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Acoustic retrofit strategies of windows in facades of residential buildings: Requirements and recommendations to reduce exposure to environmental noise

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ABSTRACT

Achieving an adequate indoor acoustic comfort environment is one of the main priorities to avoid adverse effects caused by noise. Façades are the constructive elements most likely to be retrofitted due to their delimiting function between indoor and outdoor space. This study compares the acoustic façade requirements established for new and existing buildings in current national building regulations. The assessment of regulations and the analysis of a comparison model, examining different techniques for improving sound insulation, conclude that on a global scale there is a lack of consensus on external noise insulation and acoustic requirements worldwide. It is not possible to merely summarize all requirements into a single number as the sound insulation required depends on the performance of the building element, the outdoor noise level or the indoor noise level. Therefore, there is an in-depth discussion on the harmonization of external sound insulation requirements in acoustic regulations. This study also analyses façade wall solutions of existing housing stock and compliance with current regulations, with results showing that upgrading interventions focused on windows can be sufficient to propose suitable constructive systems in compliance with requirements established worldwide when external noise amounts to 60 dB(A) measured 2 m from the façade.

1. Introduction

The construction of new buildings, when considering the adaptation to environmental conditions, must meet the demanding requirements of current regulations. However, a high percentage of social housing buildings was built decades ago [1,2], after the post-war period (1940–1980), when these legal requirements were undefined or non-existent; as a result, retrofitting is required to achieve suitable comfort conditions and to avoid health issues [3].

In recent years, the aging European social housing stock and the preoccupation with achieving a state of global comfort have become major concerns of the scientific community [4,5]. Working towards this common goal, various actions and European directives [6] have been implemented to standardize retrofitting processes within the residential sector. User behaviour and indoor environment are two essential aspects to be taken into account when retrofitting the housing stock in order to improve comfort conditions and reduce living costs [7,8].

The human perception of comfort is known to be strongly influenced by subjective and behavioural processes [9], reflected as an emotional and physiological reaction to environmental stimuli [10,11]. Regarding acoustics, several studies have demonstrated significant adverse effects on human health due to exposure to outdoor environmental noise (road traffic, railway and aircraft transportation, and leisure) [12–14]. Recently, the WHO Regional Office has developed Environmental Noise Guidelines for European Region [15], based on the growing understanding of these health impacts, in order primarily to provide recommendations and solid public advice for protecting human health. However, as the control of environmental noise levels alone is not enough to comply with legal requirements and Building Code (BC) recommendations, the acoustic performance of the building envelope must also be assessed in order to limit indoor noise levels in buildings [16].

The need for social housing has been a problem in most cities throughout the 20th century. The need for acceptable housing for the working classes who had arrived from the countryside constituted a major challenge. Façade walls are required to fulfil the insulation

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demand since this constructive element serve as the outer skin of buildings. Generally, today's renovation works have focused extensively on energy efficiency by guaranteeing more efficient air conditioning and ventilation systems. These actions have had many different aims: improving building envelope insulation ability efficiently [17]; developing modular façade retrofit solutions which integrate on-site renewable energy technologies [18]; using materials that could achieve improved thermal insulation within the construction, reducing heat usage and promoting energy savings [19] or including a multi-criteria decision analysis based on diverse evaluation topics [20]. However, acoustic retrofit interventions should also be conducted as part of the process of building renovation, as the design of façades, both the opaque sections and windows, should be suitably planned to achieve an acceptable and tolerable sound level indoors and to act as a "barrier" for incident sound fields.

Among the types of environmental noise intervention, one of the solutions provided by the WHO is the change in the path between source and receiver [15]. In this regard, previous work by the authors presented a comparative study on acoustic requirements set out in the current legislation and Building Codes (BCs) of countries worldwide, focusing mainly on the acoustic retrofit of old housing buildings [21]. However, the scope of this initial research was limited to the sound insulation descriptors between dwellings (airborne and impact sound insulation), making further research on the specific issue of façade sound insulation further. This article aims to build on the previous study by comparing national regulations in Europe and other countries worldwide and providing acoustic retrofit strategies for existing housing façades in compliance with required or recommended values worldwide.

2. Noise guidelines and effects on human health

European guidelines and several scientific studies have determined the negative impacts of noise on human health and well-being [22] and show strong evidence of non-auditory effects on health [23]. Research on specific recommendations on guideline exposure levels and/or interventions to reduce exposure is a growing concern among both scientific community and policy-makers [15].

Organizations such as the World Health Organization [24], the European Commission with the Green Paper on "Future Noise Policy", the Environmental Protection Agency (EPA) and the International Program on Chemical Safety (IPCS) highlight a major risk of increasing the main adverse effects on health: permanent hearing impairment, self-reported sleep disturbance, cardiovascular disease, and cognitive development and impairment. Noise annoyance can also be considered a health issue according to the WHO. In this regard, the analysis of surveys on annoyance due to traffic noise shows statistically significant correlations between noise levels and annoyance scores [25]. According to WHO [15], about 40% of the European population is annoyed by noise since it is exposed to road traffic noise at levels exceeding 55 dB (A).

In 1999 the WHO published the first document detailing guideline values for community noise (CNG) [26], and aimed at environmental health authorities and professionals trying to protect people from the harmful effects of noise. After evaluating noise risks, recommended maximum thresholds were obtained. Ten years later, the WHO [27] published the night noise guidelines (NNG), a document considered an extension of the CNG, but aimed at the comprehensive investigation of the immediate physiological effects of environmental noise on sleep. Experts concluded that a value of 40 dB should be the target night level (NNG) to protect users, while a level of 55 dB was provisionally recommended for countries which find it more difficult to follow the guidelines in the short term.

Almost a decade later, significant new evidence has been accumulated on the effects of environmental noise on health. In 2018 the WHO published the Environmental Noise Guidelines (ENG), updating the assessment of admissible noise levels. The main objective of this document is to provide recommendations, unlike those previously outlined by NNG, for protection from exposure to environmental noise originating from sound sources such as transport, wind turbines and leisure. The results of the referenced studies in ENG determine the quantitative risk, the number of participants in the studies, and the lowest level of noise exposure together with the quality of evidence for each health outcome.

Table 1 shows the recommended values presented by ENG [15] from different sources for average noise exposure and night noise exposure measured outdoors. When examining the effects on health, specifically sleep disturbance, it is considered that the equivalent sound level during sleep should not exceed 30 dB(A), or 45 dB(A) in the case of single events. In addition, an exposure to ambient noise of less than 55 dB(A) is recommended to minimize negative effects on cardiovascular health. Furthermore, international epidemiological studies revealed an increased relative risk of ischemic heart disease whenever traffic noise *per day* exceeded the equivalent sound level of (L_{eq}) 65 dB(A) [28–30].

The Guide Development Group (GDG) reviewed the evidence of measures to reduce noise levels, considering road traffic noise as a sound source. Actions or interventions on environmental noise were defined according to five broad categories based on previous experience and scientific literature. Various studies explored the effectiveness of interventions and the impact on annoyance by actions related to one of these categories, that of path intervention, the change in the path between source and receiver, or path control through insulation of receiver [31,32]. Some examples of this type of intervention are dwelling insulation, barrier constructions and a combination of both, as well as full-scale building intervention [33], which bring about changes to health outcomes [34]. The assessment of façade sound insulation in the aforementioned work is related to the interventions mentioned above, which protect humans from exposure to road traffic noise.

2.1. Outdoor noise indicators

Day-evening-night level (L_{den}) and night level (L_{night} or L_n) are the most frequently used average noise indicators in Europe, as defined in Environmental Noise Directive and ISO standards [35,36]. Moreover, scientific studies such as the HEARTS project (Health Effects And Risks of Transport Systems) recommend the use of both indexes, L_{den} and L_n, for correlation with health effects [37]. An important aspect is that the environmental noise laws and standards of each country can establish different time intervals or thresholds for these outdoor noise indicators. The reference time range can be specified in national or international standards or by local authorities to include typical human activities and variations in the operation of noise sources. Different levels or sets of levels can be specified for different reference intervals [38]. The most frequently used time intervals are:

- L_{den}, a noise indicator calculated as the A-weighted average sound pressure level based on energy equivalent noise level (L_{eq}), and measured over a 24-h period with a 10 dB(A) penalty for night-time noise (23:00–7:00 or 22:00–6:00), a 5 dB(A) additional penalty for evening noise (19:00–23:00 or 18:00–22:00), and no penalty added to the daytime period (07:00–19:00 or 06:00–18:00).
- L_{night} or L_n, a noise indicator calculated as the A-weighted average sound pressure level, measured over an 8-h period during night-time (23:00–7:00 or 22:00–6:00).

Table 1
Recommendations from different noise sources for average noise exposure and night noise exposure [15].

	Road traffic	Railway	Aircraft	Wind turbine	Leisure
L_{den} (dB)	53	54	45	45	–
L_{night} (dB)	45	44	40	–	–
L_{Aeq24h} (dB)	–	–	–	–	70

Other important noise indicators are day level (L_{day}) and evening level (L_e):

- $L_{day,}$ a noise indicator calculated as the A-weighted average sound pressure level, measured over a 12-h period during daytime (07:00–19:00 or 06:00–18:00).
- $L_{e,}$ a noise indicator calculated as the A-weighted average sound pressure level, measured over a 4-h period during the evening time (19:00–23:00 or 18:00–22:00).

3. Methods

Risk management is necessary for the prevention and protection of human health. The acoustic assessment of old social housing buildings determines the need for retrofit and renovation works in order to prevent dwelling users from exposure to environmental noise as façade walls do not meet the current demanding requirements. This work presents a comprehensive analysis of worldwide legislation as well as the analysis of acoustic constructive proposals of windows in facade, based on a room model, to comply with regulatory standards. One of the different noise intervention solutions provided by the WHO Regional Office for Europe [15] is a change in the path between source and receiver. Methods of this study consist of the following steps:

- General review of noise guidelines and effects on human health together with the definition of main outdoor noise indicators (Section 2).
- Compilation of information on the acoustic considerations and recommendations set out in European regulatory policies and Building Codes, consulting legislative documents, guidelines and technical handbooks of other countries. Collection of the national acoustic requirements based on a literature review analysis, focused on identifying and comparing sound insulation requirements inside buildings (Section 4).
- Assessment of different acoustic retrofit strategies to facilitate the task of proposingremedial path interventions for façade walls to meet the indoor values set forth in the regulations. Analysis of variations in the constructive solution of windows (Section 5).
- Discussion and analysis of the acoustic considerations and recommendations set out in regulatory policies and Building Codes worldwide, and the acoustic requirements worldwide for housing stock, both for new and existing buildings (Section 6).

4. Legislative and regulatory policies

4.1. Sound insulation of the external structure of buildings

During the development of the intergovernmental framework COST Action TU0901 [39], a European working group provided a first draft proposal for the most appropriate descriptors and assessment methods, in order to harmonize their use in European countries. A decade later this issue remains unresolved and there is still a need for further work on the proposal of harmonized sound insulation descriptors.

When collecting national legal requirements and comparing acoustic classification schemes of sound insulation against external noise, significant discrepancies can be observed between different countries [40]. The requirements for each country cannot be expressed as a single number given that regulation requirements are divided into two main categories:

- Firstly, the requirement for performance of the building elements, referring to the minimum airborne sound insulation of the global façade ($D_{2m,nT,w}$, $D_{2m,nT,w}$ + Ctr, $R_{\cdot w}$, $R_{tr,w}$ or $R_{\cdot w} + C_{tr}$). This index characterizes the façade's ability to insulate against airborne sound transmission. In this category, to comply with regulations for a given urban area, façade descriptors $R_{,w}$ or $R_{tr,w}$ ($R_{\cdot w} + C_{tr}$) must be specified in the acoustic project. Based on the outcomes of COST Action TU0901 [39], the need for the low frequency consideration was in doubt for many constructions, leading to an acceptance of both 50 Hz and 100 Hz as options for the start of the frequency range. This was set at the lower rate of 50 Hz ($D_{2m,nT,50,}$ $D_{2m,nT} + C_{tr,50\text{-}3150}$), considered reasonable in the case of lightweight constructions. Requirements set for façade elements, that is, the standardized façade level difference $D_{2m,nT}$, can be calculated by means of Eq. (1), which takes into account the surface area of façade, the size of the room and the absorption area, defined by EN 12354-3 [41]:

$$D_{2m,nT} = R' + \Delta L_{fs} + 10 \log \frac{V}{6T_0S} \ (dB) \tag{1}$$

Where R′ is the façade sound reduction index (dB), V is the volume of the receiving room (m^3), T_0 is the reference value of the reverberation time, 0.5 s for housing buildings, S is the total surface of the façade as seen from the inside (m^2), and ΔL_{fs} is the level difference due to façade shape (dB), calculated using Eq. (2):

$$\Delta L_{fs} = L_{1,2m} - L_{1,s} + 3 \ (dB) \tag{2}$$

Where $L_{1,2m}$ is the average sound pressure level 2 m from the façade (dB), and $L_{1,s}$ is the average sound pressure level on the outer surface of the façade, including the reflective effect of that plane (dB). The estimation of ΔL_{fs} can be conducted using a method defined in annex C of the standard [41], which considers different types of façade shape.

- Secondly, the requirement for the value of the maximum indoor sound level (L_{Aeq}, L_{pA}), expressed as equivalent A-weighted levels, considers the outdoor noise exposure L_{den}, measured inside the buildings. Although the requirement is different, in this category the insulation of the façade against external noise must also be sufficient to maintain suitable internal sound criteria. This is also the case in some countries with classification schemes.

In both cases, the sound insulation and/or indoor noise level required may depend on the outdoor sound level considered and, in turn, on the specific location of the building. Sound level distribution in a region for a defined period can be consulted on a noise map using a zoning definition, and is calculated based on the traffic data and conditions. This zoning definition is not the same generally as the limit value required for the external element component [42]. A value of 55 dB(A) - (L_{den}) - will characterize the suburban environment when outdoor noise exposure is unknown [16]. An estimated sound level inside dwellings is needed to assess indoor levels of exposure to noise. The differences between indoor and outdoor levels are usually estimated at around 10 dB(A) for open windows, 16 dB(A) for tilted or half-open windows, and around 28 dB(A) for closed windows [43].

4.2. Acoustic considerations and recommendations to limit indoor noise

As regards the classification standards proposed in some countries, quality classes and limit values established in BCs are directly linked in some cases, so that the BC value refers to a specific class. However, this is not always the case and at times both documents are not in agreement. Other countries have introduced a simpler set of criteria for higher acoustic comfort as an alternative to the classification schemes, which is considered to supplement the noise requirements defining legal documents [44].

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

- France: A minimum requirement ($D_{nT,A,tr} = D_{nT,w + Ctr}$) is established which depends on outdoor noise level, so that the limit can be higher depending on the location of the building with respect to noise pollution. A subsection is included on the acoustic characteristics of existing buildings, such as social housing, during major renovation works. The minimum requirements for acoustic performance are provided either by performing acoustic insulation work, or by using elements to apply acoustic requirements. These requirements are a function of the areas of exposure to external noise, which are zones 1, 2 and 3 of the acoustic disturbance plan (PGS), and the areas where the limit values of the road and rail noise maps are exceeded [45].

- Italy: This country established sound classification schemes for each requirement or as overall descriptor. Sound classes are determined by the average values of the performance of all field measurements carried out on different building elements. Italian acoustic classification is independent from the room type (bedroom and living room) and the external acoustic climate [46] and one of the classes is commonly associated with the limit value intended for new construction (II). The revised Italian standard UNI 11367 also include useful guidelines for its application to even partial renovation and refurbishment of buildings [47].
- Nordic countries: Denmark, Finland, Norway, Sweden, Iceland, (plus the Netherlands, and Lithuania). This group of countries also established sound classification schemes for different descriptors. In the case of class limits relating to façades, maximum indoor noise limits (L_{Aeq}) are specified according to the room type (bedroom and living room), and not to a sound insulation value like other European countries. Classes are commonly associated with the limit values intended for new housing (C or III) and a less restrictive class for renovated housing (D or IV). Based on the research by Rasmussen [44,48], none of the Nordic countries follow identical criteria, and the most noticeable contrast is the different descriptors applied for noise limits during nighttime ($L_{Aeq\ 22\text{-}07}$, $L_{pA,\ max\ 22\text{-}06}$, $L_{pAF\ max\ 22\text{-}06}$).
- United Kingdom (Scotland): Technical standards do not address environmental noise through the building façade [Technical Handbook - Domestic]. Other legislation covers these areas and further information may be obtained from Planning Advice Note (PAN) 1/2011 'Planning and Noise' [49]. PAN helps to prevent the adverse effects of noise by providing advice on the role of the planning system.
- USA: The OITC (Outdoor Indoor Transmission Class) rating System is used to measure the transmission through façades and façade elements (doors, windows, etc.). OITC is a number rating of the sound transmission loss of a constructive element tested also considering the lower frequencies, since outdoor noise tends to have a lower frequency than indoor noise. The original purpose of the OITC rating was to determine performance of façade assemblies in relation to outdoor environmental sound.

4.2.1. *Europe*

Table 2 summarizes relevant data on minimum airborne sound insulation of façades in residential buildings (bedroom) and Table 3 presents relevant data on maximum indoor levels inside residential buildings (bedroom) due to traffic noise. Data collection considered the sound insulation requirements found in the current acoustic regulations for buildings in the European countries selected.

4.2.2. *Other countries worldwide*

Table 4 summarizes relevant data on the minimum airborne sound insulation of façades of residential buildings (bedroom) found in the current building acoustic regulations in other selected countries worldwide.

5. Design criteria to comply with acoustic regulations

In general, most social residential buildings were built to meet the need for housing in minimal habitable conditions, and as a result the comfort conditions are not adequate. In order to adapt to current regulations, a comprehensive retrofit is required for buildings and urban

Table 2
Minimum airborne sound insulation of façades of residential buildings.

EUROPE				
Country	Outdoor Noise	New buildings	Existing buildings	BC or Standard
Austria (AT)	$L_d \leq 45$ dB $L_n \leq 35$ dB	Façade $R'_{w\ res} \geq 33$ dB[a] Opaque $R_w \geq 43$ dB Window $R_w \geq 28$ dB $R_{w\ +}\ C_{tr} \geq 23$ dB		OIB-330.5-002/15 2015 ÖNORM B 8115:2012
	$L_d > 80$ dB $L_n > 70$ dB	Façade $R'_{w\ res} \geq 48$ dB Opaque $R_w \geq 53$ dB Window $R_w \geq 43$ dB $R_{w\ +}\ C_{tr} \geq 38$ dB		
Belgium (BE)	$L_A \leq 60$ dB[b]	Normal $D_{Atr} \geq 26$ dB $D_{Atr} \geq L_A$-34 + m dB[c] Enhanced $D_{Atr} \geq 30$ dB $D_{Atr} > L_A$-30 + m dB[c]		NBN S01-400-1:2008
	$L_A > 70$ dB	Normal $D_{Atr} \geq 40$ dB Enhanced $D_{Atr} \geq 42$ dB Façade elements $R_{Atr} \geq D_{Atr} + 10\log^*[3 (S_{netto}+5n)/V]$ dB[d]		
France (FR)	$L_A \leq 60$ dB(A) $L_A > 80$ dB(A)	$D_{nT,w} + C_{tr} \geq$ 32 dB zone D $D_{nT,w} + C_{tr} \geq$ 45 dB zone A	$D_{nTA,tr} \geq$ 32 dB zone 3 $D_{nTA,tr} \geq$ 38 dB zone 1	CNB 2017
Germany (DE)	$L_{Aeq} \leq$ 55 dB(A) $L_{Aeq} >$ 80 dB(A)	$R'_{w\ res} \geq 30$ dB[a] $R'_{w\ res} \geq 50$ dB		DIN 4109:2018
Italy (IT)		$D_{2m,nT,w} \geq 40$ dB (II)		DPCM 5/12/1997 UNI 11367
Lithuania (LT)	$L_{den} \leq$ 55 dB(C) [e]	$D_{2mr,nT\ w} \geq 30$ dB(C) $D_{2mr,nT\ w,} + C_{rt} = D_{2mr,nT\ w} - 7$ dB	$D_{2mr,nTw} > 23$ (28) dB(E)[f]	STR 2.01.07:2003
Netherlands (NL)	$L_{den} >$ 55 dB (A)[g]	$D_{2mr,nT\ w,}+C_{rt} \geq 23$ dB(C)[h] $D_{2mr,nT\ w,}+C_{rt} \geq L_{den}$-32 dB (C)	$D_{2mr,nT\ w,}+C_{rt} >$ 18 dB	NEN 1070:1999
	Goal L_{den} indoor	Indoor: $L_{den} \leq$ 35 dB (III)	Indoor: $L_{den} \leq 45$ dB (IV)	
Poland (PO)	$L_d \leq 45$ dB $L_n \leq 35$ dB	$R'_w + C_{tr} \geq 20$ dB		PN-B-0251-3:1999
	$L_d > 75$ dB $L_n > 65$ dB	$R'_w + C_{tr} \geq 38$ dB		
Portugal (PT)	$L_{den} \leq$ 65 dB(A) $L_n \leq 55$ dB(A)	Mixed areas[i] $D_{2m,nT,w} \geq 33$ dB		RPR and RRAE (Regulamento dos Requisitos Acusticos dos Edificios) 2008

(continued on next page)

Table 2 (*continued*)

EUROPE				
Country	Outdoor Noise	New buildings	Existing buildings	BC or Standard
	$L_{den} \leq$ 55 dB(A) $L_n \leq 45$ dB(A)	Sensitive areas[i] $D_{2m,nT,w} \geq 28$ dB		
Spain (ES)	$L_d \leq$ 60dBA[j] $L_d > 75$ dB(A)	Bedroom: (di) $D_{2m,\ nT,\ Atr} \geq$ 30 dB(A) $D_{2m,\ nT,\ Atr} >$ 47 dB(A) Living room: $D_{2m,\ nT,\ Atr} \geq$ 30 dB(A) $D_{2m,\ nT,\ Atr} >$ 42 dB(A)		CTE DB HR RD 1367/2007
Switzerland (CH)	$L_d > 60$ dB(A) $L_n > 52$ dB(A)	Bedroom (di) $D_e = D_{nT,} + C_{tr} - C_v = L_{r,n} - 25$ dB $D_e \geq 27$ dB[k] Living room $D_e = D_{nT,} + C_{tr} - C_v = L_{r,j} - 33$ dB $D_e \geq 27$ dB[k] Indoor: $L_{Aeq} =$ 33 dB(A) day Indoor: $L_{Aeq} =$ 25 dB(A) night		SIA 181:2006
	$L_d \leq 55$ dB $L_n > 81$ dB	$D_{nTA,tr} \geq 30$ dB $D_{nTA,tr} \geq 45$ dB[l]		Reglementation acoustique des batiments neufs. 2017

NOTES.
Class denotations in parentheses.
Equivalences: $D_{Atr} = D_{nT,A,tr} = D_{2m,nTA} = D_{2m,\ nT,\ Atr} = D_{2mr,nT\ w,} + C_{tr}$; $R_{Atr} = R_w + C_{tr}$.
(di) different values for bedroom and living room.
[a] $R`_{w\ res}$ = sound reduction index of the assembled components.
[b] $L_A = L_{Aref} - 3$ dB (L_{Aref} measured at 2 m distance).
[c] m = 0 dB except m = 3 dB when the room has more than 2 façade panes containing building elements $R_{Atr} < 48$ dB and $L_A > 60$ dB in front of each façade pane.
[d] n = total length ventilation grids; S_{netto} = surface of building elements of the façade panes with $R_{Atr} < 48$ dB.
[e] Requirements apply when $L_{den} \leq 70$ dB(A). At higher noise levels, limit values are adjusted by calculation.
[f] Numbers: criteria for the outdoor noise class (C); numbers in brackets: when criteria for the outdoor noise class is the same as class for the façade.
[g] A minimum value of 55 dB(A) is considered if no specific sources are present.
[h] Formula of requirements for façade: $D_{2m,nTA}$-10logV/3S = L_{den}–30 dB.
[i] Limit values are increased by 3 dB, when in new housing buildings in urban centres the limit values are not exceeded by more than 5 dB(A). If window surface >60% then $D_{2m,\ nT,\ w} + C_{tr}$ must be considered.
[j] When no official data are available on the value of the day noise index, L_d = 60 dB(A).
[k] Cv = receiving room volume correction (= 0 if V < 200 m^3; up to 5 dB if V > 800 m^3.
[l] Differences depending on type of street, orientation, obstacles, exposure to noise.

environments over 50 years old, whose residents live in social and economic conditions of vulnerability, and constitute a large percentage of the aging population. In this regard, the acoustic quality of existing housing stock is obsolete and generally inadequate and deficient in complying with current regulations and reducing the level of external noise entering the dwelling. There is therefore a need for efficient management renovation work strategies for the building refurbishment and enhancement of the acoustic performance of existing residential

Table 3
Maximum indoor levels inside residential buildings from traffic noise.

EUROPE				
Country	Outdoor Noise	New buildings	Existing buildings	BC or Standard
Croatia (CR)		$L_{RAeq} \leq 35$ dB(A) day $L_{RAeq} \leq 25$ dB(A) night		HRN U.J6.201
Denmark (DK)	$L_{n\ 22\text{-}7} \leq 40$ dB (recommend)	$L_{Aeq,24h} < 30$ dB(C) Indoor L_{den} < 33 dB(C) Indoor L_{night} < 25 dB(C)	$L_{Aeq,24h} <$ 35 dB(D) $L_{den} <$ 38 dB(D) $L_{night} <$ 30 dB(D)	DS 490:2007
Finland (FI)		$L_{Aeq,7\text{-}22} <$ 35 dB(C) $L_{Aeq,22\text{-}7} <$ 30 dB(C)	$L_{Aeq,7\text{-}22} <$ 35 dB(D) $L_{Aeq,22\text{-}7} <$ 30 dB(D)	
Greece (GR)	$L_{eq} \leq 63$ dB(A) $L_{eq} > 73$ dB(A) (range recommended)	Bedroom night (di)[a] $L_{eq} \leq$ 30–35 dB(A) Living room day $L_{eq} \leq$ 35–40 dB(A) (II-III) $L_{1,AF,1h} \leq$ 30–35 dB(A)		ΕΛΟΤ 565:2010 (Greek Building Regulations) VDI 2719
Iceland (IS)		$L_{pAeq,24h} \leq$ 30 dB(C) $L_{pAF\ max} \leq$ 45 dB(C)	$L_{pAeq,24h} <$ 35 dB(C) None	IST 45:2016
Norway (NO)	$L_{den} \leq 55$ dB $L_{AF\ max} \leq 70$ dB	$L_{pAeq,24h} \leq$ 30 dB(C) $L_{pAeq,max\ 23\text{-}7}$ ≤ 45 dB(C)	$L_{pAeq,24h} <$ 35 dB(D) $L_{pAeq,max23\text{-}7} <$50 dB (D)	NS 8175:2012
Slovenia (SL)		$L_{Aeq} \leq 35$ dB (A) day $L_{Aeq} \leq 30$ dB (A) night		Uradni list RS, št. 10/12 in 61/17 – GZ
Sweden (SE)	$L_{pAeq,nT} \leq 55$ dB $L_{pAeq,max} \leq 70$ dB	$L_{pAeq,nT} \leq 30$ dB(C) $L_{pAF,max,22\text{-}06}$ ≤ 45 dB(C)	$L_{pAeq,nT} <$ 34 dB(D) $L_{pAeq,max,nT} < 49$ dB (D)	SS 25267:2004
	Continuous: $L_{pAeq,nT} \leq 45$ dB $L_{pAeq,max} \leq 50$ dB Impulsive: $L_{pAeq,nT} \leq 40$ dB $L_{pAeq,max} \leq 45$ dB	Continuous broadband: $L_{pAeq,nT} \leq 28$ dB $L_{pAeq,max,nT}$ ≤ 33 dB Impulsive/narrowband: $L_{pAeq,nT} \leq 25$ dB $L_{pAeq,max,nT}$ ≤ 30 dB		Decree by the Ministry of Acoustic environment on the Acoustic Env. 2012
Switzerland (CH)	$L_d > 60$ dB(A) $L_n > 52$ dB(A)	$L_{Aeq} = 33$ dB (A) day $L_{Aeq} = 25$ dB (A) night		

NOTES.
Class denotations in parentheses.
Equivalences: total equivalent sound pressure level from traffic and other outdoor noise source = $L_{RAeq} = L_{Aeq} = L_{pAeq,nT} = L_{pAeq,24h}$; maximum permissible indoor equivalent noise levels = $L_{pAF\ max} = L_{pAeq,max,nT}$.
(di) different values for bedroom and living room.
[a] Indoor values not dependent on outdoor level.

Table 4
Minimum airborne sound insulation of façades of residential buildings.

WORLDWIDE			
Country	Outdoor Noise	New buildings	BC or Standard
Argentina (AR)	$L_{day} \leq$ 50–80 dB (A) $L_{night} \leq$45–80 dB (A)	$D_{2m,n,T,w} \geq$ 53 dB[a] $D_{2m,n,T,w} \geq$ 36 dB[b]	IRAM 4044:2015 (recommendation)
Australia (AU)	$L_{day} \leq$ 54–74 dB (A) $L_{nigh} \leq$ 50–70 dB (A)	Bedroom night (di) $L_{Aeq} \leq$ 35 dB(A) Living room day $L_{Aeq} \leq$ 40 dB(A) $R_w + C_{tr} \geq$ 50 wall $R_w + C_{tr} \geq$ 25–40 window[c]	NCC:2018
Brazil (BR)	$L_{Aeq} \leq$ 60 dB $L_{Aeq} \leq$ 66–70 dB[d]	$D_{2m,n,T,w} \geq$ 20 dB $D_{2m,n,T,w} \geq$ 30 dB	ABNT NBR 15575:2013
Chile (CL)	$L_{day} \leq$ 60 dB $L_{day} >$ 75 dB	$D_{nT,w} + C_{tr} \geq$ 20 dB $D_{nT,w} + C_{tr} \geq$ 40 dB	O.G.U.C. 2006 NCh 352/1.Of2000
Canada (CA)	$L_{day} \leq$ 55–60 dB (A)[e]	Bedroom night (di) $L_{Aeq} \leq$ 40 dB(A) Living room day $L_{Aeq} \leq$ 45 dB(A)	ASTM E 1332:2006 CMHC NBC
Russia (RU)	$L_{Aeq} \leq$ 60 dB(A) $L_{Aeq} >$ 80 dB()A	Ra ≥ 15 dB(A)[f] Ra ≥ 25 dBA	СНиП:2003
United States (US)	$L_{den} \leq$ 65 dB(A) (recommended)	OITC-35 (80-4 kHz)[g] $L_{eq} \leq$ 45 dB(A)	IBC. 2018 CEQR Tech.Manual HUD Guidelines

NOTES.
Class denotations in parentheses.
(di) different values for bedroom and living room.
[a] for “blind” walls.
[b] for glass areas (max. 20% of façade).
[c] Range of values. Minimum Rw + Ctr of closed window depending on area of windows as % of room floor area and sound exposure category.
[d] For incident noise levels above 70 dB, a specific study should be performed to estimate the façade sound insulation.
[e] Where the daytime sound level >60 dB(A), control measures are required to reduce the sound level to ≤ 60 dB(A).
[f] Ra = L_{A2m} – $L_{Aд}$0 +10 log So – 10 log Bh – 10 log k, where: L_{A2m} = equivalent (maximum) sound level outside at a distance of 2 m from the façade, dB(A); $L_{Aд}$0 = permissible equivalent (maximum) sound level in the room, dB(A); So = window area, m^2; Bh = acoustic constant of the room, m^2 (in the octave band of 500 Hz; k = coefficient taking into account the violation of the diffuseness of the sound field in the room.
[g] Recommended value. IBC does not contain requirements for exterior wall STC or OITC. OITC tends to be 5–10 points lower than the corresponding STC for the same façade element. OITC = 100.13–10 log (Σ 10ˆ (AWRSi – Tli/10⁾), where AWRSi = the A-weighted reference Sound Level; and TLi = Sound Transmission Loss, for each one-third octave band.

buildings.

Users should be concerned about outdoor noise (transport, leisure, etc.) impacting the interior. In general, this noise is transmitted through the windows, the weakest point of the façade, both in thermal and acoustic terms. Thus, the window assemblies may require upgrades in order to enhance the acoustic category and corresponding classification.

Regarding the improvement of sound insulation of façades, different techniques and changes to the external building façade can be conducted:

- leakage sealing between frame and wall and/or frame and glazing.
- improvement of acoustic performance of the shutter box by filling it with absorbent material.
- installation of an additional window.
- window improvement or replacement which can follow different strategies:
  - type of window – sliding or tilt/turn
  - type or glazing – single leaf, double leaf, laminar, insulating units
  - Blind box – inexistent, indoor or outdoor
  - Percentage of window in total façade wall

In this study, the façade solutions of residential building stock will be analysed along with current regulations worldwide. A base model of a room and a common existing façade partition is proposed, showing different variations in window solutions.

5.1. Description of base model

To carry out the study, the following aspects are determined:

- Opaque wall: a façade solution with an acoustic insulation of 45 dB (R_{Atr}) according to laboratory analysis. Façade wall layers are: 0.115 m of perforated brick (with mortar coating), 0.04 m not-ventilated air chamber, 0.04 m hollow brick partition, and 0.015 of plaster coating.
- Window: different window solutions can be considered, with acoustic behaviour in a range of (R_w) 27–32 dB. To do this, changes are made to different types of elements such as closure type, glazing type, air chamber or blind box. Likewise, a variation in the window percentage with respect to the façade surface is established, with a range between 15% and 60%. Table 5 shows R_w value depending on window characterization.
- Room: a standard bedroom in a social housing building is considered. Table 6 shows the geometrical dimensions (length, width, height area and volume) of the room considered, which represents a standard bedroom in a existing residential building.

6. Results and discussion

6.1. Requirements and recommendations in europe and other countries worldwide

Fig. 1 a-b) shows the requirements of minimum façade sound insulation and maximum indoor noise level, determined in national standards and BCs for new and, when appropriate, also for existing social housing. As can be seen, the required values for renovated residential buildings are generally omitted or not specified in the regulations.

Table 5
R_w value depending window characteristics without blind box or outdoor blind box [50].

R_w (dB)	Type of glazing	Type of window	Air chamber	Thickness (mm)
27	Single leaf	Sliding or Tilt/turn	NO	4
	Double. Insulating units	Sliding	YES	4 – (6 … 20) – 4
28	Single leaf	Sliding or Tilt/turn	NO	6
	Double. Insulating units	Sliding	YES	6 – (6 … 20) – 6
29	Single leaf	Sliding	NO	8
	Double. Laminar	Sliding	NO	6 + 6
	Double. Insulating units	Sliding	YES	4 – (6 … 20) – 6
30	Single leaf	Sliding	NO	12
	Single leaf	Tilt/turn	NO	4
31	Single leaf	Tilt/turn	NO	6
32	Single leaf	Tilt/turn	NO	8
	Double. Laminar	Tilt/turn	NO	6 + 6
	Double. Insulating units	Tilt/turn	YES	4 – (6 … 20) – 6

Table 6
Geometrical dimensions of the room considered.

	DIMENSIONS		AREA	VOLUME
	LENGTH (m)	WIDTH (m)	(m^2)	(m^3)
Floor	2.4	3.33	8	–
Façade	2.4	2.65	6.36	–
Room	–	–	–	21.2

To present a complete summary of all the information and variations of each regulation in a single table is not possible. However, this work aims to represent the variability of criteria and peculiarities of each country. It should be noted that certain countries use a dB(A) metric instead of dB in their requirements, which further complicated comparative work.

Numerous factors may influence the determination of limit values. In most countries, a minimum façade insulation requirement is established for exposure to traffic noise ($D_{nT,A,tr}$ or $D_{2mr,\ nT\ w,} + C_{tr}$), while in other cases the requirement $D_{2m,\ nT,w}$ (IT or PT) is imposed. Some countries determined different values according to the use of the room (bedroom or living room) or the location of the building (mixed or sensitive areas). In addition, Tables 1–3 and Fig. 1 show that, in most cases, the insulation requirement varies according to outdoor noise, which is up to 50% higher in extremely high noise situations/areas [80 dB(A)]. A clear example of this are the social housing areas sometimes built on the outskirts of cities, close to airports. Façade sound insulation, $D_{2mr,nT\ w}$ values are represented with solid shading while $R{\cdot}_w$ values are represented with striped shading. Values in dB(A) are represented with point shading (ES, CR, GR and CH). $D_{2m,nT,w}$ value for IT and PT.

Although all this casuistry makes it more difficult to compare the requirements of all countries, Table 2 shows the need for harmonization between values and/or indices since variations of the same parameter are close to 10 dB (between LT, NL and FR) or even exceed this value (between PT and IT). Regarding requirements for old buildings, Fig. 1a) shows that in the cases where these values are identified, limit values vary by 5–7 dB with respect to the requirements in new buildings, depending on whether the requirement refers to the performance of façade or the equivalent indoor noise. It is also interesting to note the sound classification schemes established in Nordic countries and others (NL, LT or IT). When providing various levels of comfort (I to V or A to E) different limits are indicated for new and renovated housing, usually with a variation of 5 dB between classes.

When analysing the requirements of other countries worldwide, even greater variability is observed. In some cases, recommendations are provided instead of requirements, while in countries such as USA or CA mention is made of OITC, a new index that refers to a number rating of the sound transmission loss of a constructed assembly tested also considering lower frequencies.

6.2. *Façades of existing social housing and compliance with regulations*

Fig. 2 shows the façade acoustic performance with respect to the type of window considered and the percentage (%) of window in the total façade surface. It also shows the legal values of individual countries in order to visually determine the extent to which each solution meets the limits established. Values were calculated based on determinations established on standards [51]. An external noise level of 60 dB (Figs. 2a) and 80 dB (Fig. 2b), as an extreme case, is considered. The countries providing the data in dB(A) are not represented graphically.

When maximum indoor noise level is provided as a limiting value,

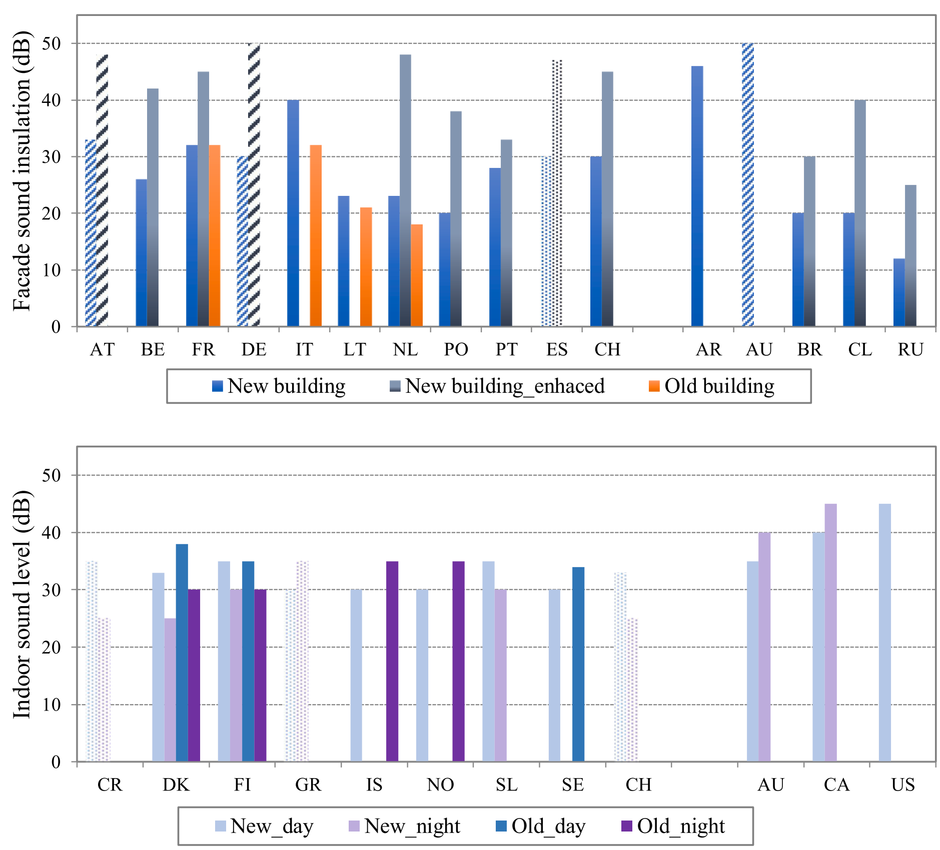

Fig. 1. Required values established in national standards and BCs for new residential buildings and renovated buildings: a) Façade sound insulation ($D_{2mr,nT\ w,}$+C_{tr}), b) Indoor Noise level (L_{Aeq}). $D_{2mr,nT\ w}$ values are represented with solid shading while $R{\cdot}_w$ values are represented with striped shading. Values in dBA are represented with point shading (ES, CR, GR and CH).

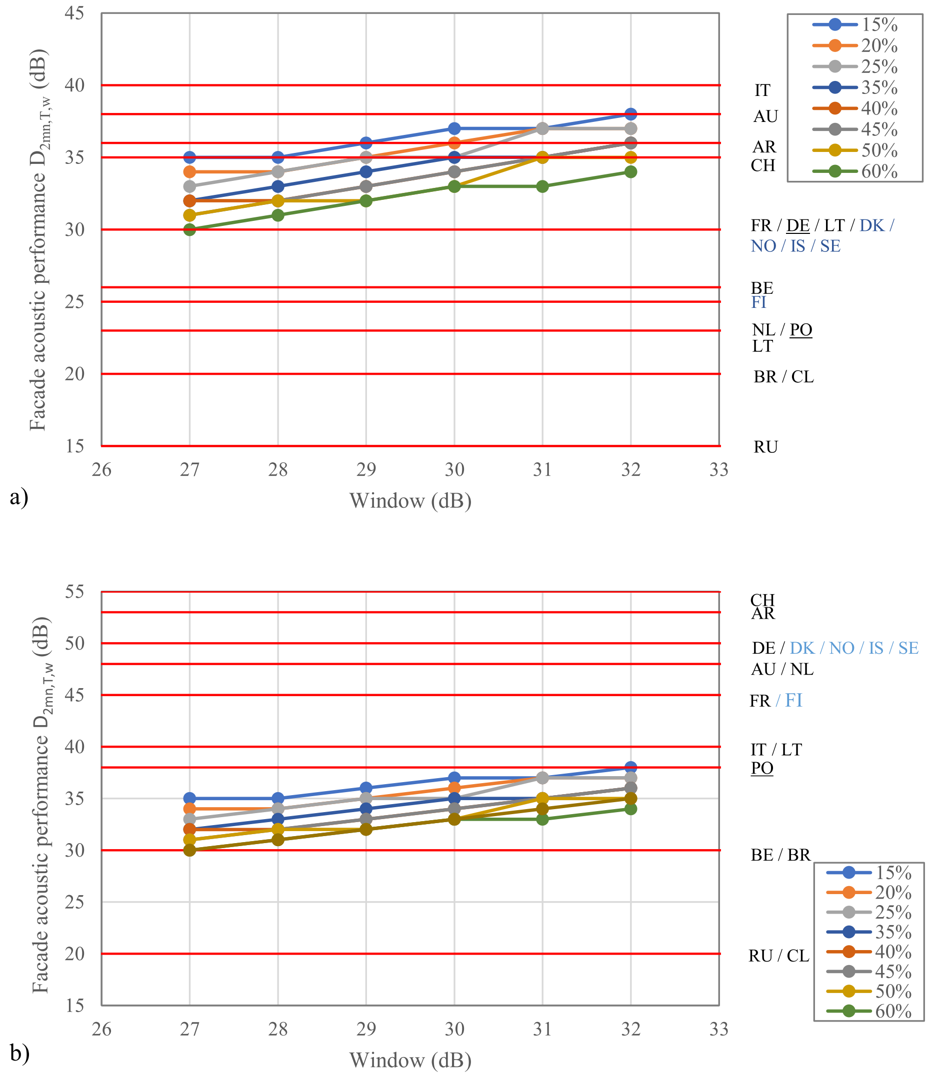

Fig. 2. Façade acoustic performance ($D_{2mn,T,w}$) depending on the type of window and the percentage of window surface in the total façade surface. Regulatory values of countries. a) A-weighted outdoor noise amounting to 60 dB b) A-weighted outdoor noise amounting to 80 dB.

the zoning definition is considered. The zoning definition concerns the sound insulation of the external structure of a building [42]. The provision is issued in the form of the difference between the outdoor noise level at the façade of the building and the noise level permitted inside the building. For example, if the average sound level emitted by traffic in the daytime at the façade amounts to 60 dB, and the requirement L_{Aeq} for a residential building amounts to 35 dB, then the zoning provision is 65 dB–35 dB = 30 dB.

The opaque façade composition considered corresponds to a standard façade solution for existing buildings. Fig. 2 shows that in general, for a R_w value of 27–28 dB and a gap percentage of 30% of the façade, the acoustic requirements of most of the countries analysed are met, in a situation of 60 dB outdoor noise. This does not occur in the case of 80 dB, since the established requirements are barely fulfilled. However, it is unusual for residential buildings to be located in such high noise areas.

The requirements of the current energy regulations are very demanding, given the need to minimize energy consumption in buildings. For this reason, the façade constructive system of new buildings displays high thermal performance, as well as acoustic, so that it will be not difficult to comply with the acoustic requirements established worldwide.

7. Conclusions

This paper documents the façade acoustic requirements of new and existing buildings established in current national building regulations. This comparative study determines and support the lack of consensus on external noise insulation between acoustic requirements worldwide by identifying the different perspectives between countries as regarding the acoustic retrofit of existing residential buildings. Façade acoustic performance cannot be expressed as a single indicator since the required sound insulation depends on different variables including the performance of the building element, the outdoor noise level, or the sound indoor level. Variations between countries of the same limiting value are close to 10 dB for new buildings. Regarding requirements for old buildings, when values are identified, limiting values vary between 5 and 7 dB with respect to the requirements in new buildings.

This study also aims to analyse the acoustic effect of variations in façade windows of residential buildings and the compliance with current regulations worldwide. Results show that acoustic retrofit works focused on windows can be sufficient to propose suitable constructive systems in compliance with requirements established worldwide when external noise amount to 60 dB (A).

Windows are considered the weakest element of facade from a thermal and acoustic point of view. The analysis of the façade acoustic performance with respect to the window characteristics determines that acoustic retrofit based on strategies focused on improving the quality of windows can determine a significant improvement in acoustic performance, facilitating compliance with the requirements. In this regard, it is important that urban regeneration plans promote this type of strategies and constructive proposals.

It is important to highlight the important effects of noise on human health, a fact corroborated by numerous scientific studies. Housing is the space in which humans spend the most time, especially since the global pandemic by COVID-19 was declared. Since then, the home has also become, in many cases, a workplace. It is difficult to understand the existing disparity in terms of acoustic requirements, even at the European level, when the objective should be common to all.

In summary, as stated by previous research studies, harmonization of concepts in terms of reference descriptors related to facade sound insulation is recommended since it is not easy to compare the requirements of different countries. Future cooperative work should focus on the need to promote worldwide discussions to coordinate acoustic criteria.

Author statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: None.

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Appendix A. Supplementary data

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