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IMPROVING SOUND INSULATION OF OLD TIMBER FLOOR CONSTRUCTIONS 1917/1937 IN MULTI-STOREY HOUSING – FIELD CASE STUDY & PERSPECTIVES

Birgit Rasmussen [1*]
[1] BUILD – Department of the Built Environment, Aalborg University, 2450 Copenhagen SV, Denmark

ABSTRACT

In Denmark, the first national requirements for sound insulation in housing were published in 1961. Most complaints about neighbour noises are from people in multi-storey housing (MSH) and relate to impact sound from both children and adults, although also annoyance due to airborne sounds are common. A mapping of the housing stock timeline and construction types showed that more than half of the MSH dwellings were built before 1961 and that most housing is brick-built with timber floor constructions.
In a project investigating air particle transfer vertically between dwellings, we had the opportunity to make a case study with test of airborne and impact sound insulation before and after mounting a new independent ceiling below the existing construction.
Measurements were made for eight floor constructions in housing built 1917/1937. The acoustic classification standard DS 490 has six classes A-F with Class C being the building code requirement for new housing. Before renovation, the airborne sound classes were D-E and impact sound F. After mounting of new ceilings, R'_w values were improved ~6 dB and $L'_{n,w}$ ~12 dB, implying that all results became Class C, thus complying with limits for new-build. The paper will describe experiences from the case study and the perspectives concerning preparation of acoustic regulations for renovated dwellings and mandatory acoustic labelling.

Keywords: *apartments, sound insulation improvement, old timber floors, acoustic labelling, building regulations.*

[*] ***Corresponding author**: bira@build.aau.dk.*

1. INTRODUCTION

Most countries in Europe have acoustic regulations for various types of buildings, including housing. This paper deals with airborne and impact sound insulation between dwellings in multi-storey housing (MSH) and the need for improvements, especially for old housing. The results for a field case study with renovated timber floor constructions in housing from 1917 and 1937 are described. Information about the Danish requirements is found in Table 1.
Sound insulation requirements for 35 countries in Europe are found in [1]. Several countries also have acoustic classification schemes (ACS), and national regulations often refer to or correspond to a specific class in a national ACS. Information about acoustic classification schemes and sound insulation descriptors in 14 countries in Europe are described in [2]. Several ACS have none or too few classes for old housing.
Both requirements and acoustic classes relate to peoples everyday life, because neighbour noise often is a significant problem in multi-storey housing (MSH), cf. [3] and [4], both based on a social media analysis of over 700 comments to two newspaper articles about neighbour noise and acoustic labelling of dwellings. The housing stock in Denmark and the case study results are described in the following Sections of the paper.

Table 1. Sound insulation main requirements [(1)] in the Danish building regulations for walls/floors between dwellings constructed in the period from 1961 until now.

Period	Housing type	Airborne sound insulation [(1)]	Impact sound insulation [(1)]
1961[(2)] –2008	Multi-storey [(3)]	$R'_w \geq 52$ dB (horizontal) $R'_w \geq 53$ dB (vertical)	$L'_{n,w} \leq 58$ dB
Since 2008	Multi-storey and row housing	$R'_w \geq 55$ dB	$L'_{n,w} \leq 53$ dB

Note 1: Limit values until 1982 are estimated by converting to the descriptors R'_w and $L'_{n,w}$ applied in the current Danish building code.

Note 2: Before 1961, there were no general national building regulations.

Note 3: For terraced housing (row housing), the limit values were: $R'_w \geq 55$ dB from 1966 and $L'_{n,w} \leq 53$ dB from 1977.

2. MULTI-STOREY HOUSING IN DK AND THE NEED FOR IMPROVED SOUND INSULATION

In Table 2 is found an overview of classes in the current Danish classification scheme, DS 490:2018 [5], which has six classes A-F covering the Danish housing stock. The table provides simple explanations of the intended application of classes for new and old housing, see [5],[6]. It also indicates the occupants' expected evaluation of the sound insulation.

In Figure 1 is found overview of the Danish ,multi-storey housing stock with construction types in different time periods, number of dwellings and estimated acoustic performance. More information is found in [6],[7],[8],[9]. Detailed construction guidelines for new housing are found in [10] and guidelines for improvement of existing housing are found in [7].

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Table 2. Occupants' expected satisfaction for different sound classes according to DS 490:2018 [5]. Summary based on information in DS 490.

Sound insulation between dwellings Main class criteria A-F in DS 490:2018		
Class	Airborne	Impact
A	$R'_w + C_{50\text{-}3150} \geq 63$ dB	$L'_{n,w} \leq 43$ dB and $L'_{n,w} + C_{I,50\text{-}2500} \leq 43$ dB
B	$R'_w + C_{50\text{-}3150} \geq 58$ dB	$L'_{n,w} \leq 48$ dB and $L'_{n,w} + C_{I,50\text{-}2500} \leq 48$ dB
C	$R'_w \geq 55$ dB	$L'_{n,w} \leq 53$ dB
D	$R'_w \geq 50$ dB	$L'_{n,w} \leq 58$ dB
E	$R'_w \geq 45$ dB	$L'_{n,w} \leq 63$ dB
F	$R'_w \geq 40$ dB	$L'_{n,w} \leq 68$ dB
Reference: DS 490:2018 "Lydklassifikation af boliger" (Sound classification of dwellings)		

Characteristics of DS 490 sound classes for dwellings and occupants' estimated evaluation Information from DS 490:2018		
Sound class descriptions	Good or very good	Poor
Excellent acoustic conditions. Occupants will be disturbed only occasionally by sound or noise.	> 90 %	
Significant improvement compared to minimum in class C. Occupants may be disturbed sometimes.	70-85 %	< 10 %
Sound class intended as the minimum for new buildings.	50-65 %	< 20 %
Sound class intended for older buildings with less satisfactory acoustic conditions.	30-45 %	25-40 %
Sound class intended for older buildings with unsatisfactory acoustic conditions.	10-25 %	45-60 %
Sound class intended for older buildings with clearly unsatisfactory acoustic conditions.	< 5 %	65-80 %
Note: Within each sound class the percentage of satisfied or dissatisfied occupants may depend on the type of criterion. The grouping is mainly based on the subjective assessments of airborne and impact sound from adjacent dwellings.		

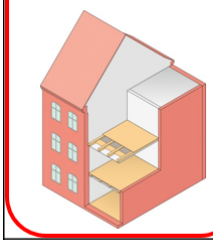
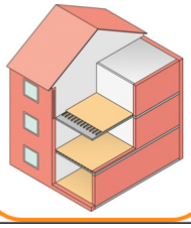
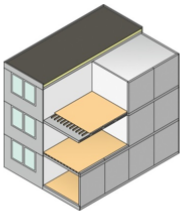
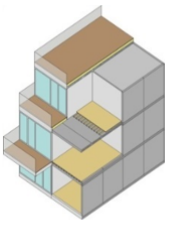
Building type E1	Building type E2	Building type E3	Building type NEW
Old brick-built buildings with timber floor constructions Period: ~ 1850 to 1930/1950 No. of dwellings in Danmark: ~ 500.000	Brick-built buildings with thin in-situ concrete slabs and wooden floors Period: ~ 1930 to 1960 No. of dwellings in Danmark: Up to ~ 100.000	Concrete elements with wooden floors Period: ~ 1960 to 2009 No. of dwellings in Danmark: ~ 400.000	Concrete elements with wooden floors Period: ~ 2010 to 2024ff No. of dwellings in Danmark: ~ 160.000 (incl. 2024)
			
Regulations: None	Regulations: None	Regulations: BR1961-BR1995	Regulations: From BR2008
Estimated performance: R'_w ~ 42-50 dB $L'_{n,w}$ ~ 63-75 dB	Estimated performance: R'_w ~ 45-53 dB $L'_{n,w}$ ~ 58-67 dB	Estimated performance: $R'_w \geq$ 52-53 dB $L'_{n,w} \leq$ 58 dB	Estimated performance: $R'_w \geq$ 55 dB $L'_{n,w} \leq$ 53 dB
Acoustic classification DS 490:2007: None DS 490:2018: Class F	Acoustic classification DS 490:2007: None DS 490:2018: Class E	Acoustic classification DS 490:2007: Class D DS 490:2018: Class D	Acoustic classification DS 490:2007: Class C DS 490:2018: Class C

Figure 1. Overview multi-storey housing stock in Denmark, number of dwellings and construction types in various time periods. Building regulations, estimated acoustic performance and expected acoustic classes indicated. More information about constructions is found in [6], [7], [8].

The housing stock in Denmark consists of about 2.8 mio dwellings [11], of these almost 1.2 mio dwellings in multi-storey (MS) housing, 450.000 row houses and most others single-family houses. In Figure 2 is found a diagram with number of MS dwellings according to construction year, and with the estimated acoustic class F, E, D, C according to DS 490:2018 [5], shown for various time periods. A Danish Health and Morbidity Survey in 2017 showed that about 36 % of people in multi-storey housing are slightly or very annoyed by neighbour noise, while for row/double housing only 12 %, see [12], [13]. The disturbing/annoying neighbour noises include for example footsteps, voices/shouting/arguments, playing/jumping children, parties, barking dogs, see e.g. [3], [9], [14], and for many people, the implications are sleep disturbances and strong negative influence on own "freedom" and activities. The result is adverse influence on quality of life.

In many old dwellings, people experience an almost total lack of privacy, since they hear, what they don't want to hear, which reminds them that even one's own ordinary activities being a part of a normal life are no longer possible without involuntarily "informing" the neighbours, [3], [9].

The relevant sound insulation improvement solutions depend on the actual performance of the existing building, the wishes/goals for the future acoustic conditions and the resources available for the upgrading. For the Danish multi-storey housing stock, the highest need is for building types E1 (almost half of Danish dwellings) and E2, cf. Figure 1 and Figure 2. The main principles for improvement of sound insulation of dwellings are indicated in Figure 3.

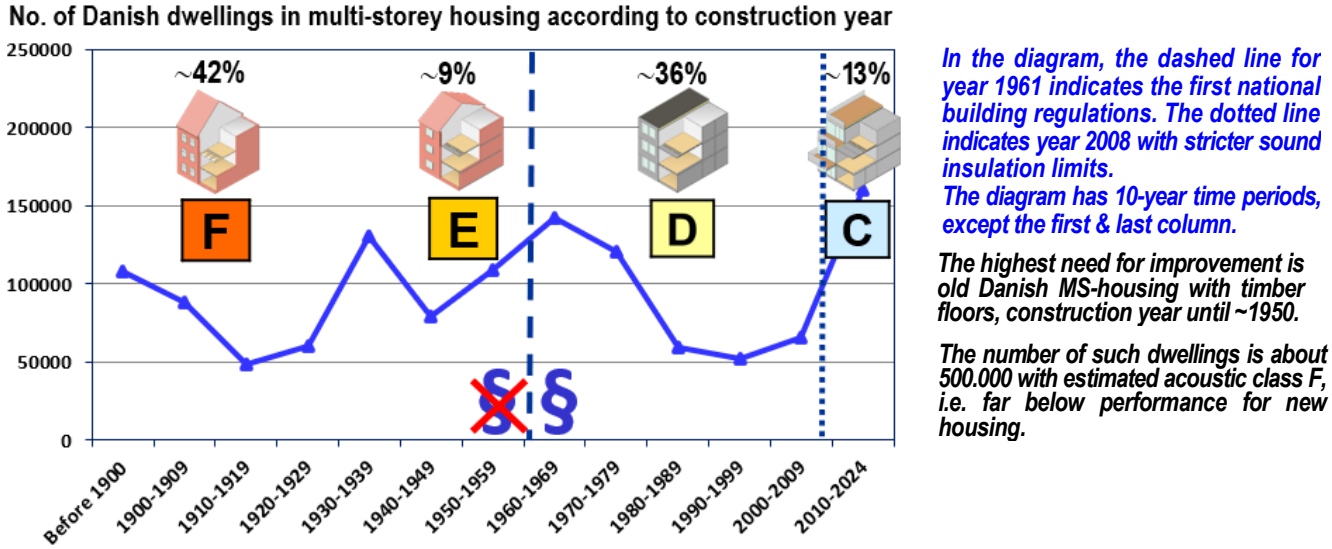


Figure 2. No. of Danish dwellings 1900-2024 in multi-storey housing according to construction year [11]. Estimated acoustic classes F, E, D, C according to DS 490:2018 [5] are indicated.

Figure 3. Left: Main principles for improvement of sound insulation in existing housing: New ceilings, wall linings, floors, see red lines. Right: A 10-page folder [9] has been published with indications of construction solutions for housing from different time periods. Detailed construction guidelines are found in [7].

3. CASE STUDY PROCEDURE AND TEST RESULTS

A case study about improvement of airborne and impact sound insulation for timber floor constructions was conducted for eight floors in two housing blocks in Copenhagen – as a supplement to a research project about air particle transfer through timber floor constructions in the same apartments.
We contacted several housing associations in the Copenhagen area, explaining the relevant construction type, purposes of project and asking about potential apartments appropriate for the case study. After inspection and evaluation, it was decided to make the renovation for eight floor constructions, four of them in apartments in 2200 CPH N (AKB, Guldbergsgade GBG, construction year 1917), and the other four in 2300 CPH S (AAB, Kirkegårdsvej KGV and Tycho Brahes Allé TBA, construction year 1937). In all cases, the occupants had made complaints about neighbour noises.
The existing timber floor constructions had a height ~27 cm, and the height of the ceiling to be installed below is ~12 cm. The ceiling consists of two gypsum plates fixed to steel profiles mounted from wall to wall and with mineral wool in the spacing above the gypsum plates, cf. Figure 4. For further details, see manufacturers' instructions. The room height in all rooms was 270 cm, and it was possible to install the ceilings without severe obstacles.

Field tests were carried out using the standardized methods [15], [16] as prescribed in the building regulations. The field tests were carried out by Rambøll [17], [18]. The project results are described in [19], section 2.
Floor areas S and room volumes V in GBG, 2200 CPH N, were 15-30 m^2, and 38-85 m^3. For KGV and TBA, 2300 CPH S, floor areas S were 14-19 m^2, and room volumes 36-51 m^3.

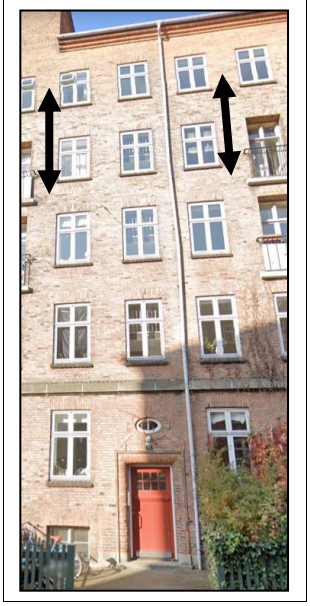
Figure 4. Timber floor constructions. The left drawing shows the original construction, the drawing to the right includes a new self-supporting ceiling. The drawings are from https://gi.dk/byggeteknisk-viden/.

The test results for GBG (CPH 2200 N) are found in [17], [19] and summarizwd in Table 3 below. The improvements in sound insulation values and classes are shown in the two last columns. The test results for CPH 2300 S were similar and also reached Class C after renovation. The results are found in [18] and in [19], Section 2.

Table 3. Test results for airborne and impact sound insulation between floor 3 and 4 before and after mounting new ceilings in GBG, rooms on 3rd floor, two rooms in each apartment (denoted Room1 and Room2). In total four constructions tested.

Address: AKB, Guldbergsgade, 2200 Copenhagen N. Construction year 1917.							
Test results airborne sound insulation R'_w between 3rd and 4th floor before and after mounting of new ceilings in rooms on 3rd floor. Test results before are in brackets.							
Test No. & direction		Source room	Receiving room	R'_w dB	Acoustic class	**Before / After**	
						$\Delta R'_w$ dB	**Acoustic class**
1	↑	GBGth3 Room2	GBGth4 Room2	57 (50)	C (D)	**+ 7**	**D → C**
2	↑	GBGth3 Room1	GBGth4 Room1	56 (49)	C (E)	**+ 7**	**E → C**
3	↑	GBGtv3 Room2	GBGtv4 Room2	56 (51)	C (D)	**+ 5**	**D → C**
4	↑	GBGtv3 Room1	GBGtv4 Room1	57 (49)	C (E)	**+ 8**	**E → C**
Test results impact sound $L'_{n,w}$ between 4th and 3rd floor before and after mounting of new ceilings in rooms on 3rd floor. Test results before are in brackets.							
Test No. & direction		Source room	Receiving room	$L'_{n,w}$ dB	Acoustic class	**Before / After**	
						$\Delta L'_{n,w}$ dB	**Acoustic class**
5	↓	GBGth4 Room2	GBGth3 Room2	53 (64)	C (F)	**– 11**	**F → C**
6	↓	GBGth4 Room1	GBGth3 Room1	53 (64)	C (F)	**– 11**	**F → C**
7	↓	GBGtv4 Room2	GBGtv3 Room2	52 (65)	C (F)	**– 13**	**E → C**
8	↓	GBGtv4 Room1	GBGtv3 Room1	52 (66)	C (F)	**– 14**	**F → C**

Apartments 3rd & 4th floor



It must be noted that the project included only investigation of timber floor constructions, i.e. vertical tests of airborne and impact sound insulation, but not all the other tests requested for a complete classification of an apartment or building according to DS 490 [5]. These tests are for example sound insulation tests between rooms in other directions, façade sound insulation, service equipment noise and reverberation time in stairwells.

Results GBG 121, 2200 CPH N (construction year 1917).
Results due to new ceilings in the apartments:
The airborne sound insulation changed from Class D/E to C.
The impact sound insulation changed from Class F to C.
For all renovated constructions, Class C is obtained, which is the building code requirement for new-build.

Results KGV & TBA, 2300 CPH S (construction year 1937)
Results due to new ceilings in the apartments:
The airborne sound insulation changed from Class D/E to C.
The impact sound insulation changed from Class E/F to C.
For all renovated constructions, Class C is obtained, which is the building code requirement for new-build.

Summary of results for all eight renovated constructions
It was a positive surprise that all timber floor constructions renovated with a new ceiling obtained acoustic class C for both airborne and impact sound insulation. It was not on beforehand a goal to reach Class C, since it was expected that flanking transmission through the walls might reduce significantly the effect of the new ceilings. The goal was mainly to observe how far we could get.
The big question is of course whether similar results could be expected for other multi-storey housing with similar constructions? A wider project is necessary to investigate variants of the housing type E1 and also to get experience with type E2 (cf. Fig. 1) with completely different construction materials and with a lower room height, typically 250 cm.

Experiences from the project process
Starting, carrying out and completing all the activities related to the renovation project depended completely on the initiatives from and active collaboration with the housing association managers and the occupants. Thus, we are grateful to all those involved during the project period, which due to Covid-19 restrictions became longer and more complicated than expected on beforehand. However, even before the mounting of new ceilings, some occupants moved, since they had found other apartments and they had already suffered from neighbour noise for a long period and didn't know how and when the renovation would end. Moving seems to be a typical way to cope with the neighbour noise situation, cf. [3] and [4], but it requires a lot of resources in more ways (expenses, find a new place, moving).

4. ACOUSTIC REGULATIONS FOR NEW AND RENOVATED HOUSING

Sound insulation requirements for New-build in 35 countries in Europe are found in [1]. Specific requirements for renovated housing are often not clear or renovation not well-defined. The increasing building costs in general and the more recent challenge to use biogenic materials (to reduce building constructions' negative influence on climate changes) is a challenge. since the building industry has very little experience with use of lightweight materials to be applied and how to fulfil sound insulation requirements and at the same time reducing costs. Since stability of constructions and fire protection *must* be complied with, reducing other performances are considered. Consequently, acoustic requirements have got "critical" attention for more reasons, one of them being uncertainty about how to design with new materials (and fulfil requirements), another one the fact that sound insulation is not visible, and parts of the building industry consider sound insulation as luxury and not something needed for wellbeing or health.
However, typical reasons for acoustic regulations are *health* related. For example, in the current DIN 4109-1 [20], the introduction refers to health protection of occupants in housing, including also confidentiality during normal speech and protection against unreasonable disturbance. It is also stated that it *cannot* be expected that noise from outside or from neighbouring apartments will no longer be perceived or found annoying, even if the requirements laid down in the standard are met. For more information about the long story behind the current DIN 4109 series of standards and the importance for building acoustics in Germany, see [21].
In Denmark, the background and development until 1994 of acoustic regulations for housing are described in [22] and current regulations indicated in e.g. [23]. Again, as in Germany, the word health is predominant in the beginning of the regulations chapter. The situation is probably similar in many other countries.
Concerning disturbing neighbour noises, results from research projects agree that impact sound (footsteps) annoy most people, see e.g. [24],[25],[26]. Several disturbing neighbour noises are listed in [27], which also – based on a representative national survey – reports examples of potential adverse health effects of neighbour noise in multi-story housing. A strong association is found between self-reported neighbour noise annoyance and perceived stress, poor mental health, fatigue, sleeping problems, sleep quality (getting enough sleep to feel rested), see [27]. In fact the DIN 4109-1 introduction refers to the EU No 305/2011 [28] stating that construction works must be designed and built in such a way that noise perceived by the occupants or people nearby

is kept to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions.
Public knowledge and awareness about how to describe acoustic performance for housing seems limited. Some countries have included acoustic quality test certificate layouts in their acoustic classification schemes, cf. DAGA 103, [29]-[30], and ÖNORM B 8115-5 [31]. However, the actual quantitative use of such certificates has not been investigated.
Some people believe that fulfilling regulations means that you cannot hear neighbours or at least not get disturbed. That is not the reality, cf. e.g. the DIN 4109-1 introduction. In Table 2 about DS 490, expected percentages of people finding classes good or very good and poor These statements help understanding the need for both higher classes, but also for lower classes, which are needed. to be able to classify before renovation and decide the gap to current regulations. ISO/TS 19488 [32] and some national schemes have lower classes, cf. [2].
Regulations are useful, but must be supported by enforcement and knowledge about design, planning, workmanship and inspection. The Danish regulations require documentation [33] uploaded as a condition for getting a permit for use. We don't have statistics for fulfilment in reality, but in several cases things go wrong. Four severe cases are described in [23]. Reasons are either lack of respect for regulations and/or lack of knowledge in parts of the whole process. Some mistakes have been well-known for decades. European collaboration about constructions, mistakes and enforcement should be strengthened to learn from other countries. Experiences from ~30 countries are found in the COST TU0901 e-books [34]-[35], but need follow-up due to many new materials and practices.

5. CONCLUSIONS AND PERSPECTIVES

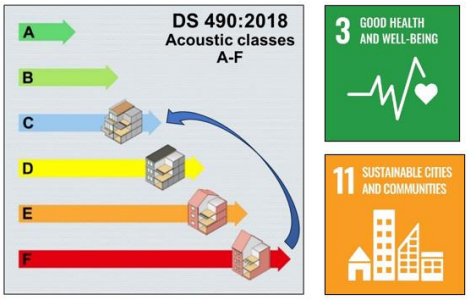
A case study about improvement of airborne and impact sound insulation R'_w and $L'_{n,w}$ for eight timber floor constructions in two old housing blocks 1917/1937 was conducted. New self-supporting ceilings were installed below the existing timber floors. The test results were very promising, since all results for the renovated constructions reached Class C, which is the requirement for New-build.
WHO and EEA have published several reports about influence of noise on health, e.g. [36]-[39]. Unfortunately, they don't deal with neighbour noise, since the focus is mainly traffic noise. However, they highlight sleep as a necessity for good health due to the restorative and consolidating effects of sleep. In the WHO-report [36], the health risks due to sleep disturbances are emphasized: "*Sleep disturbance is one of the most serious effects of environmental noise, causing both immediate effects and next-day and long-term effects on mental and cardiovascular health".* Sleep disturbance is also a typical neighbour noise problem, and it seems likely that the health risks are the same as for traffic noise.

Neighbour noise is potentially experienced 24h/7d, implying a need for more awareness, both for renovation of housing and New-build. In addition to the results of the case study, the following recommendations could be given:

- Regulations needed for renovated housing.
- Enforcement of regulations should always be respected to ensure fulfilment of requirements.
- Subjective (verbal) descriptions of classes could be included in more national acoustic classification schemes or in other ways to create more public awareness about the adverse influence of neighbour noise in housing and enhance consumer rights.
- Enhance consumer rights concerning access to acoustic quality. Occupants of dwellings should have "open access" to acoustic performance.
- Mandatory labelling [40] should be introduced as soon as possible, starting with New-build.
- Information about acoustic performance/class for dwellings should be mandatory in advertisements – as for energy.

Based on findings and quoted literature, it's hopefully obvious that sound insulation in housing is strongly related to health and quality of life. It's not just a question about comfort/luxury, but it's about protection from noise annoyances in everyday life. Proper regulations and enforcement would support healthy life for people and sustainable cities, cf. UN SDGs 3 and 11 [41].

Figure 5. The six acoustic classes A-F in DS 490 [5] and the improvement from F to C in the case study.



A strong recommendation is found in a Danish guideline from 1992: *"It should be ensured that renovation of homes also includes a decision on acoustic conditions, so that one is not subsequently left with a large housing stock that appears to have been thoroughly renovated, but is still acoustic slum."* The same reminder is unfortunately still highly relevant and included in the most recent version [7] from 2014.

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