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Compliance procedures for sound insulation between dwellings in new housing – Rules according to Danish regulations & Experiences from practice

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National building regulations have existed in Denmark since 1961 and have included acoustic regulations for housing. The housing stock in Denmark consists currently (2023) of almost 2.8 mio dwellings, of these are ~40% dwellings in multi-storey (MS) housing, ~40% one-family houses and ~15% terraced houses (row houses). This paper focuses on compliance with limits for airborne and impact sound insulation between dwellings in new-build and apply to both MS housing and terraced houses (row houses).
Issuing of building permits and permits allowing use of buildings after completion are administered by local building authorities in the municipalities, and for decades they were involved in technical details related to the building permits. However, administration of building regulations and proof of compliance changed over time – with some of the changes unfortunately implying reduced options for check of compliance. In practice, compliance with acoustic regulations suffers from various shortcomings in the building process, some related to the builders' lack of understanding of acoustic regulations or lack of inspection of the construction work, others due to lack of compliance test or building authorities' lack of expertise with how to check the validity/invalidity of field test reports. The consideration behind the building regulations' requirement for documentation is partly to ensure that buildings comply with the requirements, and partly to ensure that later users of the building have a valid documentation basis. The paper describes details of the shortcomings and provides examples of severe construction defects being noticed mainly due to field tests following user complaints. Furthermore, indications of options for improvement of documentation procedures will be described.

1 Introduction

Acoustic regulations exist in most countries in Europe for different categories of buildings. Regulations and enforcement vary considerably between countries. This paper focuses on housing and specifically on compliance with limits for airborne and impact sound insulation between dwellings. In Europe, limit values are included in building regulations in more than 30 countries, cf. [1]. The paper provides brief information about the limit values and housing stock in Denmark and the compliance rules according to the current Danish regulations. The paper includes examples of new housing with sound insulation performance far below the requirements.

2 Sound insulation regulations in Denmark for new housing

2.1 Sound insulation regulations and classification

The current sound insulation regulations in Denmark are found in [2] and [3]. The requirements for housing have not changed since 2008. In [2] is referred to [3] for limit values. Additional guidelines related to field tests in Denmark are found in [4]. Since 2008, the regulations have referred to Class C in DS 490 [5]. Table 1 shows the sound insulation limit values from 1961 until now. An overview of the acoustic classes A-F in DS 490 is found in Table 2. Test methods for check of field performance are ISO methods, see [6] and [7], which are also implemented as EN standards and as national standards in CEN member countries. The methods also include requirements for the instrumentation, e.g. [8].

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 [2].

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 regulations.

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.

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			Characteristics of DS 490 sound classes for dwellings and occupants' expected evaluation Information from DS 490:2018		
Class	**Airborne**	**Impact**	**Sound class descriptions**	**Good or very good**	**Poor**
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	Excellent acoustic conditions. Occupants will be disturbed only occasionally by sound or noise.	> 90 %	
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	Significant improvement compared to minimum in class C. Occupants may be disturbed sometimes.	70-85 %	< 10 %
C	$R'_w \geq 55$ dB	$L'_{n,w} \leq 53$ dB	Sound class intended as the minimum for new buildings.	50-65 %	< 20 %
D	$R'_w \geq 50$ dB	$L'_{n,w} \leq 58$ dB	Sound class intended for older buildings with less satisfactory acoustic conditions, e.g. for renovated dwellings.	30-45 %	25-40 %
E	$R'_w \geq 45$ dB	$L'_{n,w} \leq 63$ dB	Sound class intended for older buildings with unsatisfactory acoustic conditions.	10-25 %	45-60 %
F	$R'_w \geq 40$ dB	$L'_{n,w} \leq 68$ dB	Sound class intended for older buildings with clearly unsatisfactory acoustic conditions.	< 5 %	65-80 %
Reference: DS 490:2018 "Lydklassifikation af boliger" (Sound classification of dwellings)			**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.		

The first versions of DS 490 were published in 2001 and 2007, respectively, and with four classes A-D as in the other Nordic countries. DS 490:2001 was not formally related to the building code. DS 490:2007 was linked to the building code in 2008, since the acoustic requirements for housing were defined as fulfilment of Class C. In 2018, a revised version with two new classes E and F was published. The purpose was to have acoustic classes corresponding to older dwellings built before 1961, see Table 1 and Figure 1. For more information about the background, see [9].

2.2 Housing stock in DK

The housing stock in Denmark consists of about 2.8 mio dwellings [10], of these almost 1.2 mio dwellings in multi-storey (MS) housing, 450.000 row houses and most others single-family houses. In Figure 1 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.

The preferred type of dwellings changes over time. In the 25-year period 1990-2015, the number of dwellings in row housing and in multi-storey (MS) housing were almost identical. In the preceding 10 years (1980-1990), row houses were dominant, and since approx. 2016, MS housing has dominated.

From Figure 1, it is seen that in 2023, only about 10% of the MS dwellings can be expected to fulfil the current requirements. More information about constructions in various time periods is found in [9] and [11].

In the COST TU0901 books [12] and [13], more information is found about the housing stock in Europe (status 2013), focused on issues related to acoustic harmonization. An overview is given in [12] and information about individual countries (29 in Europe and 2 overseas) in [13].

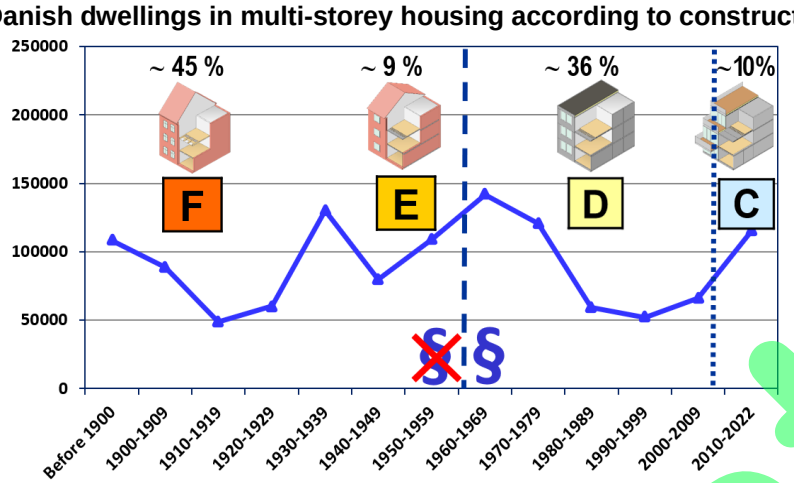

Figure 1: No. of Danish dwellings 1900-2022 in multi-storey housing according to construction year [10]. Estimated acoustic classes F, E, D, C according to DS 490:2018 are indicated. More information about constructions in various time periods is found in [9] and [11].
Note: Time periods 10 years, except the first & last column. The dashed line indicates year 1961 with the first national building regulations. The dotted line indicates year 2008 with stricter sound insulation limit values.

3 Sound insulation compliance procedures according to BR18 and shortcomings

The current administrative procedures are explained in BR2018, Ch. 1 [2] and the related guideline [14]. To obtain a permit for starting construction, the builder must define the type of building and which Building Code Chapters (technical performances) apply. This applies to both MS housing and row housing. At the end of the construction process, the builder must upload documentation according to the Ch. 1 guideline, i.e. the chapters indicated in the application for the building permit. According to the introduction in [14] the purposes of the guideline are:

- To make sure that the requirements in the building regulations are fulfilled.
- To ensure that valid documentation is available for later users of the building.

According to experiences from many acousticians in Denmark, the reality is that the two above-mentioned purposes are far from being fulfilled in practice. Many cases about poor sound insulation appear due to complaints about neighbour noise at a point in time, where permit for use has already been provided, although compliance with the sound insulation requirements is not documented.

The procedure and main rules in the current BR2018, Ch. 1 [2], are as follows – with some comments added in Italic:

- A random sample of 10% of building cases is selected by building authorities for check of documentation. – *Is 10% enough?*
- Terraced houses (row houses) are exempted from check of sound insulation by authorities. – *However, in practice severe faults are not uncommon, and the number of row houses is large as mentioned in section 2.2.*
- Calculations considered sufficient for documentation [14]. – *However, practical experiences point to the necessity of field tests, since various mistakes and misunderstandings cannot be taken into account in calculations.*

Consequences of no field check or poor-quality test reports

The importance of regulations may be obvious, but proper design and quality control are necessary to obtain the desired quality, since uncertainties related to design and errors in workmanship are unavoidable in real life, not least when applying new solutions and materials. Learning from mistakes is important for the later building projects.

If severe deficiencies in sound insulation performance are not found or found too late, after people have moved in, people must suffer from poor acoustic conditions as long as they stay, if the problems are not solved, which may take years or might never happen. – After completion of buildings, modifications are typically very expensive in time and money. In addition, the process often implies a high mental load for the people involved.

An important issue when preparing valid documentation is also the quality of the test reports. The authors have seen test reports prepared by organizations or people without competences in acoustic regulations, test methods and equipment, and the result may be test reports misleading to both builders and building authorities or even "nonsense". In one case, we observed that the building authorities considered such a "nonsense" report to be an accredited test report.

In [5], the clause about verification tests recommends that such tests are made by organizations with accreditation for building acoustic field tests or a person having a personal certification (does not yet exist in Denmark) for such field tests.

4 Field cases

Experience from practice have provided several examples of dwellings with sound insulation performance far below the limits in regulations. Thus, it is found important to initiate attention to the situation by informing about such cases from various parts of Denmark. The cases can hopefully lead to better rules and improved check of documentation.

Below is found information from four field cases:
Case 1: Row housing, airborne sound insulation.
Case 2: Multi-storey housing, impact sound insulation.
Case 3: Multi-storey housing with 240 dwellings – renovation.
Case 4: Row housing - 8 dwellings established in a former factory hall.

Case 1: Row housing with insufficient airborne sound insulation

In row-houses, double aerated concrete walls can provide very high airborne sound insulation provided they are constructed correctly. If not, in this case with 25 buildings, approximately 90 % of the dwellings did not fulfil the current requirements $R'_w \geq 55$ dB. One of the separating walls showed a 7 dB shortfall, see the lower curve in Figure 2. These results - found during control measurements between all the dwellings – would be unsatisfactory for the residents; since they would be able to hear the neighbours' conversations, thus causing complaints.

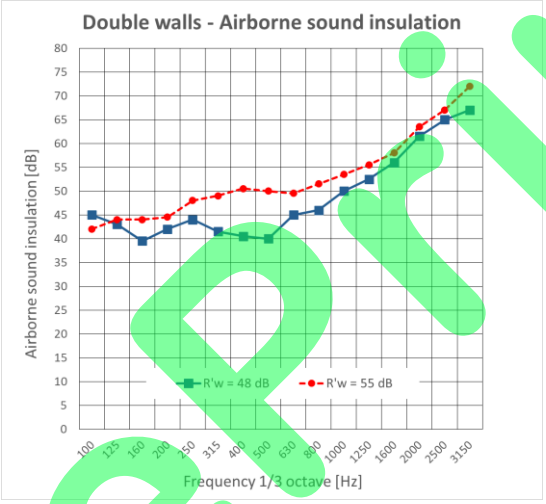

Figure 2: Diagram showing a good (R'_w = 55 dB) and a poor (R'_w = 48 dB) example from same building site

There are several possibilities for failures in double-wall constructions between dwellings, even if an elastic joint is made in the outer façade wall (to reduce flanking transmission through the facade). In this case, it was especially the foundations that messed with casting and bracing angle profiles that short-circuited the double walls, which should have otherwise been independent. After cutting the potential sound bridges, there were unfortunately still a few dB missing, which turned out to be caused by a too low separation in the foundation under the double walls (200 mm instead of 400 mm), see Figure 3.

The final solution included lining with two layers of plasterboard (one normal and one heavy weight plasterboard) directly mounted/screwed on each side of the double wall.

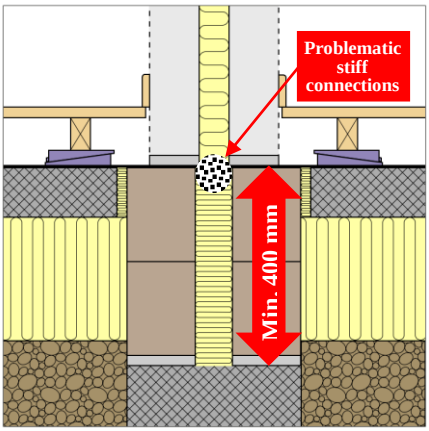

Figure 3: Vertical section showing a foundation/terrain floor assembly.

The remedy-cost was around 10.000 Euro per dwelling and the case was solved in two years. Even though the case is from before 2010 this one and several other cases show that is still highly relevant for the builders/investors of own initiative to perform control measurements, especially because it is now no longer permitted for the authorities to ask for such tests. Thereby it becomes the residents' own task to investigate and solve the problems – which more residents abstain from due to costs and lack of insight. Consequently, some residents may therefore live with unsatisfactory sound insulation, hearing noise and conversations from the neighbours.

Case 2: Multi-storey housing with too high impact noise levels

In an expensive 14-storey high-end building containing 25 dwellings with a sea view, high impact noise levels were measured in 2015 in living rooms. This resulted in resident complaints. A very extensive measurement program with 131 impact noise measurements showed that as many as 67% of the living spaces did not comply with the applicable minimum requirements in DS490 ($L'_{n,w} \leq 53$ dB) and had up to 9 dB's exceedances. Large variations in execution quality of the floors were revealed: Most exceedances were found in the dwellings in the right-hand stairwell, where 76% did not comply with limits, while it was 59% in the left-hand stairwell that did not comply. There were no impact noise problems from the very top floors. The problem turned out to be the "Foam-concrete" used (Thermotec/Thermowhite), see Figure 4, with a very variable stiffness – due to wrong mixing at the building site, i.e. elastic in the very top floors and quite hard in the other floors. This showed up as varying resonance peaks in the impact noise curves, see Figure 5.

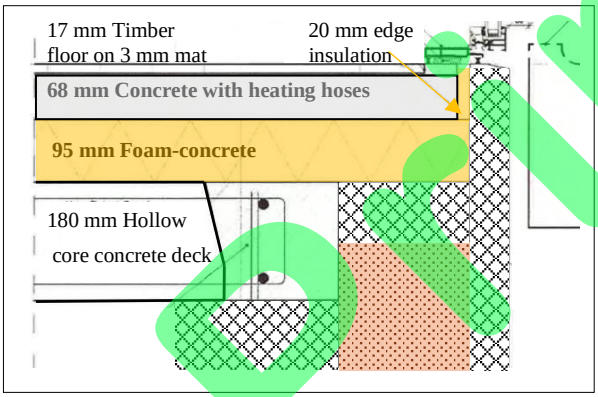

Figure 4: Vertical section at the facade showing the floating concrete floor on foam concrete.

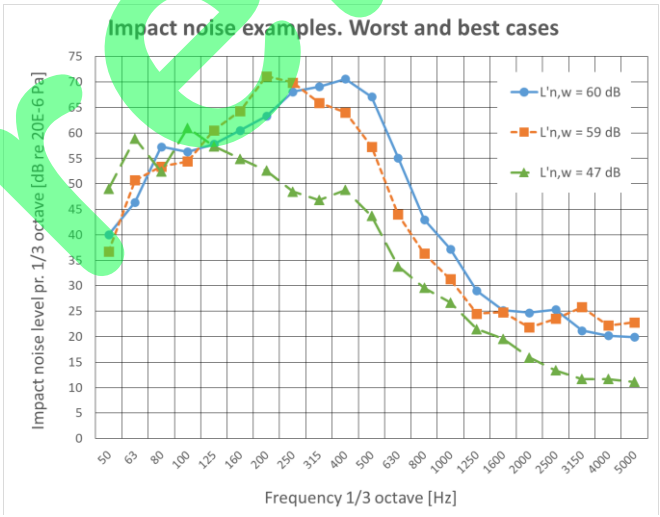

Figure 5: Diagram showing impact noise from floating floors in living rooms. One good ($L'_{n,w}$ = 47 dB from the very top floor) and two poor examples ($L'_{n,w}$ = 59-60 dB from lower floors).

The case was submitted to the opinion of an expert appointed by the court and a consequent very costly remedy (estimated to more than 100.000 Euro per dwelling): Rehousing, storage of fixtures, removal of wooden floors, concrete casting with underfloor heating hoses and Foam-concrete as well as restoration based on pressure-resistant/elastic mineral wool as a base for concrete casting with heating hoses and finished floors. A very long-lasting case that took more than 5 years. Consequently, control measurements are (still) very important and educational for both entrepreneurs and acousticians.

Case 3: Multi-storey housing with 240 dwellings – impact sound in renovated building

In a residential complex (public housing) with 240 apartments in 5-storey housing blocks, construction year 1980, a major renovation project was completed in 2022. The reasons for the renovation were a general need for maintenance, upgrading (new kitchen etc.) and a wish to have less maintenance costs in the future. Among other things, it was a goal to have maintenance-free floors that did not have to be sanded every time new residents moved into an apartment.

Original building: Walls of concrete, hollow core concrete slabs with wooden parquet on joists on underlay wedges. There was no information about neighbour noise complaints, and no sound insulation tests were made before renovation.

Goal for sound insulation in the renovated building: DS 490 Class C as for new-build, i.e. $R'_w \geq 55$ dB; $L'_{n,w} \leq 53$ dB. The old floors were removed, and new floor constructions were installed consisting of foam concrete (~50 mm), impact sound insulation mat (~6-8 mm), concrete (~40-60 mm), wooden click floor (easy to replace in the future).

After renovation people moved in. Soon after there were many neighbour noise complaints, mostly about impact sound. Consequently, vertical airborne and impact sound insulation tests were made and large deviations from the targets found:

- Impact limit $L'_{n,w} \leq 53$ dB – exceeded by more than 10-15 dB (i.e. impact levels far too high).
- Airborne limit $R'_w \geq 55$ dB – results low, more than 5 dB below limit.

From the inspection of the building, it was concluded that the concrete layer was connected to the walls, implying a strong vertical flanking transmission of both airborne and impact sound. This type of construction fault is typical and has been known for decades, see illustration in COST TU0901 book 2 [13], Ch. 5, Figure 5.12. The reminder could be that knowledge about design and details, visual inspection and early pre-completion testing are all important issues, so the same, severe construction fault could be detected and avoided, before being made in 240 apartments.

Estimated costs for improvement to comply with Class C limits were huge: ~40.000 EUR/apt, i.e. ~10 mio. EUR in total.

Conclusion: Currently (April 2024) a decision is pending about what could be done and when – and who should pay.

Case 4: Row housing - 8 dwellings established in a large, former factory hall

Case from 2017: Old brick building (factory hall) has been converted into dwellings (8 row houses). Thus, the building code requires that the sound insulation between the dwellings must fulfil DS 490 Class C.

The row houses have been constructed in the former factory building, each with basement, ground floor, first and second floor. Price around 1 mio. EUR each (2017).

All owners found the sound insulation unacceptable, and they ordered a consultant to do tests (2019). In total 16 tests of airborne and impact sound insulation were made. A few tests between rooms in the basement and in the upper floor fulfilled the required Class C. But the sound insulation tests between living rooms, ground floor and first floor, did not fulfil Class C (and also not Class D). The test results for airborne sound insulation were R'_w 40-49 dB (requirement $R'_w \geq 55$ dB) and for impact sound $L'_{n,w}$ 64-62 dB (requirement $L'_{n,w} \leq 53$ dB). Thus, the results correspond to the lower classes E and F, which are definitely not intended for new dwellings, cf. Table 2.

For a long time, there seemed to be no solution, since the builder was bankrupt (but had a large sum of money in another company), and the insurance company refused to pay for “repair” of the sound insulation. But then the house owners had contact to a lawyer, who initiated negotiations between the builder and the insurance company, and after two more years, some sound insulation improvements were made for walls and floors. It is not known exactly, which changes were made. A new sound insulation test was made, but the test report is not made available for this paper.

Experiences from DK and other countries about monitoring of compliance with building regulations

In [15] (1994) is found information about acoustic conditions in housing in Denmark, including a brief summary of legislation over time and enforcement. It is explained that the acoustic quality of dwellings depends strongly on the number of control tests, and it is stated that enforcement varies across the country. A figure from [16] shows how increased enforcement in Jutland implied a significant positive increase in compliance rate from 20% to 70% in the period 1975-1987. In [17] it is described how simple construction errors unfortunately keep reducing the sound insulation in housing significantly. International information is also included in [16], and related to the subject of this paper, there is interesting information about enforcement in Austria in 1994, where survey results for different regions showed various strategies and policies.

In [18] are found very interesting, recent survey results for Spain about compliance procedures and testing in different areas in the country. Of special interest are that testing is mandatory in some communities and that a “registry of competent entities for the performance of acoustic tests” is made by quality departments in some communities or local governments.

In UK, there is a long tradition for doing research and surveys about neighbour noise and for registering noise complaints. In [19] (from 1997) are included both information about noise sources, sound insulation field test results, how poor sound insulation affects life and emotions related to neighbour noise. A coordinated approach for improving

sound insulation in new housing is found in “Robust Details” [20], which includes construction designs, acoustic site inspection, checklists, sample field testing etc. In UK, building acoustic performance compliance levels increased from 40% (floors) and 60% (walls) before Robust Details approach to 98% and 99%, respectively, by using the robust details approach. Noise complaints have reduced by a factor of 3 for new build attached housing, see [21] and [22].

In the COST TU0901 books [12] and [13], more information is found related to the issues of this paper. In book 1 [12] see especially Ch. 9 (Monitoring & Testing Sound Insulation…) and 10 (Common Errors and Good Practice…). Book 2 [13] provides information about individual countries (29 in Europe and 2 overseas) about housing stock, typical constructions and typical construction faults in design and workmanship.

In the Danish standard DS 490:2018 [5] for acoustic classification of dwellings, the clause about verification tests (Appendix B) recommends that such tests are performed by organizations with accreditation for building acoustic field tests or a person having a personal certification for such tests. Design guidelines (in Danish) for new housing and improvement of existing housing are found in [23] and[24], respectively.

5 Conclusions and recommendations

Based on Danish field cases described in Section 4 and experiences from several countries, severe faults in building constructions are still common, even faults being well-known for decades. Several examples are found in [13]. Improved enforcement of regulations would encourage higher awareness of the regulations.

Important issues in the planning and construction process are:

- Planning of constructions
- Workmanship
- Visual inspection
- Pre-completion testing in case of new construction types, e.g. wooden constructions.
- Pre-occupancy testing
- Permit for use only obtained if requirements are complied with.

Recommendations for administration of acoustic regulations for housing in Denmark:

- Building regulations must continue to include clear requirements, including test methods and limit values.
- Row housing to be included in check of documentation for acoustic performance.
- Percentage of check by building authorities to be increased? (currently 10%).
- Field tests must be carried out as measurements. Calculations cannot replace field tests.
- Preparation of a guideline stating minimum competences for people performing acoustic field tests. A sort of approval or certification of such people would be very useful and the feasibility should be investigated.
- Preparation of a guideline for building authorities on how to check validity of acoustic field test reports.
- Enforcement of regulations to be performed by building authorities in all municipalities.
- Acoustic quality of dwellings to be included in documentation for performance of dwellings as “open access” for potential users, both tenants and buyers – in line with the intention of the guideline for documentation.

The background for the above-mentioned issues and recommendations are that residents need privacy and opportunities for own activities without disturbing neighbours. A large part of the existing housing stock built before 1961 in Denmark does not offer privacy or such opportunities and could be characterized as *acoustic slum*, cf. [24], which should be avoided both when renovating housing and especially in new and future housing. – At last, it is important to emphasize that leaving the acoustic quality check to the residents creates a very stressful situation often lasting years. Instead, the responsibility belongs to the builders and administration procedures developed by building authorities.

Acknowledgements

The cases presented in Section 4 are prepared by Sweco (Cases 1 and 2) and BUILD (Cases 3 and 4). The authors thank Lasse Møller Pedersen, Municipality of Aarhus, for discussions on administration of BR2018 compliance procedures.

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http://www.costtu0901.eu/tu0901-e-books.html
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