

Acoustical retrofit of existing residential buildings: requirements and recommendations for sound insulation between dwellings in Europe and other countries worldwide

Alonso, Alicia[1]*, Patricio, Jorge[2], Suárez, Rafael[1], Escandón, Rocío[1]

[1]Instituto Universitario de Arquitectura y Ciencias de la Construcción. Escuela Técnica Superior de Arquitectura. Universidad de Sevilla. Av Reina Mercedes 2, 41012, Seville (Spain).
[2]Laboratório Nacional de Engenharia Civil. Av do Brasil 101, 1700-066 Lisboa.

***** corresponding author: aliciaalonso@us.es

ABSTRACT

Exposure to noise is proven to have important repercussions on human comfort and health conditions. In recent decades, efforts to increase awareness among users have focused on highlighting the benefits of an appropriate acoustic indoor environment. In addition, given the significant increase in complaints about noise, the control, reduction, and limitation of sound transmission have become important issues to be considered in acoustic retrofit work in buildings. Much of the housing stock was built in a period characterized by the limitation or absence of standards, and renovation interventions should be geared towards existing buildings. However, despite the major potential to improve quality of life, only a handful of countries consider old buildings in their national Building Codes and regulations. The main aim of this work is to develop a comparative study of the acoustic requirements for indoor sound insulation between dwellings of existing buildings established in current building regulations around the world. The analysis of the documents concludes that the usual difference between requirements for new and existing buildings is 5 dB, both for airborne sound insulation and impact sound insulation. To this end, this paper provides the basis for discussion regarding future cooperation for the optimization of acoustic regulations for old buildings.

Keywords: acoustic regulations, existing buildings, acoustical retrofit, refurbishment, building renovation, indoor environmental quality.

1. INTRODUCTION

Sound or noise can be caused by a series of random and uncontrollable events, and the levels and types of noise found within dwellings have increased, causing occupants frustration and stress. Having been neglected for decades, neighbour noise is now a significant problem for both existing and new housing. In addition, the existence of shared walls in multi-unit residential buildings can have a significant impact on acoustic comfort and privacy as noise can easily be transmitted through the shared structural elements [1]. In fact, in the last 15 years, domestic complaints about noise have increased five-fold [2].

In acoustic terms, the concern of the scientific community for sound transmission control is justified by the harmful effects of noise [3], which according to the World Health Organization (WHO) can adversely impact health [4,5]. In addition, there is sufficient evidence on exposure to night noise and the risk of disease due to sleep disturbance [6]. Thus, the increasing demand and attention on this issue has promoted the analysis of regulations and guidelines [7] in order to ensure complete physical, mental, and social well-being for the occupants of dwellings, as well as improved levels of acoustic comfort.

Over the last decade, special attention has been paid to the aging of the global housing stock as a result of the deficiencies identified in existing buildings in relation to the compliance with regulatory standards. It is important to consider that knowledge about people's comfort priorities may be used as guidelines in the construction and renovation of buildings so that building occupants' satisfaction can be maximized [8]. In most countries around the world, irrespective of the climate zone, a significant percentage of housing stock was built more than 50 years ago, prior to the implementation of legal requirements, or when the values required were not as strict in some countries [9]. In this regard, having been neglected for a long time, constructive solutions used in the past are far from reaching the minimum conditions of comfort established in current standards for new dwellings.

Research on regulatory sound insulation requirements for new housing concluded that even though these legal requirements have mostly remained unchanged in the last few decades, more recently, in the face of growing concern over human health, several European countries have implemented stricter requirements [10]. Rasmussen also developed research comparing descriptors and national classification schemes in Europe and focusing on the comparison of the range of quality levels, number of quality classes, and class intervals [11,12], and Monteiro’s research provide a translation between existing and proposed harmonized descriptors based on in-situ measurements [13]. These studies contribute in some way to the to the ongoing research and the importance on the effect on adopting new harmonized descriptors and show that there was a need to harmonize the classification criteria applied for sound insulation requirements. Another documentary work, comparing the acoustic regulations of selected countries, was carried out by Machimbarrena and Rasmussen [14]. This analysis highlights the lack of regulations in several South American countries, as well as the existence of rather irregular content in European standards.

However, despite the major importance of the issue of acoustics in the current residential stock, very few studies focus on its analysis in existing buildings, and most of them focus on the evaluation of current constructive solutions. Hongisto studied a comparison between the acoustic satisfaction in residential multi-storey buildings with different constructive solutions and results suggested that when the airborne sound insulation is close to 55 dB, a value that about half of the regulations evaluated in this study consider to be within the required values, the construction type does not affect the user's satisfaction [15]. Only Rasmussen addressed the issue by analysing aspects related to sound classes for renovated housing are described in [16]. Therefore, in search of a coordinated set of descriptors, an international standard is under development by ISO TC43/SC2/WG29, and is based on the outcomes of COST Action TU0901 [17], an intergovernmental framework which aims to facilitate collaboration among the scientific community in Europe. It is also worth noting the study by Del Val, L. et al. [18], which focuses on suitability considerations aiming primarily to provide a translation equation for the individual relations between existing-proposed sound insulation descriptors.

In most cases, retrofit projects for buildings are mainly aimed at energy-saving interventions and thermal comfort is the predominant aspect studied in residential buildings [1], and always prioritised over acoustic actions even when "protection against noise" is one of the basic requirements for construction works in European regulation [19,20].

After establishing the negative effects of noise, the lack of single-factor studies that investigate the acoustic comfort as one of the four main occupant comfort aspects, and the fact that a substantial share of the residential stock is built with obsolete systems, it becomes necessary to ascertain whether the regulations of individual countries focus only on new buildings or also take older ones into consideration. Therefore, there is a need to update the acoustic conditions of indoor comfort in the existing building.

In this respect, it would be interesting to find out the different perspectives relating to acoustic regulations or whether there are any numerical requirements in place to assess noise protection for existing buildings. This study aims to fil that research gap and exposes the lack of consensus on the level of requirements, including on the evaluation parameters. It is also aiming to shed light on questions regarding acoustic retrofits, in order to find out about the verification methods when assessing the improvement of sound insulation or the proposal of suitable constructive systems and solutions in compliance with requirements. This is a complex task, especially when considering partial actions, compared to other types of actions such as energy retrofit interventions.

This work presents a comparative study of the perspectives and acoustic national requirements set out in the current legislation and Building Codes (BCs) of countries both within and outside Europe, and focusing mainly on the acoustical retrofit of existing residential buildings. This article primarily examines the regulatory framework for historic and old buildings in an attempt to develop good management strategies for retrofitting and upgrading sound insulation in existing buildings, excluding façade sound insulation and noise from service equipment.

2. THE NEED FOR BUILDING RENOVATION

2.1 The aging of housing stock

When developing major retrofits in buildings, it is important to consider the construction date of housing stock, since it provides reliable information on qualities, characteristics, and construction conditions. As stated in the previous section, building performance and health are related. Research studies even confirm that categorization of the housing stock provides information on prevalent health risks related to building characteristics that are dominant in certain periods [21]

In this regard, a study of the different construction systems that characterize the buildings within the existing stock highlights the noticeable evolution of constructive solutions for façades, whose requirements have been tightened in recent decades. However, it should be borne in mind that in some countries where legislation was introduced decades ago, the required values have undergone no significant changes.

In Europe, a substantial share of the stock is relatively old, and a large portion of these buildings does not provide users with adequate acoustic comfort conditions, partly due to poor façade insulation. In fact, this is the result of limited or no legislation on acoustic requirements. In European countries approximately 50% of the residential stock was built over 50 years ago [22], and is distributed as follows:

In northern European countries the average of dwellings built after 1970 accounts for close to 40% of the total stock [23]. Within this period, two classifications can be established: housing stock built before the Second World War (with Finland displaying the lowest percentage of stock, 10%) and the buildings constructed post-war but before the 1970s oil crisis, when Sweden built massively and reached almost 40% of the whole. Subsequently, until 1990 an average of an additional 25% of built homes was established, except in France and the Netherlands, where these dwellings accounted for more than a third of the total stock [23].

The situation is not too different in southern Europe given the extensive old housing stock. According to some studies, between 63% and 76% of the total housing stock was built prior to the implementation of regulations on energy-saving [24,25]. Italy was one of the countries with the highest percentages, while in the case of Spain, around 50% of the over 25 million residential homes were built after the Civil War. Almost 35% of these dwellings are more than 50 years old [26,27], with 85% of stock having been built prior to the implementation of the Building Code [28]. However, it is important to note the high percentage of homes built in the decade between 2000 and 2010 as during the “housing boom”, the rate of new construction soared to levels far higher than in other European countries. In Portugal, the weight of building renovation costs within the total spending of the construction sector has increased by around 34% in the last decade [29]. In this regard, a high percentage of the stock has undergone retrofits of some sort in order to meet the comfort requirements established in current standards.

In other countries such as the USA, national statistical data show that 40% of housing stock was built prior to the 1970s. This stock tends to be newer than in European countries and the average age of owner-occupied homes is 37 years [30]. In Japan, the share of old dwellings recorded is similar to that of the United States. However, it should be considered that the drastically higher housing density in Japan means that the number of dwellings per area is significantly higher [31].

Australian homes make up one of the youngest residential stock since only around 30% are older than 50 years. It should be noted that although the residential typology which has historically predominated in this country has been detached housing, usually in residential environments with lower outside noise from traffic and other sources, ‘multi-unit’ dwellings now account for 25% of the new home building stock, as this trend has picked up the pace over the course of this six-year-long new home building cycle [32].

This analysis of aging and the constructive conditions of world housing ends with the Russian Federation, where the stock can be considered fairly up-to-date compared to that in Europe. However, the low-quality construction and poor maintenance of the stock leads to generally poor comfort conditions in indoor spaces [33].

Figure 1 shows the age categorisation as the distribution expressed in percentages of the total sum of dwellings, with Spain, Europe, and the USA chosen as representative cases.

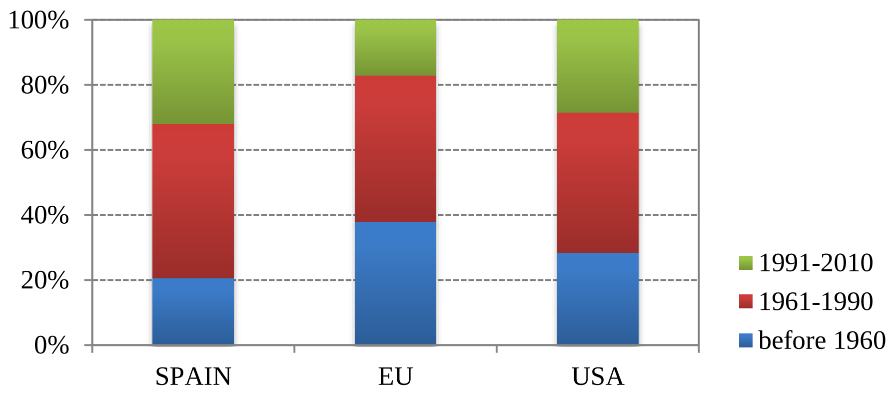

Figure 1. Age categorisation of housing stock in Spain, Europe and USA as representative cases.

Based on the data provided above, a significant part of the housing stock has been built in a context lacking building regulations. Consequently, sound insulation of existing buildings is generally far from the requirements of the new construction, being insufficient to achieve environmental comfort conditions.

2.2 Acoustic retrofit

At present, in view of growing concerns on human health and the need for building renovation to adapt all research areas to current requirements, increased attention is paid to the indoor environment of old housing stock, due to the major deficiencies in this type of building. For many years, the standards and regulations developed have typically addressed different environmental factors (energy, structure, air quality, lighting, and acoustics) separately. In this context, noteworthy is European Regulation [19] in which it is indicated that, wherever possible, uniform European methods should be laid down for establishing compliance with the basic requirements for construction works, which shall constitute the basis for the preparation of standardisation mandates and harmonised technical specifications. This document can be considered as an outstanding example of the integrated approach pursued even at an European level. However, this is not always accomplished, so that the different aspects must be combined in order to pool the efforts of different scientific communities and progress in the practical use of this information.

One of the main drawbacks is that construction activities have mainly been geared towards new buildings rather existing buildings and facilities. However, given the slow rate at which existing buildings are replaced by new ones, it has become necessary to opt for retrofits. Another significant aspect is that retrofit projects for buildings are mainly aimed at energy-saving interventions always prioritised over acoustic comfort, so that improvements of sound insulations are rarely considered in renovation projects even though the importance of noise reduction is sometimes taken into account. In this regard, certain energy-saving interventions involving passive solutions could be combined with the acoustic aspect, thus helping to improve the insulation of construction elements.

However, this begs the question of why sound insulation between dwellings in retrofitted housing is not upgraded in the same way of other qualities since “Protection against noise” is one of the basic requirements for construction works mentioned in Annex I of European regulation [19]. A possible reason for this is financial, as these measures may imply a smaller reduction in energy consumption, which in turn has economic repercussions.

Fortunately, the concept of acoustic retrofits of the housing stock is at last gaining momentum, with the increasing need to define methodologies for retrofitting while maintaining a comfortable and healthy indoor environment. Rasmussen reflects on this topic, hoping that joint efforts could help shed further light on the issue [20]. Therefore, it will be necessary to analyse interventions which contribute to more than one requirement. In fact, for the renovation of existing stock, the building codes in some countries propose strategies and interventions focusing on structures, energy, and fire protection, while acoustic retrofits are sometimes ignored.

Existing and historic buildings represent the major part of the building stock and have become the focus of particular attention due to the low annual growth rates of new construction of residential housing, around 1%. In fact, in recent years, the decrease in this rate in some countries has shown the impact of the current financial crisis in the sector [9].

Previous studies have stated retrofits should be planned and optimised for Indoor Environmental Quality (IEQ). A more systematic standards-based methodology can aid in more effective decision making to identify the issues before enhanced indoor comfort levels [34]. Based on this and the importance of ensuring acoustic comfort, as well as the improvement of quality of life in existing housing stock, architects and engineers have begun to include sound insulation and noise reduction in their designs for buildings, particularly residential ones. For the sake of clarity in this analysis, it is essential to make the distinction between “historic”, which implies that something is historically important or influential, buildings that are at least 50 years old, and “historical”, which refers to something from the past. It should be noted that in Scotland specific reference is made to the so-called "traditional buildings", which were built before 1919 and that are of ‘special’ architectural or historic interest enrich Scotland’s landscape and help chart the history of the country. The intangible heritage nature of a building greatly affects renovation work, and new difficulties emerge when historic buildings are intervened, limiting any possible acoustic upgrade interventions since there is a heritage architectural restriction, especially when it refers to the external envelope [35].

In this regard, based on the need for retrofits which can be adapted to current paradigms by avoiding the destruction of important historical elements, specialists must meet current acoustical requirements and achieve the optimum level of sound insulation in order to upgrade the quality of traditional constructive solutions [36].

3. METHODS

The analysis of the existing building stock determines that significant deficiencies can be observed in the compliance with the corresponding regulatory standards. The reason of this statement is because the regulatory requirements, before the 80s, were very lax and even non-existent, so that the constructive characteristics of the elements do not meet the current demanding parameters. The comprehensive analysis of legislation in Europe and other countries requires a special approach, so that the methodology developed includes the following elements:

- General considerations of legislation and regulatory policies together with the definition of sound descriptors and the explanation of procedures to be followed in acoustic retrofit interventions (Section 4).

- The compilation of information on the perspectives acoustic considerations and recommendations set out in the regulatory policies of European countries and worldwide. Building Codes, legislative documents, guidelines and technical handbooks were consulted (Section 5).

- Interpretation of the information about the acoustic national requirements collected based on a literature review analysis, and generally focused on identifying and comparing sound insulation requirements and descriptors (Section 6).

- Development of a detailed analysis and a discussion of the acoustical retrofit of existing residential buildings (Section 7).

- The proposal, according to different international regulations and guidelines, of general design criteria and good management strategies for retrofitting, aiming to improve the environmental comfort of existing residential stock (Section 8).

This documentary work will make it possible to identify and display the differences between countries as regards the acoustic retrofit of existing buildings, presenting remedial strategies obtained from technical handbooks on retrofitting.

4. LEGISLATIVE AND REGULATORY POLICIES FOR EXISTING BUILDINGS

Currently, regulatory policies incorporate different tendencies for existing buildings to tackle the noise issue. This is made clear not only in the different legal requirements proposed (which do not even exist for this type of building in some countries), but in the differentiation between descriptors and sound insulation indexes. Equally, when analysing the BCs and regulatory policies of different countries, it is important to note the diverse terminology, which uses terms such as “sound insulation”, “sound transmission”, “protection against noise” and “noise reduction”, as seen in these documents. This diversity, seemingly meaningless at first glance, can provide a specific approach for individual countries, as it is not the same to talk about sound insulation to guarantee adequate acoustic comfort, as to reduce the problem of noise targeting a specific cause (traffic, neighbourhood, environment, etc.).

Finally, it should be noted that retrofit interventions carried out in different countries around the world are not applied in the same way due to factors such as variable climatic environments, urban density, aging housing stock, variety of constructive solutions, and characteristics of the buildings.

4.1 Differences between sound insulation descriptors

Rasmussen and Rindel conducted an interesting work in which they analyse the legal requirements and descriptors in European regulations [9]. It is interesting to note how the main legal requirements established by countries are defined by different insulation indices, that is to say, the in situ regulatory index $D_{nT,w}$ or the laboratory index R_w. In contrast, the spectrum adaptation terms C (pink noise) and C_{tr} (road traffic noise) have been included in some cases so that the different spectra of noise sources for airborne sound insulation may be considered. Some national standards incorporate the term C_{tr} when a representative urban traffic noise is assumed as the loading noise, confirming significant differences in the descriptors and levels of each country.

The study by Rasmussen and Rindel also highlights how in recent years evaluation methods developed for sound insulation have moved away from harmonization. In order to consider all types of construction systems (light or heavyweight), it would be appropriate to extend the frequency range below 100 Hz. In addition, a series of proposed suggestions aim to help obtain a single set of harmonized indices to apply, both for airborne and impact sound insulation, together with the proposal of a common and simpler terminology, using one symbol instead of the sum of two ($D_{nT,w}$+ $C_{50\text{-}3150}$ or R'_w + $C_{50\text{-}3150}$).

As already known, in order to obtain the D_{nTw} regulatory index it is necessary to apply a conversion to the R_w parameter. Moreover, studies record different evolutions of both indices, as an increase in one of the parameters (i.e. R_w) does not necessarily imply an increase in the same proportion for the other (i.e. $D_{nT,w}$). When a noise is emitted, the real presence of indirect transmissions between constructive elements, such as internal walls and intermediate floors, becomes the main cause of the disparity of indices. This fact is justified because the descriptors between on-site and laboratory measurements cannot be directly comparable, since laboratory measurements are conducted in facilities with suppressed flanking transmissions, and this control is not possible to do during on-site measurements.

On the one hand, laboratory tests only measure the performance of the constructive solution, which means that sound insulation data of the element in question is useful in helping technicians compare and analyse one constructive system with another. However, the acoustic insulation index measured in the laboratory, expressed as R_w (dB), does not provide a real indication of the overall on-site performance of the element since it is important to also take into account the flanking sound that travel through surrounding building elements. On the other hand, on site testing includes the impact of both direct transmission and the leakage of sound through this path known as indirect transmission or flanking transmission, with test values expressed as $D_{nT,w}$ (dB). In most buildings there will always be a degree of flanking transmissions and this is why there are separate sound reduction indices for laboratory and on-site measurements. In this regard, in the case of a building with homogenous historical solutions, usually heavyweight, the value of the acoustic reduction index based on the mass law can be obtained. However, this shows that the calculation method proposed in the BC is a procedure almost impossible to apply when examining the reduction rates of the flanking transmissions [37].

All the above serves to highlight how an acoustic conditioning project for a new housing building should not be approached in the same way as an acoustic rehabilitation project in an old building. Not only must the different intervention strategies be flexible in order to adapt to the characteristics of the building, but the verification procedures and sound insulation rates should also be varied.

4.2 Procedures to be followed in acoustic retrofit interventions

The lack of information and ignorance of certain traditional solutions existing in historical buildings makes it difficult to find and adapt construction systems. Research carried out has shown the potential of enhanced options of traditional solutions which allowed acousticians to overcome the challenges posed by existing building retrofits [36].

Figure 2 shows a simplified flowchart of procedures recommended for rehabilitation interventions [38]. As can be observed, a simple process is proposed in which the noise and the sound pressure level in the room should be characterized first. Regarding one of the process stages of the flowchart, it is important to mention the important role of measurements of sound insulation as require pre-works where sound testing is undertaken before any upgrading to determine the current in-situ performance. This helps assess the technical retrofit requirements, and also importantly avoid over specification and is a more sustainable approach [2]. In addition, the existing sound insulation is tested in order to determine if the results obtained comply with current standards. Given the limitation or lack of regulations, fit is needed to adapt the traditional solutions by outlining corrective interventions and incorporating conditioning measures.

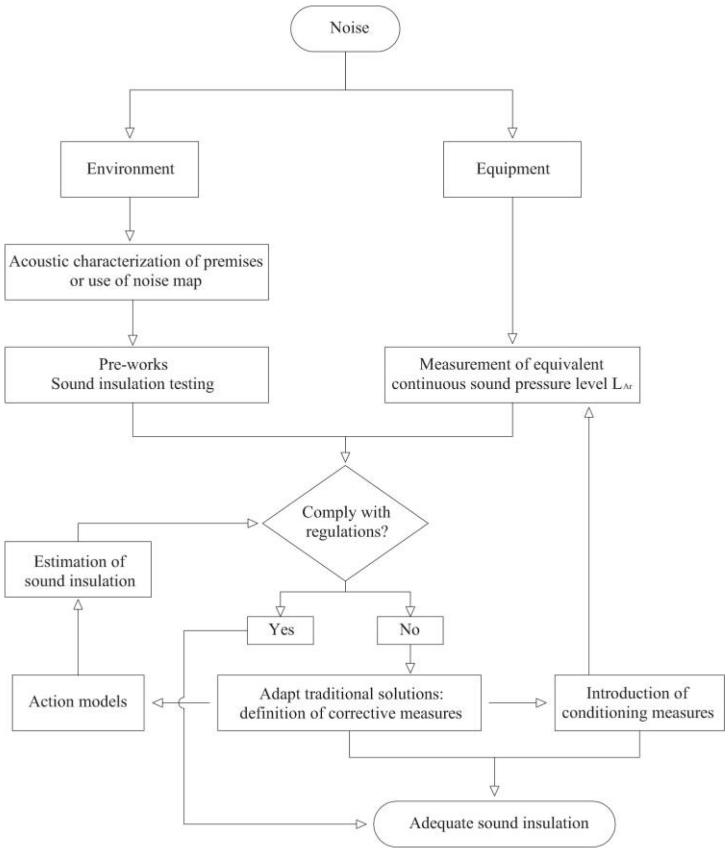

Figure 2. Sequence of recommended procedures to follow in rehabilitation interventions [38].

5. ACOUSTIC CONSIDERATIONS AND RECOMMENDATIONS WORLDWIDE

The category of existing buildings is not considered in the BC or standards of all the countries analysed in this study, as only a few of them examined noise requirements or instituted quality classes intended for renovated housing.

Existing housing buildings often undergo different alterations including change of function, extension, partial demolition, renovation, retrofitting, and simple maintenance. This type of intervention requires the adaptation to current regulations in order to improve comfort and safety conditions, not just in the acoustic field but in all others (energy, fire, structural, air quality, etc.). However, the general lack of acoustic regulatory policies for this type of building makes it difficult to find an extensive list of management and common strategies for improving acoustic performance in the residential sector.

Fortunately, as this study shows, design criteria, descriptors, indices, and limit values are provided in order to regulate or at least upgrade traditional solutions in existing stock. Some countries have implemented standards in order to fulfil acoustic requirements in old housing stock. The proposal of remedial treatments is also suggested in helpful books for technicians, based on refurbishment procedures.

5.1 Europe

Some of the main considerations of certain European countries can be summarized as below:

- France: one of the sections of the acoustic regulations document focuses on the considerations relating to existing buildings. After a previous subsection on the historical evolution of acoustic requirements, the acoustic characteristics of existing buildings are identified, along with guidelines as to when they should be considered. In residential buildings over 50 years old, any alterations to housing equipment must comply with current regulations. Required values for the façade or ceiling elements directly affected by global and important renovation works are provided in Appendix 1 of this document [39], with different parameters (location, surface area, number of air changes) conditioning the requirements.
- Ireland: the word-for-word guidance of the BC may not be appropriate in cases such as alterations or material changes in the use of existing buildings. In this regard, alternative approaches based on the stipulations of the regulations may be more appropriate [40].
- Nordic countries (Denmark, Finland, Norway, Sweden, Iceland). The existence of a Nordic Acoustic Association (NAA) for 65 years determined the decision of presenting all these countries as a single group in which considerations and requirements are very similar. Sound classification schemes were introduced in standards in these countries in order to differentiate levels of acoustic comfort. Class denotation includes different categories using letters (A to E) [41]. The levels of classification schemes are commonly associated with the limit values intended for new dwellings (generally C) and for renovated housing (generally D), which is usually less restrictive. Acoustic classification schemes could be relevant for existing housing before renovation projects by using lower classes suitable for existing housing, if available [42]. This group of countries have one quality class below regulations, moving slightly away from the original idea that classification schemes was focused on specifying better acoustic conditions than regulations. However, most of the current sound classification schemes do not present acoustic classes that are really suitable for old housing.
- Italy. A mandatory Ministry decree determines the internal acoustic requirements of new buildings and the passive acoustic requirements of buildings and their components on site, in order to reduce human exposure to noise [42]. On the other hand, sound classification schemes are introduced in standards, being the different categories expressed in Roman numerals (I to V). In this case, the levels of classification schemes are also associated with

the limit values intended for new dwellings (III) and for renovated housing (IV), which is usually less restrictive and whose class denotation is classified just below regulation values.

- Greece. As in other countries, considering that it is not a realistic option for old buildings to comply with the current standards, the need for lower class denotation arises. Different categories (*Κατηγορίας*) are therefore established (1 to 4), among which the category that is linked to the requirements of new construction (3), and with existing buildings (4).
- Portugal: the Regulation of Acoustic Requirements of Buildings [43] determines limit values for new constructions as well as for old buildings undergoing reconstruction or alteration processes. In addition, demands are stated in accordance with the type of building (residential, teaching, hospital building, etc.). As regards classification schemes, in Portugal a method for rehabilitated housing buildings is under development. This methodology has three types reserved for the new buildings, which must comply with current legal requirements, and another five types for older housing [44]. One of the most advantageous aspects of this classification system is the possibility of proposing more appropriate remedial treatments for each situation.
- Spain: heritage buildings in this country receive special consideration. In fact, there is even a law focusing on the protection of historical heritage. In this regard, there is a specific scope of application for works in existing buildings, although there are no specific requirements in terms of acoustic comfort and the compliance with the BC only applies in the case of integral rehabilitation, but not for conversions, extensions, or retrofits. However, historic buildings are exempt when adaptation works are technically unfeasible, making the adoption of alternative solutions necessary. In these cases, the scope of basic requirements is justified if the benefits of retrofit work are better or at least equal to those exposed in the BC [45].

  Technical Building Inspection is developed through the Existing Building Evaluation Report (IEE in the case of Spain initials) and is required for collective housing buildings over 50 years old. This document, recently established in Spain, includes a short section focused on the assessment of the acoustic performance of existing buildings.
- United Kingdom: in this case, different considerations are established depending on the country to which they refer.
  - On the one hand, acoustic requirements in England and Wales are specified in Approved Document E - Resistance to the passage of sound [46]. As regards existing constructions, the material change of use is the basic consideration, understood as "a change in the

purposes or circumstances for which a building is used”. This Document lists the values required for constructive elements with a separation function, such as walls, floors, or stairs.

- On the other hand, Scotland establishes that in the case of conversions, the building must meet the standard requirements, so that appropriate remedial work to the existing construction elements is implemented. There is a complete bibliography regarding the conservation and rehabilitation of buildings: a handbook for technicians focused on conversions of traditional buildings [47], or providing design proposals for upgrading conversions [1]. All conversions of existing buildings in Scotland (built after 1919) must comply with the same sound insulation standards as new build construction, except for 'Traditional Buildings'. Traditional buildings refers to those buildings built before 1919, which are often of historical context or have protected status known as 'Listed Status'. For 'traditional buildings' there is a reduced sound insulation requirement of 3dB for airborne and 2 dB for impact [48].

5.2 Other countries worldwide

A summary of the main considerations in other countries worldwide is set out below:

- Australia: like in other countries, verification methods and determination of sound insulation ratings and mandatory requirements set out in the BC, or “National Construction Code” in this case, only apply to new constructions [49]. However, although there are no specific requirements set out for existing buildings, the *Handbook of sound transmission and insulation in buildings*, a non-mandatory document, presents helpful procedures to be followed during refurbishment treatments [50]. These interventions, carried out in the acoustic retrofit process of a building, include limiting flanking paths, sealing gaps, and controlling vibrations travelling through external walls, timber floorboards, joists, beams, etc.
- South America: Argentina, Chile and Brazil are shown as a single representative sample since most of the South American population is concentrated in these three countries. In general, it is observed that the level of requirements cannot be compared to that of other countries previously examined because of the limitation or lack of requirements (both for new and existing buildings). While there are no mandatory

acoustic requirements in Argentina, the acoustic regulations in Chile and Brazil [51,52] provided lax values compared to other countries.

- USA: the International Existing Building Code [53] is a detailed BC whose requirements focus on existing buildings. The purpose of this document is to focus on repairs and other alternative approaches for conversions or extensions. However, it is striking to note that no section refers to the acoustic requirements of old buildings, thus avoiding acoustic comfort.

6. RESULTS: ACOUSTIC REQUIREMENTS WORLDWIDE

From the compilation of information set out in the regulatory policies, it is developed an interpretation of the information collected, generally focused on identifying and comparing sound insulation requirements, which are aimed at ensuring a regulatory values both in new construction and, whenever possible, in acoustic retrofit projects.

6.1 Europe

Table 1 summarizes relevant data considering the sound insulation requirements found in the current building acoustic regulations in the European countries selected.

Table 1. Relevant data considering the sound insulation requirements of European countries and the corresponding class.

EUROPE						
Country		**New buildings**		**Existing buildings**		**BC or Standard**
		Airb. Sound (dB)	**Imp. Sound (dB)**	**Airb. Sound (dB)**	**Imp. Sound (dB)**	
Austria (AT)		$D_{nTw}> 50/55$	$L_{nT,w}\leq 48$			OIB-330.5-002/15
Belgium (BE)		$D_{nTw}> 54$	$L_{nT,w}\leq 58$			NBN S01-400-1
Denmark (DK)		$R'_{w}\geq 55$ (C)	$L'_{n,w}\leq 53$ (C)	$R'_{w}\geq 50$ (D)	$L'_{n,w}\leq 58$ (D)	DS 490
England&Wales (EN & WA)		$D_{nT,w}+C_{tr}\geq 45$	$L'_{nT,w}\leq 62$	$D_{nT,w}+C_{tr}\geq 43$*	$L'_{nT,w}\leq 64$*	Building Regulations – Document E
Finland (FI)		$R'_{w}\geq 55$ (C)	$L'_{n,w}\leq 53$ (C)	$R'_{w}\geq 49$ (D)	$L'_{n,w}\leq 63$ (D)	SFS 5907
France (FR)		$D_{nT,w}+C\geq 53$	$L'_{nT,w}\leq 58$	According zones of *Plan de GêneSonore*(PGS)		Réglementations acoustiques bâtiments
Germany (DE)	Multi	$R'_{w}\geq 53$ (I)	$L'_{n,w}\leq 53$ (I)			DIN 4109
	Row	$R'_{w}\geq 57$ (I)	$L'_{n,w}\leq 58$ (I)			

Greece (GR)	D_{nTw}> 53 Κατηγορίας 3 *(category 3)*	L'$_{nT,w}$≤ 57 Κατηγορίας 3 *(category 3)*	D_{nTw}> 50 Κατηγορίας 4 *(category 4)*	L'$_{nT,w}$≤ 64 Κατηγορίας 4 *(category 4)*	λληνικόΚανονισμό Κτιριακής (Greek Building Regulation)
Island (IS)	R'$_{w}$≥ 55 (C)	L'$_{n,w}$≤ 53 (C)	R'$_{w}$≥ 50 (D)	L'$_{n,w}$≤ 58 (D)	Byggingar reglugerð (Building regulations)
Irland (IR)	$D_{nT,w}$≥ 53	L'$_{nT,w}$≤ 58			EN ISO 16283-1 EN ISO 140-7
Italy (IT)	R'$_{w}$≥ 50 (III)	L'$_{n,w}$≤ 63 (III)	R'$_{w}$≥ 45 (IV)	L'$_{n,w}$≤ 68 (IV)	UNI 11367, Ministry decree 5 December 1997
Lithuania (LT)	$D_{nT,w}$ / R'$_{w}$≥ 55	L'$_{n,w}$≤ 53	$D_{nT,w}$ / R'$_{w}$≥ 52	L'$_{n,w}$≤ 58	STR 2.01.07
The Nether-Lands (NL)	$D_{nT,w}$ + C > 52 l_{luk}*** > 0 dB	L'$_{nT,w}$ < 53 l_{ico}** > 5 dB	$D_{nT,w}$ + C >47 (IV)	L'$_{nT,w}$ <58 (IV)	NEN 5077
Norway (NO)	R'$_{w}$≥ 55 (C)	L'$_{n,w}$≤ 53 (C)	R'$_{w}$≥ 50 (D)	L'$_{n,w}$≤ 58 (D)	NS 8175
Portugal (PT)	$D_{nT,w}$≥ 50	L'$_{nT,w}$≤ 60			RRAE
Scotland (SC)	$D_{nT,w}$≥ 56	L'$_{nT,w}$≤ 56	$D_{nT,w}$≥ 56 $D_{nT,w}$≥ 53 *º	L'$_{nT,w}$≤ 56 L'$_{nT,w}$≤ 58 *º	Scotland Technical Handbook
Spain (ES)	$D_{nT,w}$ + C ≥ 50	L'$_{nT,w}$≤ 65			CTE DB-HR
Switzerland (CH)	$D_{nT,w}$ + C ≥ 53	L'$_{nT,w}$ ≤ 58			SIA 181

*º conversions refers to "traditional buildings"

Class denotations in parenthesis Y= Yes;

* Material change of use / ** plane l_{co} + L_{nTw}≈ 75 dB - descendent l_{co} + L_{nTw}≈ 65 dB / ***D_{nTw} = l_{luk} + 55 dB

6.2 Other countries worldwide

Table 2 summarizes relevant data considering the sound insulation requirements found in the current building acoustic regulations in other selected countries worldwide.

Table 2. Relevant data considering the sound insulation requirements of countries worldwide and the corresponding class

WORLDWIDE			
Country	**New buildings**		**BC or Standard**
	Airborne sound (dB)	**Impact sound (dB)**	
Australia (AU)	R_w + C_{tr}≥ 50 $D_{nT,w}$+C_{tr}≥ 45	$L_{n,w}$+C_I ≤ 62 (f) L'$_{nT,w}$ ≤ 62 (w)	NCC
Brazil (BR)	$D_{nT,w}$≥ 45	L'$_{nT,w}$≤ 80	NBR 15575-3

Canada (CA)	ASTC ≥ 47 STC ≥ 55	FIIC ≥ 50 IIC ≥ 50	
Chile (CH)	R_A / R'_A ≥ 45 (dBA)	$L'_{nT,w}$≤ 75	Manual Reglamentación Acústica O.G.U.C.
Japan (JP)	D-45	L-55	JIS 1418
Russia (RU)	R_w≥ 52	$L_{n,w}$ ≤ 60	СП 51.13330
USA	STC ≥ 50 $D_{nT,w}$≥ 45	IIC 50 $L_{n,w}$≤ 60 / $L'_{nT,w}$≤ 65	ASTM E90-09 ASTM E492-09

Acoustic requirements intended for old buildings were not identified, and it remains unclear whether the requirements indicated also refer to existing buildings. However, the difficulty of interpreting certain regulations due to language determines the need for an exhaustive analysis in collaboration with researchers from the individual countries.

7. DISCUSSION

The interpretation of the content of the documents analysed in this review work has made it possible to identify regulatory guidance for sound insulation in dwellings and to determine the differences and similarities between the requirements of different countries in terms of acoustic retrofit.

Figure 3 shows the required values of airborne and impact sound insulation, determined in national standards and BCs for new and renovated residential buildings. The required values for existing buildings in some countries are omitted as the limit values were not identified in the regulations.

On the one hand, Table 2 shows the lack of harmonization between countries, with variations greater than 15 dB in the impact sound requirements (between Austria and Spain). It has been impossible to include the different variants of each normative document in a single table. However, it should be noted that some countries establish a classification of the limit values depending on the type of building, even varying between collective or individual dwellings, while others provide a single value to regulate the entire building stock. In this regard, there are cases in which no distinction is made depending on the location of the building, that is to say, quiet or noisy areas established in noise maps. This means that the same value can be considered too restrictive for quiet areas, or in contrast, too lax for noisy areas.

On the other hand, Figure 3 shows that in the cases where both values are shown, requirements for old buildings vary between 2-6 dB with respect to the airborne insulation requirements in new buildings, and 2-10 dB in the case of impact insulation requirements, The lowest values are found in England and Wales, where the difference between parameters decreases to 2 dB. The situation in South America is similar to that found decades ago in European countries, characterized by ignorance about the impact of noise on health. At present, several publications have noted the dangers of high noise levels, although the reasons for the lack of awareness in South America are not known, they may include economic constraints and a shortage of adequate materials.

When analysed, this table shows the differences in requirements between countries, since in some cases the requirements for old buildings are equally or even more stringent than those for new buildings. As mentioned above, although this variability should not be so significant, numerous aspects may influence the determination of limit values. The climate, the age of the building, financial conditions, and constructive characteristics are clear influential factors.

It should be noted that the reference to acoustic insulation indexes of construction elements in existing buildings has been identified in most countries. In addition, sound classification schemes are established (mostly in Nordic countries) in order to differentiate levels of comfort in terms of acoustics. In these cases, the usual difference between requirements for new and existing buildings is 5 dB, both for airborne sound insulation and impact sound insulation. It is also interesting to note that certain countries present different variations depending on the type of parameter assessed, that is, using one value for airborne noise and another value for impact noise. In these cases, there are minor variations and, therefore, higher demands for airborne noise (as is the case for Finland, Greece and Lithuania).

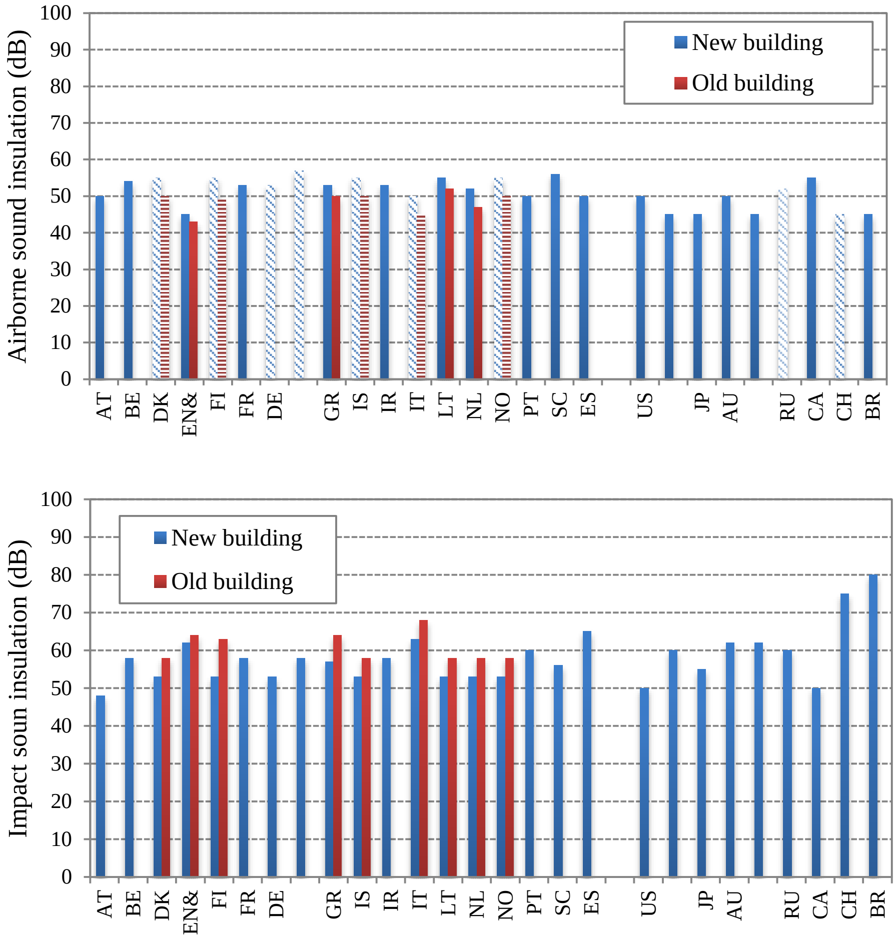

Figure 3. Required values set in national standards and BC for new residential buildings and renovated buildings: a) Airborne sound insulation, b) Impact sound insulation. NOTE: For Airborne sound insulation, D_{nTw} values are represented with solid shading while R'w values are represented with striped shading.

8. DESIGN CRITERIA DEFINED BY REGULATIONS AND GUIDELINES OF COUNTRIES WORLDWIDE

In renovation projects, a general improvement of the comfort conditions of the buildings are promoted, including acoustic retrofit. For these interventions, the basis for discussion are decision processes and practices applied for renovation of existing housing. As explained in the sections above, several countries worldwide have developed technical documents as help manuals for the technician. The main purpose of this book is to work towards the definition of general strategies and remedial treatments for interventions to improve the indoor environmental comfort of existing residential stock. This section refers to the general guidance and design criteria of constructive systems and solutions referenced in these technical handbooks, incorporating constructive solutions that comply with the current standards and minimum levels of requirements.

After an initial stage of pre-conversion or sound test carried out during the site survey process, the acoustic problems of the existing construction are identified, making it possible to define the design of tailored acoustic solutions. Remedial procedures and factors such as structure, fire, and energy must also be considered in the retrofit intervention, along with noise reduction, given their potential significant impact on acoustic performance. This phase of on-site evaluation of the current state of the building will facilitate the identification methods and descriptions of how to improve sound insulation in dwellings. It will be necessary to develop a renovation project with an intervention on all aspects relating to indoor comfort and safety.

Current research by the authors, to be published in the near future, focuses on the analysis of different constructive solutions, in order to evaluate the impact from different perspectives.

8.1 Proposal of remedial treatments in existing buildings based on documents worldwide

This section employs a critical approach to the analysis of these documents, evaluating their objective and development. In some cases, a brief theoretical explanation is provided.

Spain is one of the countries which have created an Application Design Guide to be followed during the retrofit process. The purpose of this Guide is to facilitate the practical application of the normative document. It contains interpretation criteria, comments, and application examples aiming to support the specialists participating in the building process. In other words, although not mandatory, this document, which develops the regulatory principles, can be considered complementary to the BC. In the case of certain historic buildings undergoing a material change of use it may not be practical to improve the sound insulation to the standards. As stated before, in the Spanish regulations the need to conserve the special characteristics and the heritage value of these unique buildings should be recognised [54], and the aim of the work should be to improve sound insulation as much as practically possible.

In Scotland, the Scottish Handbook of Housing and Sound Insulation is an important example of instructions for the enhancement of old dwellings which provides construction improvements, designing possibilities for conversions and upgrades [2]. This extensive document includes a lengthy section on proposals for the improvement of existing construction solutions, both horizontal and vertical systems. Guidelines and recommendations are also provided.

In the case of Portugal, Patricio published a book on acoustic rehabilitation, mainly geared towards residential buildings, to guide technicians and the general public on the best solutions, guidelines, and approach strategies, associated with rehabilitation processes from the perspective of practical application [38]. Figure 4 shows three examples of possible remedial treatments to improve the acoustic performance used in case studies in Scotland and Portugal.

In Denmark a guidance document has also been published on the soundproofing of homes in existing buildings, providing specific solutions for the improvements aiming to comply with the limit values according to the acoustic classification. In order to achieve sufficient acoustic insulation, the retrofitting project must focus largely on choosing and evaluating material properties, material thicknesses, mounting details, and flanking constructions [55].

Other documents, such as *Robust Details* [56], are mainly aimed at designing and performance interventions in new buildings. *Robust Details* was implemented in the UK as an example of a coordinated approach in which construction design, acoustic site inspection, and field testing were included. This document is mainly focused on providing detailed constructive solutions that meet the required values.

In general, common materials that can be applied to walls, floors, and ceilings to improve sound insulation are referred to, including absorption layers, additional board linings, and appropriate fixing mechanisms. However, there are also systems to treat walls, floor surfaces, and/or ceilings by applying diverse remedial treatments to alter existing dwellings:

- Wall treatments → reduce airborne noise
- Floor system and insertion treatments → reduce airborne and impact noise
- Ceiling treatments → reduce impact noise
- Service pipe treatments → reduce equipment noise

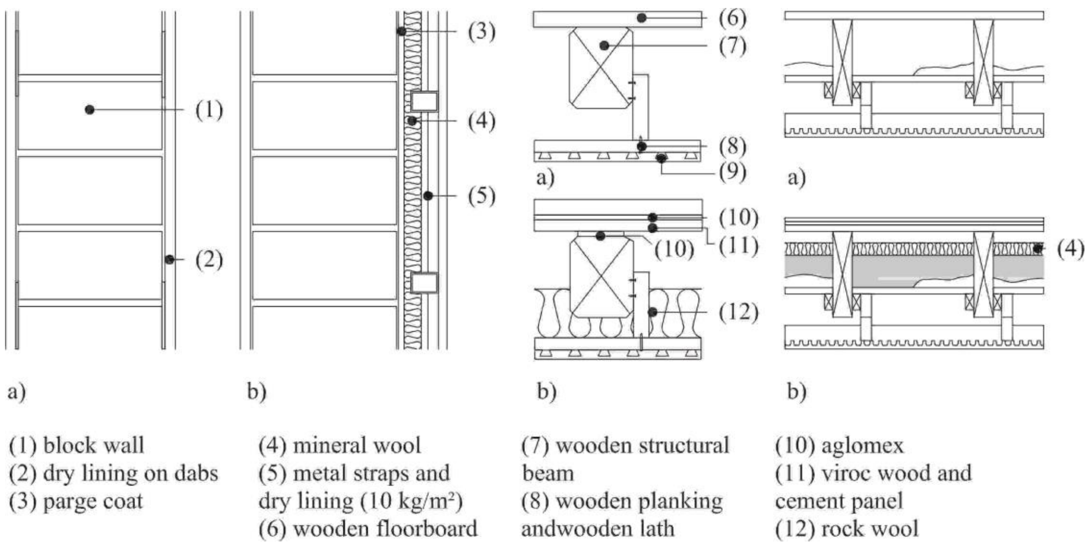

Figure 4. Examples of possible remedial treatments of separating wall or separating floors to improve the acoustic performance used in cases studies in Scotland and Portugal. a) original state and b) remedial treatment applied [2,36]

In terms of practical solutions to achieve the implementation and enforcement of sound insulation requirements, the major design considerations can be classified and summarized in two groups:

- Interventions whose acoustic improvement is based on the mass law and additional layers:
- A heavy wall or floor depends on its mass to reduce airborne noise.
- Increase or addition of thermal-acoustic insulation layer (open cell).
- A heavy solid floor or a floating floor depends on a resilient layer, preferably not too stiff, in order to reduce airborne and impact noise.
- Interventions whose acoustic enhancement is based on mass-spring systems:
- Resonance and vibrations must be avoided by removing dry linings.

Additionally, it is important to take into account that air paths must be avoided, so that porous materials and gaps at joints in the structure must be sealed.

For façade treatments, the regulations require that the exterior heat exchange be as small as possible (low U-value), and that a protection against external noise be guaranteed. In this regard, a possible solution is the addition of acoustic-thermal insulation. It is of great importance in evaluating what type of material should be used in this type of intervention, since not all thermal insulation materials display good acoustic behaviour. A lightweight material with a large amount of air and low mass might not prevent the passage of acoustic energy. However, if this material is open cell, its efficiency will increase significantly, since the sound will be absorbed by each of its open cells, improving the vibrational decoupling between the heavy layers, and therefore, improving the overall insulation of the construction element. Mineral wool, natural fibers, geotextiles, and cork are some of the materials with the best results. The same is not the case with closed cell materials such as expanded polystyrene or polyurethane foam.

Regarding a solution proposed in historic buildings, a separating floor may require the use of the same floor base which incorporates a floating layer. The floating layer could use the same existing boards if these have been carefully dismantled, preserving the elements, and re-laid on resilient strips on top of existing joists.

9. CONCLUSIONS AND FURTHER DEVELOPMENTS

The analysis of the aging of housing stock states there is a need for renovation because at the time of construction the regulations in terms of comfort were very limited or non-existent. Considering noise as a health issue, the improvement of acoustic comfort has become one of the most important variables to be taken into consideration during the building design and construction process.

In this paper a comparative study is developed on the acoustic requirements established in current building regulations on indoor sound insulation between dwellings around the world, focusing mainly on the acoustic retrofit of existing residential buildings. This analysis made it possible to determine the perspectives in terms of national acoustic regulations and national Building Codes. To this end, this paper provides the basis for discussing future cooperation on optimizing acoustic regulations for existing buildings.

Based on the review work conducted, the following main conclusions can be highlighted:

- Not all countries consider acoustic retrofits in order to enhance sound transmission in old buildings, and numerical requirements are only defined in a few national standards. Some countries, mainly Nordic, establish sound classification schemes in order to distinguish levels of comfort in terms of acoustics. However, technical documents are also provided by some countries to offer guidance to specialists, with constructive systems and solutions than comply with requirements.

- In countries where are established classification schemes, the usual difference between requirements for new and existing buildings is 5 dB, both for airborne insulation and impact sound insulation.

- In certain cases, some countries provide different variations depending on the type of parameter evaluated (airborne noise and impact noise). In these cases, the variations are smaller and, as a result, demand is higher for airborne noise where the differences in regard to new buildings are smaller.

- The demands for impact noise are also lower, and reduce impact sound insulation by up to 10 dB with respect to requirements for new constructions.

Future developments will focus on the need for good management strategies for the rehabilitation of housing buildings, which should be applied to achieve a more extensive sustainable residential stock. The basic motivation of these initiatives should be understood as the idea that every renovation work, regardless of its scale, could be considered an opportunity to enhance the acoustic performance of existing buildings. It is also important to promote tasks and tools for upgrading sound insulation requirements and to make an efficient and effective implementation of databases and guidelines for the improvement of existing housing. Another article is in preparation on façade sound insulation and noise from service equipment, not treated in the present work

Acknowledgements

This work has been financially supported by *VI Plan Propio Investigación* of Universidad de Sevilla.

REFERENCES

[1] Andargie, M. S, Touchie, M., O'Brien, W. A review of factors affecting occupant comfort in multi-unit residential buildings. Building and Environment 160, 106182, (2019).

[2] S. Smith, J.B. Wood and R. Mackenzie. "*Housing and Sound insulation - Improving existing attached dwellings and designing for conversions*". Arcamedia, Edinburgh (2006).

[3] M. Basner et al. "*Auditory and non-auditory effects of noise on health".*Lancet 383, pp.1325–32 (2014).

[4] Guidelines for Community Noise; Berglund, B., Lindvall, T., Schwela, D.H., Eds.; World Health. Organisation: Geneva, Switzerland, 1999.

[5] Burden of Disease from Environmental Noise; World Health Organization: Geneva, Switzerland,2011.

[6] Night Noise Guidelines for Europe; World Health Organisation: Copenhagen, Denmark, 2009.

[7] U. Berardi: "*Sound classification of dwellings - a comparison between national schemes in Europe and United States"*. J AcoustSoc Am 135(4) 2379 (2014).

[8] Bortolini, R., Forcada, N. A probabilistic-based approach to support the combort performance assessment of existing buildings. Journal of Cleaner Production 237, 117720 (2019).

[9] L. Mazzarella. *"Energy retrofit of historic and existing and buildings. The legislative and regulatory point of view*". Energy and Buildings 95 (2015), pp. 23-31

[10] B. Ramussen. *"Sound insulation between dwellings – requirements in building regulations in Europe"*. Applied Acoustics 71, pp. 373-385 (2010).

[11] B. Rasmussen, *"Sound classification of dwellings – Quality class ranges and intervals in national schemes in Europe*". Proceedings of Euronoise 2012. Prague, CzechRepublic

[12] B. Ramunssen. *"Sound insulation between dwellings – descriptors applied in building regulations in Europe".*Applied Acoustics 71, pp.171-180 (2010).

[13] Monteiro, C., Machimbarrena, M., Tarrero, A. I., Smith, S. Translation between existing and proposed harmonized airborne sound insulation descriptors: A statistical approach based on in-situ measurements. Applied Acoustics 116, pp. 94.106, (2017).

[14] M. Machimbarrena, B. Rasmussen. *"Comparison of acoustic regulations for housing and schools in selected countries in Europe and South America – A pilot study".*Proceedings of the 22nd ICA. Buenos Aires, Argentina, (2016).

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

[16]. B. Rasmussen, "Sound classification schemes in Europe - Quality classes intended for renovated housing". SUBURBAN 2010 "Improving the Quality of Suburban Building Stock". University of Malta, 2010.

[17] COST Action TU0901 *"Towards a common frame work in building acoustics throughout Europe"* (2013).

[18] L. Del Val, M. Machimbarrena, M. Herráez, C. Monteiro, R. Johansson. "*Translation between existing and proposed harmonized impact sound insulation descriptors and alignment within a proposed common acoustic classification scheme for buildings*". Applied Acoustics 129, pp. 204-2016 (2018).

[19] Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. Annex I.
[20] B. Rasmussen. *"Why is sound insulation between dwellings in renovated housing not upgraded like other qualities?"*Proceedings of EuroRegio, Porto, Portugal, (2016).
[21] Hasselaar, E. (2009). Health issues and the building stock. *Building Research and Information, 37*, 669-678.
[22] S. Roberts*"Altering existing buildings in the UK*" Energy Policy 36(12), pp. 4482e6 (2008).
[23] L. Itard, F. Meijer."*Towards a sustainable Northern European housing stock*", Sustainable Urban Areas, 22, TU Delft, Amsterdam: IOS Press (2008).
[24] Escandón, R., Suárez, R., Sendra, J.J. "*On the assessment of the energy performance and environmental behaviour of social housing stock for the adjustment between simulated and measured data: The case of mild winters in the Mediterranean climate of southern Europe*". Energy and Buildings 152, pp.418-433, (2017)
[25] I. Theodoridou, A.M. Papadopoulos, M. Hegger, *"A typological classification of the Greek residential building stock"*, Energy Build. 43, pp.2779–2787, (2011).
[26] Spanish National Statistical Institute (INE) Censos de Población y Vivienda. Viviendas según tipo de vivienda y año de construcción (agregado) del edificio (*Population and Housing Census. Housing according to type of housing and year of construction of the building*), (2017).
[27] Villa-Pozo, M.; Gonzales-Bustos, J.P. "*Tax incentives to modernize the energy efficiency of the housing in Spain*" Energy Policy 128, pp. 530-538, (2019).
[28] Instituto para la Diversificación y Ahorro de la Energía (IDAE). Las claves para conocer y actuar en materia de Certificación Energética de los Edificios. 2015.
[29] S. A. Magalhaes, V.P.de Freitas. "*A complementary approach for energy efficiency and comfort evaluation of renovated dwellings in Southern Europe".*Energy Procedia 132, pp, 909-14 (2017).
[30] American Community Survey (ACS). National Association of Home Builders (2016).
[31] Statistics Bureau of Japan, Ministry of Internal Affairs and Communications.
[32] Census of Population and Housing: Australia, Australian Bureau of Statistics (2016).
[33] United Nations "*Country Profiles on the Housing Sector:Russian Federation"* Geneva, (2004).
[34] Zuhaib, S., Manton, R., Griffin, C., Hajdukiewicz, M, Keane, M.M., Goggins, J. *An indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building*. Building and Environment 139, pp. 69-85, (2018).
[35] Regnier, C., Sun, K., Hong, T., Piette, M. A. Quantifying the benefits of a building retrotif using an integrated system approach: A case study. Energy and Buildings 159, pp. 332-345, (2018).
[36] D. Queirós, R. Calejo Rodrigues, N. Pereira. *"Historical building acoustical retrofit: an experimental examination of traditional wooden floors"*. Build Acoust 23(3) pp.181-91 (2016).
[37] Consejo Superior de los Colegios de Arquitectos de España. *"El Nuevo codigo técnico de la edificación y la restauración arquitectónica" ("The new technical code of building and architectural restoration").* Barcelona, Spain, (2006).
[38] J. Patricio. "*A acústica na reabilitaçao de edificios*" (*Acoustics in building rehabilitation*). 4th Ed. Ed. By Quantica Editora. Engebook, Porto (2018).
[39] Code de la construction et de l'habitation. "*Section 5-Sous-section 2: Caractéristiquesacoustiques des bâtimentsexistants*" (*Section 5 Subsection 2: Acoustic characteristics of existing buildings)* Republique Française (2018).
[40] Building Regulations 2014. "*Technical Guidance Document E – Sound*" Ireland (2014).
[41] Rasmussen, B. (2012). Sound classification of dwellings in the Nordic countries – Differences and similarities between the five national schemes. In P. Juhl (Ed.), Proceedings of BNAM2012 Nordic Acoustic Association.
[42] Associazione Nazionale per lÌsolamento Termico ed Acustico (ANIT) – *Determinazione dei requisiti acustici passivi degli edifici*. (Determination of passive acoustic requirements of buildings). Ministry Decree D.P.C.M 5 dicembre 1997. Italy.

[43] Regulamento dos Requisitos Acústicos dos Edifícios (*Building Acoustic Requirements Regulation*) , Decreto-lei 96/2008. Portugal.
[44] J. Patrício; S. Antunes. "*A classification scheme for rehabilitated buildings. The Portuguese case"*. In Proceedings of Internoise 2013, Innsbruck (Austria), 15-18 September, 2013.
[45] T. Carrascal García, A. Romero Fernández, B. Casla Herguedas. "*Noise requirements in existing buildings in Spain: New proposals and the Existing Building Evaluation Report*" Proceedings of Euronoise, Maastricht (The Netherlands) (2015).
[46] H M Government. Approved Document E.*"Resistance to the passage of sound*" The Building Regulations (2018).
[47] D. Urquhart. "*Conversion of Traditional Buildings. Application of the Scottish Building Standards. Part 1"*. Edited by D. Urquhart. Historic Scotland, Edinburgh (2007).
[48] Scottish Building Standards Technical Handbook: Domestic buildings. Section 5: Noise. Regulation 5.1 (2017).
[49] National Construction Code Australia. Part F5 – Sound Transmission and Insulation (2016).
[50] Sound transmission and insulation in buildings. Australian Building Codes Board (2018).
[51] ABNT NBR 15575-3. Edificaçoes habitacionais – Desempenho. Parte 3: Requisitos para os sistemas de pisos.
[52] Manual de Aplicación Reglamentación Acústica (*Acoustic Regulation Application Manual*). Ordenanza General de Urbanismo y Construcciones. Gobierno de Chile, Ministerio de Vivienda y Urbanismo (MINVU).
[53] International Code Council Series. "*International Existing Building Code*" (2018).
[54] BS7913:2013 "*Guide to Principles of the Conservation of Historic Buildings*" British Standards Institution (2013).
[55] SBI-Anvisning 243 "*Lydisolering mellem boliger – eksisterende byggeri"(Soundproofing between homes - existing construction)*. (2010).
[56] Robust Details Ltd., "*Robust details handbook. Part E: Resistance to the passage of sound"*. Edition 4. Milton Keynes, UK (2013).

Highlights

- Exposure to noise has important repercussions on human comfort and health.
- Aging of housing stock justify the limitation of compliance with acoustic standards
- A comparative study of the acoustic requirements of existing buildings is developed
- Usual difference between requirements for new and existing buildings is 5 dB