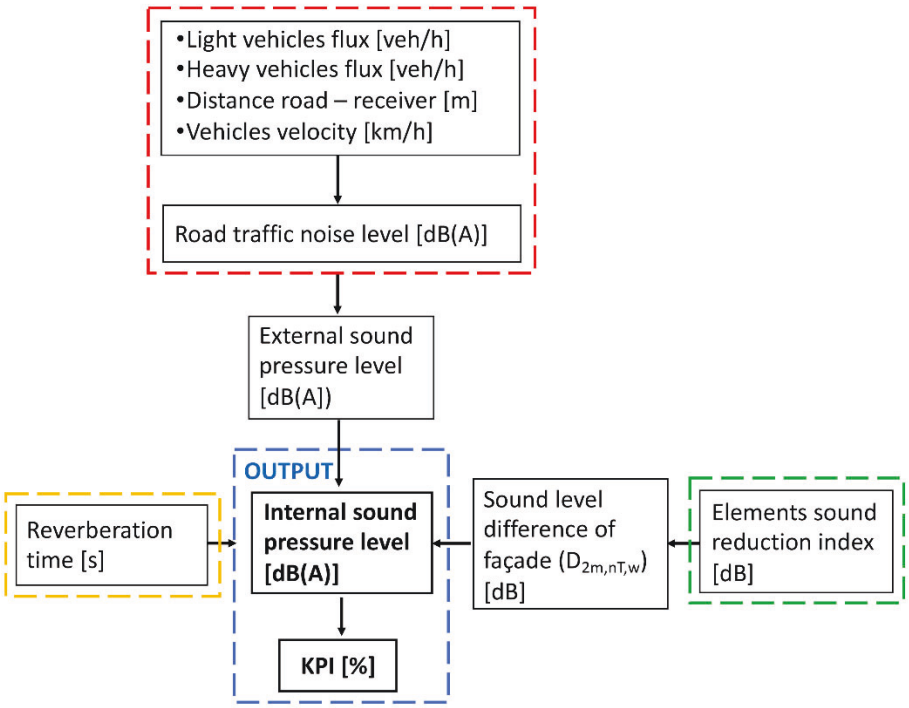


Fig. 37 Input-output scheme of configuration 1

Distributions assigned to each input variable are summarized in Table 27. The uncertainty assigned to each variable derives from several considerations. Concerning the reverberation time, it has been supposed that the quantity assumes only values higher than the reference value (0.5 s). As a matter of fact, furnished rooms having volume above 50 m^3 and without any sound optimization systems have an average reverberation time close to 0,7 s [116]. Hence, a uniform perturbation has been assigned, considering 0,6 s as reference value and an uncertainty equal to 0.1 s (0.6 s $\pm$ 0.1 s). Since the sound reduction index of wall structure was not available from technical documents, it has been calculated according to the analytical formula of EN ISO 12354 Part 1 [74] which uses the mass for unit area of the wall as input data. However, in literature, there are other predictive methods, such as mathematical formula of German Institute for Standardization (DIN) [117], Austrian Standards Institute (ÖNORM) [118], etc., that can be used for estimating the sound reduction index of wall. Thus, the wall sound reduction index has been calculated with these analytical methods, obtaining a variation of the results of $\pm$ 3 dB between them, that has been used as the uncertainty assigned to R_w. Also, for windows, the uncertainty is related to the estimation of the R_w. Windows of the case study are aged, and they are made of 3 mm single glazed with wood frame. They do not present any air sealing systems and efficient joints. Thus, an uncertainty of $\pm$ 2 dB has been supposed. Concerning the other contributors to the final uncertainty, a monitoring campaign has been performed during the different time bands of several days a

week, with the purpose to investigate the light and heavy vehicles mean flux and the mean driving speed. It has been observed that during the peak-hours of the day, traffic conditions do not change significantly. Data concerning the "noisiest" situation (when more traffic was observed) have been used as inputs on the soft-sensor to calculate the external sound pressure levels. In the following table (Table 26), some collected data for 20 minutes acquisition time are reported. From this sample results that the difference between the maximum and the minimum number of light vehicles is 29 and between the maximum and the minimum number of heavy vehicles is 9. The other acquired data fluctuate between these limits. For that reason, ± 29 [veh/time] and ± 9 [veh/time] are the uncertainties supposed for light and heavy vehicles number.

Monitoring time [hh:mm]	**Light vehicles [veh/time]**	**Heavy vehicles [veh/time]**
08:30 – 08:50	152	**6**
08:50 – 09:10	**158**	10
09:10 – 09:30	148	11
11:00 – 11:20	147	12
11:20 – 11:50	145	9
13:00 – 13:20	**129**	7
13:20 – 13:40	155	8
13:40 – 14:00	143	11
14:30 – 15:00	157	9
15:00 – 15:20	155	**15**
15:20 – 15:40	153	10

Table 26 Light and heavy vehicles flux monitoring

Concerning the vehicles velocity, it has been observed that, since the road is very congested, is approximate to 40 km/h, although the Italian regulation imposes the limits of 50 km/h for urban road. Hence, un uncertainty equal to ± 20 km/h has been adding to the vehicle's velocity reference value. Finally, the distance between the middle of the road, where it is assumed that vehicles pass, and the receiver at two meters in front of the façade has been deduced, measuring the horizontal distance between the road and the building and then using trigonometric formulas. For that reason, considering a disadvantageous situation where an error of 1 m has been committed in measuring both horizontal distance between the middle of the road and the building and also vertical distance between the base of the building and the receiver, an uncertainty equal to 1 m has been supposed.

Sensitivity coefficients have been calculated using the already mentioned variance-based approach [119]. The sensitivity indexes, one for each input variable, are calculated and shown as percentage and the sum of all indexes is equal to 100%. Analysis of results is reported in Table 27 and Fig. 38. The output of the sensitivity analysis can be displayed as a pie chart so to facilitate the interpretation of the variability budget breakdown. As shown in Fig. 38, each parameter presents a percentage of impact on the overall indicator's deviation, i.e. the indoor sound pressure level. Sensitivity indices highlight the weight of windows sound reduction index uncertainty (48.2 %) and also the high influence of the uncertainty related to data

required for the external noise simulation on the whole method. In particular, the sum of sensitivity indices concerning the quantities related to the external noise is equal to 42.1 %. The total deviation of the the indoor sound pressure level calculated, through the sensitivity analysis, for the first input data configuration is equal to ± 3 dB (A).

Input variable	Distribution	Uncertainty	Sensitivity Index [%]
R_w wall	Uniform	± 3 dB	$5.4 * 10^{-8}$
R_w windows	Uniform	± 2 dB	48.2
Road distance	Uniform	± 1 m	1.2
Vehicles velocity [km/h]	Uniform	± 20 km/h	22.8
Light vehicles flux [veh/time]	Uniform	± 29 veh/time	0.5
Heavy vehicles flux [veh/time]	Uniform	± 9 veh/time	17.6
T_{60}	Uniform	± 0.1 s	9.6

Table 27 Input-output data for configuration 1

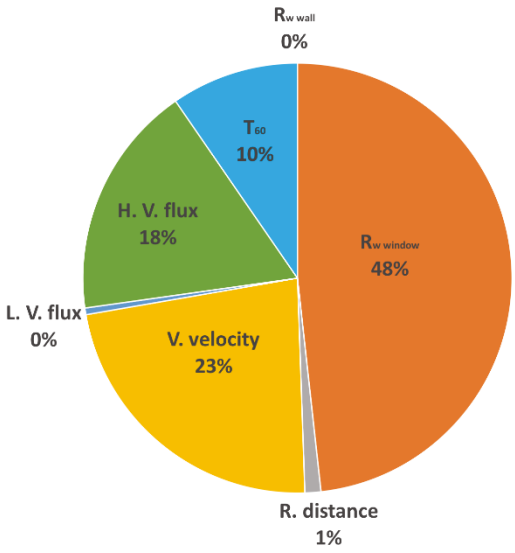


Fig. 38 Sensitivity indices for each parameter contribution for configuration 1

Sensitivity analyses have been performed for the other two soft-sensor configurations with the purpose to evaluate if the different entering data minimize the uncertainty on the output deviation.

The second input data configuration is shown in Fig. 39. The calculation of the indoor sound pressure level in each room bordering to the outside depends on the strategic noise mapping values provided by the municipality. This way to operate is the most cheap and fast,

if the sound maps are available, but, at the same time, it presents the largest uncertainty. Input parameters investigated by the sensitivity analysis are:

- Sound reduction index of wall (dB);
- Sound reduction index of window (dB);
- Strategic noise mapping value [dB(A)];
- Reverberation time (s).

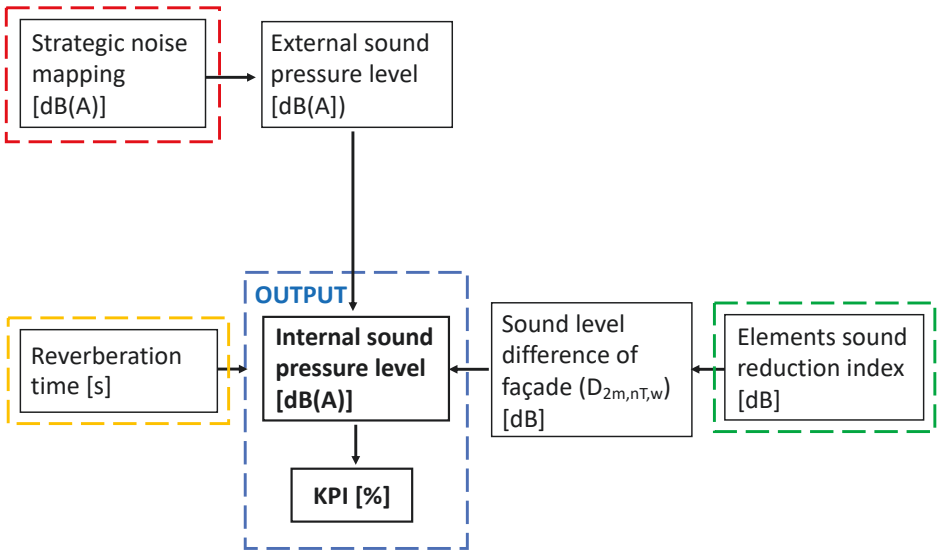


Fig. 39 Input-output scheme of configuration 2

The distributions assigned to the reverberation time and to the features of building elements are still the same. The uncertainty related to the strategic noise mapping values influence totally the determination of the internal sound pressure level in the exposed room. Usually, the strategic noise mappings do not consider the real noise at 2 meters in front of each room façade, as real measurements or simulation models developed in this research did. They are do not provide an exact value for each exposed room façade, but only a representative value of the entire area. For that reason, since the noise level can be different between a façade and another one, an uncertainty equal to ± 5 dB(A) has been assigned to the reference value of the strategic noise mapping.

Analysis of results is reported in Table 28 and Fig. 39.

Sensitivity index concerning the quantity related to the external noise is equal to 85.3 %, which is the mainly cause of the output uncertainty. The total deviation of the the indoor sound pressure level calculated for the second input data configuration is equal to ± 5.9 dB (A). Hence, the use of the strategic noise mapping values provided by the municipality, it is particularly disadvantage in terms of final uncertainty of the output, although the soft-sensor application is easier and cheaper to perform. The high value of the uncertainty calculated do

not promises good results if it would be spread on the KPI calculation model, hence the soft-sensor for the acoustic comfort measurement would be not a reliable tool to support the decision making.

Input variable	Distribution	Uncertainty	Sensitivity Index [%]
R_w wall	Uniform	$\pm$ 3 dB	$2.1 * 10^{-8}$
R_w windows	Uniform	$\pm$ 2 dB	12.2
Strategic noise mapping	Uniform	$\pm$ 5 dB(A)	85.3
T_{60}	Uniform	$\pm$ 0.1 s	2.4

Table 28 Input-output data for configuration 2

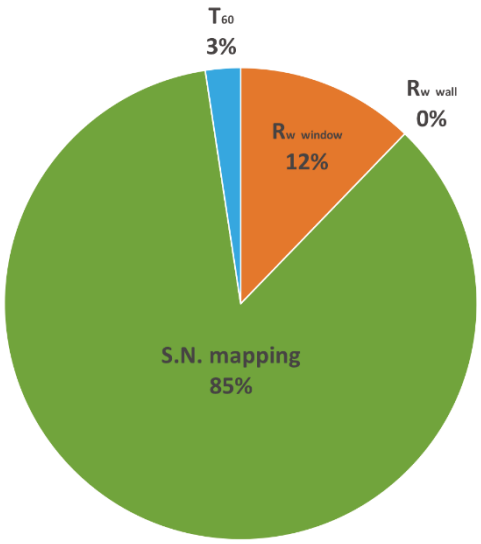


Fig. 40 Sensitivity indices for each parameter contribution for configuration 2
The third input data configuration is shown in

Fig. 41. In this case, the external noise is evaluated through direct measurements in front of each room façade, with Class 1 sensors. Input parameters investigated by the sensitivity analysis are:

- Sound reduction index of wall (dB);
- Sound reduction index of window (dB);
- Measurement sensor (dB);
- Reverberation time (s).

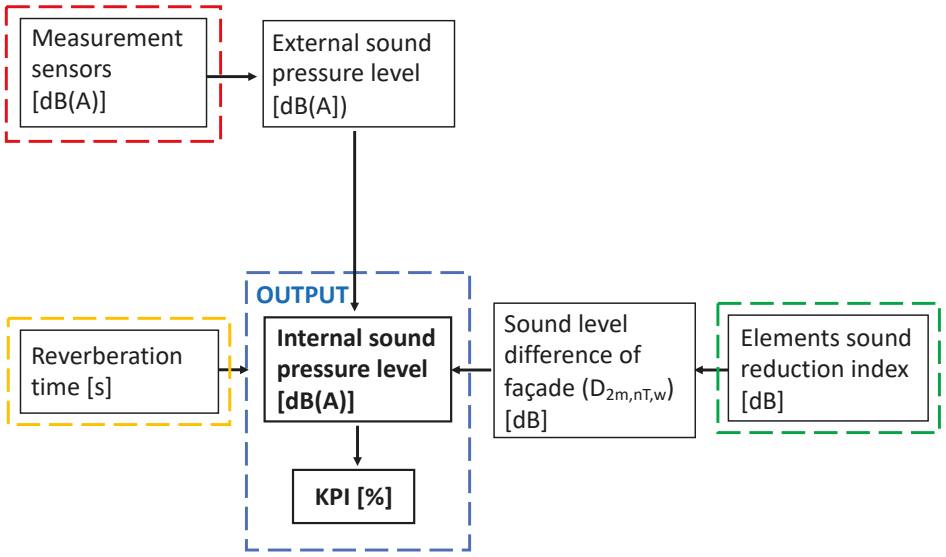


Fig. 41 Input-output scheme of configuration 3

Perturbations assigned to each input variable are summarized in Table 29. Even in the third configuration, the uniform distributions assigned to the reverberation time and to the features of building elements are the same of the ones explained in paragraph 5. The other factor in the final uncertainty evaluation concerns the measurement sensors. Since the microphone's frequency response complies with the IEC 61672-1 [65] Class 1 tolerances at reference conditions (according to sensor datasheet), sensors uncertainty has been assumed equal to the tolerance limits for Class 1: ± 1.1 dB. A normal distribution is assigned for that variable.

Analysis of results is reported in Table 29 and Fig. 42.

The sensitivity analysis provides a total deviation of ± 2.5 dB (A) on the indoor sound pressure level, mainly caused by windows sound reduction index (43.6 %) and microphones (41.5 %) uncertainties, followed by the reverberation time. Using these input data, the uncertainty on the variables required for the external noise evaluation is minimized and also the final deviation decreases.

Input variable	Distribution	Uncertainty	Sensitivity Index [%]
R_w wall	Uniform	$\pm$ 3 dB	$6.4 * 10^{-8}$
R_w windows	Uniform	$\pm$ 2 dB	43.6
Measurement sensor	Normal	$\pm$ 1.1 dB	41.5
T_{60}	Uniform	$\pm$ 0.1 s	14.9

Table 29 Input-output data for configuration 3

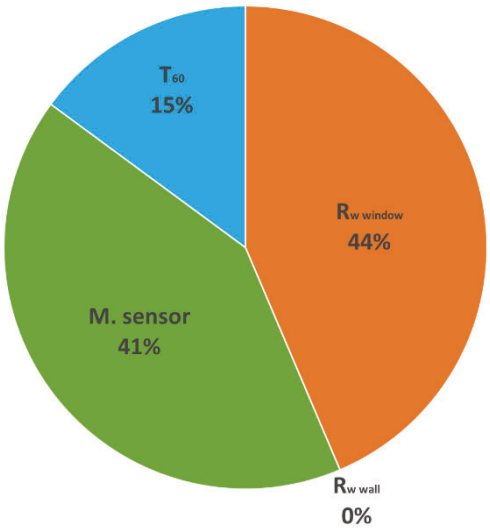


Fig. 42 Sensitivity indices for each parameter contribution for configuration 3

In Fig. 43, the comparison between the different input data configurations is shown through the deviation values of the indoor sound pressure level. For each model, related error is reported above each bar.

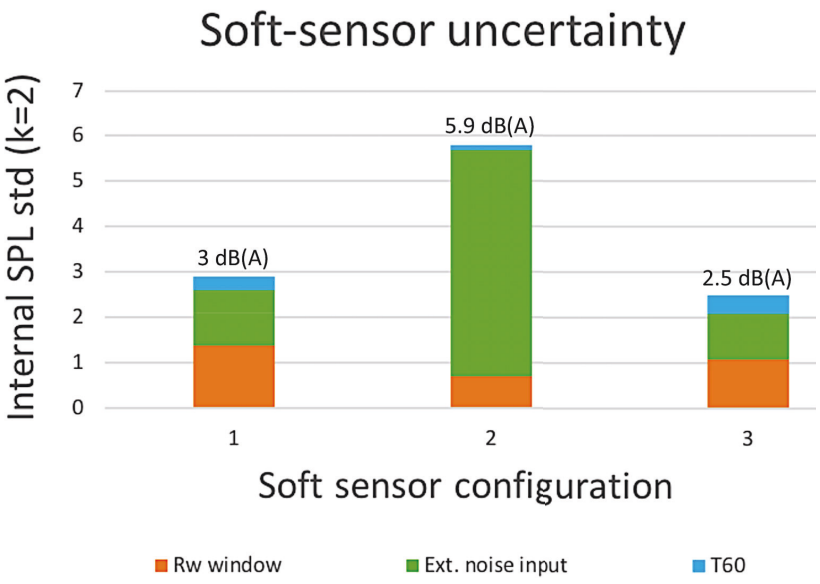


Fig. 43 Input uncertainty on total uncertainty of each configuration (k=2)

From the Monte Carlo analysis it has possible to deduce that the most suitable input data configuration able to minimize the deviation of the final output is the third one, where the external noise in front of each façade of the building is measured. In fact, the performed analyses have shown that the most critical input variables which lead to a bigger error in the determination of the indoor sound pressure level are those one related to the simulation or the assumption through strategic noise mapping of the external sound pressure levels. Instead, when direct measurements of the outside noise are performed, the error due to the external noise component is lower since it is only associated to the microphones. From these considerations, it is possible to state that the optimal methodology to provide an indirect measurement of the internal sound pressure levels is that one in which the external noise is directly measured, and the facades acoustic performance are simulated. Of course, the level of accuracy of the calculation method (Eq. 16) depends also on the correct definition of other input quantities: reverberation time, that it has been assumed from literatures and also sound reduction indices of wall and windows. Anyway, the results lead to lower sensitivity indices than the external noise ones, at least for configuration 1 and 2.

5.3 Impact of uncertainty on the decision-making process

This paragraph aims to define the level of confidence of the soft-sensor methodology, in order to guide the decision-making process for the retrofit selection [120]. An uncertainty analysis is thus performed to assess with statistical robustness how reliable is the outcome of the soft-sensor for measuring the acoustic comfort, given a certain level of uncertainty of the input data. For this analysis, the third input data configuration has been used, given that it provides the lowest uncertainty value (± 2.5 dB(A) on the indoor sound pressure level).

Since the decision-making process for the retrofit design is based on the calculation of the KPI, its accuracy has to be analyzed to determine the reliability of the soft-sensor system. For that reason, the indoor sound pressure level uncertainty (± 2.5 dB(A)) has been propagated on the *KPI* calculation model, which impacts on the decision-making process of the best retrofit solution. The uncertainty analysis is performed applying Monte Carlo simulation to the *KPI* calculation model. As already said, each input of the indoor sound pressure level calculation model is perturbed assigning distribution equal to the uncertainty of that input. The obtained deviation of the resulting indoor sound pressure level is then used to perturb the *KPI* calculation formula and derive its uncertainty, that is equal to $\pm$ 11 %. This result allows to define confidence intervals of the *KPI* scale. If the *KPI* is very close to the extremity of the lower and upper limits of the scale (called “Confident zone”), the error associated to the *KPI* does not lead to a class shift. The same is for the *KPI* values close to the middle of each class limit. For the other *KPI* values, which are included in the “Grey zone”, the uncertainty could lead to the shift in the higher or lower acoustic class respect to the estimated one (see Fig. 44).

Hence, the decision regarding the retrofit solution has to be taken carefully, because of the consequent risk of shifting to another acoustic class.

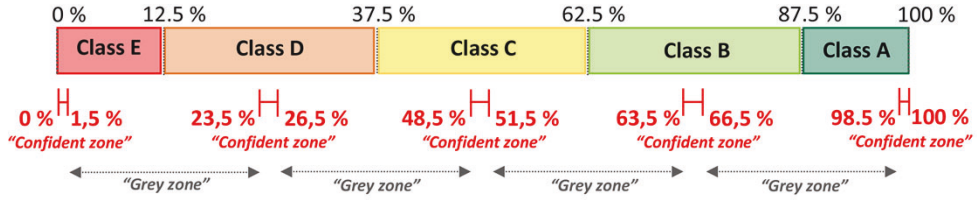


Fig. 44 "Confident" and "Grey" zones in the KPI classification scale

In order to reduce the issue, it is necessary to minimize the uncertainty of the input quantities that have been recognized as critical through the Monte Carlo simulation (see Table 29). As a matter of fact, improving the accuracy in the evaluation of the indoor sound pressure level, which depends on the accuracy of the analyzed input parameters, reduces the uncertainty on the *KPI*. In particular, results from Monte Carlo analysis have revealed that windows sound reduction index is the most influencing variable: it is necessary minimizing as far as possible the uncertainty on the R_w estimation. If this data is not available from project documents because the building is aged, as in the analyzed case study, windows sound reduction index can be measured in situ, with the consequent increase of resources needed to apply the procedure. On the contrary, since the wall sound reduction index is an insensitive variable, it is reasonable estimating this quantity, without waste of resources to determine accurately R_w. In addition, the sensor accuracy represents also a critical variable for the calculation model. For that reason, performing measurements with more accurate sensors will reduce measurement errors due to the use of low-cost systems. Finally, the reverberation time represents also a sensitive variable for the calculation model; for that reason, this quantity should be simulated, according to predictive methods [79], or measured [34] in each room, in order to provide more accurate results. On the basis of these considerations, uncertainties related to input variables may lead to risks of incorrect decision-making.

5.4 Use of the subjective response to support the decision-making

Results of the sensitivity and uncertainty analyses carried out for the case study of Viale della Vittoria have shown that, although minimizing the errors pertaining to the input data, often the designer has to face the problem of the uncertainty in the decision-making process. Sometimes it happens that the *KPI* calculated through the soft-sensor is within a confidence interval ("Grey zone") such that the designer cannot assign the acoustic class accurately, because of the risk to shift in the higher or lower acoustic class respect to the estimated one (see Fig. 44). To solve the issue of the "Grey zone", the subjective analysis comes into play. As a matter of fact, the "Socio-acoustic" KPI can influence the decision-making process by providing an indicator which guides the designer during the attribution of the right acoustic class. In order to provide a practical example, let us analyse the result of application of the soft-sensor for the Combined Mode of Viale della Vittoria (section 4.1.2.2). The "As-is" KPI

evaluated from the calculated indoor sound pressure levels is equal to 49 % (Class C). If the deviation calculated with the uncertainty analysis was to be considered, the *KPI* would fluctuate between the following values: 49 % $\pm$ 11 %. The minimum value that the *KPI* could assume is 38 % (acoustic class C), while the maximum is 60 % (acoustic class C). Considering Fig. 44, the *KPI* returns in the "Confident" zone in the *KPI* classification scale. This is a favorable case, where the error associated to the *KPI* does not lead to a class shift. Suppose that the calculated *KPI* was equal to 55 % (again acoustic class C, but "Grey zone" in the *KPI* classification scale). Associating to this value the same deviation calculated with the uncertainty analysis, the *KPI* could assume as minimum value, 44 % (acoustic class C), as maximum, 66 % (acoustic class B). In order to solve the "Grey zone" problem, the "Socio-acoustic" *KPI* takes an active role in acoustic class to assignment. As a matter of fact, since the "Socio-acoustic" *KPI* calculated in 4.1.4 is equal to 54 % (acoustic class C), the designer should use this indicator to assign the more suitable acoustic class of the building, that is, in this case, class C and not B. In this way, the designer has considered the human perception, which is a fundamental component of the acoustic comfort assessment.

In this paragraph, the application of the subjective response to solve the uncertainty's issue has been presented for the assessment of building acoustic class in current state. The same evaluation procedure can be applied in the post-retrofit case, when the designer has to compare different retrofitting scenarios, taking the most suitable decision concerning the retrofit solution which improves the acoustic comfort of the building.

CHAPTER 6
CONCLUSIONS

The purpose of building is to provide a healthy and comfortable environment for occupants, since people spend about the 90% of the day indoors. In the last years researchers have focused their attention on the effects that IEQ has over occupants' comfort, including the acoustic one. Recent studies have provided evidence that the acoustic comfort is one of the most influential factors on human perception and behaviour which significantly contributes towards the regulation of their physical and psychological well-being. Despite being recognised as an important parameter, research indicates that acoustic comfort is not considered high priority in building design and rehabilitation, leading to several related issues. In addition, only few practical guidelines on how accurately and efficiently measure acoustic comfort are available. Several studies dealt the issue to measuring acoustic quality within living environment, using different measurement approaches, both subjective and objective. As a matter of fact, acoustic comfort of buildings is not represented by a unique physical quantity, that can be directly measured, but rather, depends on the combination of different physical variables, as well as subjective parameters. Therefore, it cannot be measured by means of a "direct" measurement instrument. It can be assessed indirectly through the direct measurement of some variables, the assumptions of others difficult to measure, and also, the simulation of other data, who themselves take into account measured, simulated, assumed and in-situ collected data, including subjective ones.

Basing on literature review, it is emerged the lack of a clearly defined and detailed holistic procedure, based on a scoring/rating system, for measuring the acoustic comfort of buildings. For that reason, in the presented research, an efficient soft-sensing approach for acoustic comfort measurement has been developed, which combines experimental measurements and mathematical models, and provides outputs for acoustic comfort assessment. The developed measurement procedure includes an appropriate ranking scheme for the comparison among acoustic comfort of different existing buildings, based on Key Performance Indicators. In particular, since the noise of business activities or traffic has been shown to be the main pollutants that influence the quality life and the well-being within the buildings, the acoustic comfort is assessed on the basis of the indoor equivalent sound pressure levels.

The content of this thesis is contextualized in the European project NewTREND, funded in the call "H2020- EeB-05-2015: Innovative design tools for refurbishment of buildings at district level. The developed soft-sensor system has been included within the integrated collaborative design platform of the NewTREND project for retrofit assessment. Within the NewTREND project, the soft-sensor system, with the developed *KPIs,* has provided a valid tool for assisting the decision-making in buildings' retrofitting design, ranking different renovation options. In particular, two *KPIs* have been developed, which operate in a complementary manner, with the purpose to measure acoustic comfort though an "objective" and a "subjective" assessment. The first *KPI* is based on objective assessment of acoustic quantities, while the second *KPI* is representative of the subjective occupants' rating and it is used to validate the "objective *KPI*" and to solve the uncertainty's issue. Concerning, the "objective" *KPI*, the soft-sensor system provides three configurations for assessing the acoustic comfort of a building, which depends on the different input parameters: "Advanced", "Combined" and "Premium". All three modes provide the same output; however, they differ

in accuracy and cost. “Advanced” mode uses designed and simulated data as its main data sources: it requires high demand on data, hence the *KPI* is subjected to high uncertainty, due to the assumption and estimations made and the uncertainty caused by the adoption of simplified calculation models used to predict the acoustic quantities. “Combined” mode uses as inputs of the soft-sensor system both simulated and measured data: the external noise in is based on experimental measurements, while the building envelope performance is simulated. The accuracy depends on inputted data, both measured and collected. The mode requires the involvement of a specialist to carry out the external noise measurement campaign and this conducts to higher cost, even if the external noise evaluation accuracy improved since it depends only on the measurement sensors error. “Premium” mode requires on site-measured equivalent indoor sound pressure levels as its main data. The direct measure of the indoor noise levels allows to calculate directly the acoustic *KPI*, without any simulation process of quantities. Concerning the “subjective *KPI*”, it is based on the real user perception and it has the purpose to provide a validation of the reliability of the “objective *KPI*”. Since the evaluation scale is the same, the “subjective” and “objective *KPIs*” can be compared each other. The “Socio-acoustic” *KPI* aims to support the decision-making, considering the subjective response.

Within the NewTREND project, the developed soft-sensor for the acoustic comfort measurement of buildings intends to support the decision-making process in retrofitting design, by comparing different renovation scenarios. For that reason, the soft sensor allows, as first, to evaluate the current state of building acoustic comfort, through the “As-is” *KPI*. Afterwards, different potential renovation scenarios are simulated and the “What-if” *KPIs* are assessed and compared between each other. The feasibility of the developed approach for measuring the acoustic comfort and supporting the decision-making process has been shown through the application to real buildings, making use measured and simulated data.

A significant case study is represented by an historical residential building in Ancona. “Combined” and “Premium” modes have been applied and the results compared. The “As-is” *KPI* obtained from “Combined” mode is equal to 49 %, which returns in acoustic class C (“Acceptable level of building acoustic comfort”). Whereas, the “As-is” *KPI* obtained from direct measured of indoor sound pressure levels is 52% (Class C). The values can be easily compared, and it is possible to state that the “Combined” mode results suitable for the assessment of building acoustic comfort, even considering the assumptions made and the uncertainty due to the simplified calculation model proposed by the standard. Then, two retrofit solutions that enhance building envelope sound insulation have been supposed in order to evaluate different retrofitting scenarios to improve noise protection against external noise and related “What-if” *KPIs* calculated. Significant improvement has been obtained (What-if” *KPI* = 100 %) with the old windows replacement with double insulated glazed (4+4 mm), coating, filled with argon. In addition, in order to provide a validation of the reliability of “objective *KPIs*”, the human acoustic perception has been taken into account by calculation the “subjective *KPI*”, which results equal to 54 %. The subjective investigation confirms the results obtained with the both soft-sensor systems for the acoustic comfort measurement, which use measured and simulated data.

As already stated in this research, the acoustic comfort is an indirect measure, which depends on a several parameters. The uncertainty level of the acoustic comfort measure depends on the combination of the uncertainties of each input variables. For that reason, uncertainty and sensitivity analyses, through the Monte Carlo simulation, have been

performed, in order to point out the most critical variables of the presented soft-sensor. The sensitivity analysis has also highlighted the optimal input data configuration able to minimize the uncertainty in the prediction of indoor noise level. The best configuration is those one in which is that one in which the internal sound pressure levels is obtained through the external noise experimental measurement and the facades acoustic performance simulation.

The impact of uncertainty on the decision-making process has been analyzed for the best configuration identified. The result is that the uncertainty on the *KPI* can achieve the $\pm$ 11 %. This turned out to provide confidence levels to be considered when using the acoustic *KPI* to make decision on the building retrofit. This because the *KPI* value can fall within a "Grey zone", or rather a non-confident zone in which the acoustic class is not defined for sure.

The uncertainty analysis highlighted the need of reducing the soft-sensing uncertainties, otherwise the buildings classification could be uncertain and compromise the decision-making process.

More accurate investigations and the use of more higher quality hardware-sensors can increase resources spent; however, since only in certain conditions a shift in the acoustic category can take place because of uncertainty associated to the model, cost-benefit and timing analyses have to be considered as well.

Nomenclature

KPI: Key Performance Indicator (-)
$D_{2m,nT,w}$: Weighted standardized sound level difference of façade (dB)
$D_{2m,nT}$: Standardised level difference of façade (dB)
R'_w: Apparent weighted sound reduction index of the façade (dB)
V: Volume of the receiving room (m^3),
T_0: Reference reverberation time (s)
S: Total area of the façade as seen from the inside (m^2)
ΔL_{fs}: Level difference due to façade shape (dB)
R_w: Sound reduction index (dB)
A_0: Reference equivalent sound absorption area (10 m^2)
$D_{n,e,wi}D_{n,e,wi}$: Weighted normalized sound level difference of small element (dB)
R_{wi}: Sound reduction index of element (dB)
S_i: Area of the elements and of the small elements of the façade (m^2)
K: Correction due to the contribution of flanking sound transmission (dB)
L_2: Average sound pressure level in the receiving room (dB),
$L_{1,2m}$: Average sound pressure level at 2 m in front of the room façade (dB)
T: Reverberation time in the receiving room (s)
L_{Aeq}: Indoor A-weighted equivalent sound pressure level (dB(A))
A_i: Reference floor area of each room bordering to the external environment i (m^2)
RA_i: Score assigned to each room i (-)
A_{tot}: Total reference floor area of all the rooms bordering to the external environment *i* (m^2)
RF: Room Façade (-)
x_i: Input parameter
$\delta(x_i)$: Variability of the input parameter
k: Coverage factor (-)
σ_{xi}: Standard deviation of the input parameter

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Appendix A:
"Socio-acoustic" questionnaires

Survey purpose:

[INSTITUTE NAME] has been commissioned by [COMMISSIONER AUTHORITY] to investigate if the building in [ADDRESS] has satisfactory acoustic comfort conditions with regards of the external noise or if it needs to be renovated.

Your answers to the attached questionnaire help us defining appropriate retrofitting interventions, with respect of Country regulations and analysis of cost-efficient solutions to use.

We thank you for taking your time. Your responses will be treated confidentially, and the results and personal data are only used for this investigation and will not be used for any other scope.

Personal data:

- **Room / office / classroom, etc. identification (i.e. the number that identify the space in the building):**

- **Your name:**

- **You are**:
  - ◇ Student
  - ◇ Teacher
  - ◇ Office worker
  - ◇ Dwelling inhabitant
  - ◇ Other….

How to fill out the questions:

During the questionnaire, you can find several main questions and the related answer scale. Make an X in the box with you answer. If you wrong, fill the box in black and mark a new X in the new box. Choose the answer which expresses better your opinion. In case of a

residential apartment, repeat the questionnaire in each room bordering to the external environment. In case of a school, office, etc. fill the questionnaire only for the room that you are used to attend.

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1. Thinking about the period in which you have lived/worked/frequented this area until now, how do you find the acoustic comfort of the room?

   ◇ High level
   ◇ Good level
   ◇ Acceptable level
   ◇ Bad level
   ◇ Very bad level

2. Thinking about the period in which you have lived/worked/frequented this area until now, how do you perceive the noise generated from external noise sources (road traffic, railway traffic, industrial activities, etc.) when you are inside the room with closed windows?

   ◇ Very high
   ◇ High
   ◇ Acceptable
   ◇ Low
   ◇ Very low

3. How much do you think that building envelope interventions (e.g. increasing wall and windows sound insulation) are necessary in order to improve your acoustic comfort inside building?

   ◇ Absolutely required
   ◇ Required
   ◇ Suggested
   ◇ Not required
   ◇ Totally useless

4. Is the noise generated from external noise sources the main source of sound that interfered with your activities inside building?

   ◇ Extremely yes
   ◇ Mainly yes
   ◇ Acceptable level
   ◇ Bad level

◇ Very bad level

5. How sensitive are you to noise in general?

◇ Very sensitive
◇ Sensitive
◇ Normal sensitive
◇ Low sensitive
◇ Unsensitive

Appendix B:
"Advanced" mode attributes for acoustic data collection

Attribute	Attribute Value	Unit	Level
Building		[-]	Building
Storey		[-]	Building
Room		[-]	Room
Façade		[-]	Facade
Land use category	Countryside Residential area Urban area		Building
Floor	Ground floor First floor Second floor ….		Room
End use	Bedroom Living room Hotel bedroom Classroom Nursery school Office Conference room Hospital Retail shop		Room
Strategic noise mapping value		[dB]	Facade
Road presence	Yes No		Facade
Road type	Extra-urban motorway Urban motorway Extra-urban high-speed highway Urban high-speed highway Urban road Local road		Facade
Road slope	Flat Up Down		Facade
Road surface	Porous surface Smooth asphalt Cement concrete and corrugated asphalt Paving gravels/stones		Facade

Road traffic	Continuous fluid Not-differentiated pulsed		Facade
Railway station presence	Yes No		Facade
Railway station type	Large station Medium station Small station		Facade
Building presence between façade and railway	Yes No		Facade
Industry presence	Yes No		Facade
Industry type	Process industry Construction works Chemical industry Multi-purpose transfer Warehousing Shipyard Refineries Wind turbines (production surface) Rubble / scrap breakers Concrete / asphalt machine Low sound emission Medium sound emission High sound emission		Facade
Other external noise source type	Garden / court /car park bordering to road / railway / industry Garden / court /car park Congested car park		Facade
Shape of façade	Type 1 Type 2 Type 3 Type 4 Type 5 Type 6 Type 7 Type 8 Type 9 Type 10		Facade
Balcony material	Plaster Soundproof plaster Wood Rough concrete Glass sheet		Facade
Balcony width		[m]	Facade
Number of façade elements		[-]	Facade

Element type	Wall Window Door Small element		Façade
Element sound reduction index (only for wall, window door)		[dB]	Façade
Element mass for unit area (only for wall, window door)		[kg/m^2]	Facade

Appendix C:
"Combined mode" attributes for acoustic data collection

Attribute	Attribute Value	Unit	Level
Building		[-]	Building
Storey		[-]	Building
Room		[-]	Room
Façade		[-]	Facade
Floor	Ground floor First floor Second floor ….		Room
End use	Bedroom Living room Hotel bedroom Classroom Nursery school Office Conference room Hospital Retail shop		Room
External equivalent sound pressure level [dB(A)]		[dB(A)]	Facade
Shape of façade	Type 1 Type 2 Type 3 Type 4 Type 5 Type 6 Type 7 Type 8 Type 9 Type 10		Facade
Balcony material	Plaster Soundproof plaster Wood Rough concrete Glass sheet		Facade
Balcony width		[m]	Facade
Number of façade elements		[-]	Facade

Element type	Wall Window Door Small element		Façade
Element sound reduction index (only for wall, window door)		[dB]	Façade
Element mass for unit area (only for wall, window door)		[kg/m^2]	Facade

Appendix D:
"Premium" mode attributes for acoustic data collection

Attribute	Attribute Value	Unit	Level
Building		[-]	Building
Storey		[-]	Building
Room		[-]	Room
Façade		[-]	Facade
End use	Bedroom Living room Hotel bedroom Classroom Nursery school Office Conference room Hospital Retail shop		Room
Internal equivalent sound pressure level [dB(A)]		[dB(A)]	Facade

Appendix E:
Technology Library

Attribute	Attribute Value	Unit	Level
Fabric opaque wall inner (polystyrene insulation layer) (k = 0.03 W/mK)	Wall inner insulation 25 mm Wall inner insulation 50 mm Wall inner insulation 100 mm	[-]	Building
Fabric opaque wall outer (polystyrene insulation layer) (k = 0.03 W/mK)	Wall outer insulation 40 mm Wall outer insulation 60 mm Wall outer insulation 80 mm Wall outer insulation 100 mm Wall outer insulation 120 mm Wall outer insulation 140 mm Wall outer insulation 160 mm Wall outer insulation 200 mm Wall outer insulation 240 mm Wall outer insulation 300 mm	[-]	Building
Fabric opaque wall cavity (cellulose blow-in insulation) (k = 0.03 W/mK)	Wall cavity insulation 25 mm Wall cavity insulation 50 mm Wall cavity insulation 100 mm	[-]	Building
Fabric opaque wall timber frame (k = 0.03 W/mK)	Wall timber frame insulation 100mm Wall timber frame insulation 200mm Wall timber frame insulation 250mm Wall timber frame insulation 300mm	[-]	Building
Fabric opaque doors (k = 0.03 W/mK)	Doors solid -> Wood door (45 mm) Doors insulated + seals -> Heavy wood door with edge sealing		Building
Fabric glazed	Windows single (U = 5 W/m^{2}K) Windows single + retrofit secondary glass (U = 3.5 W/m^{2}K) Windows double glazed (air) (U = 2.8 W/m^{2}K) Windows double glazed (gas) (U = 2.2 W/m^{2}K) Windows double glazed (gas low E) (U = 1.6 W/m^{2}K) Windows double glazed (gas low E warm edge) (U = 1.4 W/m^{2}K) Windows triple glazed (gas low E warm edge) (U = 0.8 W/m^{2}K)	[-]	Building