Universidad de Valladolid

ESCUELA TECNICA SUPERIOR DE ARQUITECTURA

DEPARTAMENTO DE FÍSICA APLICADA

TESIS DOCTORAL:

Estudio de la problemática asociada a la armonización de los descriptores de aislamiento acústico en la edificación

Presentada por Dª Carolina Rodrigues A. Monteiro
para optar al grado de doctora por la Universidad de
Valladolid

Dirigida por María de la O Machimbarrena Gutiérrez

Valladolid, 2016

Agradecimientos

A mí directora y amiga María Machimbarrena. Entré por la puerta del Departamento de Física Aplicada con la intención de ayudarla, y al final ella ha sido mi ayuda en estos años. Tanto por su dedicación a nivel académico, como por su cariño a nivel personal.

A Daniel de la Prida, Reine Johansson, Stefano Pedersoli y Lara del Val. Por su colaboración, sin la que este trabajo sería imposible, y por su amistad que han hecho el camino más llevadero.

A mi madre, Izabel y mi hermana, Renata. Porque son mi vida. Por las horas en FaceTime, por su infinito apoyo y amor, siempre presentes, a pesar de la distancia. También agradezco a mi familia por vibrar con todas mis conquistas.

A Alberto. Por ser mi compañero de aventuras. Porque "*é algo assim, é tudo para mim, é mais que eu esperava*".

A los amigos que la Arquitectura me ha regalado: Caven, Ceci, Gabi, Lila, Iana.

A los amigos que España me ha regalado: Ana, David, Esti, Germán, Laura, Marga, Pepo, Quiro, Roberta, Roberto, Trejo, Vicky, Verónica. Por haber sobrevivido a tener una amiga doctoranda. También agradezco especialmente a Rodrigo, el culpable de que la Acústica entrara en mi vida.

A los médicos Guillermo Galván, Pilar Lobo, Celia Hortelano, Juan José Madrigal, Lourdes del Olmo, Ignacio Bravo y Pablo Ocaña. Por haber sido el equipo responsable por mantener mi cuerpo de pie para concluir este trabajo.

Par les dieux, les claires danseuses !... Quelle vive et gracieuse introduction des plus parfaits pensées !... Leurs mains parlent, et leurs pieds semblent écrire. Quelle précision dans ces êtres qui s'étudient à user si heureusement de leurs forces moelleuses !... Toutes mes difficultés me désertent, et il n'est point à présent de problème qui m'exerce, tant j'obéis avec bonheur à la mobilité de ces figures ! Ici, la certitude est un jeu ; on dirait que la connaissance a trouvé son acte, et que l'intelligence tout à coup consent aux grâces spontanées... Regardez celle-ci !... la plus mince et la plus absorbée dans la justesse pure... Qui donc est-elle ?... Elle est délicieusement dure, et inexprimablement souple...Elle cède, elle emprunte, elle restitue si exactement la cadence, que si je ferme les yeux, je la vois exactement par l'ouïe. Je la suis, et je la retrouve, et je ne puis jamais la perdre ; et si, les oreilles bouchées, je la regarde, tant elle est rythme et musique, qu'il m'est impossible de ne pas entendre les cithares.

Paul Valéry, 1921

Índice

Resumen 7

Abstract 9

1. Introducción 11

1.1 Antecedentes 13

1.1.1 Hacia un marco común Europeo en descriptores de aislamiento acústico 16

1.1.2 Revisión de normas de acústica en la edificación 17

1.2 Motivación 24

1.3 Objetivos 25

1.4 Estructura de la Tesis Doctoral 26

2. Investigación A: Determinación de la incertidumbre asociada a medidas de aislamiento a ruido aéreo in situ **29**

2.1 Introducción 31

2.2 Descripción de la Investigación A 33

2.3 Conclusiones de la Investigación A 33

3. Investigación B: Estudio de la correlación existente entre la evaluación objetiva y subjetiva del aislamiento acústico, mediante *listening tests* **35**

3.1 Introducción 37

3.2 Descripción de la Investigación B 38

3.3 Diseño del *Listening test* 40

3.4 Conclusiones de la Investigación B 42

4. Investigación C: Traducción de descriptores únicos de aislamiento a ruido aéreo **43**

4.1 Introducción 45
4.2 Descripción de la Investigación C 46
4.3 Conclusiones de la Investigación C 48
5. Conclusiones y líneas futuras de investigación 51
5.1 Conclusiones 53
5.2 Líneas futuras de investigación 55
6. Referencias 57
7. Artículos publicados 67
7.1 Artículo A 69
7.2 Artículo B 83
7.3 Artículo C 97
8. Trabajos relacionados al desarrollo de la Tesis Doctoral 123
8.1 Trabajos presentados durante el desarrollo de la Tesis 125
8.1.1 Capítulos de libros 125
8.1.2 Principales artículos presentados en congresos 125
8.2 Artículos en desarrollo 127
8.3 Estancias investigadoras y Cursos Cortos 127

Resumen

Una serie de demandas técnicas y sociales han contribuido para que, en la última década, el campo de la acústica en la edificación haya despertado un gran interés, motivando nuevas líneas de investigación y la revisión de normas de gran impacto. En este contexto, la propuesta de armonización de los descriptores de aislamiento acústico y la revisión de la norma que regula el cálculo de los valores únicos en acústica en la edificación, norma ISO 717- partes 1 y 2, han sido objeto de gran debate a nivel científico y político.

En esta Tesis Doctoral se presentan contribuciones originales que ayudan a elucidar algunos de los puntos más conflictivos de ambas propuestas. La investigación ha abordado concretamente tres problemas diferenciados, aunque todos ellos directamente relacionados con el contexto de armonización de descriptores de aislamiento acústico y revisión de normativa anteriormente mencionados. Cada uno de los problemas abordados se corresponde con una ramificación del trabajo que se presenta. La primera rama se ha dedicado a proponer un método de cálculo e investigar la incertidumbre asociada a un descriptor único de aislamiento acústico a ruido aéreo con el rango de frecuencias ampliado y obtenido a partir de medidas in situ. La segunda rama se ha dedicado a investigar la relación entre la evaluación objetiva del aislamiento a ruido aéreo mediante un descriptor único con el rango de frecuencias ampliado, y la correspondiente evaluación subjetiva efectuada por los usuarios. La herramienta empleada para esta investigación es un *listening test* específicamente diseñado para esta aplicación. Por último, la tercera rama se dedica a investigar métodos de traducción entre descriptores de aislamiento a ruido aéreo y proponer una traducción de un conjunto de descriptores existentes a un descriptor armonizado de ruido aéreo con el rango de

frecuencias ampliado. Cada una de las tres ramas de investigación se ha plasmado en un artículo publicado en una revista de impacto científico.

Los resultados obtenidos en la investigación contribuyen significativamente a evaluar y valorar la idoneidad y posibles consecuencias de una propuesta de armonización de descriptores de aislamiento acústico con rango de frecuencias extendido por debajo de 100 Hz. Se espera que el conjunto de trabajos presentado sea de gran utilidad para futuros investigadores, legisladores, comités nacionales de normalización y demás agentes responsables de que el aislamiento acústico en la edificación sea un instrumento de protección y confort del ciudadano, mejorando su calidad de vida.

Abstract

In the last decade, the field of building acoustics has raised a great interest due to the conjunction of technical and social demands, encouraging new research and the revision of high-impact standards. In this context, the proposed harmonization of sound insulation descriptors and the revision of the standard that defines the rating of sound insulation in buildings , ISO 717- parts 1 and 2, have been the subject of considerable debate both at the scientific and political levels. Original contributions are presented in this thesis in order to clarify some of the most contentious points of the previous two previously mentioned issues. The research has focused on three distinct topics, although all of them are directly related to the framework of harmonization of sound insulation descriptors and revision of aforementioned standards.

Each of the tackled issues corresponds to a branch of the developed study. The first branch is dedicated to propose a method for calculating and investigating the uncertainty associated with a single-number airborne sound insulation descriptor with extended frequency range and obtained by in-situ measurements. The second branch is dedicated to investigate the relationship between the objective assessment of airborne sound insulation by a single-number descriptor with extended frequency range and the corresponding subjective assessment. For this research a listening test tool was specifically designed. Finally, the third branch is dedicated to investigate methods of translation between different airborne sound insulation descriptors and to propose a translation of a set of existing airborne sound insulation descriptors into a proposed harmonized descriptor with extended frequency range. Each of the three branches of research has resulted in an article published in a scientific journal with significant impact factor.

The results of research presented in this thesis contribute significantly to assess and evaluate the suitability and possible consequences of sound insulation descriptors harmonization proposal with a frequency range extended below 100 Hz. It is expected that the set of articles presented will be useful for future researchers, legislators, national standardization committees and other stakeholders in charge to maintain sound insulation in buildings as an instrument of protection and comfort for citizens, improving their quality of life.

1. Introducción

En este primer capítulo se presentan los antecedentes más relevantes en el ámbito de la acústica en la edificación que han motivado la realización de este trabajo. Además de presentan los principales objetivos pretendidos y la organización de la Tesis Doctoral.

1.1 Antecedentes

Desde la Conferencia de Naciones Unidas sobre el Medio Humano de Estocolmo de 1972 [1], organizado por la O.N.U., el ruido ha sido declarado como agente contaminante, físico y socioeconómico que influye en la calidad del medio ambiente. Los efectos nocivos del ruido sobre la salud se han puesto de manifiesto a lo largo de las dos últimas décadas y han sido objeto de numerosos estudios [2–4], así como fundamento de medidas políticas regionales, nacionales e internacionales para combatirlos.

En Estados Unidos, la principal medida a nivel nacional se remonta a 1972, cuando se publicó el Noise Control Act [5]. A través de la Agencia de Protección Ambiental (EPA) esta ley busca por una parte establecer un medio para la coordinación eficaz de la investigación y las actividades de lucha contra el ruido a nivel federal; por otra autorizar el establecimiento de normas federales sobre emisiones acústicas para varios tipos productos comercializados; y, por último, proporcionar información al público con respecto a las características de emisión y reducción de ruido dichos productos.

En Europa, una de las medidas de más impacto ha sido la publicación de la Directiva Europea 49/2002 [6] sobre evaluación y gestión del ruido ambiental también conocida como END (Environmental Noise Directive). Esta directiva determina que todas las ciudades y las aglomeraciones de más de 100.000 habitantes evalúen la exposición al ruido de sus residentes, así como que se estudien el ruido en carreteras con mucho tráfico, vías férreas y aeropuertos, para evaluar la exposición de los habitantes que viven en la zona de influencia de estas infraestructuras. Por medio de mapas de ruido y planes de acción contra el ruido elaborados por los Estados miembro el objetivo es mejorar la calidad de vida y el impacto sobre la salud de los ciudadanos.

Como forma de apoyar a los Estados miembro en la prevención y el control de la exposición al ruido excesivo en el ámbito europeo, la Organización Mundial de la Salud - OMS (WHO por sus siglas en inglés) ha establecido recomendaciones de valores límite de exposición al ruido [7,8], además de publicar un importante documento para evidenciar los principales efectos del ruido ambiental en la salud [9] , identificando las necesidades de los grupos más vulnerables.

Por otra parte, la importancia y efectos nocivos del ruido vecinal también han sido objeto de estudio en Europa especialmente en desde principios del siglo XXI. En 2004 se llevó a cabo una investigación en tres países europeos [10] que reunían un tercio de la población total de la EU. En este estudio se concluye que el ruido vecinal en Europa es un problema significante, dado el gran porcentaje de molestia observado en las encuestas realizadas. También existen investigaciones más recientes que se sirven de encuestas con el objetivo de conocer y evaluar la molestia producida por el ruido en los usuarios de las viviendas [11,12].

En esta misma línea cabe destacar una de las conclusiones encontradas en el informe WHO LARES [13], también auspiciado por la OMS, dedicado a investigar la calidad de la vivienda y los efectos sobre la salud de los defectos encontrados. El estudio identificó el ruido y la molestia producida por el ruido vecinal como un problema de salud, concluyendo lo siguiente: "*el efecto de las molestias ocasionadas por los ruidos de los vecinos está aproximadamente en el mismo rango que las molestias sobre la salud provocadas por el ruido del tráfico. Los resultados señalan que es necesario mejorar el aislamiento acústico en los edificios residenciales*". Esta afirmación implica que no sólo el ruido ambiental es nocivo para la salud, sino que otras fuentes de ruido en el interior de los edificios son tan nocivas como el ruido ambiental y por tanto debe procurarse un adecuado aislamiento también frente estas fuentes de ruido.

Una de las fuentes de ruido cada vez más común en las viviendas es el equipo de sonido tipo *home theater*. Estos equipos son cada vez más potentes y refuerzan los sonidos graves de música, películas o videojuegos, los cuales son altamente molestos para un usuario con una audición sana,

Así mismo se ha observado que el desarrollo de nuevas tecnologías de construcción centradas en el ahorro energético e impulsadas por las directivas Europeas relativas a la eficiencia energética de los edificios [14,15], en ocasiones ha resultado en deficiencias significativas respecto al desempeño acústico del edificio.

La intrusión de cualquier tipo ruido en un hogar influye en una serie de aspectos de la vida familiar, tanto en la salud física [13] como la psicológica [16] y, como tal, es muy importante la existencia de viviendas construidas de forma que los sonidos producidos por la vida normal de los vecinos sean atenuados.

Para garantizar la protección de sus ciudadanos por medio del aislamiento acústico en viviendas, la mayoría de los estados miembro de la Unión Europea y muchos países del mundo (EEUU, Canadá, Australia, Nueva Zelanda, Chile, Brasil…) cuentan con normativa que obliga a los edificios de nueva construcción, e incluso en casos de rehabilitación y/o reforma, a cumplir con unas exigencias de aislamiento.

Sin embargo, la experiencia de algunos países pioneros en el campo de la acústica en la edificación, ha motivado que al inicio de la segunda década de los años 2000 se in iniciara un intenso proceso de revisión y evaluación de normas, procedimientos y metodologías existentes, buscando mejorar el desempeño y evaluación del aislamiento acústico. Una legislación apropiada sumada a buen diseño y una esmerada ejecución/construcción, constituyen la clave para hacer frente a los nuevos estilos de vida y ofrecer el aislamiento acústico esperado por los ciudadanos en el ámbito doméstico [17].

1.1.1 Hacia un marco común Europeo en descriptores de aislamiento acústico

En el escenario descrito anteriormente, surge en 2010 el proyecto europeo de investigación denominado COST Action TU0901: *Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions* [18].

El origen del proyecto se encuentra en los estudios de Rasmussen [19,20], en los cuales una comparativa de los requisitos de aislamiento acústico y esquemas de clasificación acústica en Europa, demuestra el alto grado de diversidad existente. En estos estudios se concluye que la armonización de descriptores de aislamiento acústico es necesaria pues facilita el intercambio de datos y experiencias entre países, reduce barreras comerciales y en última instancia redunda en un beneficio para el usuario final de los edificios. Por otra parte, la implementación de descriptores armonizados de aislamiento acústico en Europa motivaría la revisión de los requisitos de aislamiento acústico en los Estados miembro, así como la convergencia en lo que respecta a exigencias y normativa, con el fin último de provocar una mejora en la construcción y atender a las necesidades de los usuarios.

Uno de los principales objetivos del proyecto COST TU 0901, por lo tanto, era proponer un conjunto armonizado de descriptores de aislamiento acústico a ruido aéreo, de fachadas, de impacto e instalaciones, además de proponer un esquema de clasificación acústico común para viviendas en Europa.

Además, el proyecto contaba con dos objetivos secundarios no menos ambiciosos: correlacionar el aislamiento acústico con la molestia percibida por los usuarios y crear un catálogo de soluciones constructivas europeas basado en datos experimentales.

Como resultados más destacables relacionados con estos objetivos cabe destacar un documento que resume las directrices para la realización de encuestas armonizadas a los usuarios de las viviendas y para la realización de *listening tests* [21] y un documento que recoge los sistemas constructivos más comunes en los países participantes y sus prestaciones acústicas, con directrices para la mejora de las prestaciones acústicas de viviendas existentes o de nueva ejecución [22].

Como parte de la metodología de trabajo, los participantes del proyecto COST TU0901 han contactado y colaborado con otros expertos, tanto del ámbito de la normalización como de la investigación aplicada (otros proyectos COST, proyectos de investigación de ámbitos nacionales e internacionales, grupos de trabajo de CEN, ISO, CIB etc.)[23].

Concretamente, cabe señalar que la autora ha participado en el proyecto COST TU0901 entre los años de 2011 y 2013, como representante de España en el grupo de trabajo 3 , WG 3: *Design and acoustic performance of building constructions for multi-storey housing.* A lo largo de estos años ha participado activamente en el proyecto acudiendo a todas las reuniones, a diversos cursos de acústica, auspiciados total o parcialmente por el COST TU0901, y efectuando aportaciones a la investigación conjunta que han quedado reflejadas en publicaciones en congresos [24–27], así como en las publicaciones finales asociadas al proyecto [28,29].

1.1.2 Revisión de normas de acústica en la edificación

El hecho de ser la Directora de Tesis miembro del ISO TC/43/SC2 Building Acoustics ha facilitado el acceso de la autora a información puntual y siempre actualizada relativa al proceso de revisión de la normativa de acústica en la edificación.

Previo al nacimiento del proyecto COST TU0901, la Organización Internacional de Normalización se encontraba en un proceso de revisión de varias normas del campo de acústica de la edificación. Se puede decir que, de alguna manera, ha existido una retroalimentación mutual entre el ISO TC/43/SC2 - Building Acoustics y los miembros del COST TU0901, lo cual ha favorecido el debate e intercambio de evidencias científicas entre ambos grupos.

El proceso de revisión que ha abarcado más atención y, ha fomentado más debate e investigación ha sido el de la norma ISO 717, partes 1 y 2 [30,31]. Esta norma trata de la evaluación del aislamiento acústico, tanto en los edificios como en los elementos de construcción, indicando varias posibilidades normativas para convertir una magnitud espectral en un valor único. Colateralmente, el hecho de revisar esta norma ha forzado la revisión de la normativa de medida de aislamiento *in situ* (actual norma ISO 16283, partes 1, 2 y 3) [32–34], así como la norma relativa a la determinación de la incertidumbre asociada a las medidas de aislamiento (actual norma ISO 12999-1)[35].

Por último, más recientemente se ha iniciado el proceso para aprobar una nueva norma inspirada en los resultados del proyecto COST TU 0901, cuyo objetivo es el desarrollo de un esquema de clasificación acústico para edificios residenciales análogo a los existentes para clasificación energética [36]. El borrador de norma ISO/CD 19488 – Acoustic Classification Scheme for Dwellings [37] se encuentra actualmente en fase de desarrollo.

Todos los procesos de revisión y desarrollo normativa anteriormente mencionados han coincidido en el tiempo con la realización de esta Tesis Doctoral y, por su interés, también han motivado parte de la investigación que en ella se presenta.

La norma ISO 717 tiene su origen en 1968, y desde entonces ha sido sometida a varias revisiones, siendo la última en 2013. Como ya se ha comentado, contiene los diversos métodos para la obtención de descriptores únicos de aislamiento acústico en la forma de valores globales, dado que el comportamiento del aislamiento acústico en los edificios y de los elementos constructivos es función de la frecuencia. Por medio de los descriptores únicos contemplados en las normas ISO 717-1 e ISO 717-2 [30,31] es posible simplificar la elaboración de requisitos legales y determinar las prestaciones del aislamiento acústico de productos y edificios de una forma más comprensible para no expertos.

Los métodos presentados en esta serie incorporan la posibilidad de calcular los llamados “términos de adaptación espectral” [38] que acompañan al valor único de aislamiento calculado e incorporan información adicional teniendo en cuenta el tipo de fuente predominante. Además, los términos de adaptación espectral pueden ser calculados utilizando diferentes rangos de frecuencia, lo cual abre un amplio abanico de posibilidades a la hora de referirse al aislamiento acústico de un producto o un edificio. Esta versatilidad que ofrece la norma ha contribuido a la gran diversidad de descriptores de aislamiento acústico adoptados internacionalmente como normativos [20].

El objetivo principal de la revisión de la norma ISO 717 [39–41] era optimizar el método de evaluación de aislamiento acústico para ruido aéreo y de impacto. Se buscaba la simplificación de los métodos de cálculo de descriptores únicos, abandonando el uso de la curva de referencia ISO y sus correspondientes términos de adaptación espectral en favor de otros métodos de ponderación que permitieran a su vez reducir la cantidad de descriptores existentes.

También se planteaba la adopción de un descriptor único al que se pudiera incorporar información sobre la molestia percibida por los usuarios y que, por tanto, aumentara la correlación entre el descriptor objetivo de aislamiento y la evaluación subjetiva de la molestia correspondiente. Para ello, se proponía tener en cuenta las componentes de bajas frecuencias de las fuentes de ruido domésticas, ampliando el rango de frecuencias de evaluación del aislamiento hasta los 50 Hz.

El proceso decisivo de revisión de esta norma se inició en 2011, llegándose a otorgar en el seno de ISO una nueva numeración a la norma que la debería sustituir, la futura ISO 16717.

Sin embargo, el último de los objetivos de la revisión anteriormente mencionados es muy controvertido, ya que ampliar el rango de frecuencias por debajo de 100 Hz y hasta 50 Hz no sólo afecta a los valores de aislamiento global obtenidos, sino que influye en otros aspectos directamente relacionados como se explica a continuación.

El debate acerca de la incorporación de bajas frecuencias en el cálculo del valor global de aislamiento a lo largo de los últimos años se ha centrado esencialmente en los siguientes puntos:

a) Insuficiencia de evidencias científicas respecto al efecto sobre la incertidumbre de las medidas *in situ* de aislamiento acústico;

b) Insuficiencia de evidencias científicas en cuanto a la correlación entre la molestia percibida por los usuarios y su relación con componentes de ruido a bajas frecuencias;

c) Insuficiencia de evidencias científicas sobre cómo los descriptores únicos adoptados por cada país deberían ser traducidos a un nuevo descriptor único y las consecuencias de dicha traducción;

d) Dificultades técnicas en la realización de medidas *in situ* de aislamiento acústico.

Desafortunadamente las divergencias de opiniones entre los expertos y la escasez de evidencias científicas provocó que en 2014 el borrador de la norma denominado ISO/CD 16717 fuera cancelado, manteniéndose en vigor la norma ISO 717-1:2013[30] para ruido aéreo, e ISO 717-2:2013[31] para ruido de impacto. Se acordó posponer la revisión/actualización de la norma hasta que la comunidad científica hubiera recopilado evidencias suficientes en todos los ámbitos anteriormente mencionados y desde el ISO TC/43/SC2 se solicitó fomentar activamente la investigación en estos campos.

A continuación, se detallan los aspectos más relevantes asociados a los puntos a), b) c) y d) mencionados anteriormente así como su posible vinculación al proceso de revisión de otras normas del campo de la acústica en la edificación.

Punto a) Las consecuencias de la extensión del rango de frecuencias fueron tratadas en el desarrollo de la norma ISO 12999-1[35] de determinación y aplicación de las incertidumbres de medición en la acústica de edificios. En esta norma se presentan valores generales de incertidumbre basados en ensayos efectuados por laboratorios acreditados para ensayos de aislamiento a ruido aéreo y de impacto, tanto para valores en 1/3 de octava como para valores globales a partir de 50 Hz. La norma contempla situaciones específicas de medida (condiciones de reproducibilidad, repetibilidad y situaciones mixtas no encontradas en ningún otro documento metrológico). Sin embargo, a pesar de consistir en un primer paso para la evaluación de la incertidumbre de medidas de aislamiento acústico, la norma no incorpora la posibilidad de cálculos individuales de incertidumbre, ni valora los posibles efectos asociados a la ampliación del rango de frecuencias hasta 50 Hz en la evaluación de los valores globales de aislamiento.

Punto b) Para la propuesta de nuevos descriptores de aislamiento acústico, una de las principales características deseada es que tengan una mayor correlación con la evaluación subjetiva de aislamiento reportada por los usuarios de las viviendas.

En este contexto, evaluar el desempeño acústico de las viviendas, así como la percepción del aislamiento por sus ocupantes a través de un descriptor único, se ha convertido en un objetivo importante en el campo de la investigación de la acústica de edificios y objeto de varios estudios [21,42–47] .

Punto c) Otra línea de investigación abierta ha sido la de proponer métodos para traducir los valores de los descriptores existentes a los valores correspondientes, considerando nuevos descriptores armonizados que puedan ser adoptados en el futuro. En este escenario, la mayoría de los países necesitaría estimar la influencia de adoptar el nuevo descriptor en sus requisitos de aislamiento acústico, así como determinar las prestaciones acústicas de los sistemas de construcción existentes en base a los nuevos descriptores.

Asimismo, la traducción de descriptores a uno común, resulta de gran interés y utilidad a una gran diversidad de agentes implicados en el sector de la construcción, pues posibilita la comparación de exigencias de aislamiento acústico entre diferentes países y el intercambio de información entre fabricantes de materiales de construcción en el ámbito internacional.

Por último, el contar con un método para la traducción de descriptores es imprescindible para apoyar las decisiones que habrá que adoptar en el seno del ISO/TC 43/SC 2, a lo largo de los últimos meses de 2016, en el contexto de la redacción de la futura norma ISO/CD 19488 – Acoustic Classification Scheme for Dwellings [37].

Punto d) Entre los años 2009 y 2016 se ha llevado a cabo el proceso de revisión y publicación de una nueva serie de normas de medición del aislamiento acústico aéreo, de impacto y fachada en condiciones de campo o *in situ*. La nueva serie 16283 [32–34] es el resultado de un proceso de revisión de algunas de las partes de la serie ISO 140 [48–50] llevado a cabo como consecuencia de demandas técnicas y administrativas. En el ámbito administrativo los cambios se debieron a la necesidad de convergir con la serie ISO 10140 de medición en laboratorio del aislamiento acústico de los elementos de construcción. Las razones técnicas estaban relacionadas con el aumento en la realización de medidas de aislamiento acústico *in situ* llevadas a cabo en varios países como parte del proceso de verificación del cumplimiento de las correspondientes normativas nacionales.

Según Hopkins [51], frente a casos donde el aislamiento medido fuera del mismo orden que los requisitos establecidos, era necesario aumentar la repetitividad y la reproducibilidad de las medidas para evitar sanciones y conflictos legales. Este aumento de repetitividad y reproducibilidad se veía necesario principalmente para medidas de aislamiento por debajo de 100 Hz en recintos pequeños, con volúmenes entre 10 m^3 y 25 m^3 pues en esas condiciones las hipótesis de campo difuso no se cumplen y por tanto la variabilidad y dispersión de los resultados es mayor. Para poder exigir medidas por debajo de 100 Hz (y por tanto descriptores globales que incorporaran los valores de aislamiento en las bandas de 50,63 y 80 Hz) en un entorno normativo, era por tanto imprescindible aumentar la repetitividad y reproducibilidad de los resultados.

Para ello, en las tres partes de la nueva serie ISO 16283 el ámbito de aplicación ha sido extendido a recintos con volúmenes desde 10 m^3 hasta 250 m^3, con medidas en 1/3 de octava entre 50 Hz y 5 kHz.

Además, entre otras incorporaciones, se ha incluido un procedimiento de muestreo del nivel de presión sonora por barrido manual y otro específico para medidas por debajo de 100 Hz en recintos con volumen de menos de 25 m^3.

Todo lo anteriormente expuesto pone de manifiesto que en la última década el ISO TC/43/SC2 ha sido especialmente activo y ha abordado la revisión de normas de gran impacto, despertando un gran interés y considerable debate en la comunidad científica.

1.2 Motivación

Como se ha podido observar en el apartado 1.1 de este capítulo, un entorno de renovación normativa, innovación científica y nuevas demandas sociales ha traído a la luz cuestiones que han motivado el desarrollo de esta Tesis.

Como miembro del proyecto COST Action TU0901, la autora ha podido participar de forma activa en el debate sobre cambios importantes en el ámbito de la acústica en la edificación tanto a nivel político como científico.

Concretamente, se puede decir que la propuesta de armonización de los descriptores de aislamiento sumada a la revisión de la norma que regula el cálculo de los valores únicos en acústica en la edificación, norma ISO 717-partes 1 y 2, son el eje motivador de prácticamente toda la investigación desarrollada en el cuerpo de esta Tesis. Los resultados de las investigaciones llevadas a cabo, no obstante, se aplicarán más directamente en el desarrollo del borrador de norma que propone un esquema común de clasificación acústica de edificios de alcance internacional [37].

1.3 Objetivos

A fin de contribuir con discusiones y soluciones a los principales puntos de la problemática relacionada con la armonización de los descriptores de aislamiento acústico, la investigación se ha centrado en los puntos a),b) y c) del apartado 1.1 de este capítulo y se ha estructurado en tres líneas de trabajo diferenciadas cuyos objetivos se describen a continuación.

Investigación A: Investigar sobre el estado del arte relativo al cálculo de incertidumbre en medidas de aislamiento acústico. Proponer un método de cálculo de incertidumbre en medidas de aislamiento a ruido aéreo de acuerdo a las recomendaciones de la ISO/IEC Guide 98-3:2008[52]. Evaluar el efecto de ampliar el rango de frecuencias utilizado para la determinación de un descriptor de aislamiento a ruido aéreo, sobre la incertidumbre asociada a dicho descriptor;

Investigación B: Investigar sobre el estado del arte relativo a la correlación entre descriptores objetivos de aislamiento y la percepción del mismo por parte de los usuarios. En concreto se ha tomado como objetivo investigar la relación existente entre la evaluación objetiva del aislamiento a ruido aéreo considerando un descriptor único que tenga en cuenta el rango de frecuencias ampliado y la evaluación subjetiva del aislamiento reportada por los usuarios por medio de *listening tests*.

Investigación C: Conocer los métodos de traducción entre descriptores de aislamiento acústico propuestos en la bibliografía y efectuar una propuesta alternativa basada en datos empíricos. Concretamente se trata de proponer una traducción de un conjunto de descriptores existentes a un descriptor único de ruido aéreo con el rango de frecuencias ampliado. Así mismo se ha planteado como objetivo alcanzar el mismo tipo de traducción empírica para varios descriptores de aislamiento a ruido de impacto, estando la correspondiente publicación en fase de redacción final en el momento del depósito de esta Tesis.

1.4 Estructura de la Tesis Doctoral

De acuerdo con la normativa vigente, el Real Decreto 99/2011, de 28 de enero, por el que se regulan las enseñanzas oficiales de doctorado, esta Tesis Doctoral se presenta por el modelo de compendio de publicaciones, difiriendo por tanto del modelo tradicional de documento extenso cuyo contenido es autosuficiente.

En correspondencia con las tres líneas de investigación desarrolladas, se han publicado tres artículos en la revista científica Applied Acoustics, con factor de impacto 1.462 según ©Thomson Reuters Journal Citation Reports 2016 En lo sucesivo los artículos se denominarán Artículo A, Artículo B y Artículo C, respectivamente.

El presente documento se organiza en ocho capítulos, siendo el número 1 dedicado a la exposición de los antecedentes y motivación de la realización de la Tesis Doctoral, así como a los objetivos perseguidos y estructura de la misma.

Los capítulos 2, 3 y 4 se corresponden con las líneas de investigación A, B y C anteriormente citadas, que a su vez se vinculan con los artículos A, B y C. Cada capítulo cuenta con una breve introducción, una descripción de los principales objetivos del estudio y la metodología empleada y, por último, un resumen de las conclusiones más relevantes.

En el capítulo 5 se presentan las conclusiones más relevantes del trabajo realizado, así como líneas de investigación futura en el ámbito de esta Tesis Doctoral.

Las referencias bibliográficas consultadas para la elaboración de este documento están listadas en el Capítulo 6.

El capítulo 7 contiene los artículos A, B y C en su formato original, incluyendo las referencias de las publicaciones y los nombres y filiación de todos los autores.

Los artículos publicados que conforman la Tesis Doctoral son:

7.1 Artículo A: Uncertainty determination of in situ airborne sound insulation measurements - doi:10.1016/j.apacoust.2014.09.018 ;

7.2 Artículo B: Subjective and objective acoustic performance ranking of heavy and light weight walls - doi:10.1016/j.apacoust.2016.03.008 ;

7.3 Artículo C: Translation between existing and proposed harmonized airborne sound insulation descriptors: A statistical approach based on in-situ measurements - doi:10.1016/j.apacoust.2016.09.017 .

Finalmente, en el capítulo 8 se enumeran otros artículos en proceso de realización en el marco en las mismas líneas de investigación así como diversos trabajos y artículos presentados en congresos internacionales a lo largo de los años en los que se ha desarrollado la presente Tesis Doctoral.

2. Investigación A: Determinación de la incertidumbre asociada a medidas de aislamiento a ruido aéreo *in situ*

En este capítulo se describen las bases de la investigación dedicada al estudio del estado del arte relativo al cálculo de incertidumbre en medidas de aislamiento acústico y proponer un método de cálculo de incertidumbre en medidas de aislamiento a ruido aéreo de acuerdo a las recomendaciones de la guía GUM. Además se evalúa el efecto de ampliar el rango de frecuencias utilizado para la determinación de un descriptor de aislamiento a ruido aéreo, sobre la incertidumbre asociada a dicho descriptor. Esta investigación ha sido plasmada en el Artículo A.

2.1 Introducción

Una correcta estimación de la incertidumbre en el ámbito de las medidas de aislamiento acústico en edificios es muy importante tanto para medidas realizadas en laboratorio como *in situ*. Por sentido común, debería ser obligatorio reportar la incertidumbre asociada a un ensayo de aislamiento acústico, ya sea un ensayo solicitado por un fabricante sobre una solución constructiva o un ensayo solicitado por un constructor para verificar el cumplimiento de las exigencias de aislamiento legales en un edificio. Sin embargo, hasta la fecha, no es práctica habitual casi en ningún país de la UE, aunque muchos países incorporan niveles de tolerancia para los resultados de medidas de aislamiento en sus normativas [22]. La escasez de informes de incertidumbre de ensayos de aislamiento acústico consiste en un hecho anómalo , y lo es todavía más si se tiene en cuenta que en varios países el cumplimiento de determinados requisitos de aislamiento acústico (de materiales de construcción y/o de obra ejecutada) condiciona el permiso de ocupación de la vivienda y que si se dan resultados de incumplimiento esto puede desencadenar severas medidas legales (e.g.: puniciones económicas a la constructora responsable, obligatoriedad de demolición y reconstrucción del edificio).

El marco para la estimación de la incertidumbre en medidas en es la Guía para la expresión de la incertidumbre de medida ISO/IEC Guide 98-3:2008 [52], en esta tesis denominada guía GUM, aplicable a un amplio espectro de mediciones. Esta guía especifica métodos de estimación de la incertidumbre basados en un modelo matemático completo del procedimiento de medida.

Por lo que respecta a las medidas de aislamiento acústico, todavía no se ha alcanzado un consenso respecto al posible modelo matemático cerrado. Uno de los aspectos más problemáticos apuntados por Wittstock [53,54] es el hecho de que tanto el tiempo de reverberación como los niveles de presión sonora no son medidos directamente, sino que son estimados.

Además, para el cálculo de los descriptores únicos de aislamiento acústico según la ISO 717-1[30] se utilizan algoritmos no lineares que no pueden ser escritos en una única fórmula.

Otro de los aspectos a tener en cuenta a la hora de desarrollar un procedimiento de cálculo de incertidumbre es la posible correlación entre parámetros, lo cual apenas ha sido investigado en este campo. En la investigación de Wittstock [53] se demuestra con datos experimentales que existe correlación entre las diferentes bandas de 1/3 de octava cuando se considera la incertidumbre de descriptores únicos de aislamiento, pero no se investiga el peso de dicha correlación. Una de las dificultades está en identificar la magnitud de esta correlación en todas las medidas

Como consecuencia, las normativas de determinación de la incertidumbre en medidas de aislamiento acústico, tanto la antigua ISO 140-2 [55] como la actual ISO 12999-1 [35], consideran que la incertidumbre debe de ser tratada bajo un enfoque de repetitividad y reproducibilidad [56].

La recién publicada ISO 12999-1 incluye valores generales de incertidumbre tanto en 1/3 de octava como para descriptores únicos. Estos valores se presentan para mensurandos típicos como aislamiento a ruido aéreo y de impacto en diferentes condiciones de medida.

Desde esta perspectiva la incertidumbre de la medida pasa a ser la del método de medida, basándose en resultados de ensayos interlaboratorios, y no se realiza un cálculo individual de la incertidumbre.

Diversos autores [57–63] han investigado y apoyado la posibilidad de realización de cálculos individuales de aislamiento acústico de acuerdo con la guía GUM. En el artículo derivado de esta investigación, en la sección 7.1, se detallan los principales factores por los cuales se demuestra que el cálculo individual de la incertidumbre se hace fundamental y agrega beneficios al ámbito de la acústica de edificios.

Como se ha explicado en el Capítulo 1, a estas cuestiones se ha sumado el debate en relación al aumento de la incertidumbre por la ampliación del rango de frecuencias de los descriptores únicos de aislamiento acústico, también apoyado por las investigaciones de Hongisto y Mahn [64,65].

2.2 Descripción de la Investigación A

El principal objetivo de esta investigación es demostrar que es posible estimar la incertidumbre de medidas de aislamiento acústico de ruido aéreo siguiendo las recomendaciones de la guía GUM. Así mismo se ha planteado como objetivo secundario investigar las consecuencias de la incorporación de bajas frecuencias a los cálculos de valores globales de aislamiento y la convergencia del método presentado con lo propuesto en la ISO 12999-1.

Para ello, se ha calculado la incertidumbre individual de 300 medidas *in situ* de aislamiento a ruido aéreo. En 200 de estas medidas, las paredes separadoras de recintos eran pesadas y las 100 restantes se trataba de paredes ligeras. La estimación de la incertidumbre se ha llevado a cabo de acuerdo con las recomendaciones de la guía GUM y, para estudiar los efectos de la ampliación del rango de frecuencias, los resultados se han presentado para los rangos de 100–5000 Hz y 50–5000 Hz.

El procedimiento y la metodología empleados en la investigación están detallados en el artículo presentado en la sección 7.1 de este documento.

2.3 Conclusiones de la Investigación A

El estudio llevado a cabo en la investigación A es pionero en el campo de la acústica en la edificación, dado que en la literatura revisada no se han encontrado apenas referencias proponiendo la realización de cálculos individualizados de incertidumbre asociada a ensayos de aislamiento acústico.

Además en ningún caso el estudio se ha realizado sobre una base de datos de medidas de aislamiento *in situ* tan extensa, ni incluye el estudio de los efectos asociados a incorporar el rango de frecuencias por debajo de 100Hz en la estimación del aislamiento a ruido aéreo.

Los resultados obtenidos demuestran que es posible realizar estimaciones individuales para medidas de aislamiento a ruido aéreo, hipótesis que también puede ser extendida a medidas de aislamiento de fachadas así como ruido de impacto.

La necesidad de hacer cálculos individuales también es apoyada por los resultados obtenidos para la dispersión de los valores de incertidumbre. Para tipologías de soluciones constructivas idénticas, construidas en situaciones similares, las correspondientes curvas de incertidumbre asociadas al descriptor de aislamiento a ruido aéreo $D_{nT,}$ presentan una dispersión bastante alta.

Así como en los estudios de Hongisto y Mahn [64,65], también se puede concluir de esta investigación, que el rango de frecuencias utilizado para la evaluación afecta la incertidumbre de los descriptores únicos. Concretamente, cuando el cálculo de los valores globales se efectúa utilizando el rango de frecuencia extendido, 50–5000 Hz, la incertidumbre resultante es generalmente mayor y no permanece invariante o disminuye como señala Wittstock en su artículo [53]

3. Investigación B: Estudio de la correlación existente entre la evaluación objetiva y subjetiva del aislamiento acústico, mediante *listening tests*

En este capítulo se describen las bases de la Investigación B, dedicada a estudiar el estado del arte relativo a la correlación entre descriptores objetivos de aislamiento y percepción subjetiva del mismo. En concreto se ha tomado como objetivo investigar la relación existente entre la evaluación objetiva del aislamiento a ruido aéreo considerando un descriptor único que tenga en cuenta el rango de frecuencias ampliado y la evaluación subjetiva del aislamiento reportada por los usuarios por medio de *listening tests*.

3.1 Introducción

En la norma ISO 717, partes 1 y 2, se describe el procedimiento para determinar los descriptores únicos de aislamiento acústico más utilizados en el ámbito internacional [20]. Estos descriptores se utilizan desde hace cinco décadas y están incorporados al etiquetado habitual de los fabricantes de materiales de construcción y a los requisitos legales de aislamiento en diversas recintos en todo el mundo. Sin embargo, en las últimas décadas han surgido estudios relevantes [66–68] que han aportado evidencias de que los descriptores de aislamiento acústico utilizados actualmente no reflejan adecuadamente la experiencia del usuario en cuanto al confort acústico de su vivienda.

Como se ha comentado en el capítulo 1, las nuevas costumbres del estilo de vida contemporáneo sumadas a nuevas demandas técnicas han favorecido un entorno de investigación acerca de la relación entre los diversos descriptores de aislamiento acústico y la percepción humana.

Esta investigación también ha sido fomentada por el hecho de iniciarse el proceso de revisión de la serie de normas ISO 717. Como se ha comentado en el apartado 1.1.2, uno de los objetivos de dicha revisión era aumentar la correlación entre la evaluación objetiva y la valoración subjetiva del aislamiento acústico [39]. También en el proyecto COST TU 0901 [18], uno de los objetivos era el de atender a la necesidad de desarrollar nuevos modelos de descriptores de aislamiento acústico de tal forma que las normas y requisitos legales se correspondieran mejor con la percepción humana.

Sin embargo, evaluar el desempeño acústico de los edificios y el confort de los usuarios por medio de un descriptor único de aislamiento acústico no es una tarea fácil, ya que en el estado del arte no se ha encontrado ninguna herramienta adecuada que correlacione datos psicofísicos y fisiológicos con el desempeño acústico de las edificaciones [69].

La propuesta de ampliar el rango de frecuencias utilizado para la evaluación por descriptor único de aislamiento hasta los 50 Hz. , incorporada en la revisión de la serie ISO 717, se apoya principalmente en la investigación de Park y Bradley [70]. En este estudio se concluye que los valores de aislamiento acústico a bajas frecuencias están relacionados con la molestia percibida por los usuarios. Sin embargo, es de destacar que la muestra de estudio sólo contaba con pocos casos y aplicados siempre a la misma tipología constructiva.

Dada la escasez de estudios dedicados a investigar la correlación entre la evaluación subjetiva y objetiva del aislamiento acústico usando un descriptor único de aislamiento con el rango de frecuencias ampliado, y dado que pocos estudios existentes se han realizado, y se han llevado a cabo siempre usando una misma tipología constructiva y un número muy bajo de casos de estudio, la propuesta de ampliación del rango de frecuencias ha resultado ser muy controvertida.

Esta falta de consenso precisamente, junto con el debate generado por la revisión de la serie ISO 717, ha dado lugar a que en los últimos años se hayan llevado a cabo diversas investigaciones en este campo [11,21,42–46,71].

3.2 Descripción de la Investigación B

El principal objetivo genérico de esta investigación ha sido aportar nuevas evidencias al campo de la evaluación subjetiva del desempeño acústico de diversos tipos de sistemas constructivos.

De forma más concreta, el objetivo específico de esta publicación era el de clasificar distintas soluciones constructivas (paredes en este caso) de acuerdo a la valoración subjetiva emitida por los usuarios en base al nivel de presión sonora percibido y posteriormente comparar dicha clasificación con la obtenida usando un descriptor objetivo de aislamiento acústico a ruido aéreo. Así mismo se trataba de detectar si existen diferencias en la evaluación subjetiva de paredes de sistemas constructivos masivos y ligeros.

Para ello se han seleccionado cinco pares de paredes masivas y ligeras, de forma que cada par presentaba el mismo $R_{A,50\text{-}5000}$ pero diferente R_{w}. Los usuarios reales han valorado (mediante diversos métodos que se detallan más adelante y en el Artículo B, en la sección 7.2 de este documento) las paredes basándose en el nivel sonoro percibido. Con la valoración efectuada por los usuarios se ha procedido a clasificar las soluciones constructivas de mejor a peor y posteriormente la clasificación obtenida en base a la valoración de los usuarios ha sido comparada con la clasificación obtenida usando R_{w}.

La evaluación subjetiva se ha realizado por medio de *listening tests* en un entorno controlado de laboratorio en la Katholieke Universiteit Leuven, Bélgica, y en la Universidad de Valladolid.

El descriptor elegido ha sido $R_{A,50\text{-}5000}$., dado que en el momento del desarrollo de la investigación, este descriptor era el propuesto en el documento de revisión de la ISO 717-1.

En una primera etapa, el sonido de muestra, en este caso ruido rosa, se ha filtrado a través del espectro del índice de reducción sonora R del elemento que se interpone entre la fuente y el oyente, es decir, el R de los cinco pares de paredes. El resultado de este filtrado es un conjunto de 10 estímulos diferentes que se utilizan posteriormente para efectuar el *listening test*.

Se ha contado en total con treinta y tres individuos que han participado en el ensayo de forma voluntaria. Una vez informados sobre el procedimiento, cada participante ha evaluado un par de estímulos sonoros por lo que respecta al nivel sonoro percibido, mediante comparación por pares. Las 45 comparaciones posibles entre todos los estímulos han sido presentadas en las dos direcciones posibles (a-b y b-a) y en orden aleatorio.

Una vez registradas todas las respuestas, los datos han sido analizados y sometidos a diferentes procedimientos estadísticos para obtener el ranking subjetivo además de evaluar la significancia de los resultados.

El procedimiento y la metodología empleados en la investigación están detallados en el artículo presentado en la sección 7.2 de este documento.

Tanto para el filtrado de los estímulos, como para la parte experimental del test y el procesamiento de los datos se han desarrollado tres aplicaciones en MATLAB®en colaboración con Daniel de La Prida [72].

3.3 Diseño del *Listening test*

Para poder realizar el *listening test* mencionado en la investigación B con participantes reales fue necesario previamente diseñar la forma y contenido del *listening test.* Se incorpora en este punto de la memoria una breve descripción del proceso, pues es parte de la investigación desarrollada por la autora que no ha quedado reflejada como parte de la publicación B.

Los *listening tests,* o test de escucha, son un tipo de prueba sensorial, donde el órgano sensorial protagonista es el oído. Estos tipos de test permiten recoger información acerca de la sensación subjetiva de los individuos frente a estímulos sonoros determinados. Sin embargo, no sólo el oído está involucrado, sino también el cerebro, la percepción y los mecanismos de respuesta de cada individuo.

Las capacidades sensoriales y el procesado mental de las sensaciones son únicos para cada individuo[73], por lo tanto el diseño de un *listening test* debe de tener esto en cuenta en todas sus etapas. Dada la imposibilidad de calibrar a los participantes del test como si se trataran de un equipo, es necesario tomar precauciones para reducir el posible sesgo en los resultados del test.

En concreto, en el diseño de este test se ha considerado la influencia de los siguientes factores: tamaño de la muestra, sesgos introducidos por los participantes, por las condiciones del experimento o por el experimentador, el método de consulta y el método de escalado de las respuestas.

Así mismo, durante el proceso de desarrollo de las tres aplicaciones que se emplean en el estudio [72] se ha tenido especial cuidado de tomar en consideración los principios de diseño centrado en el usuario, especialmente al diseñar la interfaz destinada a recoger las respuestas de los participantes.

El diseño centrado en el usuario o UCD (User Centred Design) es una filosofía de diseño en la que se tienen muy en cuenta las necesidades, peticiones y usos habituales de los usuarios. Se trata en resumen de un conjunto de métodos y/o técnicas que deben ser aplicados durante la fase de diseño y que aportan una mayor usabilidad a las aplicaciones [74].

Además, una experiencia de usuario con la carga cognitiva adecuada ayuda a superar una fuente común de sesgo, como la fatiga causada por cuestionarios largos, o la intervención del investigador para dar instrucciones y / o para ayudar el participante en la gestión de interfaces de test complejas.

En este caso, estos principios generales se han aplicado buscando minimizar las barreras de interacción que pudieran existir a fin de reducir el esfuerzo por parte del participante al completar el test. Concretamente algunas de las características de la aplicación que han seguido estos principios son las siguientes:

- El participante tiene autonomía para controlar los botones que le permiten oír los estímulos y decidir cuándo se siente listo para responder y pasar a la siguiente pregunta en su propio tiempo;
- La duración de la prueba es más corto ya que el participante controla la prueba y no necesita esperar por instrucciones por parte del investigador;

- El participante visualiza el progreso de la prueba, lo que reduce la sensación de complejidad y la fatiga debido a la duración de la sesión;
- La simplicidad de completar la prueba reduce el problema de falta de motivación, una causa recurrente de sesgo.

3.4 Conclusiones de la Investigación B

La investigación B ha resultado ser una aportación importante para el desarrollo de nuevas normas en el ámbito de la acústica de edificaciones ya que contribuye al debate alrededor de la obtención de un descriptor único de aislamiento acústico que se correlacione con la molestia percibida por el usuario.

Los resultados de la Investigación B sugieren que el nivel sonoro percibido de un estímulo de ruido rosa filtrado por el Índice de Reducción Sonora de una pared ligera en general es menor que el filtrado por una pared pesada si estas tiene el mismo $R_{A,50-000}$. Se ha demostrado que aunque tengan el mismo $R_{A,50-000}$, las paredes ligeras son percibidas como "mejores aislantes" por los participantes en un intervalo de confianza del 95%.

Esto indica que, para este estudio de caso, $R_{A,50-000}$ no refleja adecuadamente la evaluación subjetiva del aislamiento a ruido aéreo. Por otro lado la clasificación obtenida utilizando es descriptor de aislamiento $Rw + C \approx R_{A,100-3150}$ es idéntico al resultante de la evaluación subjetiva, denotando una mejor correlación entre este último descriptor y la percepción del nivel sonoro.

Los resultados indican que la adopción de $R_{A,50-000}$ en una futura normativa de un descriptor único de aislamiento a ruido aéreo puede subestimar el desempeño de paredes ligeras para ruidos domésticos de banda ancha y plana, comparables al ruido rosa.

4. Investigación C: Traducción de descriptores únicos de aislamiento a ruido aéreo

En este capítulo se describen las bases de la Investigación C, dedicada a conocer los métodos de traducción entre descriptores de aislamiento acústico a ruido aéreo propuestos en la bibliografía y efectuar una propuesta alternativa basada en datos empíricos.

4.1 Introducción

Como se ha comentado en el Capítulo 1, la gran variedad de descriptores de aislamiento acústico utilizados en los requisitos legales de distintos países, así como en los esquemas de clasificación acústica existentes [75], es un obstáculo para el intercambio de conocimiento y experiencias entre los agentes involucrados en garantizar un aislamiento acústico adecuado en las viviendas en el ámbito internacional. La armonización de los descriptores de aislamiento y de los criterios incluidos en los esquemas de clasificación acústica, han sido los principales objetivos del proyecto COST Action TU0901. En el marco de una propuesta de descriptores y de clasificación acústica armonizada, se proponía respetar la autonomía de cada estado miembro para establecer los niveles de exigencia en su territorio. De esta forma tanto la comunidad científica como los gobiernos y la industria se verían beneficiados.

También en el proceso de revisión de la serie de normas ISO 717, descrito en el Capítulo 1, se ha tratado de obtener un consenso respecto a qué parámetros son los más adecuados para evaluar el desempeño acústico de los edificios considerando así mismo el confort del usuario.

A pesar de la dificultad para alcanzar el consenso, el proyecto COST Action TU0901 ha propuesto de esquema común de clasificación acústica para ruido aéreo, de fachada, de impacto e instalaciones en viviendas [17], suponiendo un conjunto armonizado de descriptores de aislamiento.

Esta propuesta ha despertado bastante interés en el ámbito de la normalización y ha servido de base para el desarrollo de una nueva norma actualmente en fase de desarrolloISO / CD 19488 – Acoustic Classification Scheme for Dwellings[37].

4.2 Descripción de la Investigación C

La elaboración de un esquema de clasificación acústica de viviendas que pueda ser utilizado a nivel Europeo (países CEN), o incluso a nivel mundial (países ISO), se basa en la utilización de descriptores armonizados para cada tipo de aislamiento acústico. En concreto, para el aislamiento a ruido aéreo, los descriptores propuestos son $D_{nT,50} \approx D_{nT,w} + C_{50-3150}$ y/o $D_{nT,100} \approx D_{nT,w} + C_{100-3150}$.

Para que la propuesta sea adoptada por el mayor número de países posible es necesario que cada país pueda traducir sus actuales valores de exigencias legales de aislamiento acústico al valor correspondiente empleando los nuevos descriptores. De esta forma los legisladores pueden evaluar cómo estos cambios afectan a las normativas o esquemas de clasificación acústica existentes en sus respectivos países.

La traducción entre descriptores de aislamiento acústico en general es por tanto un tema de gran interés. Para efectuarla correctamente es necesario tener en cuenta tres aspectos: definición matemática del descriptor, procedimiento empleado para determinar el valor global y rango de frecuencia incluido en la evaluación del aislamiento. La relación matemática entre descriptores no es compleja y ya ha sido investigada [76], así como la traducción entre los dos principales métodos de cálculo de valores únicos (ISO 717 y ponderación espectral)[77,78], sin embargo, no existen apenas estudios en los que se incorporen las tres variables simultáneamente. En el contexto del proyecto COST Action TU0901 se realizó una propuesta preliminar de traducción [79,80] basada en relaciones matemáticas y empleando relaciones empíricas obtenidas de un número muy reducido de ensayos, sin embargo hasta la fecha no se ha realizado ninguna investigación exhaustiva, incluyendo un gran número de ensayos *in situ* y tomando en consideración los tres aspectos anteriormente mencionados.

El objetivo principal de la Investigación C es aportar nuevas evidencias al procedimiento de traducción de descriptores de aislamiento acústico a ruido. Para ello se plantea los siguientes objetivos específicos:

- Investigar el efecto de la tipología constructiva (paredes pesadas y ligeras) en las ecuaciones de traducción entre descriptores de aislamiento a ruido aéreo.
- Investigar el efecto de proponer traducciones entre descriptores de aislamiento a ruido aéreo calculados utilizando rangos de frecuencias diferentes (el tradicional y el extendido por debajo de 100 Hz)
- Proponer ecuaciones de traducción actualizadas, basadas en una gran base de datos de medidas *in situ* utilizando un método estadístico. Las ecuaciones se utilizarán para traducir la mayoría de los descriptores de aislamiento a ruido aéreo adoptados actualmente a los descriptores propuestos, $D_{nT,50}$ y $D_{nT,100}$;
- Comparar las ecuaciones obtenidas con las propuestas por Gerretsen [79,80];
- Presentar los requisitos de aislamiento a ruido aéreo en vigor en treinta y dos países y traducirlos al valor correspondiente expresado en función $D_{nT,50}$, descriptor propuesto tanto en el ámbito ISO como en el proyecto COST Action TU 0901.
- Evaluar la posición de los requisitos de estos mismo países en el esquema de clasificación acústica propuesto por el proyecto COST Action TU0901 e incorporado al borrador de norma ISO / CD 19488.

El procedimiento y la metodología empleados en la investigación están detallados en el artículo presentado en la sección 7.3 de este documento.

4.3 Conclusiones de la Investigación C

Se ha podido observar que las ecuaciones de traducción de los diversos descriptores de aislamiento acústico a ruido aéreo existentes a $D_{nT,100}$ son prácticamente independientes de la tipología constructiva en los casos en que el rango de frecuencia del descriptor original no es extendido. En este caso las ecuaciones que se obtienen usando la base de datos completa y las bases de datos diferenciadas por tipología constructiva (paredes pesadas y ligeras) son muy similares, lo cual indica que para el proceso de traducción es más significativo el rango de frecuencias considerado en ambos descriptores que el cambio de un descriptor basado en índice de reducción sonora (R') frente a uno basado en la diferencia de niveles (D).

En las traducciones a $D_{nT,50}$, se observan diferencias significativas entre las ecuaciones basadas en datos de paredes ligeras y pesadas. Esto es así porque la mayor parte de los descriptores existentes no incluyen el rango de frecuencias ampliado por debajo de 100 Hz. El aislamiento acústico a ruido aéreo de las paredes ligeras está fuertemente condicionado por su comportamiento a bajas frecuencias, lo cual se refleja de forma inmediata en el proceso de traducción desde un descriptor que no incluye los efectos por debajo de 100 Hz y otro que sí lo hace. Este efecto es mucho menos crítico en el caso de paredes pesadas lo cual hace que se observen diferencias entre las traducciones basadas en datos de paredes pesadas y ligeras de hasta 5 dB.

Se han propuesto ecuaciones de traducción basadas en la base de datos completa y se han comparado con las obtenidas por Gerretsen. Las diferentes propuestas convergen cuando $D_{nT,w}$, $D_{nT,w} + C_{tr}$ y $D_{nT,w} + C$ son traducidos a $D_{nT,50}$, pero no se da lo mismo para R'_w

A pesar de considerar que la mejor opción para abordar el proceso de traducción de exigencias de aislamiento en los distintos países es tomar como punto de partida las ecuaciones obtenidas en esta investigación, se ha observado una alta dispersión de los datos respecto a las ecuaciones de traducción propuestas. Esto debe ser tenido en cuenta en caso de usarse estas traducciones en un ámbito técnico y/o legislativo.

También se ha observado que si se adoptara el parámetro D_{nT50} y la propuesta de esquema de clasificación acústica incluida en el borrador ISO CD/19488 las exigencias de aislamiento acústico a ruido aéreo de muchos países quedarían en la clase D, esto es, por debajo de la clase pensada para edificios de nueva construcción, la C. Esto refleja que, o las exigencias propuestas para la clase C son muy altas, o muchos países cuentan con exigencias de aislamiento acústico a ruido aéreo excesivamente bajas.

Los resultados de esta investigación ofrecen la posibilidad de traducir los requisitos de aislamiento a ruido aéreo existentes a un único descriptor común (D_{nT50}) así como de situar los niveles de exigencias de diversos países en el marco de la clasificación acústica de edificios que se está desarrollando en el seno de ISO. Esto permite a los legisladores y agentes implicados en general hacer una evaluación preliminar de las posibles consecuencias asociadas a un cambio de descriptor de aislamiento acústico a ruido aéreo con un rango de frecuencias extendido

5. Conclusiones y líneas futuras de investigación

En este capítulo se presentan las conclusiones de la investigación presentada en la Tesis Doctoral. Se destacan las principales contribuciones de este trabajo al ámbito de la acústica en la edificación y se presentan las principales líneas de investigación futuras, ya en proceso o porvenir.

5.1 Conclusiones

Puesto que las conclusiones específicas de cada línea de investigación ya han sido presentadas en las correspondientes secciones de los capítulos 2, 3 y 4 y se recogen así mismo en los correspondientes artículos de impacto, en este apartado se exponen de forma más general las principales contribuciones de la Tesis Doctoral en el ámbito de la investigación en acústica en la edificación.

a) Frente a la **insuficiencia de evidencias científicas respecto al efecto de la inclusión de las bajas frecuencias sobre la incertidumbre de las medidas *in situ* de aislamiento acústico**, se ha comprobado el aumento de la incertidumbre de los descriptores únicos de aislamiento acústico cuando las bajas frecuencias son incorporadas a su evaluación. Esta comprobación converge con los resultados obtenidos por Mahn y Hongisto [64,65], y se hace muy relevante por basarse, de forma original, en una gran base de datos de medidas de aislamiento a ruido aéreo *in situ*;

b) Respecto a los **métodos de determinación de la incertidumbre en ensayos de aislamiento acústico** se ha realizado una propuesta de metodología de cálculo acorde a las indicaciones expresadas en la GUM. El método presentado puede ser extendido a medidas de aislamiento de fachada y ruido de impacto y permite que cada ensayo de aislamiento *in situ* conlleve su estimación de incertidumbre única frente a los valores preestablecidos de la ISO 12999-1. Así mismo, la propuesta impulsa la convergencia de la expresión de los resultados de ensayos de aislamiento acústico con las directrices metrológicas recomendadas por ILAC – entidad responsable de la Cooperación Internacional de Acreditación de Laboratorios [81];

c) Por lo que respecta la **insuficiencia de evidencias científicas en cuanto a la correlación entre la molestia percibida por los usuarios y su relación con componentes de ruido a bajas frecuencias**, en la Investigación B, se ha presentado el diseño y aplicación de un método de evaluación subjetiva del nivel sonoro, enfocado a minimizar las diversas posibilidades de sesgo en los resultados y que puede ser aplicado a diversos tipos de *listening tests*. Los resultados del estudio concluyen de forma significante que $R_{A,50–5000}$ no refleja adecuadamente la evaluación subjetiva del aislamiento a ruido aéreo para el caso estudiado. El aislamiento proporcionado por una pared ligera, con mismo valor de $R_{A,50–5000}$ que una pesada, pero con mejor desempeño a medias y altas frecuencias, ha sido mejor evaluado por los participantes en el experimento.

d) En lo referente a la **insuficiencia de evidencias científicas sobre cómo los descriptores únicos adoptados por cada país deberían ser traducidos a un nuevo descriptor único**, la investigación C ha presentado un método de traducción basado en una gran base de datos de medida de aislamiento a ruido aéreo *in situ*, tanto para $D_{nT,50}$ como para $D_{nT,100,}$. Se han obtenido ecuaciones de traducción generales y también para diferentes tipologías constructivas (paredes ligereas y pesadas)

e) En cuanto a **las consecuencias de dicha traducción**, se ha demostrado que hay demasiada variabilidad en los resultados (dependencia de factores tales como la tipología constructiva) cuando se realizan traducciones a descriptores que incorporan bajas frecuencias desde 50 Hz basándose en datos desde 100 Hz. En concreto, se ha observado que la traducción empírica entre los descriptores existentes y los propuestos, $D_{nT,50}$ y $D_{nT,100}$, es más dependiente de la tipología constructiva cuando los rangos de frecuencia de los descriptores (original y traducido) son diferentes.

f) También por lo que respecta **las consecuencias de la traducción**, los requisitos de treinta y dos países han sido traducidos al a la propuesta de descriptor $D_{nT,50}$, y han sido incorporados al esquema de clasificación acústica propuesto por la COST Action TU0901 y adoptada en el borrador de norma ISO/CD 19488. Se ha observado que en caso de que el esquema de clasificación sea adoptado, los requisitos de aislamiento acústico a ruido aéreo entre viviendas de varios países resultarían en la clase D, lo cual indica que o bien la clase C (originalmente destinada a incorporar los requisitos nacionales) es excesivamente exigente o algunos países deberían considerar elevar sus requisitos de aislamiento a ruido aéreo.

Finalmente, cabe señalar que algunos de los artículos publicados como fruto de la investigación asociada a esta Tesis Doctoral han servido como referencia para investigaciones relevantes en el ámbito de la acústica en la edificación. Como ejemplo, el trabajo de Scrosati et al. [82] y el de Navacerrada et al. [83], ambo sobre la evaluación de la incertidumbre de aislamiento de fachadas, y el de Hopkins [51] sobre los antecedentes de los principales cambios técnicos relativos a medidas *in situ* de aislamiento acústico en la nueva serie ISO 16283.

5.2 Líneas futuras de investigación

En el desarrollo de esta Tesis Doctoral se ha evidenciado que muchos puntos de debate relacionados a la armonización de descriptores de aislamiento acústico necesitan una investigación más profunda.

Como línea de investigación general a ser desarrollada, se propone aplicar los métodos presentados en este trabajo al ruido de impacto, ámbito en el cual todavía hay escasa bibliografía. Concretamente se pretende trabajar en los siguientes puntos.

a) Evaluar el efecto de ampliar el rango de frecuencias, y la incorporación o no del término de adaptación espectral $C_{I,}$ sobre la incertidumbre asociada a dicho descriptor;

b) A la vista de la propuesta descriptores de aislamiento a ruido de impacto armonizados efectuada desde la COST Action TU0901, proponer una traducción de un conjunto de descriptores existentes a dichos descriptores armonizados, estudiando la influencia de la incorporación o no del término de adaptación espectral C_I así como del rango de frecuencias incluido en el cálculo. . Los primeros resultados de esta investigación están en la publicación oficial del 22nd International Congress on Acoustics titulada *Translation of existing impact sound insulation descriptors into new proposed ones, based on a large set of in-situ measurements* [84] . Se espera publicar próximamente los resultados detallados en una revista científica de impacto, dado que el correspondiente artículo se encuentran en fase de redacción en el momento del depósito de esta Tesis.

c) Investigar la correlación entre descriptores objetivos de aislamiento a ruido de impacto y percepción subjetiva del mismo por medio de *listening tests*. Para ello se cuenta con la ventaja de las herramientas y métodos desarrollados en esta tesis

6. Referencias

[1] Declaración de Estocolmo. Informe de la Conferencia de las Naciones Unidas sobre el Medio Humano. 1972. http://www.upv.es/contenidos/CAMUNISO/info/U0579218.pdf.

[2] Stansfeld SA. Noise pollution: non-auditory effects on health. Br Med Bull 2003;68:243–57.

[3] Basner M, Brink M, Bristow A, de Kluizenaar Y, Finegold L, Hong J, et al. ICBEN review of research on the biological effects of noise 2011-2014. Noise Health 2015;17:57–82.

[4] Marquis-Favre C, Premat E, Aubrée D, Vallet M, Vallett M. Noise and its effects - A review on qualitative aspects of sound. Part I: Notions and acoustic ratings. Acta Acust United with Acust 2005;91:613–25.

[5] U. S. Congress. Noise Control Act of 1972. Congressional Printing Office; 1972.

[6] Directiva 2002/49/CE del Parlamento Europeo y del Consejo sobre evaluación y gestión del ruido ambiental. D Of Las Comunidades Eur 2002.

[7] Berglund B, Lindvall T, Schwela D. WHO Guidelines for community noise. World Health Organization; 1999.

[8] WHO Regional Office Europe. Night noise guidelines for Europe. World Health Organization; 2009.

[9] Hänninen O, Knol AB, Jantunen M, Lim T-A, Conrad A, Rappolder M, et al. Environmental Burden of Disease in Europe: Assessing Nine Risk Factors in Six Countries. Environ Health Perspect 2014;122:439–46.

[10] Van den Berg M. Neighbour Noise: A rational Approach. 2nd WHO Int. Hous. Heal. Symp., Vilnius: World Health Organization; 2004, p. 151–4.

[11] Ljunggren F, Simmons C, Hagberg K. Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound. Appl Acoust 2014;85:57–68. doi:10.1016/j.apacoust.2014.04.003.

[12] Hongisto V, Mäkilä M, Suokas M. Satisfaction with sound insulation in residential dwellings – The effect of wall construction. Build Environ 2015;85:309–20. doi:10.1016/j.buildenv.2014.12.010.

[13] Niemann H, Maschke C. WHO LARES Final report Noise effects and morbidity. World Health Organization; 2004.

[14] Directiva 2010/31/UE del Parlamento Europeo y del Consejo, relativa a la eficiencia energética de los edificios. D Of La Unión Eur 2010:13–35.

[15] Directiva 2012/27/UE del Parlamento Europeo y del Consejo, relativa a la eficiencia energética. D Of La Unión Eur 2012:L 315/1.

[16] Scannell L, Hodgson M, Garcia Moreno Villarreal J, Gifford R. The Role of Acoustics in the Perceived Suitability of, and Well-Being in, Informal Learning Spaces. Environ Behav 2015;48:769–95. doi:10.1177/0013916514567127.

[17] Rasmussen B, Machimbarrena M, Fausti P, TU0901 C. Building acoustics throughout Europe. Volume 1: Towards a common framework in building acoustics throughout Europe. 2014.

[18] COST Action TU0901: Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions. http://www.costtu0901.eu/ n.d. http://www.costtu0901.eu/.

[19] Rasmussen B. Sound insulation between dwellings – Requirements in building regulations in Europe. Appl Acoust 2010;71:373–85. doi:10.1016/j.apacoust.2009.08.011.

[20] Rasmussen B, Rindel JH. Sound insulation between dwellings – Descriptors applied in building regulations in Europe. Appl Acoust 2010;71:171–80. doi:10.1016/j.apacoust.2009.05.002.

[21] Rychtáriková M, Horvat M. Developing a Methodology for Performing Listening Test...In: Build. Acoust. throughout Eur. Vol. 1 Towar. a common Framew. Build. Acoust. throughout Eur., 2014.

[22] Rasmussen B, Machimbarrena M, Fausti P, COST Action TU0901. Building acoustics throughout Europe Volume 2: Housing and construction types country by country. 2014.

[23] Machimbarrena M, García L, Herráez M, González J, Tarrero AI, M^{a} ;, et al. Integración y armonización de parámetros acústicos en el marco de edificaciones urbanas sostenibles: acción COST TU0901. Tec. 2009, Cádiz: Sociedad Española de Acústica; 2009.

[24] Marino CM, Machimbarrena M, Monteiro CRA. Comparison of some global indices to adequately assess airborne sound insulation. Euronoise 2012, Prague: European Acoustics Association; 2012.

[25] Monteiro CRA, Marino CM, Torchia F, Robertson N, Smith RS, Machimbarrena M. Comparative analysis of airborne sound insulation field measurements using different ISO 717-1 performance descriptors - Lightweight separating walls and floors. Euronoise 2012, Prague: European Acoustics Association; 2012.

[26] Monteiro CRA, Marino CM, Torchia F, Robertson N, Smith RS, Machimbarrena M. Comparative analysis of airborne sound insulation field measurements using different ISO 717-1 performance descriptors - Heavyweight separating walls and floors. Euronoise 2012, Prague: European Acoustics Association; 2012.

[27] Monteiro C, Mondaca C, Machimbarrena M, Smith S. Typical heavyweight walls performance: variability and density function distribution of airborne sound insulation single number quantities. AIA-DAGA 2013, Int. Conf. Acoust., Merano: German Acoustical Society (DEGA); 2013.

[28] Carrascal T, Machimbarrena M, Monteiro C. Chapter 25: Spain. In: Rasmussen B, Machimbarrena M, Fausti P, editors. Build. Acoust. throughout Eur. Vol. 2 Hous. Constr. types Ctry. by Ctry., COST Action TU0901; 2013, p. 427–52.

[29] Fausti P, Carrascal T, Ingelaere B, Machimbarrena M, Monteiro C, Santoni A, et al. Chapter 11 - Design and Acoustic Performance of Building Constructions for Multi-Storey Housing: Compendium. Build. Acoust. throughout Eur. Vol. 1 Towar. a common Framew. Build. Acoust., 2014, p. 213–44.

[30] ISO 717-1: 2013 Acoustics -- Rating of sound insulation in buildings and of building elements -- Part 1: Airborne sound insulation. International Organization for Standardization; 2013.

[31] ISO 717-2: 2013 Acoustics -- Rating of sound insulation in buildings and of building elements -- Part 2: Impact sound insulation. International Organization for Standardization; 2013.

[32] ISO 16283-1:2014 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation. Geneva, Switzerland: International Organization for Standardization; 2014.

[33] ISO 16283-2: 2015 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 2: Impact sound insulation. International Organization for Standardization; 2015.

[34] ISO 16283-3:2016 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 3: Façade sound insulation. International Organization for Standardization; 2016.

[35] ISO 12999-1:2014 Acoustics -- Determination and application of measurement uncertainties in building acoustics -- Part 1: Sound insulation. International Organization for Standardization; 2014.

[36] Directiva 2002/91/CE del Parlamento Europeo y del Consejo, relativa a la eficiencia energética de los edificios. Diario Oficial de la Unión Europea; 2002.

[37] ISO/CD 19488:2016 -- Acoustic classification scheme for dwellings. International Organization for Standardization; 2016.

[38] Smith S, Mackenzie R, Mackenzie R, Waters-Fuller T. The implications of ISO 717 spectrum adaptation terms for residential dwellings. Proc. Inst. Acoust., 2003, p. Vol25;Pt 5.

[39] Scholl W, Lang J, Wittstockh V. Rating of Sound Insulation at Present and in Future. The Revision of ISO 717. Acta Acust United with Acust 2011;97:686–98.

[40] Scholl W. Revision of ISO 717: Why Not Use Impact Sound Reduction Indices Instead of Impact sound Pressure Levels? Part 2: Application to Different Impact Sources. Acta Acust United with Acust 2013;97:503–8.

[41] Scholl W. ISO 16717 - Revision of single-number quantities for sound insulation in buildings: State of discussion. 42nd Int. Congr. Expo. Noise Control Eng. 2013, INTER-NOISE 2013, Innsbruck: Austrian Noise Abatement Association; 2013, p. 1482–91.

[42] Rychtáriková M, Roozen B, Müllner H, Stani M, Chmelík V, Glorieux C. Listening test experiments for comparisons of sound transmitted through light weight and heavy weight walls. Akustika 2013;19:1–10.

[43] Rychtáriková M. Influence of temporal and spectral features of neighbour's noise on perception of its loudness. Internoise 2013, Innsbruck: Institute of Noise Control Engineering; 2013.

[44] Rychtáriková M, Muellner H, Chmelík V, Roozen NB, Urbán D, Garcia DP, et al. Perceived Loudness of Neighbour Sounds Heard Through Heavy and Light-Weight Walls with Equal Rw + C50-5000. Acta Acust United with Acust 2016;102:58–66. doi:10.3813/AAA.918924.

[45] Hongisto V, Oliva D, Keränen J. Subjective and Objective Rating of Airborne Sound Insulation – Living Sounds. Acta Acust United with Acust 2014;100:848–63.

[46] Ordoñez R, Vicentini C, Markovic M, Fausti P. Objective and subjective evaluation of façade sound insulation. Internoise 2013, Innsbruck: Institute of Noise Control Engineering; 2013.

[47] Bradley JS. Evaluation of revised ISO airborne sound insulation ratings. NRC Constr 2012.

[48] ISO 140-4:1998 Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 4: Field measurements of airborne sound insulation between rooms. International Organization for Standardization; 1998.

[49] ISO 140-5:1998 Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 5: Field measurements of airborne sound insulation of façade elements and façades. International Organization for Standardization; 1998.

[50] ISO 140-14:2004 Acoustics - Measurement of sound insulation in buildings and of building elements - Part 14: Guidelines for special situations in the field. International Organization for Standardization; 2004.

[51] Hopkins C. Revision of international standards on field measurements of airborne, impact and facade sound insulation to form the ISO 16283 series 2015;92:703–12. doi:10.1016/j.buildenv.2015.05.043.

[52] ISO/IEC Guide 98-3:2008 - Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995). International Organization for Standardization; 2008.

[53] Wittstock V. On the uncertainty of single-number quantities for rating airborne sound insulation. Acta Acust United with Acust 2007;93:375–86.

[54] Wittstock V, Bethke C. On the uncertainty of sound pressure levels determined by third-octave band analyzers in a hemianechoic room. Forum Acusticum, Budapest,Hungary: 2005.

[55] ISO 140-2:1991 Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 2: Determination, verification and application of precision data. International Organization for Standardization; 1991.

[56] Luque P, Fernández D, Colina C de la, Simón F. Convergencia de la repetibilidad de ensayos de aislamiento a ruido aéreo in situ. Tec. 2005, Sociedad Española de Acústica; 2005.

[57] Castillo JC. Evaluación de la incertidumbre de medida en un supuesto de aislamiento in situ a ruido aéreo. Universidade de Vigo, 2007.

[58] Castillo Cid SS. Uncertainty evaluation for airborne noise acoustic insulation measurements. 19th Int. Congr. Acoust., Madrid, Spain: International Commission for Acoustics; 2007.

[59] Michalski, R.; Nabuco, M.; Ripper G. Uncertainty Investigation of Field Measurements of Airborne Sound Insulation. XIX IMEKO World Congr., Lisbon, Portugal: International Measurement Confederation; 2009.

[60] Michalski R. Metodologias para medição de isolamento sonoro em campo e para expressão da incerteza de medição na avaliação do desempenho acústico de edificações. Universidade Federal do Rio de Janeiro - COPPE, 2011.

[61] Seddeq HS. Evaluated uncertainties for measurements of airborne sound attenuation between rooms in buildings. Build Acoust 2010;17:69–82.

[62] Wszolek T. Uncertainty of airborne sound insulation index measurement in laboratory conditions. J Acoust Soc Am 2008;123:3616.

[63] Rebollo BP. Aislamiento a ruido aéreo entre locales: estimación de la incertidumbre de medida. Universidad Carlos III de Madrid, 2011.

[64] Hongisto V, Keränen J. Reproducibility of the present and the proposed single-number quantities of airborne sound insulation. Acta Acust United with Acust 2012;98:811–9.

[65] Mahn J, Pearse J. The Uncertainty of the Proposed Single Number Ratings for Airborne Sound Insulation. Build Acoust 2012;19:145–72. doi:10.1260/1351-010X.19.3.145.

[66] Schönbäck . Wilfried, Lang J, Pierrard R. Sound Insulation in Housing Construction. Vienna: 2006.

[67] Rindel JH. Acoustic quality and sound insulation between dwellings. J Build Acoust 1999;5:291–301.

[68] Bradley J. Grouped subjective ratings of airborne sound in- sulation. Jt. Meet. ASA/EAA/DAGA, Berlin: 1999, p. (Abstract in: J. Acoust. Soc. Am. 105 (2) 1175–117.

[69] Muellner H. Correlating Objective and Subjective Sound Insulation. In: Rasmussen B, Machimbarrena M, editors. Build. Acoust. throughout Eur. Vol. 1 Towar. a common Framew. Build. Acoust. throughout Eur., 2014.

[70] Park HK, Bradley JS. Evaluating standard airborne sound insulation measures in terms of annoyance, loudness, and audibility ratings. J Acoust Soc Am 2009;126:208. doi:10.1121/1.3147499.

[71] Bailhache S, Jagla J, Guigou C. Effet des basses fréquences sur le confort acoustique - tests psychoacoustiques, Rapport USC-EA-D1_A2.1.4_2. Centre Scientifique et Technique du Bâtiment CSTB 2014.

[72] de la Prida D. Los listening test como método de valoración subjetiva e implementación de software de evaluación. Universidad de Valladolid, 2014.

[73] Civille GV, Seltsam J. Sensory evaluation methods applied to sound quality. Noise Control Eng J 2003;51:262. doi:10.3397/1.2839722.

[74] Santamaría SO. Introducción a la usabilidad y su evaluación. Barcelona: Universitat Oberta de Catalunya; 2011.

[75] Berardi U, Rasmussen B. A Comparison Between National Scheme for the Acoustic Classification of Dwellings in Europe and in the U.S. Int J Acoust Vib 2015;20:63–8.

[76] Hopkins C. Sound insulation. Routledge; 2012.

[77] Parmanen J. Comments on "The dependence of Rw on the shape of the transmission loss curve. Towards a definitive understanding of the correlation between Rw, and RA." J Sound Vib 1988;124:390–3. doi:10.1016/S0022-460X(88)80198-6.

[78] Moreno-Arranz A, Pfretzschner J, Zaragoza JG. Comparison of dBA and ISO ratings in assessing sound isolation. J Acoust Soc Am 1984;75:476. doi:10.1121/1.390471.

[79] Gerretsen E, Dunbavin PR. Chapter 4: How to translate sound insulation descriptors and requirements. Build. Acoust. throughout Eur. Vol. 1 Towar. a common Framew. Build. Acoust. throughout Eur., 2014.

[80] Gerretsen E. European variety of descriptors for building acoustic performance and translation into proposed harmonized descriptors. 42nd Int. Congr. Expo. Noise Control Eng. 2013, INTER-NOISE 2013 Noise Control Qual. Life, vol. 2, OAL-Osterreichischer Arbeitsring fur Larmbekampfung; 2013, p. 1459–66.

[81] ILAC – Cooperación Internacional de Acreditación de Laboratorios n.d. http://ilac.org/.

[82] Scrosati C, Scamoni F, Prato A, Secchi S, Fausti P, Astolfi A, et al. Uncertainty of facade sound insulation by a Round Robin Test. Evaluations of low-frequency procedure and single numbers. Build Environ 2016;105:253–66. doi:10.1016/j.buildenv.2016.06.003.

[83] Navacerrada MA, Pedrero A, Díaz C. Study of the uncertainty of façade sound insulation measurements: Analysis of the ISO 12999-1 uncertainty proposal. Appl Acoust 2016;114:1–9.

doi:10.1016/j.apacoust.2016.03.033.

[84] Machimbarrena M, del Val L, Monteiro C, Herráez, Marta Johansson R. Translation of existing impact sound insulation descriptors into new proposed ones, based on a large set of in situ measurements. 22nd Int. Congr. Acoust., Buenos Aires: Ibero-american Federation of Acoustics; 2016.

7. Artículos publicados

En este capítulo se presentan los tres artículos publicados en la revista Applied Acoustics que conforman la Tesis Doctoral.

7.1 Artículo A

Uncertainty determination of in situ airborne sound insulation measurements

---

María Machimbarrena [a], Carolina Rodrigues A. Monteiro [a], Stefano Pedersoli [b], Reine Johansson [c], Sean Smith [d]

a. Universidad de Valladolid, Applied Physics Department Avenida de Salamanca s/n ,
47014 Valladolid, Spain
b. Empa, Laboratory for Acoustics & Noise Control, Ueberlandstrasse 129, 8600
Duebendorf, Switzerland
c. Swedish Metrology and Quality AB, Dragspelsgatan 21, 504 72 Borås, Sweden
d. Edinburgh Napier University, Institute for Sustainable Construction, Colinton Rd 42,
EH10 5BT Edinburgh, Scotland, UK

Applied Acoustics ,Volume 89, March 2015, Pages 199–210
doi:10.1016/j.apacoust.2014.09.018
Recibido: 15 de Julio de 2014
Aceptado: 19 de Septiembre de 2014

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Uncertainty determination of in situ airborne sound insulation measurements

María Machimbarrena [a,*], Carolina Rodrigues A. Monteiro [a], Stefano Pedersoli [b], Reine Johansson [c], Sean Smith [d]

[a] *Universidad de Valladolid, Applied Physics Department Avenida de Salamanca s/n , 47014 Valladolid, Spain*
[b] *Empa, Laboratory for Acoustics & Noise Control, Ueberlandstrasse 129, 8600 Duebendorf, Switzerland*
[c] *Swedish Metrology and Quality AB, Dragspelsgatan 21, 504 72 Borås, Sweden*
[d] *Edinburgh Napier University, Institute for Sustainable Construction, Colinton Rd 42, EH10 5BT Edinburgh, Scotland, UK*

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form 15 September 2014
Accepted 19 September 2014

Keywords:
Uncertainty
Sound insulation measurement
Building acoustics

ABSTRACT

In building acoustics the measurement uncertainty of sound insulation measurements is traditionally either not reported or reported as stated in the corresponding standard ISO 12999-1:2014. *Determination and application of measurement uncertainties in building acoustics—Part 1: Sound insulation* (former ISO 140-2). An alternative procedure is presented in this paper, aiming at evaluating the need of performing individual uncertainty calculations and the effect of extending the frequency range used to calculate sound insulation single number quantities. A large set of in situ airborne sound insulation measurements is investigated following the ISO Guide to the Expression of Uncertainty in Measurement (GUM) both for D_{nT} 1/3 octave bands values and for single number rating D_{nTA}. Two alternative assessment frequency ranges (50/100–5000 Hz) have been considered. The paper describes a methodology for uncertainty determination to emphasize that it is possible to determine such individual uncertainties following the ISO GUM approach to a certain extent and that each individual measurement needs a corresponding measurement uncertainty calculation. In addition, the results show that if the assessment frequency range is extended below 100 Hz, the uncertainty of the single number quantity is increased.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Building acoustics is going through a moment of change and renewal in several different ways. Standards relating to laboratory sound insulation measurements have recently been revised and improved and a new series was published, ISO10140 [1–5]. Currently, the revision of "in-situ" or non-laboratory sound insulation measurements is taking place by corresponding working groups (WG) and Ad Hoc Group (AHG) under ISO TC43/SC2/WG18.

Furthermore, the series ISO 717 [6,7] is under revision [8] with the aim of improving and eventually substituting existing single number ratings by new proposals such as R_{living} and $R_{traffic}$, considering two alternative frequency ranges for the evaluation i.e. 50–3150 Hz and 100–3150 Hz [9]. Additionally, between 2009 and 2013 the research and networking program COST TU0901 [10] has been working in close co-operation with ISO TC43/SC2/WG18 in all these areas.

Over and above the previous mentioned standards, the corresponding standard dealing with application of measurement uncertainties in building acoustics, ISO 140-2 [11], has been revised and a new standard ISO 12999-1 [12] has recently been approved. This includes general uncertainty values for typical measurands such as airborne and impact sound insulation under different measurement situations, both for 1/3 octave bands and single number quantities. The uncertainty values reported in the standard might be used to determine whether a building complies or not with the corresponding regulatory performance requirements. In some countries court proceedings might be implemented depending if requirements are fulfilled or not, and such legal arguments are likely to take uncertainties into account.

There has been much research in this field over recent years. According to some authors [13,14], it is not possible to follow a GUM [15] approach to determine uncertainties of sound insulation measurements, or it seems reasonable to keep the idea of reproducibility and repeatability concepts as used in ISO 12999-1 for building acoustics measurements [16]. One of the claimed problematic aspects [13,14] is that some quantities, like reverberation time and sound pressure levels, are not directly measured. They are derived and often determined by integrating over a field region, which implies some underlying assumptions. When underlying assumptions are not fully met it is difficult to obtain a full mathematical model including all relevant effects and this is the main reason why so far uncertainty of sound insulation measurements has not yet been determined using a GUM approach. As a consequence, some parts consider that the uncertainty of a sound insulation measurement shall be stated as the uncertainty of the corresponding measurement method, based on the results of inter-laboratory measurements described in ISO 140-2 or ISO 12999-1 and no individual uncertainty calculation is performed. However, this leads to some problems such as the measurement uncertainty contribution from the object is not fully included in the results.

1.1. Reasons to perform uncertainty calculations for building acoustics measurements

The purpose of a measurement is to determine the value of a quantity of interest, the measurand. The measurand can for example be the sound pressure level, sound power level, sound reduction index or a single number quantity like D_{nTA}. In reality this usually means to sample one value out of a universe of possible values, since in general, when one repeats a measurement, one will obtain different answers. This observed variability in the results of repeated measurements arises because the influence parameters that can affect the measurement result are changing. In general, there are many influence parameters affecting a measurement result. Although it is impossible to identify all of them, the most significant can normally be identified and the magnitude of their effects on the measurement result can be estimated. Moreover, the way they influence the measurement result can, in many cases, be mathematically modeled. These models can be retrieved theoretically, empirically or as a mixture between these two methods.

There are many ways to estimate measurement uncertainties. However, accreditation bodies that are members of the International Laboratory Accreditation Cooperation Mutual Recognition Arrangement (ILAC MRA) have agreed on requiring their accredited calibration laboratories to determine uncertainties in compliance with ISO 17025 [17], GUM, including its supplements, and/or ISO Guide 35 [18]. Also for test laboratories GUM is a basic document for estimating uncertainties [19], although some exceptions exist for test laboratories, e.g. when the process for evaluation of the measurement uncertainty is included in a test standard. ILAC G17 [20] however states that these standards should be reviewed and revised accordingly. This means that any new standard that aims at being used within the ILAC MRA should, whenever it is possible, use GUM, or corresponding documents from the accreditation bodies, as basic documents when estimations of measurement uncertainties are made within the standard.

When working with standard deviations, one usually makes a difference between the experimental standard deviation (s) and the real standard deviation (σ) to stress that it is impossible to know the real standard deviation exactly without having access to the full population. The experimental standard deviation has in itself an uncertainty which depends on the degrees of freedom and can be compensated for by using student's *t*-distribution when the probability density function is Gaussian.

Some technical areas by tradition only work with repeatability and reproducibility while trying to attribute a value describing the quality of the measurement result. This may be satisfactory as long as the reproducibility gives the major contribution to the total measurement uncertainty, and the other measurement uncertainty components give negligible contributions. Nevertheless, to fulfil the requirements in ISO 17025 it is important to investigate and document other possible uncertainty components that may influence the measurement results.

A recurrent argument for not using GUM within building acoustics is that no complete model exists for the measurands. However, although some kind of model is needed by GUM, there is no requirement that it shall be complete. In fact the word model itself implies that it is not a perfect description of the real world. In GUM it is also pointed out that one uncertainty component that always shall be considered is the uncertainty introduced by the model used in the measurement uncertainty analysis.

When considering single number quantity uncertainty, experimental data [13] shows that correlations exist between different 1/3 octave bands, but it is not possible to identify exactly how big they are in all measurements. Correlations are often possible to investigate by experiments and calculations, but if for some reason, it is impossible to retrieve correlations this way, GUM is permissive and will allow estimations based on experience. According to Wittstock's study [13], if the single number quantity uncertainty is determined considering full positive correlation between 1/3 octave bands, the result is higher than the one obtained if no correlation between 1/3 octave bands is considered. The same study also describes the full correlation uncertainty as an upper limit of the uncertainty of the single number ratings. Under the GUM approach, when estimating the measurement uncertainty, if there is no knowledge at all, the normal procedure is to make a conservative estimation until more knowledge is obtained. In the case of correlations, it means that a correlation coefficient equal to 1 should be used until more experience is acquired to make a better judgment. However, if experience indicates that the estimated correlation coefficient is not bigger than for example 0.8, then this is the number to use in the measurement uncertainty calculations.

Traditionally in building acoustics, estimations of method uncertainties have been performed according to ISO 5725 [21,22]. The two approaches in ISO 5725 and in GUM are different. ISO 5725 considers the measurement system like a "black box" and has a top-down approach where one does not need to have detailed knowledge about how different parameters affect the measurement results, whereas GUM has a bottom-up approach which demands a form of model for undertaking a measurement uncertainty analysis.

The former problem for GUM, with strongly non-linear systems, has been solved by introducing a GUM Supplement [23]. This is where Monte Carlo simulations can be used for propagating probability density functions through the models, to give an estimate of the measurement uncertainty. GUM also gives examples of how to use higher-order terms in the Taylor expansion series to handle non-linear systems.

The approach for dealing with sound insulation measurements described in ISO 140-2 or ISO 12999-1, where no individual uncertainty calculation is performed is somehow contradictory with ISO 17025 and some accreditation procedures, as mentioned before. In some countries, e.g. Spain and Portugal, the accreditation bodies demand from the test laboratories measurement uncertainty budgets in accordance to GUM or EA-4/02 [24]. As different laboratories have different environments, personnel, equipment, test objects etc. and are spread all over the world, it often makes sense to give different measurement uncertainties even though the method used is the same. This is why making individual uncertainty calculations also in the field of building acoustics is encouraged in this paper.

2. Objectives

As mentioned above, ISO12999-1 and ISO 140-2 state uncertainty of sound insulation measurements and of corresponding single number figures based on the results of previous inter-laboratory tests. If this approach is adopted as the generalized or harmonized procedure, all measurements made according to one method and under similar circumstances will yield the same uncertainty and no uncertainty calculation would be required after performing a measurement using that method. Moreover, if the measurement uncertainties are reported as an average spread from round robin measurements, about half of the measurements performed will report a measurement uncertainty that is underestimated. This study questions such an approach both for field (in-situ) and for laboratory measurements and their subsequent reporting.

The main objective of this paper is to show that, for airborne sound insulation measurements, making uncertainty estimations following GUM's recommendations is possible and the average of the results are coherent with those reported in ISO12999-1. By comparing our results to those shown in ISO 12999-1 the objective is to point out that there is a general similarity in results. Determining airborne and/or impact sound insulation measurement uncertainties from method uncertainties is, under certain circumstances, a valid procedure, although the development of alternative GUM based calculation methods is preferred.

In this paper impact and façade sound insulation are not considered, but the suggested approach is exportable to both parameters as well. It is also important to point out that for the purpose of this paper, not all possible uncertainty contributions have been considered, but only major ones. More rigorous calculations would be needed to fully follow GUM, but the work procedure would be very similar.

With the results and discussion included in this paper, the underlying three objectives are:

(a) To investigate the rationale that each individual airborne sound insulation measurement needs a corresponding measurement uncertainty estimation.
(b) To assess the possibility of determining individual measurement uncertainty and single number ratings uncertainty following GUM indications.
(c) To evaluate the effect on the uncertainty of single number quantities if low frequencies are taken into account. For the purposes of this study, comparisons have been performed between the frequency ranges of 100–5000 Hz and 50–5000 Hz.

Points (a) and (b) are extremely relevant from a market/quality point of view as all laboratories should develop their uncertainty calculation procedure based on agreed guidelines. For accredited laboratories, the uncertainty calculation procedure must have been assessed by an expert.

Similar studies have already been published by other authors [25–33]. However none of the papers found in the literature reviews have shown calculated uncertainty data for such a large set of experimental field (in-situ) data nor with such extensive analysis, as presented in this paper.

3. Data set description

For the purpose of this work, a set of 2081 field airborne sound insulation measurements on 22 different types of separating walls was originally available. All walls were constructed in the UK in compliance with the relevant Robust Details [34] specifications. Testing and on-site inspections were carried out on a sample of structures in dwellings under construction to ensure compliance with the construction system by workmanship and with Building Regulations. Four different types of walls have been evaluated. These walls have been selected because they represent very typical heavy and light weight solutions and are described as shown in Fig. 1.

Among all available measurements a selection has been made in order to have rather homogeneous measurement environment conditions. For each type of wall, measurements with common partition area and receiving room volume values far from the mean value were eliminated. Thereby, for each wall, a group of tests under similar conditions has been obtained and successively used in this work. The resulting groups are summarized in Table 1.

The idea behind this selection is that each selected sub set, corresponds to the same defined test object, built in different real dwellings but in quite similar conditions in all cases and measured by different teams. This does not correspond to any of the situations described in ISO 12999-1.

All field measurements were made by different accredited or registered testing organisations, following the corresponding measurement standard, ISO 140-4 [35], now substituted by ISO 16283-1 [36].

The uncertainty study which will be shown in this paper has been made both using the data corresponding only to each type of wall and also using all the selected data (TOTAL), in order to evaluate if the wall type could have any effect on the uncertainty result.

4. Methodology

4.1. General method description

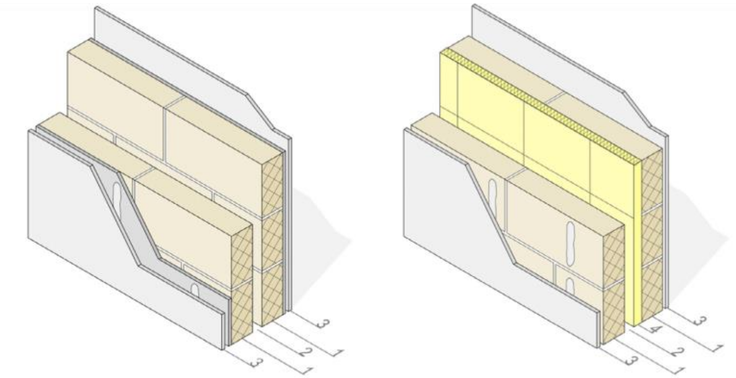
For better understanding, a definition of some specific terms used in this paper follows:

L_1: measured sound pressure level in the source room.
L_2: measured sound pressure level in the receiving room.
L_b: measured background sound pressure level in the receiving room.
T_{20}: reverberation time (using 20 dB decay).
$s(x)$: experimental standard deviation of measured input quantity "x".
$s(\bar{x})$: experimental standard deviation of the mean (of measured input quantity "x"). The standard uncertainty $u(\bar{x})$ associated with the input estimate $\bar{x}$ is the experimental standard deviation of the mean, i.e. $u(\bar{x}) = s(\bar{x})$. This standard uncertainty is denoted as $u_{rep}(x)$ in this paper.
$u_{rep}(x)$: standard uncertainty of measured quantity "x" measured under repeatability conditions.
$u(x)$: standard uncertainty of input quantity "x".
The sub-indexes "i" and "k" refer to 1/3 octave bands.
The sub index "j" refers to measurement position "j".
The sub index "ins" refers to the sound level meter instrument used.
The prime symbol (′) is also used to refer to measurement positions.

The following section describes how the individual uncertainty calculations have been undertaken in this paper. It is not the intention to suggest this procedure as the only possible one, but rather to show that there can be a procedure to determine individual uncertainties according to GUM. The uncertainty determination procedure used in this paper, divided in five steps, is outlined in this section. A detailed description follows in Section 4.2.

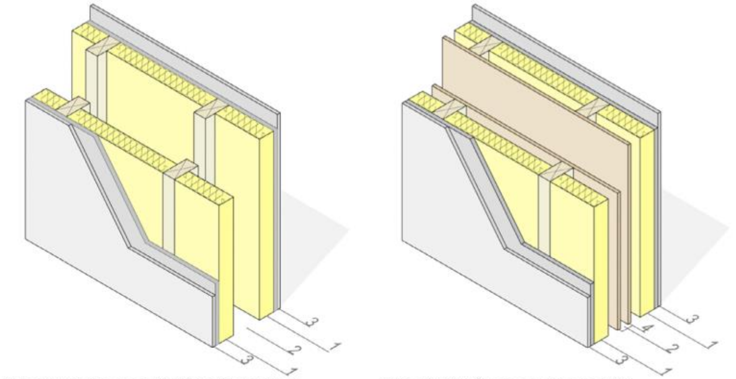
Table 2 summarizes the different steps described ahead.

Step 1: Collect raw measured data of the 300 selected separating walls. For each airborne sound insulation field test, there are



Type HWA: Empty cavity
1- Lightweight aggregate blocks (min. 100 mm)
2- Cavity (min. 75 mm)
3- Gypsum-based board mounted on dabs on cement/parge render (min 8 mm)

Type HWB: Partially filled cavity
1- Lightweight aggregate blocks (min. 100 mm)
2- Cavity (min. 75 mm)
3- Gypsum-based board mounted on dabs
4- Foil-faced mineral wool* (min. 35 mm)
* The mineral wool used in HWB is a singular specification product



Type LWA: Open cavity with mineral wool
1- Mineral wool batts or quilt (min. 60 mm)
2- Air cavity: (Min 50 mm between studs; typically 100 to 120 mm between mineral wool batts)
3- Two or more layers of gypsum-based boards (min. 240 mm cavity between wall inner linings)

Type LWB: 50 mm sheathed cavity
1- Mineral wool batts or quilt (min. 60 mm)
2- Air cavity (min. 50 mm between timber sheathing boards)
3- Two or more layers of gypsum-based boards (min. 240 mm cavity between wall inner linings)
4- Timber sheathing boards (min. 9 mm)

Fig. 1. Wall specifications for the four structure types analyzed in this study (HW – Heavyweight wall) and (LW – Lightweight wall).

in principle a minimum number of measurements for L_1, L_2, L_b and T_{20}. In this case, L_1 and L_2 have been measured twice in each room with a moving microphone, L_b has been measured once also with a moving microphone, and T_{20} has been measured six times. Fixed microphone positions would provide a larger set of measured data.

Step 2: Determine the standard uncertainty for each input estimate. Section 4.2 describes in detail how $u(L_1)$, $u(L_2)$, $u(L_b)$, u_{ins} and $u(T)$ have been obtained and how it has been dealt with the relation Pascal/dB, moving microphones and reverberation time. In the case presented in this paper, the standard uncertainty $u(L)$ of measured sound pressure levels will only consider $u_{rep}(L)$. Other possible uncertainty contributions to sound pressure level measurements will either be treated separately, e.g. the instrument uncertainty, or not be considered at all.

Output 2: $u(L_1) = u_{rep}(L_1)$; $u(L_2) = u_{rep}(L_2)$; $u(L_b) = u_{rep}(L_b)$; u_{ins} and $u(T)$.
This is shown, as an example, for P_1 (associated to the input quantity L_1). The experimental standard deviation is:

$$s(P_1^2) = \sqrt{\frac{1}{n-1} \cdot \sum_{j=1}^{n} \left(P_j'^2 - \overline{P_1^2}\right)^2} \tag{1}$$

Table 1
Data set description.

Type of wall	Cavity width (mm)	Number of measurements			Common partition area (m^2)			Receiving room volume (m^3)			D_{nTw} (dB)		
		Available	Selected		Min	Max	Average	Min	Max	Average	Min	Max	Average
HWA	75	197	50	25.4%	6.0	9.6	7.4	21.2	37.5	28.3	53	66	59
	100	160	50	31.3%	6.0	9.7	7.7	20.4	39.6	31.2	55	67	61
HWB	75	205	50	24.4%	6.0	9.1	7.3	23.7	36.0	30.4	54	65	60
	100	134	50	37.3%	6.0	9.7	7.6	21.3	39.0	30.0	54	67	60
LWA	50	250	50	20.0%	6.2	9.0	7.7	24.0	35.4	29.3	54	67	63
LWB	50	156	50	32.1%	6.0	9.6	7.5	21.3	39.0	29.4	55	69	64
Total		1102	300	27.2%	6.0	9.7	7.5	20.4	39.6	29.8	53	69	61

Table 2
General method description.

Step 1	Collection of raw measured data	Output 1	Input data: L_1, L_2, L_b and T_{20} measurement data
Step 2	Evaluate the standard uncertainty $u(x)$ of each input estimate x, e.g. calculation of experimental standard deviation	Output 2	Uncertainty of the corresponding input quantities
Step 3	Calculation of combined standard uncertainty	Output 3.1 Output 3.2	Individual uncertainty curves Average uncertainty curve
Step 4	Calculation of uncertainty for the corresponding single number quantity (two different frequency ranges)	Output 4.1 Output 4.2	Individual single number quantity uncertainties Average of single number quantity uncertainties
Step 5	Calculation of the expanded uncertainty for the corresponding single number quantity	Output 5	Expanded uncertainty for two frequency ranges (50–5000 Hz and 100–5000 Hz)

where P_1 stands for sound pressure in the source and P'_j stands for the sound pressure measured at the "j" position in the source room. This notation is also used in Eqs. (6)–(8).

From the experimental standard deviation, the corresponding uncertainty of the measurement is determined using the experimental standard deviation of the mean, $s\left(P_1^2\right)$. This corresponds to the uncertainty due to the repeatability of the measured quantities and is thus noted as u_{rep}.

$$s\left(P_1^2\right) = u_{rep}\left(P_1^2\right) = \frac{s\left(P_1^2\right)}{\sqrt{n}} \tag{2}$$

Step 3: Determine the $D_{nTi,}$ combined uncertainty $u(D_{nTi})$ where "i" stands for each 1/3 octave band. The uncertainty calculation model has been made based on the development found in [26,30,31] and only the most relevant uncertainty contributions were included.

The main input for this calculation is the output of Step 2 plus the sensitivity coefficients as explained in Section 4.2.6. Notice that in this model, the uncertainty due to the equipment has been considered separately for sound pressure levels and for time. The term $u(T)$ includes the uncertainty contribution due to the resolution of the time meter, whereas many of the possible contributions of the sound pressure level meter itself are included in u_{ins} as explained in Section 4.2.4. Furthermore, the effect of background noise correction is described in Section 4.2.5 so Eq. (3) is only used exactly as such under certain background noise conditions.

$$u(D_{nT_i}) = \sqrt{\left[u_{rep}(L_1)\cdot c_{L_1}\right]^2 + \left[u_{rep}(L_2)\cdot c_{L_2}\right]^2 + \left[u_{rep}(L_b)\cdot c_b\right]^2 + \left[u(T)\cdot c_T\right]^2 + \left[u_{ins}\cdot c_{ins}\right]^2} \tag{3}$$

Note: In Eq. (3) and subsequent Eqs. (17)–(19) the sub index "i" is omitted in all terms under the square root. It is understood that the uncertainty is a frequency dependent parameter and so are the sensitivity coefficients.

Outputs 3.1 and 3.2: For each of the 300 field measurement data, individual uncertainty curves have been calculated. Average uncertainty curves have also been calculated for each type of wall and for the full data set.

Step 4: Calculate the uncertainty for the corresponding single number quantity; in this case, according to [32] and assuming full positive correlation between the 1/3 octave band uncertainties input. The assumption of full correlation will likely overestimate the standard uncertainty, but due to lack of knowledge, and one does not want to risk underestimating the uncertainty, this is the assumption that has been made. For this calculation the previously obtained individual uncertainties data from Step 3 have been used as input. This can be done using different frequency ranges (i.e. starting at 50 Hz or 100 Hz and ending at 5000 Hz). For example for $D_{nTA(50-5000)}$:

$$u\left(D_{nTA(50-5000)}\right) = \sum_{i=1}^{N}\left(\frac{10^{(L_i - D_{nTi})/10}}{\sum_k 10^{(L_k - D_{nTk})/10}}\right)\cdot u(D_{nTi}) \tag{4}$$

Due to the assumption of full correlation, formula (4) consists of a linear addition instead of the square root of a sum of squares.

Outputs 4.1 and 4.2: Individual single number quantity uncertainties $u\left(D_{nTA(50-5000)}\right)$ have been calculated using two different frequency ranges (50–5000 Hz and 100–5000 Hz), and an average $\overline{u\left(D_{nTA(50-5000)}\right)}$ has been calculated. This was done for each type of wall and for the full data set.

Step 5: Determine the expanded uncertainty for the full data set. In calibration and test certificates issued by accredited laboratories the expanded uncertainty for a measurement value is normally given with the coverage factor $k = 2$, which for a Gaussian distribution corresponds to a coverage probability of approximately 95%. In this case the coverage factor selected was $k = 1.7$, defining an interval having a level of confidence of approximately 95% for single sided test used when verifying compliance, although a different coverage factor might be chosen. For example for $D_{nTA(50-5000)}$:

$$U(D_{nTA(50-5000)}) = k \cdot u(D_{nTA(50-5000)}) \tag{5}$$

Output 5: Expanded uncertainty values.

4.2. Detailed method description

The procedure followed in Steps 2 and 3 is explained in detail below. As previously mentioned [26,30,31], findings have been used and compared while developing the method.

4.2.1. How to deal with continuously moving microphones

When performing calculations described in Step 2, n corresponds to the number of different measurements made in each room using fixed microphone positions.

In this study, sound pressure levels were obtained with a moving microphone in a circular path with a radius of 0.7 m. L_1 and L_2 where measured twice, so one option was to use $n = 2$. On the other hand one can consider that a continuously moving microphone corresponds to a different number of uncorrelated samples in each 1/3 octave band, depending on path radius, speed and averaging time. According to [37,38], for a radius of 0.7 m, the equivalent number of uncorrelated samples is more than two above 80 Hz, (increasing rapidly with frequency). For both approaches $n = 2$ corresponds to the most unfavourable situation so it was assumed that $n = 2$ for L_1 and L_2. More discussion is needed on how to treat standard deviation of input data when obtained from moving microphones. L_b was measured using the same procedure but only once, so for this study it was assumed that $u_{rep}(L_b) \approx u_{rep}(L_2)$.

4.2.2. How to deal with input data in decibels and pressure levels uncertainty

Working with a logarithmic quantity might be an issue when dealing with uncertainties. Some solutions to overcome this problem is to work in Pascal [26] or linearizing [30] the model. In this study it was chosen to work in Pascal.

For example for L_1 (j stands for the number of measurement position in the source room and the prime symbol is used to avoid notation conflicts, i.e. sound pressure measured in the position 1 is "P'_1", and sound pressure in the source room is "P_1"):

$$P'^2_j = 10^{L'_j/10} \cdot P_0^2 \tag{6}$$

$$\overline{P_1^2} = \frac{\sum_{j=1}^{n} P'^2_j}{n} \tag{7}$$

$$s(P_1^2) = \sqrt{\frac{1}{n-1} \cdot \sum_{j=1}^{n} \left(P'^2_j - \overline{P_1^2}\right)^2} \tag{8}$$

$$u_{rep}\left(\overline{P_1^2}\right) = \frac{s(P_1^2)}{\sqrt{n}} \tag{9}$$

$$u_{rep}(L_1) = \sqrt{u_{rep}^2\left(\overline{P_1^2}\right) \cdot c_{P_1^2}^2} \tag{10}$$

where the sensibility coefficient is determined as per [30]:

$$c_{P_1^2} = \frac{\partial L_1}{\partial P_1^2} = \frac{10}{\log 10} \cdot \frac{1}{\overline{P_1^2}} \tag{11}$$

Similarly for L_2:

$$u_{rep}(L_2) = \sqrt{u_{rep}^2\left(\overline{P_2^2}\right) \cdot c_{P_2^2}^2} \tag{12}$$

Since calculating $u_{rep}(L_b)$ was impossible because there was only one measurement with a moving microphone for L_b, then it was assumed that $u_{rep}(L_b) \approx u_{rep}(L_2)$.

4.2.3. How to deal with reverberation time uncertainty

Concerning T_{20} the uncertainty calculations include the uncertainty due to the sampling or experimental standard deviation of the mean, u_{rep}, and the uncertainty due to the resolution of the equipment u_{res}.

Eq. (13) corresponds to the u_{rep} according to ISO 3382-2 [39] for $T_{20.}$ A similar equation can be found for T_{30}. As stated in [39], $T_{20,}$ is the average value of the measurements, n is the number of decays measured in each position, N is the number of independent measurement positions (combination between sound source and microphone) and B is the bandwidth:

$$u_{rep}(T) = 0.88 \cdot T_{20j} \cdot \sqrt{\frac{1 + (1.9/n)}{N \cdot B \cdot T_{20j}}} \tag{13}$$

For the resolution of the instrument, if a rectangular distribution is assumed and the resolution is 0.01 s, then:

$$u_{res}(T) = \frac{0.01}{2\sqrt{3}} \tag{14}$$

So the standard uncertainty associated to the measured reverberation time is:

$$u(T) = \sqrt{u_{rep}^2(T) + u_{res}^2(T)} \tag{15}$$

Another possible approach for estimating $u_{rep}(T)$ uncertainty could be using the experimental standard deviation to determine the uncertainty as explained in Step 2.

4.2.4. How to deal with sound level meter uncertainty

For those cases where it is not possible to estimate the uncertainty associated to sound pressure level meters, u_{ins}, ISO 1996-2 [40] suggests using $u_{ins} = 1$ dB. Several references have deeply discussed how to include such uncertainty and it is considered to remain far below 1 dB when using class 1 equipment. According to [25,41,42], it is possible to consider up to 15 different type B sources of error. Each laboratory should make its own study and include it in the corresponding uncertainty calculation procedure. As an example the proposal given by [42] could be used:

$$u_{ins} = \sqrt{u_{PFE}^2 + u_{PFA}^2 + u_{LS}^2 + u_{RMS}^2 + u_{PT}^2 + u_{CA}^2 + u_{CC}^2 + u_{ES}^2 + u_{OB}^2 + u_{TS}^2 + u_{PS}^2 + u_{CS}^2 + u_{PA}^2} \tag{16}$$

The subscripts refer to the different contributions according to the following:

(a) Those related to the operation of the sound level meter: sound pressure level electrical calibration correction (PFE); sound pressure level acoustic calibration correction (PFA); linearity of sound level meter (LS); sound level meter RMS detector (RMS); temporal weighting function (PT); calibration of sound level meter with calibrator (CA); certified value of acoustic calibrator (CC); resolution of display (ES).
(b) Those related to the use of the sound level meter: influence of the observer (OB); influence of temperature variations (TS); influence of variations in relative humidity (H); influence of variations in atmospheric pressure (PS); influence of sound level meter housing (CS); influence of the wind screen (PA).

In this study it was estimated that: $u_{ins} = 0.5$ dB for all 1/3 octave bands.

4.2.5. How to deal with background noise

Another issue to take into account is the L_2 correction due to background noise. Three cases where considered depending on the relation between L_2 and L_b and for each measurement. This means that the contribution has been calculated according to Eq. (17) in those frequency bands where there has been no correction to L_2 due to background noise, according to Eq. (18) when the correction was as described in Eq. (8) of Ref. [35] and according to Eq. (19), when the correction was 1.3 dB.

Case 1: Combined standard uncertainty when $L_2 > L_b + 10$ dB

$$u(D_{nT_i}) = \sqrt{[u_{rep}(L_1) \cdot c_{L_1}]^2 + [u_{rep}(L_2) \cdot c_{L_2}]^2 + [u(T) \cdot c_T]^2 + [u_{ins}]^2} \tag{17}$$

In this case $u_{rep}(L_b)$ is not considered, as no correction to L_2 is needed.

Case 2: Combined standard uncertainty when ($L_b + 6\text{ dB} < L_2 < L_b + 10\text{ dB}$)

$$u(D_{nT_i}) = \sqrt{[u_{rep}(L_1) \cdot c_{L_1}]^2 + [u_{rep}(L_2) \cdot c_{L_{21}}]^2 + [u_{rep}(L_b) \cdot c_{L_{22}}]^2 + [u(T) \cdot c_T]^2 + [u_{ins}]^2} \tag{18}$$

As mentioned in Section 4.2.2, calculating $u_{rep}(L_b)$ was impossible in this specific case because there was only one L_b so it was decided to consider $u_{rep}(L_b) = u_{rep}(L_2)$ as an estimate. Derivation of c_{L21} and c_{L22} is described in Section 4.2.6.

Case 3: Standard combined standard uncertainty when $L_2 < L_b + 6$ dB

$$u(D_{nT_i}) = \sqrt{[u_{rep}(L_1) \cdot c_{L_1}]^2 + [u_{rep}(L_2) \cdot c_{L_{21}}]^2 + 0.2 + [u(T) \cdot c_T]^2 + [u_{ins}(L_i)]^2} \tag{19}$$

Based on the observation of the 300 input measurements, and the calculated values for the term $[u_{rep}(L_b) \cdot c_{L_{22}}]^2$ in case 2, it was decided to estimate a maximum value for the contribution of the uncertainty due to background noise correction of 0.2 dB for case 3 situations.

4.2.6. How to determine the sensitivity coefficients

The sensitivity coefficients have been used as derived in Ref. [30].

In case of no background noise correction:

$$c_{L_1} = \frac{\partial D_{nT}}{\partial L_1} = 1 \quad c_{L_2} = \frac{\partial D_{nT}}{\partial L_2} = -1 \tag{20}$$

In case of including background noise correction (case 2 in Section 4.2.5), then

$$c_{L_{21}} = \frac{\partial D_{nT}}{\partial L_2} = \frac{-10^{L_2/10}}{10^{L_2/10} - 10^{L_b/10}} \tag{21}$$

$$c_{L_{22}} = \frac{\partial D_{nT}}{\partial L_b} = \frac{10^{L_b/10}}{10^{L_2/10} - 10^{L_b/10}} \tag{22}$$

For the reverberation time:

$$c_T = \frac{\partial D_{nT}}{\partial T} = \frac{10}{\log 10} \cdot \frac{1}{T} \tag{23}$$

For the instrumentation, c_{inst} is considered to be equal to 1, since a fixed value has been chosen for u_{ins}, as explained in Section 4.2.4.

5. Outcomes of the study

5.1. Individual and average results for each type of tested wall: Outputs 3.1 and 3.2

For each of the available measurements, individual uncertainty curves $u(D_{nTi})$ have been calculated according to the methodology previously described. Where i stands for each 1/3 octave band.

Fig. 2 shows a random selection out of the 300 calculated uncertainty curves obtained. As it can be seen, the spread in the values is significant and supports the need of making detailed uncertainty calculations when performing sound insulation tests.

This spread is more evident at low frequencies than in the medium–high frequency range, although a considerable spread is also found in the higher end of the frequency range.

For each type of wall an average uncertainty curve $\overline{u(D_{nT_i})}$ has also been obtained.

Figs. 3–5 show individual uncertainty values $u(D_{nTi})$ and the average $\overline{u(D_{nT_i})}$ results obtained for similar types of walls, grouped as presented in Table 1.

Even when representing the same type of wall in a figure, the spread of individual uncertainty curves is considerable. The col-

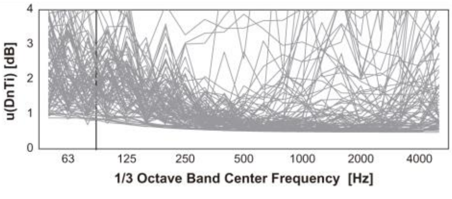


Fig. 2. Spread of individual values $u(D_{nTi})$ for full data set.

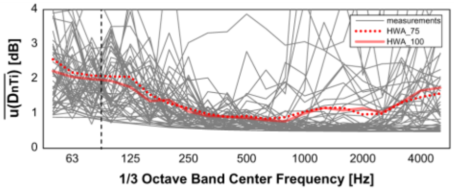


Fig. 3. Spread of individual values $u(D_{nTi})$ and average uncertainty curve $\overline{u(D_{nT_i})}$ for walls type HWA (75 mm and 100 mm cavity).

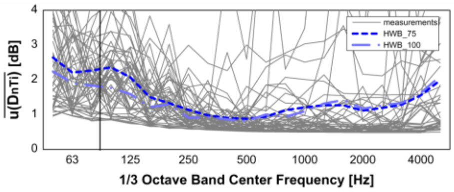


Fig. 4. Spread of Individual values $u(D_{nTi})$ and average uncertainty curve $\overline{u(D_{nT_i})}$ for walls type HWB (75 mm and 100 mm cavity).

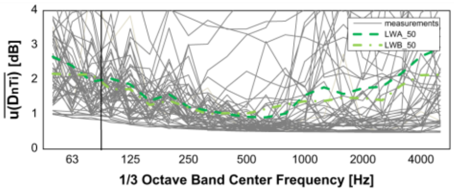


Fig. 5. Spread of Individual values $u(D_{nTi})$ and average uncertainty curve $\overline{u(D_{nT_i})}$ for walls type LWA and LWB (50 mm cavity).

ored bold lines in Figs. 3–5 represent the corresponding average for each type of wall.

For HWA (heavyweight –75/100 mm empty cavity wall) the average uncertainty curves vary at low frequencies and are similar at mid and high frequencies where transmission may be dominated by the wall ties connecting the two wall leafs. A similar result is observed for HWB (heavyweight –75/100 mm cavity partly filled with a singular specification product). Even when looking at exactly the same defined object with different cavity width, measured by experts following the same standard and with similar equipment, one can observe different uncertainty results.

In the case of lightweight walls LWA and LWB a similar result is observed. All selected cases have the same central cavity widths although LWA has the absorption facing the cavity and LWB facing the timber sheathing board. Slight different mineral wool absorption coefficients can be used within the specification permissible range. The resonant behavior and transmission of sound through the wall is highly influenced at higher frequencies by the cavity facing materials and this may explain the divergence between LWA and LWB average uncertainty curves, in this case more noticeable at high frequencies.

The range of results presented again support the need of making individual uncertainty calculations when performing airborne sound insulation measurements in the field. The uncertainty calculation methodology described in this paper is a good approach but not the only method.

As an exercise, the "full data set average uncertainty curve" or overall average uncertainty curve $\overline{u(D_{nTi})}$ has been compared to the uncertainty curves given in ISO 12999-1 for situations B and C. The data set used in this paper do not correspond exactly to the situations A, B or C described in ISO 12999-1. It is interesting to note that the overall average uncertainty curve (considering trend/shape/tendency) agrees quite well with ISO 12999-1 suggested curves. This can be observed in Fig. 6. These results again confirm the need of making individual uncertainty calculations for each situation, since in many real cases, such as those presented in this paper, the measurement setup does not fully correspond to any of the scenarios presented in the ISO standard.

5.2. Uncertainty of single number quantities and effect of frequency range extension: Outputs 4.1 and 4.2

In order to evaluate the effect of including low frequencies, the corresponding single number quantity uncertainty was calculated for the two frequency ranges: 100–5000 Hz ($D_{nTA(100\text{–}5000)}$) and the extended frequency range, 50–5000 Hz ($D_{nTA(50\text{–}5000)}$) using Eq. (4). This was done for the full data set and considering each of the four types of walls separately.

Fig. 7 shows the results for the full data set whereas Figs. 8–10 show the same analysis for each type of wall described in Table 1. All figures represent the spread of the uncertainty values for the single number quantity D_{nTA} and the corresponding uncertainty

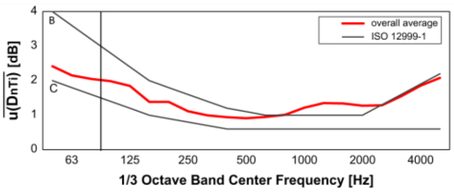


Fig. 6. Overall average uncertainty curve $\overline{u(D_{nT_i})}$ for full dataset and ISO 12999-1 situations B and C.

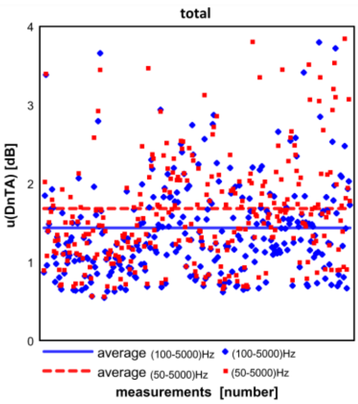


Fig. 7. Spread of $u(D_{nTA})$ values and average $\overline{u(D_{nTA})}$ for the full dataset.

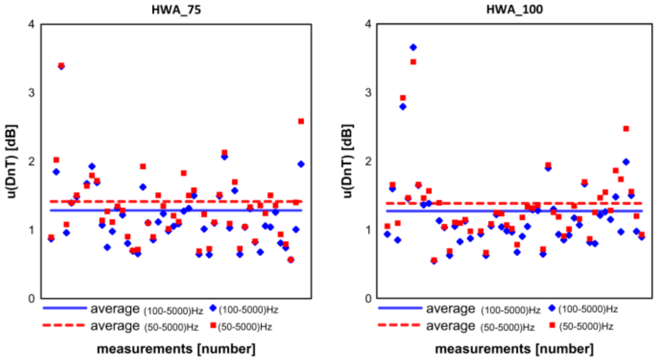


Fig. 8. Spread of $u(D_{nTA})$ values and average $\overline{u(D_{nTA})}$ for walls type HWA (75 mm and 100 mm cavity).

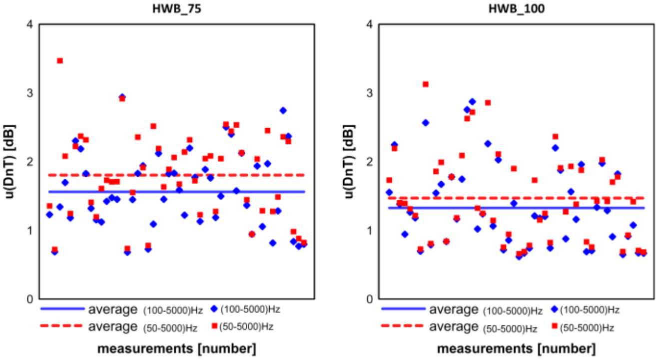


Fig. 9. Spread of $u(D_{nTA})$ values and average $\overline{u(D_{nTA})}$ for walls type HWB (75 mm and 100 mm cavity).

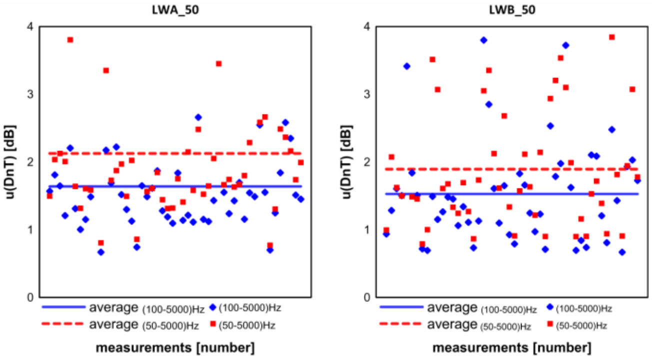


Fig. 10. Spread of $u(D_{nT})$ values and average $\overline{u(D_{nT})}$ for walls type LWA and LWB (50 mm cavity).

average, using both frequency ranges. One can from the data state with a confidence level higher than 99.9% that $\overline{u(D_{nTA})_{50-5000}}$ is bigger than $\overline{u(D_{nTA})_{100-5000}}$.

For the same type of wall built in different places, measured by different operators belonging to accredited institutions and using similar equipment, the spread of the calculated uncertainty of the single number quantity is in many cases considered quite large. This result reinforces the suggestion of undertaking individual uncertainty estimations in future.

Fig. 11 shows that in most of the cases the uncertainty of the extended frequency range single number quantity $u(D_{nTA})_{50-5000}$ is higher than the uncertainty of the corresponding frequency range single number quantity $u(D_{nTA})_{100-5000}$. All results above the line "$x = y$" correspond to cases where there is an uncertainty increase when extending the frequency range. This is very similar to the results found by Mahn and Pearse [32]. This supports the relevance of undertaking further investigations into the effects of frequency range extension, especially when it is related to compliance with requirements.

5.3. Study of expanded uncertainty of single number quantities

In building acoustics it is not common practice to present uncertainty data with measurement reports, nor to include the corresponding expanded measurement uncertainty with the results. According to ISO 12999-1, if expanded uncertainty shall be reported the minimum coverage factor to be used shall be $k = 1$ which, when verifying compliance with a single sided requirement, corresponds to 84% confidence level.

Some countries allow for a certain tolerance in an unfavourable direction when verifying compliance with requirements such as Belgium, Italy, France or Spain while others have no indications in the corresponding building code on how to verify compliance [43]. If in future harmonized sound insulation descriptors in Europe [44] are achieved, the use of a consistent approach by national bodies on verifying compliance and uncertainty would be very useful. For accredited laboratories the document "ILAC G8:03/2009 Guidelines on the Reporting of Compliance with Specification" [45] provides guidelines for testing and calibration laboratories (and their customers) in relation to the decision and reporting of compliance or non-compliance with specific requirements. However, the implementation of this guide seems limited within the area of building acoustics. Reporting the corresponding expanded measurement uncertainties seems the most adequate procedure thus far.

Table 3 shows the calculated average expanded uncertainty of the single number quantity D_{nTA} for each type of wall described in Table 1. It has been assumed that D_{nTA} has a Gaussian distribution, which could be discussed [32,46], and a coverage factor $k = 1.7$ which corresponds to approximately 95% confidence level for a cumulative distribution (single sided).

Although average values are shown, in almost 10% of the case studies presented $u(D_{nTA})_{50-5000} > 3$ dB and the corresponding expanded uncertainty for the reported $D_{nTA(50-5000)}$ was found to

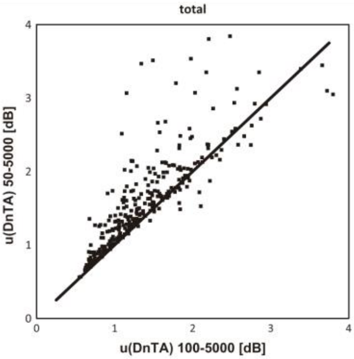


Fig. 11. Effect of frequency range extension for the full data set.

Table 3
D_{nTA} and corresponding expanded uncertainty values (average). (dB)

(Average values) Type of wall	$\overline{D_{nTA_{50-5000}}}$	$\overline{U(D_{nTA})_{50-5000}}$	$\overline{D_{nTA_{100-5000}}}$	$\overline{U(D_{nTA})_{100-5000}}$
HWA_75	57.45	2.41	58.11	2.18
HWA_100	59.62	2.35	60.43	2.16
HWB_75	57.45	3.07	58.76	2.65
HWB_100	57.24	2.50	58.17	2.25
LWA_50	58.23	3.61	61.52	2.79
LWB_50	57.22	3.22	61.48	2.60

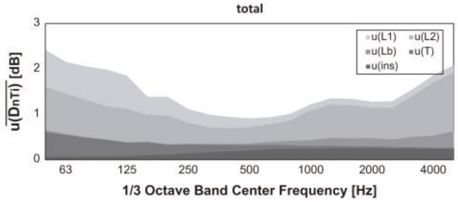


Fig. 12. Contribution of each of the uncertainty sources to $\overline{u(D_{nTi})}$ for the full data set.

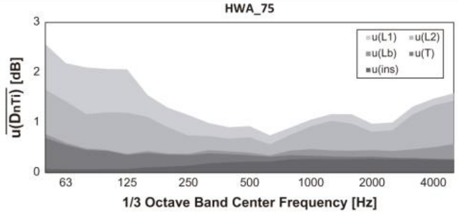


Fig. 13. Contribution of each of the uncertainty sources to $\overline{u(D_{nTi})}$ for wall type HWA (75 mm empty cavity).

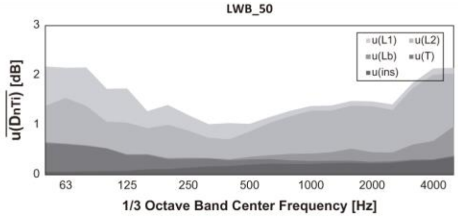


Fig. 14. Contribution of each of the uncertainty sources to $\overline{u(D_{nTi})}$ for wall type LWB (50 mm sheathed cavity).

be $U > 5.1$ dB. This can make a significant difference when trying to fulfil a performance requirement.

The results of this study confirm that expanded uncertainties vary considerably for different types of walls and/or different frequency ranges and thus should be determined individually for each field measurement.

5.4. Contribution of each input quantity to the standard uncertainty

In this study, only five major sources of uncertainty have been considered: L_1, L_2, L_b, T_{20} and sound level meters equipment. Figs. 12–14 show the contribution of each of the sources to the calculated uncertainty. This has been done for the full data set and for two specific types of walls.

Some interesting results are:

(a) The uncertainty due to the instrumentation is much more relevant at medium to high frequencies for all types of walls.
(b) Below 125 Hz, the contribution of L_1, L_2 and T_{20} is similar and much larger than instrumentation or background noise sources.
(c) The background noise contribution becomes significant at high frequencies and slightly more so for quite well performing lightweight walls.
(d) The reverberation time contribution is relevant below 500 Hz, and becomes almost insignificant above this frequency.
(e) If one compares the contribution of L_1 and L_2, it can be seen that $u(L_1)$ decreases with frequency but this is not equally so for $u(L_2)$. (A plausible explanation is the presence of background noise in the receiving room.)

Being aware of the relative weight of each of the uncertainty sources can also help reduce the uncertainty of the single number quantity by trying to develop new measurement methods aimed at decreasing some of the uncertainty sources.

6. Conclusions and future research

The building industry needs, like other industries, a continuous improvement to be not only competitive but also sustainable. There are high demands on a building's performance concerning energy saving, low carbon, safety and acoustic performance. Future directions may require new buildings to be graded according to their acoustic "quality" [44]. It is of high importance to adequately assess and report such performance with a sustainable methodology which reflects the uncertainty or tolerance. Moreover, in many countries the corresponding administration will not permit the use of a building unless many requirements are fulfilled and duly certified. This already occurs for some cases concerning acoustic performance, and will increase in the future. Sound insulation measurement uncertainty should be reported both for laboratory measurements (element's or constructive solution performance) and for in-situ field measurements (building performance).

For a large set of in situ airborne sound insulation measurements, individual uncertainty estimations have been performed. The estimation of the corresponding uncertainty has been done following GUM to a close extent and a detailed procedure is included in the paper. Although the detailed methodology is presented only for D_{nT}, it is possible to make similar calculations for all types of sound insulation measurements.

From the literature review and from the results obtained, it is concluded that it is possible to make such individual uncertainty estimations for airborne sound insulation. This thesis can be extended to impact and façade sound insulation in a similar way. There is not a unique procedure and most likely some type of guidelines should be included in the next version of ISO 12999-1, if only as an alternative to inter-laboratory based uncertainties. If the standard is to be used in relation to accredited measurement services, it should be revised to follow the basic documents mentioned in ILAC's guidelines.

Furthermore, the results show that for the same type of wall built in similar situations, the corresponding D_{nT} uncertainty curves show a rather high dispersion. This supports the need of making individual uncertainty calculations and particularly for in-situ or field measurements. Similar results are also observed for D_{nTA}.

Concerning the single number quantity D_{nTA} calculated using A weighting over a specific frequency range, the results show that, as suggested by Mahn and Pearse [32], it is preferable to determine the uncertainty of the single quantity following GUM's indications. The choice of full positive correlation between 1/3 octave band uncertainties is in coherence with Annex B in ISO 12999-1 and with the fact that there is not enough knowledge about the correlation. The frequency range used for the evaluation will affect the uncertainty of the single number quantity. In almost all the cases shown in this paper, the uncertainty is increased when the frequency range is extended, which is also in accordance also to other author's results [32,33]. This is especially relevant when expanded uncertainty is considered and compliance with requirements is under question. This shall not be neglected when developing the future ISO 16717.

Further research is needed concerning how to deal with the uncertainty when using moving microphones to sample sound pressure levels [47] since this sampling technique is becoming more and more popular during field testing and new such techniques have been included in ISO 16283. It is also necessary to evaluate and rank all possible sources of uncertainty, although some authors consider sound pressure levels, reverberation time, background noise correction and instruments as the most relevant uncertainty sources [40].

Smith et al. [48] illustrated the effect of increased uncertainty and complications with field testing when the frequency range was not extended but emphasis was placed on lower frequencies (100–160 Hz) using spectrum adaptation term No. 2 (C_{tr}) for airborne sound insulation. The evidence from this current paper investigating uncertainty for extended frequencies suggests that uncertainty has a significant role in the adequate reporting of individual in-situ field measurements.

Last, but not least, it will be interesting to investigate how the recently approved ISO 16283-1 will fit with the also recently updated ISO 12999-1, since measurement methods differ significantly from the former ISO 140-4.

Acknowledgements

Authors want to thank COST Action TU0901 and Robust Details Ltd for inspiring this research and providing the data.

References

[1] ISO 10140-1:2010 Acoustics. Laboratory measurement of sound insulation of building elements – Part 1: Application rules for specific products. Geneva (Switzerland): International Organization for Standardization; 2010.
[2] ISO 10140-2:2010 Acoustics. Laboratory measurement of sound insulation of building elements – Part 2: Measurement of airborne sound insulation. Geneva (Switzerland): International Organization for Standardization; 2010.
[3] ISO 10140-3:2010 Acoustics. Laboratory measurement of sound insulation of building elements – Part 3: Measurement of impact sound insulation. Geneva (Switzerland): International Organization for Standardization; 2010.
[4] ISO 10140-4:2010 Acoustic. Laboratory measurement of sound insulation of building elements – Part 4: Measurement procedures and requirements. Geneva (Switzerland): International Organization for Standardization; 2010.

[5] ISO 10140-4:2010 Acoustic. Laboratory measurement of sound insulation of building elements – Part 5: Requirements for test facilities and equipment. Geneva (Switzerland): International Organization for Standardization; 2010.

[6] ISO 717-1:2013 Acoustics. Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation. Geneva (Switzerland): International Organization for Standardization; 2010.

[7] ISO 717-2:2013 Acoustics. Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation. Geneva (Switzerland): International Organization for Standardization; 2010.

[8] Scholl W, Lang J, Wittstockh V. Rating of sound insulation at present and in future. The Revision of ISO 717. Acta Acust United Acust 2011;97:686–98.

[9] CD 16717-1: Proposal Acoustics. Evaluation of sound insulation spectra by single-numbers – Part 1: Airborne sound insulation. Geneva (Switzerland): International Organization for Standardization TC 43/SC; 2010.

[10] COST Action TU0901: integrating and harmonizing sound insulation aspects in sustainable urban housing constructions. <http://www.costtu0901.eu/n.d>.

[11] ISO 140-2:1991 Acoustics. Measurement of sound insulation in buildings and of building elements – Part 2: Determination, verification and application of precision data. Geneva (Switzerland): International Organization for Standardization; 2010.

[12] ISO 12999-1 Acoustics. Determination and application of measurement uncertainties in building acoustics – Part 1: Sound insulation. Geneva (Switzerland): International Organization for Standardization; 2010.

[13] Wittstock V. On the uncertainty of single-number quantities for rating airborne sound insulation. Acta Acust United Acust 2007;93:375–86.

[14] Wittstock V, Bethke C. On the uncertainty of sound pressure levels determined by third-octave band analyzers in a hemianechoic room. Forum Acusticum, Budapest, Hungary; 2005.

[15] JCGM 100:2008. Evaluation of measurement data – guide to the expression of uncertainty in measurement, vol. 50. Joint Committee for Guides in Metrology; 2008.

[16] Luque P, Fernández D, Colina C de la, Simón F. Convergencia de la repetibilidad de ensayos de aislamiento a ruido aéreo in situ. Tec. 2005, Sociedad Española de Acústica; 2005.

[17] ISO 17025:2005. General requirements for the competence of testing and calibration laboratories. Geneva (Switzerland): International Organization for Standardization; 2005.

[18] ISO Guide 35:2006. Reference materials – general and statistical principles for certification. Geneva (Switzerland): International Organization for Standardization; 2006.

[19] ILAC P14:01/2013. ILAC policy for uncertainty in calibration. International Laboratory Accreditation Cooperation; 2013.

[20] ILAC-G17:2002. Introducing the concept of uncertainty of measurement in testing in association with the application of the standard ISO/IEC 17025. International Laboratory Accreditation Cooperation; 2002.

[21] ISO 5725-1:1994. Accuracy (trueness and precision) of measurement methods and results – Part 1: General principles and definitions. Geneva (Switzerland): International Organization for Standardization; 1994.

[22] ISO 5725-2:1994. Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method. Geneva (Switzerland): International Organization for Standardization; 1994.

[23] JCGM 101:2008. Evaluation of measurement data—supplement 1 to the "guide to the expression of uncertainty in measurement"—propagation of distributions using a Monte Carlo method, vol. 2. Joint Committee for Guides in Metrology; 2008.

[24] EA-4/02 M:2013. Evaluation of the uncertainty of measurement in calibration. European Co-operation for Accreditation; 2013.

[25] Castillo Cid SS. Uncertainty evaluation for airborne noise acoustic insulation measurements. In: 19th Int Congr Acoust. Madrid, Spain: International Commission for Acoustics; 2007.

[26] Castillo JC. Evaluación de la incertidumbre de medida en un supuesto de aislamiento in situ a ruido aéreo. Universidade de Vigo; 2007.

[27] Michalski R. Metodologias para medição de isolamento sonoro em campo e para expressão da incerteza de medição na avaliação do desempenho acústico de edificações. Universidade Federal do Rio de Janeiro – COPPE; 2011.

[28] Seddeq HS. Evaluated uncertainties for measurements of airborne sound attenuation between rooms in buildings. Build Acoust 2010;17:69–82.

[29] Wszolek T. Uncertainty of airborne sound insulation index measurement in laboratory conditions. J Acoust Soc Am 2008;123:3616.

[30] Rebollo BP. Aislamiento a ruido aéreo entre locales: estimación de la incertidumbre de medida. Universidad Carlos III de Madrid; 2011.

[31] González VV. Medición y evaluación de la incertidumbre de auditorías en el aislamiento acústico. Universidad Politécnica de Valencia; 2011.

[32] Mahn J, Pearse J. The uncertainty of the proposed single number ratings for airborne sound insulation. Build Acoust 2012;19:145–72.

[33] Hongisto V, Keränen J. Reproducibility of the present and the proposed single-number quantities of airborne sound insulation. Acta Acust United Acust 2012;98:811–9.

[34] Robust details handbook. Part E: Resistance to the passage of sound. 3rd ed. Milton Keynes (UK): Robust Details Ltd.; 2013.

[35] ISO 140-4:1998 Acoustics. Measurement of sound insulation in buildings and of building elements – Part 4: Field measurements of airborne sound insulation between rooms. Geneva (Switzerland): International Organization for Standardization; 1998.

[36] ISO 16283-1:2014 Acoustics. Field measurement of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation. Geneva (Switzerland): International Organization for Standardization; 2014.

[37] Lubman D. Effectiveness of continuous spatial averaging in a diffuse sound field. J Acoust Soc Am 1973;53:650.

[38] Hopkins C. Sound insulation. Routledge; 2012.

[39] ISO 3382-2:2008 Acoustics. Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms. Geneva (Switzerland): International Organization for Standardization; 2008.

[40] ISO 1996-2:2007 Acoustics. Description, measurement and assessment of environmental noise – Part 2: Determination of environmental noise levels. Geneva (Switzerland): International Organization for Standardization; 2007.

[41] Payne R. Uncertainties associated with the use of a sound level meter; 2004. NPL REPORT DQL-AC 002. National Physical Laboratory. Queens Road, Teddington, Middlesex, UK.

[42] Mondaray J, Yebra F, Lorenzo L. Empleo en campo de los sonómetros. Factores a considerar y su contribución a la incertidumbre de medida. Congr Español Metrol, Zaragoza; 2005.

[43] COST TU0901. Building acoustics throughout Europe. Volume 2: housing and construction types country by country. DiScript Preimpresion, SL; 2014.

[44] COST TU0901. Building acoustics throughout Europe Volume 1: towards a common framework in building acoustics throughout Europe. DiScript Preimpresion, SL; 2014.

[45] ILAC G8:03/2009. Guidelines on the reporting of compliance with specification. International Laboratory Accreditation Cooperation; 2009.

[46] Mondaca C, Monteiro CRA, Machimbarrena M. Análisis de la variabilidad e incertidumbre de medidas "in situ" del aislamiento acústico a ruido aéreo de paredes pesadas. VIII Congr. Iberoam. Acústica, Evora; 2012.

[47] Critchley C, Dunbavin PR, Lawrence R, McNeill D. An empirical study of the effects of occupied test rooms and a moving microphone when measuring airborne sound insulation. IOA spring conference 2008; 2008. p. 1–54.

[48] Smith RS, Macdonald R, Lurcock D, Mackenzie R. Sensitivity analysis of ISO 717-1 spectrum adaptation terms. In: Proceedings of the institute of acoustics, Institute of Acoustics, Cambridge, UK; 2007.

7.2 Artículo B

Subjective and objective acoustic performance ranking of heavy and light weight walls

---

Carolina Rodrigues A. Monteiro [a] , María Machimbarrena [b],Daniel de La Prida [a] , Monika Rychtarikova [c,d]

a. Applied Physics Department, Architecture School Universidad de Valladolid, Spain
b. Applied Physics Department, Architecture School, Universidad de Valladolid, Spain
c. KU Leuven, Dep. of Physics and Astronomy, Belgium
d. STU Bratislava, KKPS, Slovakia

Applied Acoustics, Volume 110, September 2016, Pages 268–279
doi:10.1016/j.apacoust.2016.03.008
Recibido: 28 de Enero de 2016
Aceptado: 16 de Marzo de 2016

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Subjective and objective acoustic performance ranking of heavy and light weight walls

Carolina Monteiro [a,1], María Machimbarrena [b,*], Daniel de la Prida [a], Monika Rychtarikova [c,d]

[a] *Universidad de Valladolid, Spain*
[b] *Applied Physics Department, Architecture School, Universidad de Valladolid, Spain*
[c] *KU Leuven, Dep. of Physics and Astronomy, Belgium*
[d] *STU Bratislava, KKPS, Slovakia*

ARTICLE INFO

Article history:
Received 28 January 2016
Received in revised form 11 March 2016
Accepted 16 March 2016

Keywords:
Listening tests
Loudness
Single number ratings

ABSTRACT

This study presents a comparison between heavyweight and lightweight walls, in terms of perceived loudness of pink noise transmitted through 10 different walls. The objective is to investigate whether the single number descriptor $R_{A,50-5000}$ adequately reflects the subjective perception of the acoustic performance of a wall and if the sound reduction index spectral behaviour affects the subjective rating. To perform the experiment, a Matlab® based digital tool was developed and a pairwise comparison listening test was performed in laboratory conditions with thirty three subjects. The sound samples consisted of only one stimulus – pink noise-, filtered by the sound reduction index spectrum of 5 heavy weight walls and 5 corresponding lightweight walls with the same $R_{A,50-5000}$ but different R_w.

The results were analysed and used to rank the walls from best to worst according to the perceived loudness of the sound samples. It has been shown that lightweight walls are better ranked than heavy walls, not only when compared to those with the same $R_{A,50-5000}$, but in some cases also when the $R_{A,50-5000}$ of the heavy wall is higher than the $R_{A,50-5000}$ of the lightweight one. Furthermore, the ranking obtained from the listening test results matches very well with the ranking made according to $R_w + C \approx R_{A,100-3150}$.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

In the last years, a scenario of renovation in the field of building acoustics resulted in the revision of many International Standards. Concerning laboratory sound insulation measurements, the revised ISO10140 series [1] was launched in 2010, and the in-situ sound insulation measurements series ISO 16283 [2,3] is almost finalized (part 3 to be published early 2016). Regarding sound insulation ratings, there was an intention to review the ISO 717 [4–6] aiming at optimizing the evaluation method at different levels: simplifying the calculation methods, reducing the amount of existing descriptors, identifying which single number ratings correlate better with the perceived annoyance, and taking into account the low frequency components of sound sources in households. Furthermore, this revision partly inspired the harmonization of sound insulation descriptors suggested by the European research and networking project COST Action TU0901 [7].

Nevertheless, given the lack of agreement among the participant countries and the need for more research, the standard proposal [8] was finally cancelled and the project postponed until more evidences in this field are available.

The idea of delivering better sound insulation ratings is a result of the interaction between new technical and social demands. The main characteristic desired is that descriptors *"should be better, or more accurate indicators of the acceptability of the sound insulation"* [9] by the people. To assess the acoustics performance of buildings and at the same time evaluate building occupants comfort using a unique single number rating is an important goal in the building acoustics research field [10–13].

One of the most controversial proposals of the extinct ISO/CD 16717 draft was to extend the frequency range used for airborne sound insulation assessment below 100 Hz. The proposed extension of the assessment frequency range intended to provide a better correlation between the objective acoustic performance of the construction solutions, and the subjective perception of the users, related to annoyance.

Over the last years important research has been initiated in this field [10,13–18]. Still there is no consensus on how to adequately

---

[*] Corresponding author.
E-mail address: mariao@opt.uva.es (M. Machimbarrena).
[1] Sponsored by CNPq – Brazil.

include the lower frequency range in to the assessment of airborne sound insulation.

2. Objective

The main purpose of this research is to provide new evidence in the field of subjective perception of acoustic performance of different construction solutions.

The specific objective of the designed listening test is to investigate how people would rank ten different walls from best to worst based on perceived loudness and to compare such ranking to the one obtained using the objective sound insulation descriptor $R_{A,50-5000}$.

In this case study the set of walls consisted of five pairs of heavyweight and lightweight walls, each pair with the same $R_{A,50-5000}$ but different $R_{w,}$ similar to experiment performed in [19]. In the aforementioned paper, however, the comparisons were done only within pairs and not between pairs, and the main focus was placed on understanding the differences between temporal and spectral features of stimuli.

The subjective evaluation was carried out by listening tests performed in a laboratory. All the details related to the test are further described in Section 3.

3. Listening tests

3.1. Listening protocol

The participants were comfortably seated in a low background noise environment, a semi anechoic chamber. They listened to the audio stimuli through headphones.

The audio stimuli were obtained by filtering pink noise through the extended frequency spectrum of the sound reduction index (SRI) of 10 different partition walls (details in Section 5.1). This procedure assumes that, when listening, only direct transmission occurs.

The 10 different stimuli were presented to the participants in pairs, making all possible combinations in random order. The task of participants was to indicate which of the two presented sounds was louder. After validating the significance of the data and analysing them adequately, a ranking from best to worst sound insulation as perceived by subjects in terms of loudness was delivered.

3.2. Laboratory

The experiment took place at two different locations: the semi anechoic chamber at the Laboratory of Acoustics at KU Leuven, Belgium (from now on KUL) and the semi anechoic chamber of the School of Industrial Engineering of Universidad de Valladolid-Spain (from now on UVa).

Both at KUL and UVa tests, all the electronic equipment involved in the test was placed in an adjacent room, assigned as control room (Fig. 1). Inside the semi anechoic chambers there was only a screen, a mouse, a signal amplifier and the headphones, so there was no noticeable source of noise. According to measurements performed by the authors, the background noise level inside the semi-anechoic chambers was $SPL_{Background\ (UVa)} < 17$ dB and $SPL_{Background\ (KUL)} < 0$ dB. At the control room there was another screen and mouse so that the test tool could be operated/followed from both rooms. This allows the experimenter to set up the test, and to monitor the progress of the participant without entering the test chamber.

3.3. Equipment

The equipment used for both experiments is listed in Table 1. It should be noted that in both experiments, open-back headphones were used because of their particular characteristics. The perforated shells allow certain sound leakage, delivering a much wider sound spatiality, which is desirable for the purpose of the test.

Not only the headphones were selected based on quality requirements, but also all the other elements of electroacoustic chain. Precise equipment was necessary as some stimuli could be reproduced with a very low level (when the basic stimulus was filtered by walls with a high sound insulation performance), and electric noise from electroacoustic devices might be an issue.

A dummy head and torso were used for test calibration which is further described in Section 4.

3.4. Subjects

Thirty three normal hearing participants took part on the experiment: 11 at KUL – Belgium and 22 at UVa – Spain; 12 female, 21 male. Demographic data can be observed in Fig. 2. The participants are not representative of Belgian or Spanish population. The statistical analysis performed in Section 6.1 demonstrates the reliability

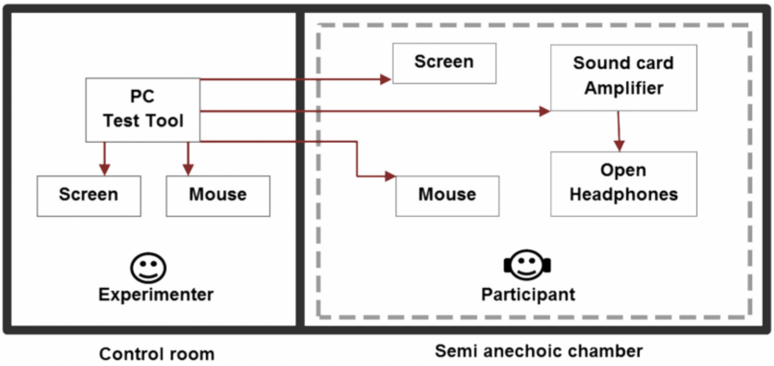


Fig. 1. Test set up.

Table 1
Equipment list.

KUL – Belgium	UVA – Spain
PC – Ericom Core 2 Duo 1.7 GHz 2 Gb RAM	Laptop – Asus Core i5 1.8 GHz &Gb RAM
Screen – TFT DELL superior 20″ (control room) Screen – TFT LG superior 20″ (test room)	Screen from laptop (control room) Screen – TFT LG superior 20″ (test room)
Sound Card – 24bit/96 KHz SPDIF output	External sound card with amplifier and equalizer – Tascam US-366
Head acoustics HPS IV Amplifier – Head acoustics 2485 PVA IV.2 Equalizer Head acoustic 2482 PEQ IV	Brüel & Kjær PULSE analyser
Open Headphones – Head acoustics HM-1	Open-back headphones – ATH-AD900X
Dummy head and torso – Head acoustics HMS III digital	Dummy head and torso – Bruel and Kjaer

of the experiment results. Most subjects were recruited at the campus of both universities, but not all, and ten of them had background in Acoustics. The subjects were told that the purpose of the experiment was to evaluate the loudness of different sound samples and that all the personal data collected would be treated confidentially. None of the subjects had previously participated in similar experiments at UVa, but eight subjects had participated in listening tests experiments at KUL.

To have a better knowledge on participants' noise sensibility, at the end of the experiment they were required to answer to two questions taken from COST Action TU0901 Questionnaire on annoyance by neighbour noise [20]. The first questions was: "Before moving to the apartment, how important to you was the protection against noise, with respect to noise in general?". The second question was: "How tolerant are you with respect to noise in general?". Fig. 3 shows the results and it is observed that most of the participants consider themselves very/extremely sensitive respect to noise in general and that protection against noise is an important point when moving to their apartments.

It should be noted that in Spain the experiment was carried out in Spanish, as all the subjects were natives. On the other hand, at KUL there are an important number of international students, so the test was performed in English.

Since the experiment took place in a semi anechoic chamber, where some people can feel uncomfortable, subjects were told that they were free to withdraw from the experiment and leave the room for any reason.

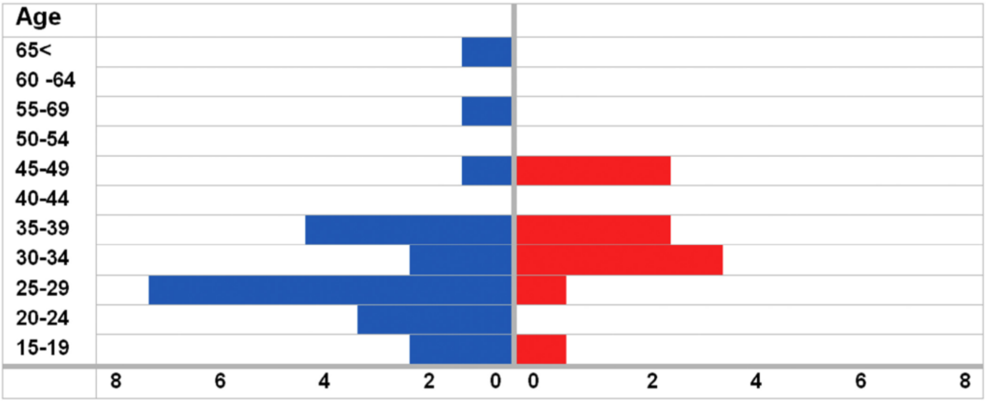


Fig. 2. Age and gender distribution of the experiment panel.

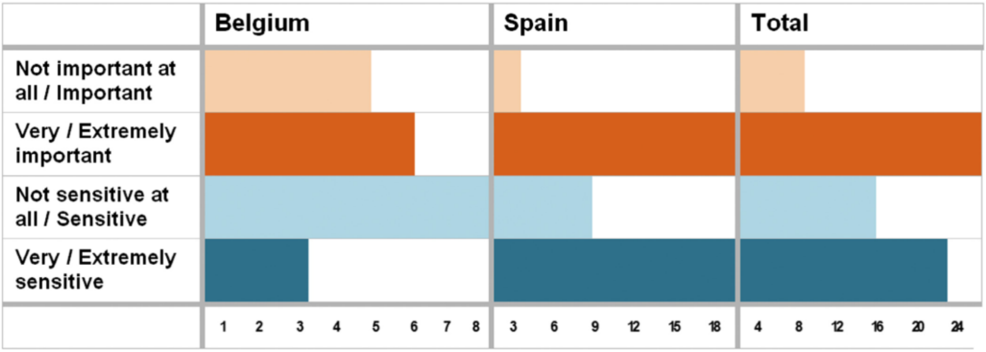


Fig. 3. Number of respondents to Q1 and Q2 from COST TU 0901 Questionnaire on annoyance by neighbour noise.

After the experiment, participants were offered snacks and drinks and no financial reward was provided.

4. Methodology

The duration of the listening experiment was about 18–25 min. Prior to the participants' arrival, the test setup was calibrated as described below. A scheme of the phases of the test, inspired by Hongisto et al. [13], can be seen in Fig. 4:

1. Set up calibration (30 min approx.): Since the listening test was performed in two different institutions and during several days, it was important to ensure that all sound samples were played to all participants under the same controlled and reproducible conditions, in which the absolute sound levels were guaranteed.

It was therefore decided to use the pink noise sound of 80 dB, (which was also the basic source room sound, e.g. sound before filtering) to verify the correct absolute sound level played through the headphones. Before the listening tests experiment performed at KU Leuven, the sound level in the headphones was adjusted by means of volume button on the listening unit of the Head acoustics, while monitoring the sound level in the headphones placed on an artificial ear. For the reason of simplicity and purity of future calibration, a pure tone of 1000 Hz was generated and adjusted to level of 80 dB of the pink noise signal. Both the pink noise and 1000 Hz.wav files were saved for future use. When the listening test was performed in UVa, both the pink noise and the 1000 Hz pure tone were verified by means of the dummy head.

The sound pressure level in the headphones was verified (using the described calibration procedure) before each listening test. However, the system was very stable and there were no fluctuations in sound level found during the time span of several days when the test was performed (see Fig. 5).

2. Familiarizing phase (5 min approx.): Some time was dedicated to allow the participants to become familiar with the test environment and with the listening test application. In this phase the experimenter helped the subject feel comfortable at the semi anechoic chamber, explained the test procedure and introduced the listening test application.
3. Rehearsal phase (3 min approx.): The participants were encouraged to launch the learning application and the experimenter left the semi anechoic chamber. The learning application is intuitive, provides all information about the experimental phase and guides the participants in practicing the subjective rating with the listening test tool. It has been designed using the same interface as for the experimental phase but in this case

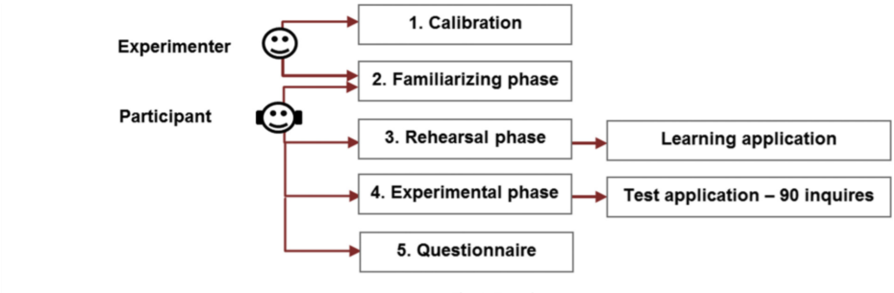


Fig. 4. Test phases.

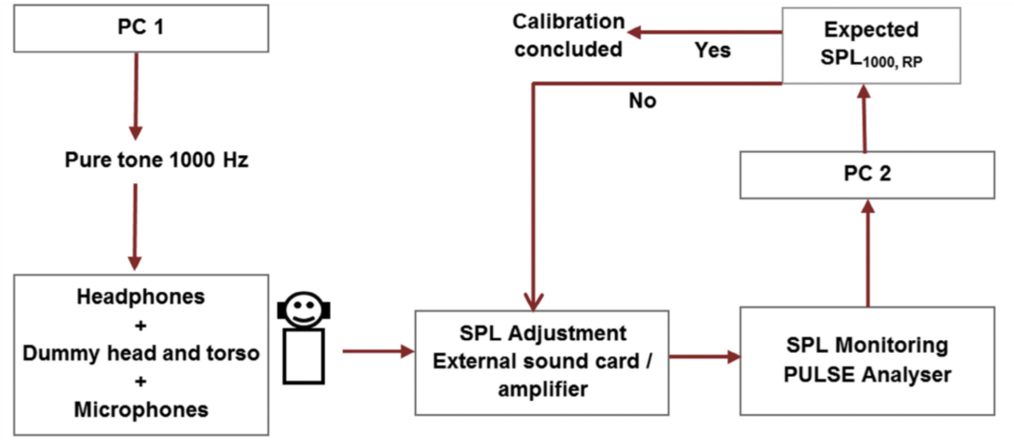


Fig. 5. Set up calibration scheme.

only dummy sound samples are played in order to minimize the bias. Participants were free to spend as much time as they judged necessary to familiarise themselves with the tool. They then decided when they were ready to begin the test.

4. Experimental phase (12 min approx.): As mentioned in Section 3, the sound samples were based on only one type of sound signal, a pink noise, filtered by the sound reduction index spectrum of ten different partition walls. The resulting ten different sound samples were presented to the listener in randomly chosen pairs. In order to avoid bias, each pair was presented in both directions (A–B, B–A). A combination without repetition of the 10 samples taken 2 in 2, $C_{10,\,2}$, produced 45 pairs of samples, resulting in 90 pairs of samples evaluated by each participant in total. When evaluating a pair, the participant was free to click on the play button to listen to each sample and then rate which one sounded louder. In case of not hearing any sound or not being able to perceive a difference between sound samples, the participants had a choice to choose “I didn’t hear anything” option, although they were instructed to try to avoid this answer and replay the samples as much as needed before answering. This option was included to evaluate the effect of a “null” answer.
5. Questionnaire (2 min approx.): Before finalizing the test, the participants were asked to answer to two questions taken from COST Action TU0901 questionnaire on annoyance by neighbour noise [7] and to provide general demographic data.

5. Listening test tool

Based on the literature review, a self-developed listening test has been designed, implemented and applied to a mixed population group.

A MATLAB® application has been developed with a friendly user interface (UI) to present the sound samples and collect the participant’s answers. The purpose of the application is not only to collect the data but rather to provide a platform to run this specific listening test and potential future ones, including a data base of sound samples and improving the experience both for the participant and the experimenter.

Apart from data collection, the developed tool allows the experimenter to perform two more tasks: To select and prepare the sound samples and to make a preliminary analysis of the collected data and deliver a ranking of the sound samples based on the loudness perception from the respondents. Thus, the complete tool is composed of three different modules that work together to simplify the whole process:

- Module 1 – Sound samples preparation tool.
- Module 2 – Perception assessment tool.
- Module 3 – Data analysis tool.

Each of the modules will be further described hereinafter.

5.1. Sound samples preparation tool

This tool was designed to allow the experimenter to prepare the sound samples by filtering any original sound signal (stimulus) through any chosen filter. In this case study, the original stimulus was pink noise and the filters correspond to frequency spectrum sound reduction index of ten different walls. In order to investigate only the influence of the sound reduction index, the sound samples were kept mono, without filtering with HRTF. Other factors such as the position of the wall, the distance of the listener to the wall or the reverberation time and volume of the “living room” were neglected in this experiment.

As previously mentioned, five pairs of walls (10 in total) have been selected. Each pair is composed by a heavyweight and a lightweight wall with the same $R_{A(50-5000)}$ but different spectral sound reduction index performance as it can be seen in Fig. 6. The R_w values were obtained from laboratory tests at the KUL (Belgium) following ISO 10140-2 [21]. The $R_{A,50-5000}$ values were obtained from calculation, according to [6].

The selected walls (light/heavy) and R_w values (39–65 dB) are considered to be representative of normal building constructions in Europe, as referred in [22].

Hereinafter the walls will be referred to according to the following code: HW for heavyweight and LW for lightweight walls; a number (from 1 to 5) precedes the wall code, using number 1 for the lowest $R_{A,50-5000}$ and 5 for the highest $R_{A,50-5000}$.

To design the corresponding filters, several approaches such as IIR and FIR bandpass filter cascades [23,24], biquadratic peaking filters [25], high order recursive filters [26], multi-rate filters [27] and FFT filtering have been evaluated.

Although there is still discussion [28–31] about the effects of non-linear phase on listening through headphones, it was considered convenient to reduce any source of bias related to this fact, so FIR features such as linear phase and stability were highly recommended. Considering the purpose of the designed study and tool, finally a FIR approach was chosen.

The principle of this approach consists in designing a FIR filter which approximates the frequency response curve for the desired amplitudes and frequencies. The quality of the approximation is related to the length of the filter. A high order and low efficiency filter has been selected for this purpose. Additionally, zero-phase distortion is achieved by performing a forward-backward filtering implementation.

To check the effectiveness of this approach, several predefined signals have been filtered both with Audacity for Windows® and with the sound sample preparation tool. The match between samples exceeded 90% both for magnitude and phase.

As an example, Table 2 shows the input data to the filtering algorithm and Fig. 7 shows the obtained result.

For the SRI defined in the range between 50 Hz and 5000 Hz, the experimenter inputs the selected ⅓ octave SRI in the corresponding boxes of the sound sample preparation tool interface. This produces a table with SRI data between 50 Hz and 5000 Hz similar to Table 2. Then, the filtering algorithm takes the data as input to generate the FIR filter. Fig. 7 represents the frequency response of the generated FIR filter corresponding to SRI shown in Table 2. As it can be seen, the selected points in Fig. 7, fit almost perfectly with the two corresponding pairs in Table 2.

The figure also shows that below 50 Hz and above 5000 Hz the magnitude of the response is flat. This was the approach chosen for the frequency bands beyond the selected frequency range (50–5000 Hz).

5.2. Stimuli presentation – Perception assessment tool

When human subjects are treated as measurement instruments, they are quite variable over time, variable among themselves, and highly prone to bias. There can be also many different unwanted effects that influence the perception assessment [32]. While working with humans as “sensors”, it is necessary to ensure the quality of the results, just like in more traditional areas, however, the use and development of metrological concepts like uncertainty and traceability is in its initial stage for measurements based on human beings [33] and these concepts have not been included in this study.

Bearing all of the above in mind and in order to develop a digital perception assessment tool, well known psychoacoustics and

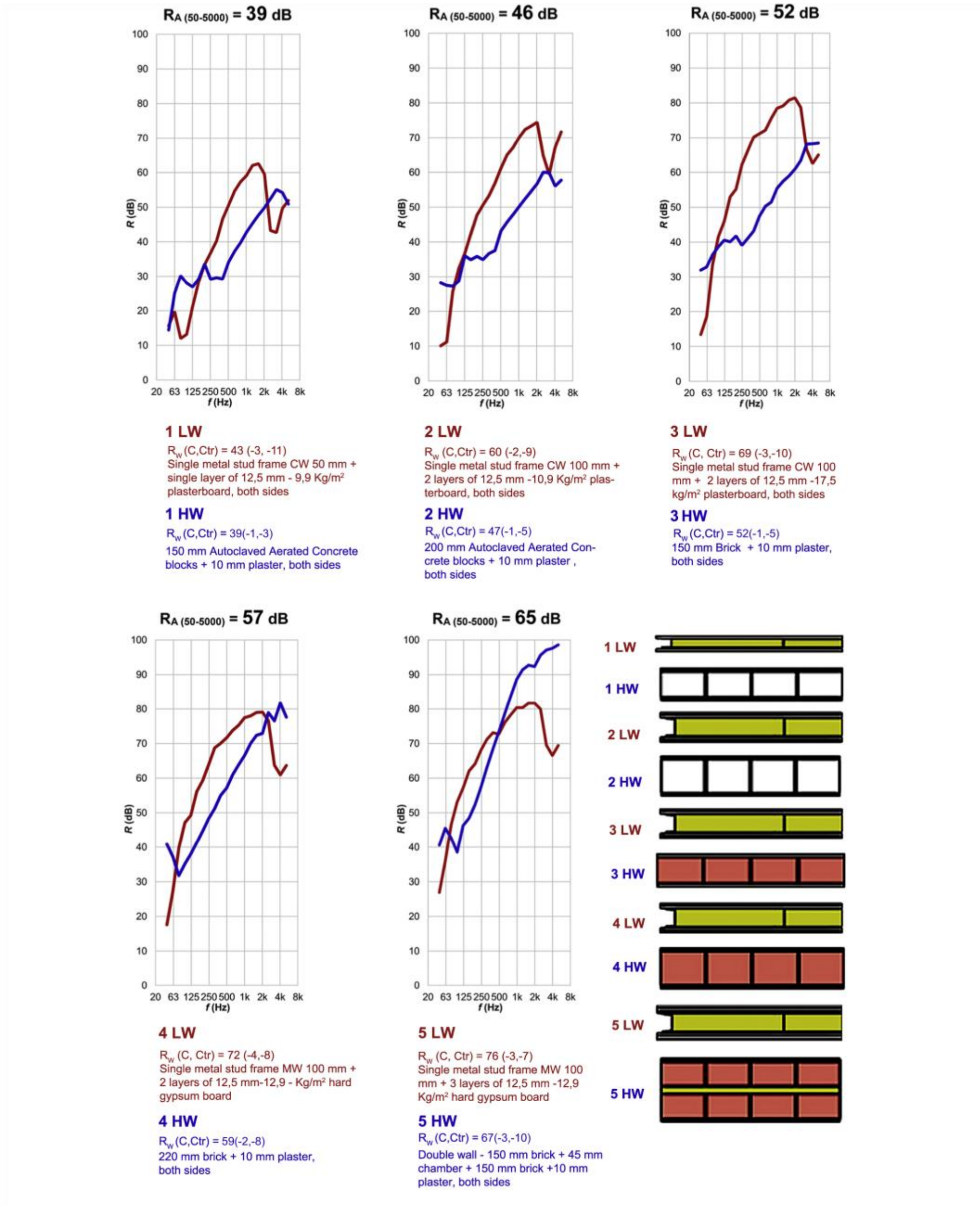


Fig. 6. Walls' description.

sensory evaluation techniques [32,34] have been explored as well as human-computer interaction [35]. Also the idea of using User-Centred Design techniques [36] was permanently part of the project. The "developed" product (perception assessment tool) is in fact a dedicated User Interface (UI) for the subject to perform the listening test.

Table 2
SRI values used for the filter example shown in Fig. 7. Bold figures correspond to points represented in Fig. 7.

Frequency (Hz)	Magnitude (dB)	Frequency (Hz)	Magnitude (dB)
50	17.8	630	65.3
63	18.8	800	63.3
80	27.7	**1000**	**64.6**
100	36.3	1250	68.1
125	38.1	1600	68.1
160	40.0	2000	67.5
200	45.6	25,000	67.4
250	**46.2**	3150	70.5
315	56.7	4000	75.2
400	57.5	5000	77.6
500	62.6		

Providing a seamless experience to the test participant, with proper cognitive load, helps overcome common source of bias, such as fatigue caused by large questionnaires, or the intervention of the researcher to give instructions and/or to help managing complex interfaces. In general, having some feedback on status and task progress reduces the feeling of complexity and fatigue due to the session length and the simplicity of completing the test reduces the lack of motivation problem, a recurring cause of bias [35]. To avoid such sources of bias, the UI was developed so that the participants could trigger the stimuli and decide when to move on to the next question; this allowed them to have some control over the test and set their own pace since there was no need to wait for instructions from the researcher. A test completion/status bar was also available (see Fig. 8).

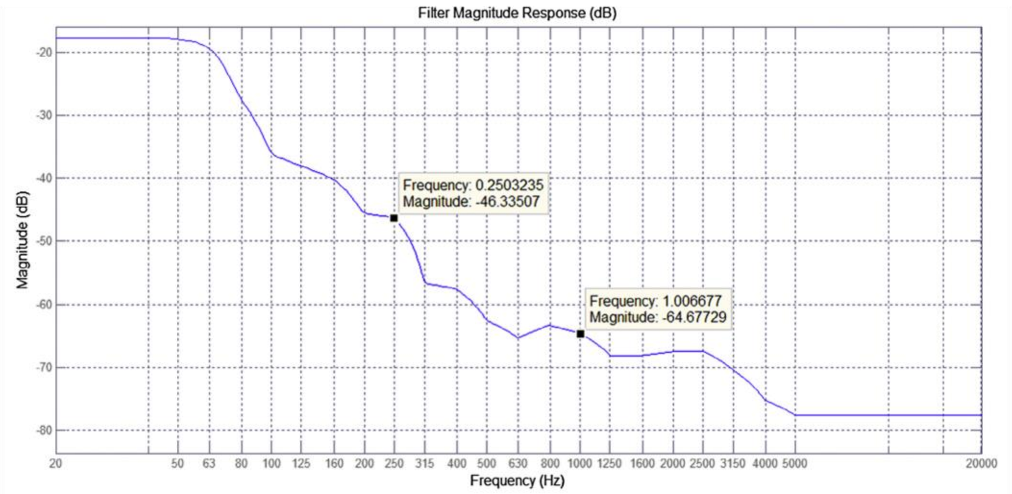
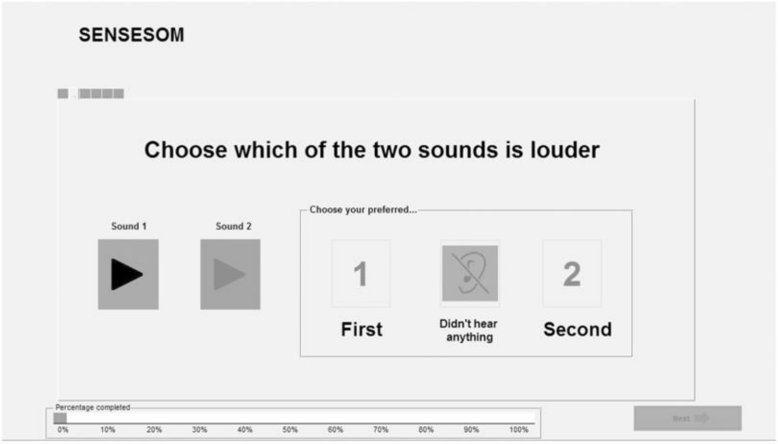


Fig. 7. Frequency response of the designed FIR filter based on the ⅓ octave SRI data input by the user.



SENSESOM

Choose which of the two sounds is louder

Fig. 8. Example of the UI of the perception assessment tool.

5.2.1. Why using loudness as a perception descriptor?

The choice between loudness and annoyance as perception descriptor is not obvious. By reviewing the literature on this issue [37–40], it can be inferred that both loudness and potential annoyance can be tested in laboratory conditions with some limitations.

More recent studies [10,12,13] have opted for evaluating annoyance in order to deliver a correlation with different sound insulation performance descriptors.

One of the limitations related to potential annoyance evaluation is that it is necessary to take into account that qualitative aspects of the sound always play a role when annoyance is caused [37]. In laboratory context, not all the factors related to the acoustic comfort (annoyance/pleasantness) can be assessed. Subjects are presented to a scenario and the exposure will always be too short if compared to the real life one.

With reference to loudness, Fastl and Zwicker [41], state that loudness is an incomplete subjective descriptor and that when considering annoyance it is necessary to add psychoacoustic indices such as fluctuation strength and sharpness to loudness.

However, other studies concluded that loudness is considered to correlate well with annoyance [37,38,42]. It is clear that a unique perception descriptor, on its own, is not sufficient to predict the annoyance.

Bearing all this in mind, in this test, subjective assessment of sound insulation was evaluated in terms of loudness. Considering the purpose of this study, where one stimulus, pink noise, with no semantical content was filtered by the different types of walls, annoyance was judged to be a difficult concept, just as explained in [11].

5.2.2. Why using pairwise comparisons as a ranking tool

In human decision making, the comparative approach is intuitively appealing and, moreover, supported by evidence from cognitive psychology [43]. For subjects it is simpler to compare alternatives by pairwise comparison instead of ranking all alternatives.

Pure ranking tests are also easy to understand and adequate for naive listeners, but one of its main disadvantages is that all the stimuli in the test have to be evaluated. This often results in long and time consuming tests which generate fatigue in the respondent.

In this case study, a pure ranking test would be time consuming and difficult to perform for the respondents. An alternative mixed procedure was used, including a paired comparison listening test and a ranking via data analysis. The paired comparison listening test is described in Section 4 (Experimental phase) and the ranking procedure in Section 5.3 (two ranking methods: ranking by mode and ranking by Q score.)

In classic pair comparison tests, subjects are asked to choose between one option or the other but often they cannot make a choice and either mark both or none of the choices. The normal procedure is that, when this happens, these answers are not considered in the data analysis. To avoid this ambiguity, Salesses et al. [44] suggest an alternative method where an "equal or null" option can be incorporated to the calculations.

In this experiment the "equal or null" option was introduced by including the "I didn't hear anything" option mentioned in Section 4 (experimental phase).

5.3. Data analysis tool

Once each listening test was finished, the participants' answers were automatically saved and used as input into the data analysis tool. The application allows researchers to monitor the results in real time, and includes a basic statistical analysis program and results visualization output.

The responses from all the paired comparisons made by all the participants were processed in order to rank the 10 sound samples (walls) according to two different procedures: RbM (Ranking by Mode) and RbQS (Ranking by Q Score).

In the RbM procedure, for each subject, a personal wall ranking was made. The ranking criterion was "the number of times the subject selected a sound sample related to the wall as louder". Then, for each subject, the walls (sound samples) were ranked from the less selected (number 1 – best), to the most selected (number 10 – worst).

In order to make a final ranking based on the set of personal rankings (33 personal rankings in this case), the statistical parameter "mode" was used. The mode score is the most frequently occurring number in a set of scores and informs about the central tendency in the set. The data were arranged in a specific way (RbM matrix) so as to use the mode to identify the tendency and rank the results.

The RbM matrix had ten rows (ranking positions), and the columns corresponded to the personal ranking made by each of the respondents (33 columns). Once the data were organized in such a matrix, the mode of each row was calculated and used to rank the sound samples related to walls from best to worst.

It is worth to remark that, in this case, all rows (ranking positions) turned out to have a different mode. In the case that two or more positions would have had the same mode, further analysis based on different statistical parameters would have been used.

An extract of the RbM matrix can be seen in Table 3, where only the results for the KUL participants are shown. It should be noted that for this method, the option "I didn't hear anything" was not taken into account for the data analysis.

In order to include the "equal or null" option in the data analysis and to verify the robustness of the previously made analysis, a second alternative analysis procedure was programmed. The underlying objective was to check the influence of including all the possible answers on the ranking results. The RbQS method is based on the suggestions used by Salesses et al. [44]. Win (W_p) and loss (L_p) ratios of any wall p are defined in Eqs. (1) and (2), where w_p is the number of times a wall p is selected as louder over any paired wall, l_p is the number of times a wall p was not chosen over, and t_p is the number of times that subjects selected the option "I didn't hear anything" when comparing wall p to another wall.

Eqs. 1–3 are calculated considering the full data set (all responses from all subjects).

$$W_p = \frac{w_p}{w_p + l_p + t_p} \tag{1}$$

$$L_p = \frac{l_p}{w_p + l_p + t_p} \tag{2}$$

The corrected score, or Q_p score, of a wall p is based on the corresponding win ratio of that specific wall W_p corrected by the "w in" W_{j^*} and "loss" L_{k^*} ratios of the walls with which it was compared, as expressed in Eq. (3).

Q_p corrects a wall's win ratio, $W_{p,}$ by adding the average win ratio of the walls that it was selected over and by subtracting the average loss ratio of the walls that were selected over it. This is done to incorporate information about the walls that were paired together with each wall. The numerical factors of 10/3 and 1 are used to scale the score to fit the range (0–10) [44]. A score of 10 represents the maximum possible score for "perceived as louder" (always perceived as louder) whereas $Q = 0$ represents the minimum (never perceived as louder). In this case, since the samples were chosen in pairs with the same $R_{A(50-5000)}$, it is normal that the Q score is in the central range – between 6.81 and 3.57 as shown in Table 4.

Table 3
RbM matrix for KUL participants – personal ranking.

	BE 1	BE 2	BE 3	BE 4	BE 5	BE 6	BE 7	BE 8	BE 9	BE 10	BE 11
1st	5 LW	5 LW	5 LW	5 LW	5 LW	5 LW	5 HW	5 LW	5 LW	5 LW	5 LW
2nd	5 HW	4 LW	3 LW	4 LW	3 LW	4 LW	4 HW	4 LW	4 LW	4 LW	5 HW
3rd	4 LW	5 HW	4 LW	5 HW	5 HW	5 HW	3 HW	5 HW	3 LW	5 HW	3 LW
4th	3 LW	3 LW	5 HW	3 LW	4 LW	3 LW	5 LW	3 LW	4 HW	3 LW	4 LW
5th	4 HW	4 HW	4 HW	4 HW	4 HW	4 HW	2 HW	4 HW	5 HW	4 HW	4 HW
6th	2 LW	2 LW	2 LW	1 LW	2 LW	2 LW	2 LW	2 LW	2 LW	2 LW	2 LW
7th	3 HW	3 HW	3 HW	3 HW	3 HW	3 HW	3 LW	3 HW	3 HW	3 HW	3 HW
8th	2 HW	2 HW	2 HW	2 HW	2 HW	2 HW	4 LW	2 HW	2 HW	2 HW	2 HW
9th	1 HW	1 LW	1 LW	2 LW	1 LW	1 LW	1 HW	1 LW	1 HW	1 LW	1 LW
10th	1 LW	1 HW	1 HW	1 HW	1 HW	1 HW	1 LW	1 HW	1 LW	1 HW	1 HW

Table 4
Obtained Q scores.

L W1	H W1	L W2	H W2	L W3	H W3	L W4	H W4	LW5	HW5
6.81	6.32	5.43	4.94	4.11	4.95	3.76	4.09	3.57	4.00

$$Q_p = \frac{10}{3}\left(W_p + \frac{1}{n_p^w}\sum_{j^*} W_j - \frac{1}{n_p^l}\sum_{k^*} L_{k,p} + 1\right) \tag{3}$$

In Eq. (3) the index j^* means that, in the first summation, only the walls that lost when compared to wall p shall be considered, and n_p^w is the number of types of walls that wall p was selected over (the maximum value of n_p^w in this case is 9). Similarly, the index k^* means that, in that second summation, only the walls that won when compared to wall p shall be considered, and n_p^l is the number of types of walls that wall p was not selected over (the maximum value of n_p^l also in this case is 9 and $n_p^w + n_p^l = 9$).

The walls were then ranked according to their corresponding Q score. The ranking results are shown in Tables 5 and 6 in the next section.

6. Results

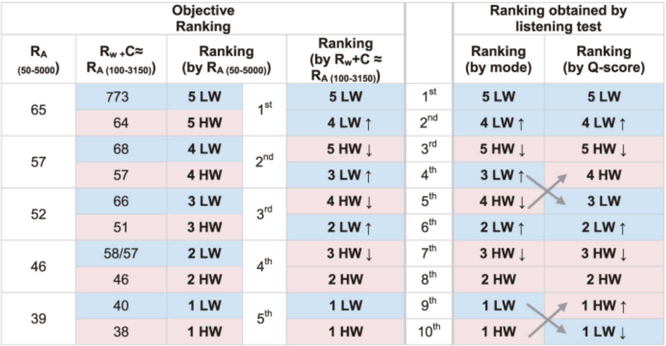
Since each participant has assessed 90 pairs of sound samples, and there were 33 participants, the total amount of responses was 2970. Each wall i was compared to wall j twice by each respondent, resulting to 66 comparisons per pair. An intuitive

Table 5
Cumulative preference matrix ($N = 66$).

	1 HW	1 LW	2 HW	2 LW	3 HW	3 LW	4 HW	4 LW	5 HW	5 LW
1 HW		19	0	2	0	1	0	0	1	0
1 LW	47		4	1	1	0	0	0	0	0
2 HW	66	62		6	3	1	2	1	2	4
2 LW	64	65	60		**43**	10	12	9	8	6
3 HW	66	65	63	**22**		6	10	6	8	4
3 LW	65	66	65	51	60		**39**	21	19	14
4 HW	66	66	63	49	52	**17**		15	16	10
4 LW	66	66	65	51	59	32	46		**29**	15
5 HW	65	66	64	54	55	35	37	**25**		18
5 LW	66	66	61	51	61	39	46	37	33	

Note: In red, cases with more than 6 clicks on the "I didn't hear anything" button.

Table 6
Walls' ranking: $R_{A(50-5000)}$, $R_w + C$, RbM and RbQS.



Objective Ranking						Ranking obtained by listening test	
R_A (50-5000)	$R_{w}+C \approx R_{A\,(100-3150)}$	Ranking (by $R_{A\,(50-5000)}$)		Ranking (by $R_w+C \approx R_{A\,(100-3150)}$)		Ranking (by mode)	Ranking (by Q-score)
65	773	5 LW	1st	5 LW	1st	5 LW	5 LW
	64	5 HW		4 LW ↑	2nd	4 LW ↑	4 LW ↑
57	68	4 LW	2nd	5 HW ↓	3rd	5 HW ↓	5 HW ↓
	57	4 HW		3 LW ↑	4th	3 LW ↑	4 HW
52	66	3 LW	3rd	4 HW ↓	5th	4 HW ↓	3 LW
	51	3 HW		2 LW ↑	6th	2 LW ↑	2 LW ↑
46	58/57	2 LW	4th	3 HW ↓	7th	3 HW ↓	3 HW ↓
	46	2 HW		2 HW	8th	2 HW	2 HW
39	40	1 LW	5th	1 LW	9th	1 LW	1 HW ↑
	38	1 HW		1 HW	10th	1 HW	1 LW ↓

Note: Up and down arrows indicate the position change compared to the ranking by $R_{A\,(50-5000)}$ assuming only a five level classification.

way to show these results is using a cumulative preference matrix indicating the number of times a sound sample in a column was judged to be louder than a sound sample in the row. Table 5 represents such a cumulative preference matrix, with the singularity that the answers “I didn't hear anything” are not included in the table, so when comparing two well performing walls, the sum of the responses does not always add up to 66.

All the results have been analysed using the Ranking by Mode and Ranking by Q score methods described in Section 5.3. Table 6 presents four possible different rankings: according to the objective single value sound reduction indexes $R_{A,50-5000}$ and $R_w + C \approx R_{A,100-3150}$, to the RbM and to the RbQS methods. Walls are ranked from the best sound insulation performance – sound sample perceived as less loud – to the worst.

The results shown in Table 6 will be further discussed in Section 7, but preliminarily it can be said that the ranking made according to $R_{A,50-5000}$ does not match the ranking obtained when analysing the results from the listening test in two different ways.

6.1. Significance of the results

When performing listening tests, participants are treated as measuring instruments. As described in Section 5.2, human subjects are quite variable and highly prone to bias and the quality assurance of human-based measurement is on which the quality assurance of the process rests [33]. Just like in other scientific fields, three basic criteria have to be taken into account to ensure the test's quality: objectivity, reliability and validity [45].

Objectivity and reliability of the test was aimed at and achieved at the design stage, where different issues were considered to minimize the bias and guarantee the reproducibility of the measurements (as described in Sections 4 and 5). Concerning the validity of the test, a single statistic parameter is not enough to guarantee it, but considering the dimensions of this study, *t*-test's statistical significance was accepted as satisfactory. This type of test indicates if the difference between two groups' averages reflects a real difference in the population from which the groups were sampled.

In order to assure the correct interpretation of the results, it was critical to check that participants really perceived a difference when judging the loudness of sound samples filtered by two walls (one heavyweight and one lightweight) with the same $R_{A,50-5000}$. As it can be seen in Table 6, for this specific test, sound samples related to lightweight walls were rated as less loud than those filtered by a heavyweight wall with the same $R_{A,50-5000}$. Consequently the hypothesis that will be defined in the statistical test will not just focus in verifying if there is a perception difference, but will also indicate the direction of this difference.

In summary, the objective of the statistical test is to verify if the difference observed when rating a heavy wall as louder when compared to its corresponding lightweight wall (same $R_{A,50-5000}$) corresponds to a real difference.

Thus, considering the statistical test, the independent variables were *sound sample* and *walls* and the dependent variable was *perceived loudness.* Null hypothesis and Alternative hypothesis were:

H0. Sound sample filtered by a lightweight wall will be rated as louder than those filtered by a heavyweight wall with the same $R_{A,50-5000}$.

H1. Sound sample filtered by a lightweight wall will be rated as less loud than those filtered by a heavyweight wall with the same $R_{A,50-5000}$.

T-tests were run for each pair of walls having same $R_{A,50-5000}$, considering all answers obtained, that is: each respondent evaluated each pair two times (A–B, B–A). When comparing the data of a pair of walls it was attributed a 0 when the wall was not selected by the respondent and a 1 when it was. Then large values of the returned statistic *t*, would suggest higher probability of the null hypothesis being false. In other words, the higher the t value, the more likely the two means were different.

As for each pair of walls under evaluation the answers were contributed by the same group of respondents, a paired sample *t*-test was performed. Furthermore, as the hypothesis indicates the direction of the difference, one tailed *t*-test was appropriate

According to the results of the *t*-tests shown in Table 7, it can be stated with 95% confidence interval for significance tests ($p < 0.05$) that:

The null hypothesis is false and that sound samples filtered by a lightweight wall will be rated as less loud than those filtered by a heavyweight wall with the same $R_{A,50-5000}$.

This is true for all the cases shown, but it shall be noted that the statistical indicators (t, p) are closer to the limit (0.05) in the case of very well performing walls 5 HW and 5 LW.

7. Discussion

Although the results obtained from this study are valid for this specific experiment set up (stimulus, walls and population), it is also true that the walls used are representative of the constructions in Europe [22] and that pink noise stimulus is generally accepted as representing living noise [4].

From the cumulative preference matrix shown in Table 5 it can be observed that sounds filtered by all the lightweight walls 1 LW, 2 LW, 3 LW, 4 LW and 5 LW are clearly selected as less loud when compared to their corresponding paired heavyweight walls: 1 HW, 2 HW, 3 HW, 4 HW and 5 HW. This is a little less obvious for the better performing walls, pair 5 LW/5 HW. The reason for this is that for high $R_{A,50-5000}$ values, the corresponding sound sample levels were very low, so it turned out to be difficult to perceive the loudness difference. One can see that the sum of the responses when comparing 5 LW/5 HW is 18 + 33 = 51, which means that the button “I didn't hear anything” was selected 15 times. This is corroborated by the results of the significance test shown in Table 7. The results of the *t*-test reveal that although in all paired cases, the lightweight wall is rated as less loud than the corresponding heavy wall, this is a little more difficult to perceive by the respondents in the case of the best performing walls 5LH and 5 HW where the *p* value is 0.04.

Furthermore, 2 LW, 3 LW and 4 LW are rated as less loud not only when compared to 2 HW, 3 HW and 4 HW but also when

Table 7
T-tests results.

	1 HW	1 LW	2 HW	2 LW	3 HW	3 LW	4 HW	4 LW	5 HW	5 LW
Med	0.73	0.27	0.91	0.09	0.91	0.09	0.73	0.27	0.61	0.39
Varia	0.20	0.20	0.08	0.08	0.08	0.08	0.20	0.20	0.24	0.24
t	4.11		11.47		11.47		4.11		1.75	
p	5.58E−05		1E−17		1.42E−17		5.58E−05		0.04	
CV	1.67		1.67		1.67		1.67		1.67	

compared to 3 HW, 4 HW and 5 HW respectively, that is, when compared to a heavyweight wall with a higher $R_{A,50-5000}$. These results are highlighted in bold/underlined in Table 5.

Looking at the ranking shown in Table 6, both RbM and RbQS analysis yield the same result: all the five lightweight walls are ranked as less loud than their paired heavyweight wall. This is in accordance with previous results [11,46], where for two walls, one heavyweight and one lightweight with the same $R_{A,50-5000}$, the lightweight wall was better evaluated in terms of loudness as perception descriptor. Once again, in some cases a lightweight wall can even be rated as less loud than a heavyweight wall with higher $R_{A,50-5000}$. It is also observed that the ranking obtained from the listening test results matches very well with the ranking made according to $R_w + C \approx R_{A,100-3150}$, but not so well with $R_{A,50-5000}$.

Looking at the SRI spectrum of each pair of walls with identical $R_{A,50-5000}$ in Fig. 6, it can be observed that in all cases the lightweight walls have a better performance in mid and high frequencies and worse at the low end of the spectrum. This is reflected by the corresponding objective descriptors $R_{A,50-5000}$ and $R_w + C$ as seen in Table 6 and, as mentioned in the introduction, is one of the focus of debate when researching about the most adequate sound insulation descriptor.

At this point it is important to remember what have been the main objectives of this study: to provide new evidence in the field of subjective perception of acoustic performance of different construction solutions and to enlighten the existing debate: *Does the objective $R_{A,50-5000}$ adequately reflect the subjective perception of the acoustic performance of a wall?* In view of the results, the answer is: "not in this case".

The results show that $R_{A,50-5000}$ (descriptor including low frequency performance of walls) does not correlate as well as $R_w + C$ to the ranking made on the basis of perceived loudness.

Of course these results are limited to this study, but point at the need of further research on subjective perception of sound insulation and on the usefulness of introducing the low frequency range (50, 63 and 80 Hz third octave bands) when assessing airborne sound insulation.

Despite annoyance/disturbance evaluation not being the objective of this study, it was explained in Section 5.2.1, that annoyance can be correlated to loudness as a perception descriptor. In this sense, the results of this study converge to a great extent with those obtained by Hongisto et al. [13], who state that *"it seems that the disturbance caused by a spectrally flat wide-band sound is more dependent on the sound insulation at low-mid frequencies (125–1000 Hz) than the lowest frequencies (50–100 Hz)"*. It would be interesting to study the effect on the ranking when excluding the 100 Hz third octave band as well as the upper end frequency bands (4 kHz, 5 kHz), thus focusing only in the frequency range 100–3150 Hz.

The outcomes of the present research also converge with those obtained by another study focused on the correlation between performance descriptors and perceived annoyance. Results from [10] show that the correlation between $R_w + C$ and perceived annoyance can be acceptable and that incorporating the lowest frequency range (50–80 Hz) in the evaluation of the airborne sound insulation descriptors does not deliver a better correlation.

8. Conclusions

This study presents results from perception experiment supported by a self-developed application for laboratory listening tests in the context of perception of airborne sound insulation.

The results suggest that the perceived loudness of a pink noise stimulus filtered by a lightweight wall SRI (R) is in general rated as lower than the perceived loudness of the same pink noise stimulus filtered by a heavyweight wall SRI (R), having both the same $R_{A,50-000}$.

Regarding the debate on whether the objective descriptor $R_{A,50-5000}$ adequately reflects the subjective perception of the acoustic performance of a wall, it has been shown that, with a 95% confidence interval, lightweight walls are perceived as less loud than their corresponding heavy wall with same $R_{A,50-5000}$. Sometimes, not only when compared to those with the same $R_{A,50-5000}$, but also when the $R_{A,50-5000}$ of the heavy wall was higher than the $R_{A,50-5000}$ of the lightweight one. This indicates that $R_{A,50-5000}$ does not adequately reflect the subjective perception of airborne sound insulation, for the case study. On the other hand, the ranking obtained with $R_w + C \approx R_{A,100-3150}$ is identical to the RbM ranking obtained from the listening test, that is, $R_w + C \approx R_{A,100-3150}$ reflects a better correspondence with the subjective perception of loudness.

In general terms, this could indicate that the adoption of $R_{A,50-5000}$ as a SNQ/descriptor underestimates the perceived sound insulation performance of lightweight walls for flat wide-band domestic sounds that could be compared to pink noise.

More research is necessary on this field, since the debate on delivering an adequate sound insulation descriptor that gives answer to contemporary social and technical demands is still open. By itself, a descriptor cannot guarantee the protection or the acoustic comfort desired by users, although, finding a descriptor that adequately correlates with the annoyance/disturbance perceived by users can be a key input for building acoustics regulations development.

Acknowledgements

Authors would like to thank Dr. Marta Herráez, and Dr. Lara del Val from UVa, Dr. Daniel Urban and Dr. David Pellegrini from KUL, for all help and advice, and CNPq – Brazil, for supporting the research.

References

[1] ISO 10140. Acoustics – laboratory measurement of sound insulation of building elements – Parts 1 to 5. International Organization for Standardization; 2010.
[2] ISO 16283-1. Acoustics – field measurement of sound insulation in buildings and of building elements – Part 1: airborne sound insulation. International Organization for Standardization; 2014.
[3] ISO/DIS 16283-2. Acoustics – field measurement of sound insulation in buildings and of building elements – Part 2: impact sound insulation. International Organization for Standardization; 2014.
[4] ISO 717-1. Acoustics – rating of sound insulation in buildings and of building elements – Part 1: airborne sound insulation. International Organization for Standardization; 2013.
[5] ISO 717-2. Acoustics – rating of sound insulation in buildings and of building elements – Part 2: impact sound insulation. International Organization for Standardization; 2013.
[6] Scholl W, Lang J, Wittstockh V. Rating of sound insulation at present and in future. The revision of ISO 717. Acta Acust United Acust 2011;97:686–98.
[7] COST Action TU0901. Integrating and harmonizing sound insulation aspects in sustainable Urban housing constructions; 2013. http://www.costtu0901.eu/.
[8] CD 16717-1. Proposal acoustics – evaluation of sound insulation spectra by single-numbers – Part 1: airborne sound insulation. International Organization for Standardization TC 43/SC; 2013.
[9] Cattelan M. Models for paired comparison data: a review with emphasis on dependent data. Stat Sci 2012;27:412–33.
[10] Bailhache S, Jagla J, Guigou C. Effet des basses fréquences sur le confort acoustique – tests psychoacoustiques, Rapport USC-EA-D1_A2.1.4_2, France; 2014.
[11] Rychtáriková M, Roozen B, Müllner H, Stani M, Chmelík V, Glorieux C. Listening test experiments for comparisons of sound transmitted through light weight and heavy weight walls. Akustika 2013;19:1–10.
[12] Ljunggren F, Simmons C, Hagberg K. Correlation between sound insulation and occupants' perception – proposal of alternative single number rating of impact sound. Appl Acoust 2014;85:57–68.
[13] Hongisto V, Oliva D, Keränen J. Subjective and objective rating of airborne sound insulation – living sounds. Acta Acust United Acust 2014;100:848–63.

[14] Rasmussen B, Machimbarrena M, Fausti P, TU0901 C. Building acoustics throughout Europe. Volume 1: Towards a common framework in building acoustics throughout Europe; 2013. http://www.costtu0901.eu/tu0901-e-books.html.

[15] Rychtáriková M, Horvat M. Chapter 7: Developing a methodology for performing listening tests related to building acoustics. In: Building acoustics throughout Europe. Vol. 1: Towards a common framework in building acoustics throughout Europe; 2013, p. 121–42. http://www.costtu0901.eu/tu0901-e-books.html.

[16] Park HK, Bradley JS. Evaluating standard airborne sound insulation measures in terms of annoyance, loudness, and audibility ratings. J Acoust Soc Am 2009;126:208–19.

[17] Bradley JS. Evaluation of revised ISO airborne sound insulation ratings. NRC Constr; 2012.

[18] Ordoñez R, Vicentini C, Markovic M, Fausti P. Objective and subjective evaluation of façade sound insulation. Internoise 2013. Innsbruck: Institute of Noise Control Engineering; 2013.

[19] Rychtáriková M, Roozen B, Müllner H, Stani M, Chmelík V, Glorieux C. Listening test experiments for comparisons of sound transmittřed through light weight and heavy weight walls. Akustika - odborný časopis o akustice a vibracích, No. 19, Czech Republic; 2013.

[20] Simmons C., Chapter 5: Developing a uniform questionnaire for socio-acoustic surveys in residential buildings. In: Building acoustics throughout Europe. Vol. 1: Towards a common framework in building acoustics throughout Europe; 2013, pp. 98–120.

[21] ISO 10140-2. Acoustics – laboratory measurement of sound insulation of building elements – Part 2: measurement of airborne sound insulation. International Organization for Standardization; 2010.

[22] Rasmussen B, Machimbarrena M, Fausti P, COST Action TU0901. Building acoustics throughout Europe Volume 2: housing and construction types country by country; 2014.

[23] Kumar S, Rao M. M-band graphic equalizer. Int J Comput Sci Eng 2011;3:2955–64.

[24] Couvreur C, Couvreur IC. Implementation of a one-third-octave filter bank in Matlab; 1997.

[25] Bristow-Johnson R. Cookbook formulae for audio EQ biquad filter coefficients. <http://www.musicdsp.org/files/Audio-EQ-Cookbook.txt> [accessed August 30, 2014].

[26] Holters M, Zölder U. Graphic equalizer design using higher-order recursive filters. In: 9th Int conf digit audio eff, vol. 1, Montreal: EU-COST-G6 "Digital Audio Effects"; 2006, p. 37–40.

[27] Bregoviç R, Saramaki T. Multirate systems and filter banks. In: Jovanovic-Dolecek G, editor. Multirate syst des appl, Idea Group Publishing; n.d.

[28] Choisel S, Martin G. Audibility of phase response differences in a stereo playback system. Part 1: headphone reproduction. Audio Eng Soc Conv 2008;124.

[29] Choisel S, Martin G. Audibility of phase response differences in a stereo playback system. Part 2: narrow-band stimuli in headphones and loudspeakers. Audio Eng Soc Conv 2008;125.

[30] Berkovitz R, Edvardsen B-E. Phase sensitivity in music reproduction. Audio Eng Soc Conv 1977;58.

[31] Lipshitz SP, Pocock M, Vanderkooy J. On the audibility of midrange phase distortion in audio systems. J Audio Eng Soc 1982;30:580–95.

[32] Meilgaard MC, Carr BT, Civille GV. Sensory evaluation techniques. 4th ed. CRC Press; 2006.

[33] Pendrill L. Man as a measurement instrument. NCSLI Meas J Meas Sci 2014;9:24–35.

[34] Civille GV, Seltsam J. Sensory evaluation methods applied to sound quality. Noise Control Eng J 2003;51:262.

[35] Lazar DJ, Feng DJH, Hochheiser DH. Research methods in human-computer interaction. John Wiley & Sons; 2010.

[36] ISO 9241-210. Ergonomics of human-system interaction – Part 210: human-centred design for interactive systems. International Organization for Standardization; 2010.

[37] Marquis-Favre C, Premat E, Aubrée D, Vallet M, Vallett M. Noise and its effects – a review on qualitative aspects of sound. Part I: notions and acoustic ratings. Acta Acust United Acust 2005;91:613–25.

[38] Marquis-Favre C, Premat E, Aubrée D, Aubrédue D. Noise and its effects – a review on qualitative aspects of sound. Part II: noise and annoyance. Acta Acust United Acust 2005;91:626–42.

[39] Morel J, Marquis-Favre C, Gille L-A. Noise annoyance assessment of various urban road vehicle pass-by noises in isolation and combined with industrial noise: a laboratory study. Appl Acoust 2016;101:47–57. http://dx.doi.org/10.1016/j.apacoust.2015.07.017.

[40] Huang Y, Di G, Zhu Y, Hong Y, Zhang B. Pair-wise comparison experiment on subjective annoyance rating of noise samples with different frequency spectrums but same A-weighted level. Appl Acoust 2008;69:1205–11. http://dx.doi.org/10.1016/j.apacoust.2007.10.006.

[41] Fastl H, Zwicker E. Psychoacoustics: facts and models. 3rd ed. Springer Berlin Heidelberg; 2007.

[42] Ellermeier W, Mader M, Daniel P. Scaling the unpleasantness of sounds according to the BTL model: ratio-scale representation and psychoacoustical analysis. Acta Acust 2004;90:101–7.

[43] Fünkranz J, Hüllermeier E. Preference learning and ranking by pairwise comparison. Prefer learn. Berlin: Springer Berlin Heidelberg; 2011. p. 65–82.

[44] Salesses P, Schechtner K, Hidalgo CA. The collaborative image of the city: mapping the inequality of urban perception. PLoS ONE 2013;8:e68400.

[45] Muellner H. Methodology for laboratory listening tests with focus on building acoustics requirements – appropriate test statistical applications. Leuven; 2013.

[46] Rychtáriková M. Influence of temporal and spectral features of neighbour's noise on perception of its loudness. Internoise 2013. Innsbruck: Institute of Noise Control Engineering; 2013.

7.3 Artículo C

Translation between existing and proposed harmonized airborne sound insulation descriptors: A statistical approach based on in-situ measurements

Carolina Rodrigues A. Monteiro [a] , María Machimbarrena [a], Ana Tarrero [b] , Sean Smith [c]

a. Applied Physics Department, Architecture School, Universidad de Valladolid, Spain
b. Applied Physics Department, Industrial Engineers School, Universidad de Valladolid, Spain
c. Edinburgh Napier University, Institute for Sustainable Construction, Colinton Rd 42, EH10 5BT Edinburgh, Scotland, UK

Applied Acoustics, Volume 116, January 2017
doi:10.1016/j.apacoust.2016.09.017
Recibido: 27 de Junio de 2016
Aceptado: 13 de Septiembre de 2016

Translation between existing and proposed harmonized airborne sound insulation descriptors: A statistical approach based on in-situ measurements

Carolina Monteiro[1*], María Machimbarrena[2], Ana Isabel Tarrero[3], R. Sean Smith[4] .

1. PhD Candidate, Universidad de Valladolid, Spain.
2. Applied Physics Department, Architecture School, Universidad de Valladolid, Spain.
3. Applied Physics Department, Industrial Engineers School, Universidad de Valladolid, Spain.
4. Institute for Sustainable Construction, Edinburgh Napier University, Edinburgh, Scotland, UK.

Abstract

A standard defining a common acoustic classification scheme for dwellings is under development by ISO TC42/SC2/WG29 based on the outcomes of European project COST Action TU0901. The proposal stands on the assumption that in the long term many countries will establish building acoustic requirements using a harmonized set of descriptors, and the hypothesis of an extended low frequency range for airborne sound insulation evaluation is considered.

In this scenario most countries will need to estimate the influence on their current airborne sound insulation requirements due to the new descriptor. This can better be evaluated if translation equations between existing and new proposed descriptors can be used.

This paper initially evaluates the adequacy of performing such translations based on the geometrical relation between the sound reduction index R and the standardized level difference D_{nT}. This procedure is shown to be acceptable when both descriptors (original and translated) use the same assessment frequency range. For the cases where a different assessment frequency range is considered, a different approach is studied. The paper investigates a statistical method to obtain translation equations between existing and proposed descriptors, based on the analysis of a significant set of in-situ measurements. Several translation equations are proposed, and the effect of the frequency range extension on such translations is studied for two typical building systems such as heavy and lightweight walls.

Results show that, although it is possible to propose a single translation equation for each existent descriptor, in some cases the spread around the proposed translation line is significant. It is also observed that the effect of building system is more noticeable if different frequency range descriptors are involved in the translation. This points out the difficulty of obtaining a unique translation equation independent of the building type when the descriptors' assessment frequency range is not the same.

For some existent descriptors, the obtained translation is compared with the theoretical method proposed within the findings of COST TU0901. When considering only lightweight walls or the full data set, there is no good agreement between both methods, but for heavyweight walls they converge.

Existing requirements in thirty-two countries have been translated into the proposed descriptor $D_{nT,50} \approx D_{nT,w} + C_{50\text{-}3150}$ using the obtained equations. This provides valuable information and an insight for government and building regulation policy makers when updating their legislation.

Keywords: Building regulations; Descriptors; Sound insulation requirements; Acoustic classification scheme; Dwelling

1. Introduction

The protection against noise both outdoors and with-in the built environment is being increasingly demanded by experts and society as a consequence, among other factors, of the negative effects of noise, and drive to improve the quality of life within the work, educational and habitat environment. The negative effects of noise have been studied and outlined for some time. More recent reports have again summarized these findings such as the WHO Environmental Burden of Disease in Europe [1], the reports from Basner et al. [2,3], and several others.

In the field of building acoustics, the protection of citizens' health is covered by national regulations, but there is a growing demand by inhabitants for higher acoustic performance in order to obtain better levels of acoustic comfort. In several countries, sound insulation classifications schemes are being developed or already entered into force, although *due to the lack of coordination among countries, a significant diversity in terms of descriptors, number of classes, and class intervals occurred between national schemes* [4]. Beyond defining acoustic classes according to different levels of sound insulation, developing a common classification scheme could stimulate the reduction of trade barriers, support further innovation in construction material systems and design and lead to multi-country improvement of the sound insulation of dwellings.

A common acoustic classification scheme with a number of quality classes was proposed within COST Action TU0901 European research and networking project [5], where thirty-two countries participated. Due to the existing high degree of diversity of regulatory requirements and descriptors [6,7], the proposed classification scheme [8] was based in a set of harmonized descriptors for airborne and impact sound insulation also proposed by the same action.

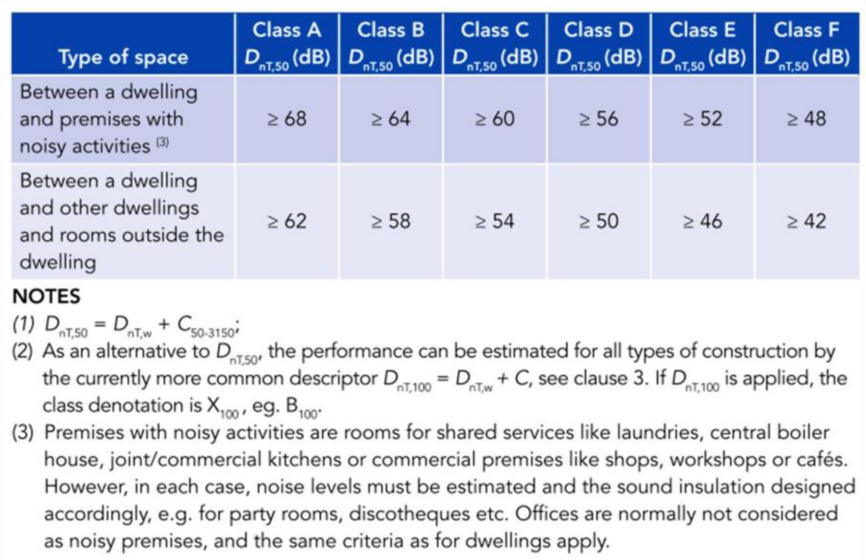
Simultaneously to the COST Action TU0901 proposal of harmonized descriptors, the revision of ISO 717 series [9,10] was being performed by ISO TC43/SC2/WG18. This revision aimed not only at harmonizing sound insulation descriptors (reducing the amount of possible sound insulation descriptors and pointing out the preferred ones), but also at providing alternative methods to determine single number quantities that would give answer to old and new technical and social demands [11]. One of the revised proposals suggested that the traditional ISO 717 weighting reference curves could be removed and other weighting methods introduced providing two alternative frequency ranges for airborne sound insulation evaluation: 50–3150 Hz, important for lightweight buildings, and most used 100–3150 Hz [12]. The ideal objective was to adopt a single number rating method that would characterize the sound insulation of buildings despite its heterogeneous frequency behaviour and would also take into account the subjective evaluation of annoyance produced by different sound sources.

No consensus was reached among participant countries and the ISO 717 revision was cancelled, encouraging experts to provide more conclusive research in the field to enlighten its main controversial topics. It is important to point out that in spite of not having come to an agreement in many aspects, there was a general agreement on the fact that often low frequency sounds are disturbing and thus it is important to provide sufficient protection against noise sources with strong low frequency content. Taking this into consideration, the recently reviewed sound insulation field measurement standards [13–15] have included a specific low frequency measurement procedure to be used under certain circumstances.

The debate is still open and relevant research is being done on different topics such as measurement procedures at low frequencies topics [16], effect of low frequency inclusion on measurement uncertainty assessment ratings [17–19] and subjective/objective aspects of sound insulation descriptors [20–23], just to mention some of the most recent studies related to the harmonization of sound insulation descriptors.

Given the difficulty found in coming to a perfect agreement on harmonized descriptors, the COST TU0901 Acoustic Classification Scheme - ACS - for dwellings proposal was designed using most agreed descriptors and preliminary proposing a frequency range assessment from 50 Hz. For airborne sound insulation the selected descriptors were $D_{nT,50} \approx D_{nT,w} + C_{50\text{-}3150}$ and/or $D_{nT,100} \approx D_{nT,w} + C_{100\text{-}3150}$.

Figure 1 presents the COST Action TU0901 ACS proposal. Advantages and justification for this proposal, including frequency range and assessment methods can be found in [5]. Due to the interest of this initiative, the proposal has been used as a draft input for developing a new ISO standard ISO/CD 19488 – Acoustic Classification Scheme for Dwellings [24].



Type of space	Class A $D_{nT,50}$ (dB)	Class B $D_{nT,50}$ (dB)	Class C $D_{nT,50}$ (dB)	Class D $D_{nT,50}$ (dB)	Class E $D_{nT,50}$ (dB)	Class F $D_{nT,50}$ (dB)
Between a dwelling and premises with noisy activities (3)	≥ 68	≥ 64	≥ 60	≥ 56	≥ 52	≥ 48
Between a dwelling and other dwellings and rooms outside the dwelling	≥ 62	≥ 58	≥ 54	≥ 50	≥ 46	≥ 42

NOTES

(1) $D_{nT,50} = D_{nT,w} + C_{50\text{-}3150}$;

(2) As an alternative to $D_{nT,50}$, the performance can be estimated for all types of construction by the currently more common descriptor $D_{nT,100} = D_{nT,w} + C$, see clause 3. If $D_{nT,100}$ is applied, the class denotation is X_{100}, eg. B_{100}.

(3) Premises with noisy activities are rooms for shared services like laundries, central boiler house, joint/commercial kitchens or commercial premises like shops, workshops or cafés. However, in each case, noise levels must be estimated and the sound insulation designed accordingly, e.g. for party rooms, discotheques etc. Offices are normally not considered as noisy premises, and the same criteria as for dwellings apply.

Figure 1: Class criteria for airborne sound insulation as proposed by COST TU0901. from Chapter 5 [5].

In order to adopt a classification scheme, it is necessary to translate existing descriptors into new harmonized ones. These translations have already been studied within the COST TU0901 project [25–27] although only references [12,27] present results for performing such translations. In reference [28] Gerretsen and Dunbavin present two different proposals, one based on basic building acoustics equations, and the other using a similar approach as the one presented in this paper. This last approach will be described in section 4 and consists in determining correlations between different descriptors and obtaining the correspondent translation equations. Reference [27] points out the need of studying the problem more deeply since only data from a few lightweight walls were included their research.

2. Objectives

Elaborating and proposing a classification scheme for dwellings which could be used all over Europe (CEN countries) or even in a great part of the world (ISO countries) is an ambitious objective. The adoption of such proposal is very difficult to achieve unless the corresponding authorities and policy makers can easily translate the existing requirements into new proposed sound insulation descriptors. Policy makers are required to adequately evaluate the effects and consequences of adopting new proposed standards and classification schemes in their country. This is often undertaken as part of the 'impact of proposed changes' within the policy development and wider consultations with industry.

This paper aims at providing valuable evidence for the airborne sound insulation descriptors translation procedure. Most of the existent airborne sound insulation descriptors and requirements have been translated into the proposed harmonized ones ($D_{nT,50} \approx D_{nT,w} + C_{50\text{-}3150}$ and/ $D_{nT,100} \approx D_{nT,w} + C_{100\text{-}3150}$). In the first step the strict geometrical translation between R and D_{nT} has been studied. Secondly, a statistical method based on the analysis of a large set of in-situ measurements has been used to obtain translation equations between existing and proposed descriptors. This translation will undoubtedly be a valuable tool for national authorities and industry organisations to interpret how the proposed acoustic classification scheme would affect the existing legislation and reporting boundaries.

The main objectives of the paper can then be summarized as follows:

- Based on a large set of in-situ airborne sound insulation measurements, study the effect of the frequency range assessment when performing a pure geometrical translation between R and D_{nT};
- Based on the same data set, to propose updated translation equations between existing airborne sound insulation descriptors and proposed ones $D_{nT,50}$ and $D_{nT,100}$;
- To compare the obtained translation equations with those proposed by Gerretsen in [27,28];
- To investigate assessment frequency range effects on the resulting translation equations for heavy and lightweight walls;
- For thirty-two countries, to deliver their current airborne sound insulation national requirements translated into $D_{nT,50;}$

- For the same countries, to evaluate their possible position in the acoustic classification scheme proposed by COST Action TU0901.

3. Data set description

The input data consisted on a set of over 1000 field airborne sound insulation measurements involving 9 different types of separating walls (7 heavyweight and 2 lightweight). All walls were constructed in the United Kingdom in compliance with the relevant Robust Details [29] specifications. The construction system of the seven types of heavyweight walls (from 1 HW to 7 HW) and the two types of lightweight walls (1 LW and 2 LW) is summarized in Figures 2, 3 and 4. All measurements were performed in the horizontal direction in newly built dwellings.

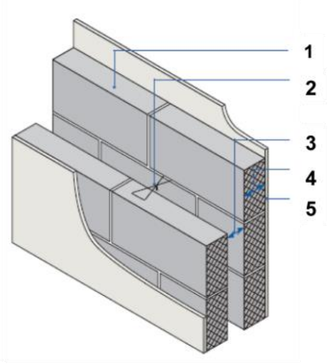
<table>
<tr><th colspan="2">Heavyweight walls</th></tr>
<tr><td>Plaster finished walls</td><td>5- Wall finish : 13mm plaster or cement both sides</td></tr>
<tr><td rowspan="3">
</td><td>1 HW
1- Dense aggregate Block (1850 to 2300 Kg/m^3)
2- Wall Ties
3- Cavity width 75mm (min)
4- Block thickness 100mm (min), each leaf</td></tr>
<tr><td>2 HW
1- Lightweight aggregate Block (1350 to 1600 Kg/m^3)
2- Wall Ties
3- Cavity width 75mm (min)
4- Block thickness 100mm (min), each leaf</td></tr>
<tr><td>3 HW
1- Dense aggregate Block (1850 to 2300 Kg/m^3)
2- Wall Ties
3- Cavity width 100mm (min)
4- Block thickness 100mm (min), each leaf</td></tr>
</table>

Figure 2: Construction system of plaster finished heavyweight walls.

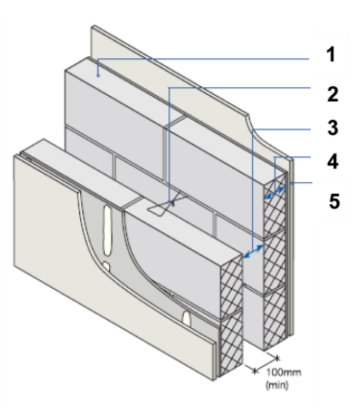
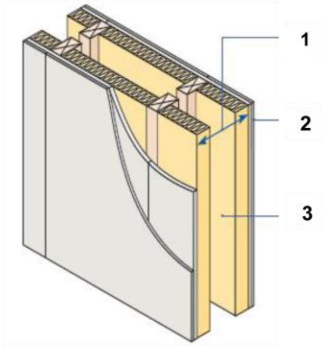
Heavyweight walls	
Gypsum board finished walls	5- Wall finish : gypsum-based board (nominal 8 kg/m2) mounted on dabs on cement
	**4 HW** 1- Dense aggregate Block (1850 to 2300 Kg/m^3) 2- Wall Ties 3- Cavity width 75mm (min) 4- Block thickness 100mm (min), each leaf
	5 HW 1- Lightweight aggregate Block (1350 to 1600 Kg/m^3) 2- Wall Ties 3- Cavity width 75mm (min) 4- Block thickness 100mm (min), each leaf
	6 HW 1- Lightweight aggregate, or Hollow or cellular blocks (1350 to 1600 Kg/m^3) 2- Wall Ties 3- Cavity width 100mm (min) 4- Block thickness 100mm (min), each leaf
	7 HW 1- Lightweight load bearing blocks (1050 Kg/m^3) 2- Wall Ties 3- Cavity width 75mm (min) 4- Block thickness 100mm (min), each leaf

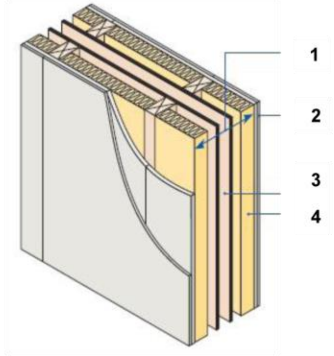
Figure 3: Construction system of gypsum board finished heavyweight walls.

Lightweight walls



1 LW

1- 240mm (min) between inner faces of wall linings. 50mm (min) gap between studs
2- Wall lining: 2 or more layers of gypsum-based board (total nominal mass per unit area 22 kg/m^2), both sides
3- 60mm (min) mineral wool material batts or quilt (density 10 – 60 kg/m^3) both sides.



2 LW

1- 240mm (min) between inner faces of wall linings. 50mm (min) gap between the faces of the sheathing
2- Wall lining: 2 or more layers of gypsum-based board (total nominal mass per unit area 22 kg/m^2), both sides
3- Sheathing: 9mm (min) thick board
4- 60mm (min) mineral wool material batts or quilt (density 10 – 60 kg/m^3) both sides.

Figure 4: Construction system of lightweight walls

Tables 1 and 2 show the number of samples, average and standard deviation for $D_{nT,50}$ for each of the wall types considered in this study. Figure 5 and Table 3 show the probability density values, average and standard deviation for $D_{nT,50}$ considering the full data set. All $D_{nT,50}$ average values are above 56 dB and, for the full data set, the average is close to 58 dB so it can be said that it is a set of mainly well performing walls. Receiving room volumes varied from 12m^3 to 80m^3 and common partition area varied from 6m^2 to 20m^2 approximately.

Table 1: Heavyweight walls data set information

Heavy walls	Total	1 HW	2 HW	3 HW	4HW	5 HW	6HW	7 HW
Average $D_{nT,50}$ (dB)	57,80	57,45	57,40	58,75	57,40	59,30	56,15	57,00
Standard deviation (dB)	4,10	3,70	3,85	4,45	4,00	4,20	3,75	2,70
No of samples	654	53	63	110	337	69	13	9

Table 2: Lightweight walls data set information.

Lightweight walls	**Total**	**1 LW**	**2 LW**
Average $D_{nT,50}$ (dB)	58,10	58,25	57,90
Standard deviation (dB)	3,60	3,50	3,80
No of samples	445	245	200

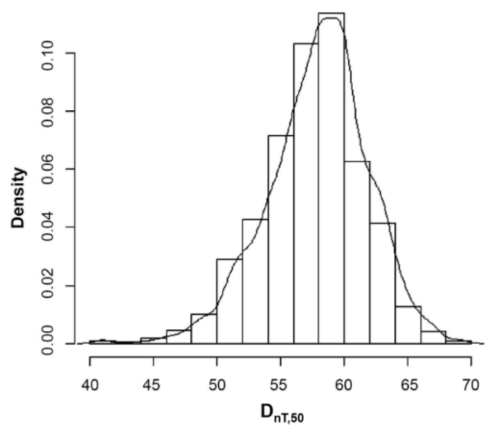


Figure 5: Probability density values of $D_{nT,50}$ (full data set).

Table 3: Full data set information.

Average $D_{nT,50}$ (dB)	57,97
Standard deviation (dB)	3,94
No of samples	1099

4. Translation of most commonly used single number descriptors of airborne sound insulation into $D_{nT,50}$ / $D_{nT,100}$

As explained by Gerretsen and Dunbavin [28], the translation between different sound insulation descriptors is not a simple task and appears to depend on the type of building. In reference [27] Gerretsen suggests a translation between descriptors based on a two steps procedure:

Step one: translation between descriptors according to equation (1). A compromise value for the receiving room volume *V*=52,5m^3 and the volume/area ratio *V/S*=2,5m was used.

$$D_{nT} = R' + 10\log\frac{0.16V}{T_0\,S_s} \qquad (1)$$

Equation (1) does not consider the possibility of using a different assessment frequency range and/or a different weighting procedure for both descriptors (D_{nT} and R), so a second step is necessary when this is needed.

Step two: translation between weighting procedures. This second step was based on a previous study performed by Scholl et al. considering only heavyweight walls [12].

It is questionable nevertheless whether it is possible to find a unique translation equation between two descriptors that do not share the same frequency range, e.g. between R'_w and $D_{nT,50}$, especially when considering that for certain building systems, like lightweight walls, sound insulation is strongly influenced by the low frequencies.

In order further to investigate the effect of the frequency range assessment when performing a pure geometrical translation between R' and D_{nT}, this paper presents a detailed analysis where the geometrical translation is compared to the corresponding descriptor obtained from the field data. For the full data set, the translation proposed in equation (1) has been calculated for the following descriptors:

Table 4 – Input data and corresponding calculated descriptor in equation (1).

Input measured data		Calculated descriptor
R'_w	Surface S ; Volume V	**$^gD_{nT,w}$**
$R'_w + C$	Surface S ; Volume V	**$^gD_{nT,w} + C$**
$R'_w + C_{(50\text{-}3150Hz)}$	Surface S ; Volume V	**$^gD_{nT,w} + C_{(50\text{-}3150Hz)} \approx {}^gD_{nT,50}$**

Note: The descriptors translated according to equation (1) are marked by a preceding superscript "g".

The resulting translated data set have been compared to corresponding descriptors obtained from the experimental field data.

Table 5 shows the correlation equations between the same identical descriptors in both data sets (experimental descriptors and calculated with equation (1). As could be expected, if the weighting procedure and the frequency range are the same for R' and D_{nT} the predictions given by equation (1) are in good agreement with the experimental results.

Table 5 - Correlation between field data and calculated descriptors

	Values obtained from field data		
(x) (y)	**$D_{nT,w}$**	**$D_{nT,w} + C$**	**$D_{nT,w} + C_{(50\text{-}3150Hz)} \approx D_{nT,50}$**
$^gD_{nT,w}$	y = x + 0,20		
$^gD_{nT,w} + C$		y = x + 0,36	
$^gD_{nT,w} + C_{(50\text{-}3150Hz)}$			y = x + 0,60

The same type of correlation between descriptors obtained from field data and calculated with equation (1) is shown in Table 6. In this case the correlations have been made for the complete dataset - "All"- and also sub categorized in "Heavy" and "Light". This terminology will be used hereinafter when referring to results obtained from the corresponding restricted data set (only heavyweight walls, only lightweight walls or the full data set). The assessment frequency range in this case is not always identical.

Table 6 - Correlation between calculated descriptors for the categorized data, and field data.

(x) (y)	$D_{nT,w} + C_{(50\text{-}3150Hz)} \approx D_{nT,50}$	
${}^{g}D_{nT,w} + C$	**All**	y = 0,80x + 11,12
	Heavy	y = 0,94x + 3,88
	Light	y = 0,76x + 12,04
${}^{g}D_{nT,w} + C_{(50\text{-}3150Hz)}$	**All**	y = x + 0,60
	Heavy	y = x + 0,60
	Light	y = x + 0,62

From the results obtained in Table 6 one can observe that the correlation between two descriptors using different assessment frequency range is strongly dependent on the building type as pointed out in reference [28]. When trying to perform such translations there is a need for additional information not included in equation (1).

Bearing in mind that finding a unique translation equation independent of the building type would be of great interest in the field of building acoustics legislations, this paper proposes a different approach based on the statistical analysis of a large set of field measurements. The statistical correlations between most frequent existent descriptors and the ones proposed for the common classification scheme, $D_{nT,50}$ / $D_{nT,100}$, have been determined for the full data set and later analyzed and discussed.

The calculations have been performed according to the following steps:

- Using the data of the complete set of airborne sound insulation measurements (1.099), the seven most adopted single number descriptors for airborne sound insulation around Europe [7] were calculated (that is R'_w ; $R'_w + C$; $R'_w + C_{(50\text{-}3150Hz)}$; $D_{nT,w}$; $D_{nT,w} + C_{tr}$; $D_{nT,w} + C$; $D_{nT,A\ (100\text{-}5KHz)}$)
- $D_{nT,50}$ and $D_{nT,100}$ were also calculated.
- Pearson correlation coefficient between $D_{nT,50}$ / $D_{nT,100}$ and the seven airborne sound insulation descriptors was calculated. Results are presented in Table 7
- Finally, a scatter plot and a simple linear regression between $D_{nT,50}$ / $D_{nT,100}$ and each of the previously selected descriptors were made. These linear regressions are in fact the corresponding "translation equations" between each pair of descriptors. Table 8 presents the obtained translation equations if only a restricted data set is considered (either measurement data from heavy or on lightweight walls). In this case two different linear regressions (translation equations) are obtained for each pair of descriptors. Table 9 presents the obtained translation equations when using the full data set as well as the translation equations proposed by Gerretsen et al. (from now on labelled as Gerretsen) in [28].

Table 7 – Pearson correlation coefficient between existent descriptors and new ones

(y)	(x)	R'_w	R'_w + C	R'_w + C (50-3150Hz)	$D_{nT,w}$	$D_{nT,w}$ + C_{tr}	$D_{nT,w}$ + C	$D_{nT,A}$ (100-5KHz)
$D_{nT,50}$	All	0,74	0,78	0,90	0,81	0,87	0,87	0,86
	Heavy	0,89	0,90	0,91	0,96	0,95	0,98	0,98
	Light	0,60	0,66	0,89	0,70	0,72	0,76	0,76
$D_{nT,100}$	All	0,90	0,92	0,78	0,97	0,93	1,00	1,00
	Heavy	0,91	0,92	0,89	0,99	0,96	1,00	1,00
	Light	0,84	0,89	0,68	0,94	0,93	1,00	1,00

If the Pearson correlation coefficients shown in Table 7 are analysed, it is found that the values are always smaller for lightweight walls than for heavyweight walls. This indicates that, for lightweight walls, the spread of the data around the lineal regression equation will be wider. Furthermore, in Table 8 it is possible to observe that the translation equations between existing and new proposed descriptors are not completely independent on the building system and different equations are found when considering heavy and lightweight walls separately.

Table 8 - Translation equations between descriptors for the categorized data.

(x) (y)	Type of Walls	$D_{nT,50}$	$D_{nT,100}$
R'_w*	Heavy	y = 0,82x + 9,95	y = 0,87x + 7,54
	Light	y = 0,58x + 22,00	y = 0,81x + 11,17
R'_w + C	Heavy	y = 0,85x + 9,25	y = 0,91x + 7,07
	Light	y = 0,64x + 19,89	y = 0,86x + 9,96
R'_w + C (50-3150Hz)	Heavy	y = 0,90x + 7,32	y = 0,92x + 7,09
	Light	y = 0,88x + 8,59	y = 0,67x + 23,67
$D_{nT,w}$*	Heavy	y = 0,89x + 4,74	y = 0,95x + 2,06
	Light	y = 0,70x + 13,57	y = 0,95x + 1,51
$D_{nT,w}$ + C_{tr}*	Heavy	y = 0,97x + 6,03	y = x + 4,52
	Light	y = 0,69x + 19,99	y = 0,89x + 12,62
$D_{nT,w}$ + C*	Heavy	y = 0,94x + 3,73	y = x + 1,13
	Light	y = 0,76x + 12,13	y = x + 1,34
$D_{nT,A}$ (100-5KHz)	Heavy	y = 0,94x + 2,97	y = x + 0,23
	Light	y = 0,76x + 11,32	y = x + 0,17

*Comparison of the translation equations of these descriptors to $D_{nT,50}$ and Gerretsen's proposal is represented in Figure 7

A detailed analysis on the differences between each pair of equations is out of the scope of this paper, but a simple analysis is shown in Figure 6.
Considering the objective of obtaining translation equations between existing descriptors and new proposed descriptors $D_{nT,50}$ and $D_{nT,100}$, the translation of all the descriptors included in Table 8 has been calculated for values within the limits of the existing requirements in the legislation [6] in 5 dB steps , that is 45, 50, 55, 60 and 65 dB. The corresponding translated values are represented in Figure 6 as blue squares for the heavyweight dataset and as red dashes for the lightweight data set.

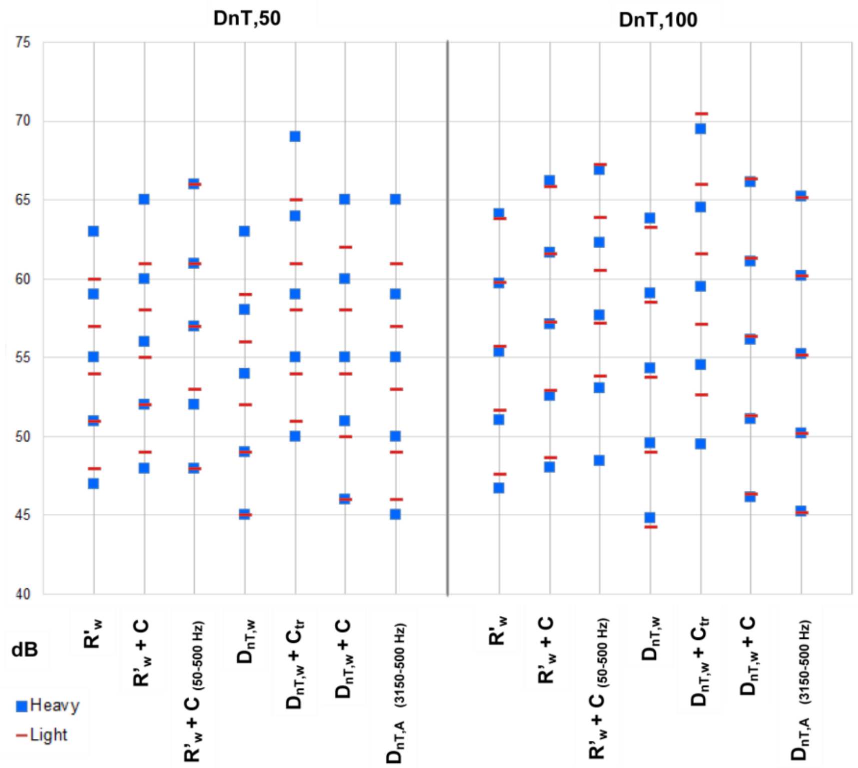


Figure 6: Translation of existing descriptors for values 45, 50, 55, 60 and 65 dB, into new proposed ones according to equations in table 8. Left $D_{nT,50}$; Right $D_{nT,100}$.

Looking at the equations shown in Table 8 and Figure 6, one can detect a similar trend as observed in Table 6. When the translation is made between descriptors that use the same assessment frequency range, the building type is less critical and the differences become smaller. In these cases, the blue squares and red dashes almost overlap or are within 1 dB away. When using different assessment frequency range, the translation between existing and proposed descriptors is more dependent on the building type, blue squares and red dashes show differences between 2 dB and 5 dB.

Since, as previously mentioned, one of the ultimate objectives of this paper is to translate the existing airborne sound insulation requirements into corresponding values using the proposed $D_{nT,50}$ and $D_{nT,100}$, it is necessary to evaluate whether it is reasonable to use the same equation independently of the building system or if a different translation equation should be obtained for each construction type. Table 9 summarizes the corresponding translation equations obtained when considering the full data set and includes as well the translation equations proposed by Gerretsen in [28]

Table 9 – Single translation equations between descriptors, considering the full data set.

(y) (x)	$D_{nT,50}$	$D_{nT,100}$	Gerretsen
R'_w*	y = 0,63x + 20,23	y = 0,83x + 9,60	y= 0,88x+4,2
R'_w + C	y = 0,71x + 16,89	y = 0,90x + 7,40	
R'_w + C (50-3150Hz)	y = 0,89x + 7,77	y = 0,85x + 12,30	
$D_{nT,w}$*	y = 0,71x + 14,77	y = 0,92x + 3,63	y= 0,88x+5,08
$D_{nT,w}$ + C_{tr}*	y = 0,85x + 12,02	y = x + 5,83	y=0,88x+9,48
$D_{nT,w}$ + C*	y = 0,80x + 11,02	y = x + 1	y=0,88x+5,96
$D_{nT,A}$ (100-5KHz)	y = 0,79x + 10,64	y = x + 0,23	

*Comparison of the translation equations of these descriptors to $D_{nT,50}$ and Gerretsen's proposal is represented in Figure 9

If $D_{nT,100}$ and $D_{nT,50}$ columns in Tables 8 and 9 respectively are compared, it is again observed that, for each existing descriptor (x), the translation equations in both tables show better agreement between them when the assessment frequency range remains unchanged. In these cases the translation equations obtained in Table 9 could be used regardless of the building system.

Unfortunately, the majority of the existing descriptors use an assessment frequency range starting at 100 Hz while one of the proposed descriptors, $D_{nT,50,}$ starts at 50 Hz. In this case the use of the equations found in Table 9 is not evident and further research is needed. In the next section the two different equations obtained for $D_{nT,50}$ in Table 8 are further investigated,

5. Evaluating $D_{nT,50}$ translation equations and comparing to existing proposal

In this section the difference between each pair of equations (heavy/light) shown in Table 8 for $D_{nT,50}$ is investigated. This is done in two stages.

As a first step, in section 5.1 the translation equations found in Table 8 for heavy and lightweight walls are represented. When available, a comparison with Gerretsen's proposal [28] is also included.

The second step, presented in section 5.2, aims at evaluating if, for each descriptor, it is acceptable to use one single translation equation regardless of the building system, and how close is the proposed translation equation to Gerretsen's proposal.

5.1 Translation equations obtained for different building system

Although the pair of equations shown in Table 8 for each set of descriptors may seem different, when considering certain confidence intervals, both equations could lie within the same limits. To verify this point, Figures 7 and 8 represent the corresponding pairs of regression lines including the 95% confidence intervals.

The descriptors having a translation proposal by Gerretsen (R'_w, $D_{nT,w}$, $D_{nT,w} + C_{tr}$, $D_{nT,w} + C$ and $D_{nT,50}$) are shown in Figure 7 together with the corresponding Gerretsen's proposal. The remaining descriptors ($R'_w + C$, $R'_w + C_{(50\text{-}3150Hz)}$ and $D_{nT,A\ (100\text{-}5KHz)}$) are represented in Figure 8.

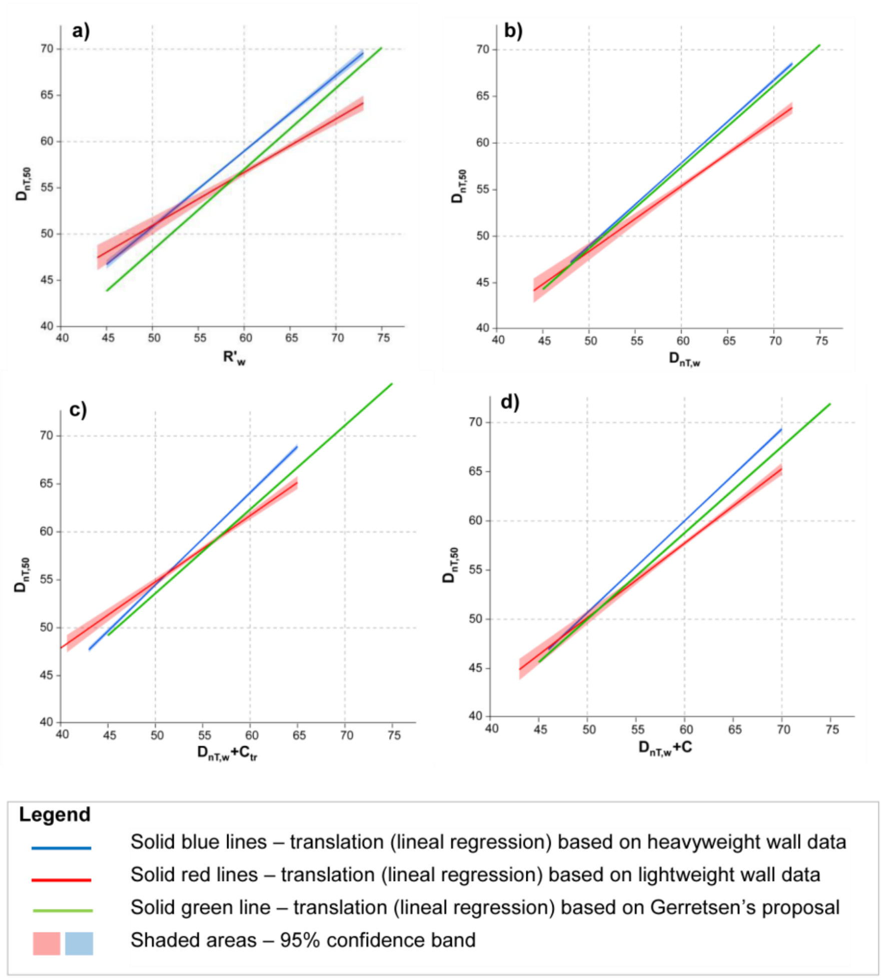
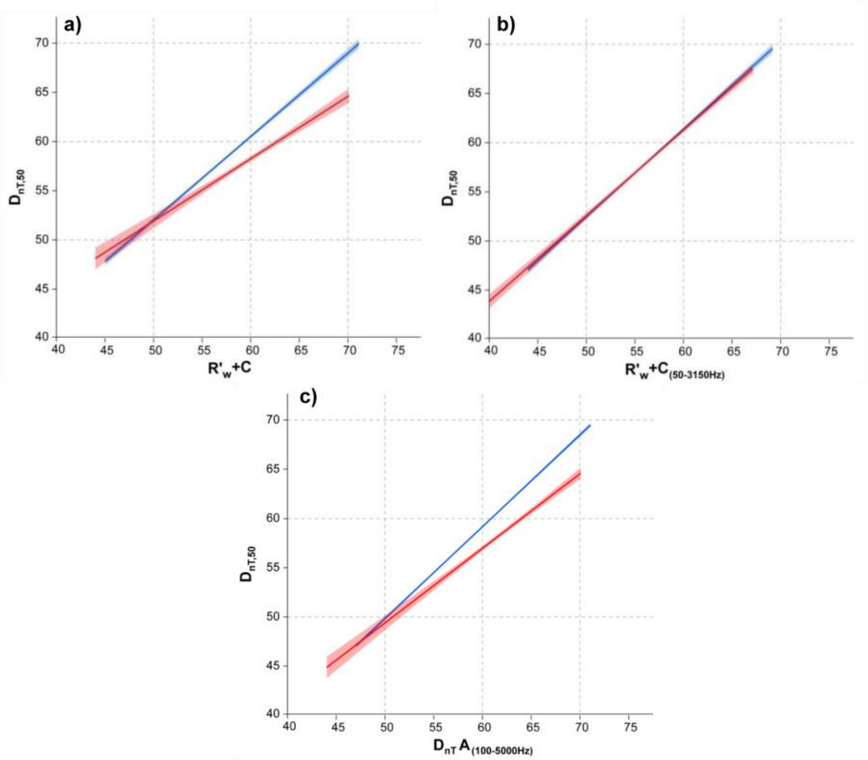


Figure 7: Comparison of translation equations obtained for different building systems and the existent proposal (Gerretsen).

As can be observed in Figures 7 and 8, the translation equations obtained using heavyweight walls and lightweight walls separately, including the 95% interval confidence bands, only overlap within a very small range, which varies depending on the descriptor. In fact, both equations can be considered different for all descriptors except for $R'_w + C_{(50\text{-}3150Hz)}$ [Figure 8 b)].

Due to the effect of the spectral adaptation term $C_{(50\text{-}3150Hz)}$, the corresponding effective frequency range assessment in this case is the same as for $D_{nT,50}$, that is, from 50 Hz to 3150 Hz. This indicates the relevance of the assessment frequency range when calculating airborne sound insulation descriptors.

In general, for all the other descriptors, the heavyweight and the lightweight equations converge only for airborne sound insulation values (x axis) around 48-51 dB. For higher values (x axis), the corresponding differences between the heavy/light translated values (y axis) increase significantly, although differently depending on the pair of descriptors.



Legend

―	Solid blue lines – translation (lineal regression) based on heavyweight wall data
―	Solid red lines – translation (lineal regression) based on lightweight wall data
🟥 🟦	Shaded areas – 95% confidence band

Figure 8: Comparison of the translation equations obtained for different building systems.

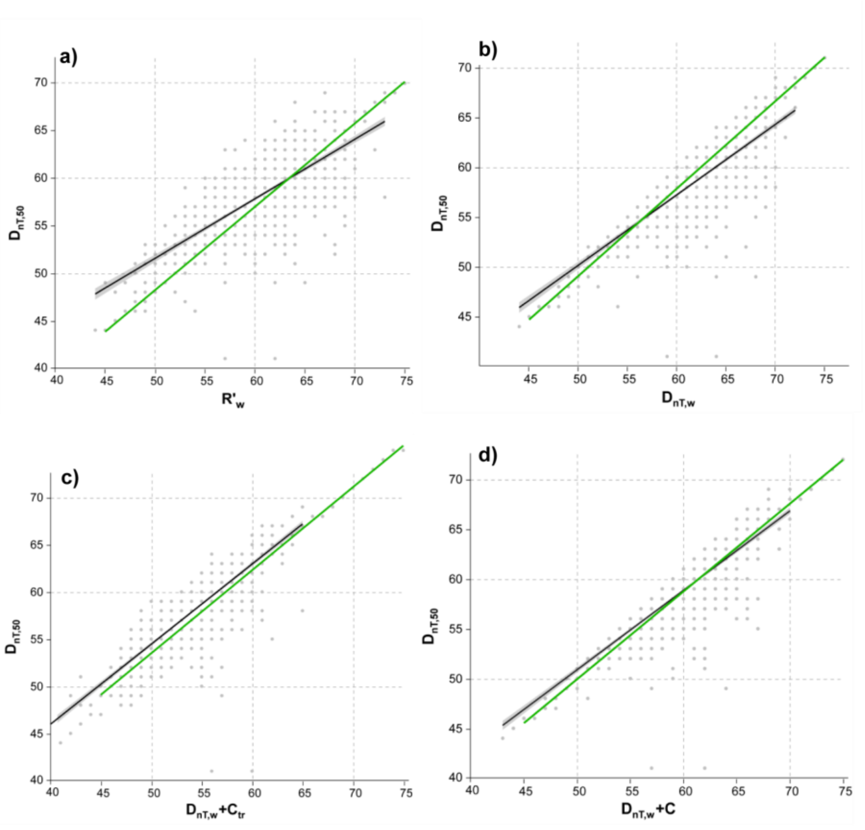
In Figure 7 the heavy/light regression lines are also compared to Gerretsen's translation proposal. It can be observed that there is fairly good agreement between the translation equations obtained using only the heavyweight walls and Gerretsen's proposal for those airborne sound insulation descriptors, based on level difference b), c) and d). For R'_w, a), the differences are more evident. This behaviour will reappear in section 5.2 and thus will be further analysed in that section

5.2 Single translation equations

In the previous section it has again been shown that there is a dependence on the building type when trying to translate existing airborne sound insulation descriptors into new proposed descriptors, especially when different assessment frequency ranges are considered. Nevertheless, from a practical point of view, it can be convenient to propose a single translation equation which could be used regardless of the building system. The proposal is to use, in a preliminary stage, the translation equations obtained with the full data set (Table 9) and verify how these equations converge to Gerretsen's proposal.

Figure 9 represents the obtained single translation equations for the descriptors marked (*) in Table 9, with the 95% confidence band. Gerretsen's proposal and the scatter data are also included in the plots.

Plots a), b), c) and d) represent the linear regression between R'_w, $D_{nT,w}$, $D_{nT,w} + C_{tr}$, $D_{nT,w} + C$ and $D_{nT,50}$, according to both proposals.



Legend

▬	Solid black line – translation (lineal regression) based on the full data set
▬	Solid green line – translation (lineal regression) based on Gerretsen's proposal
■	Shaded area – 95% confidence band

Figure 9: Comparison of obtained single translation equations and Gerretsen's proposal

As observed in section 5.1, the translations between descriptors based on level difference [plots b), c) and d)] show small differences with Gerretsen's proposal, with deviations of ±2 dB. This is not the case for the translation from R'_w to $D_{nT,50}$ (plot a), where the differences can reach up to ±5 dB.

The differences found between the statistical approaches presented in this paper and the proposal made by Gerretsen can be due to divergences found between the underlying hypothesis in Gerretsen's proposal and the in-situ actual buildings statistical data source.

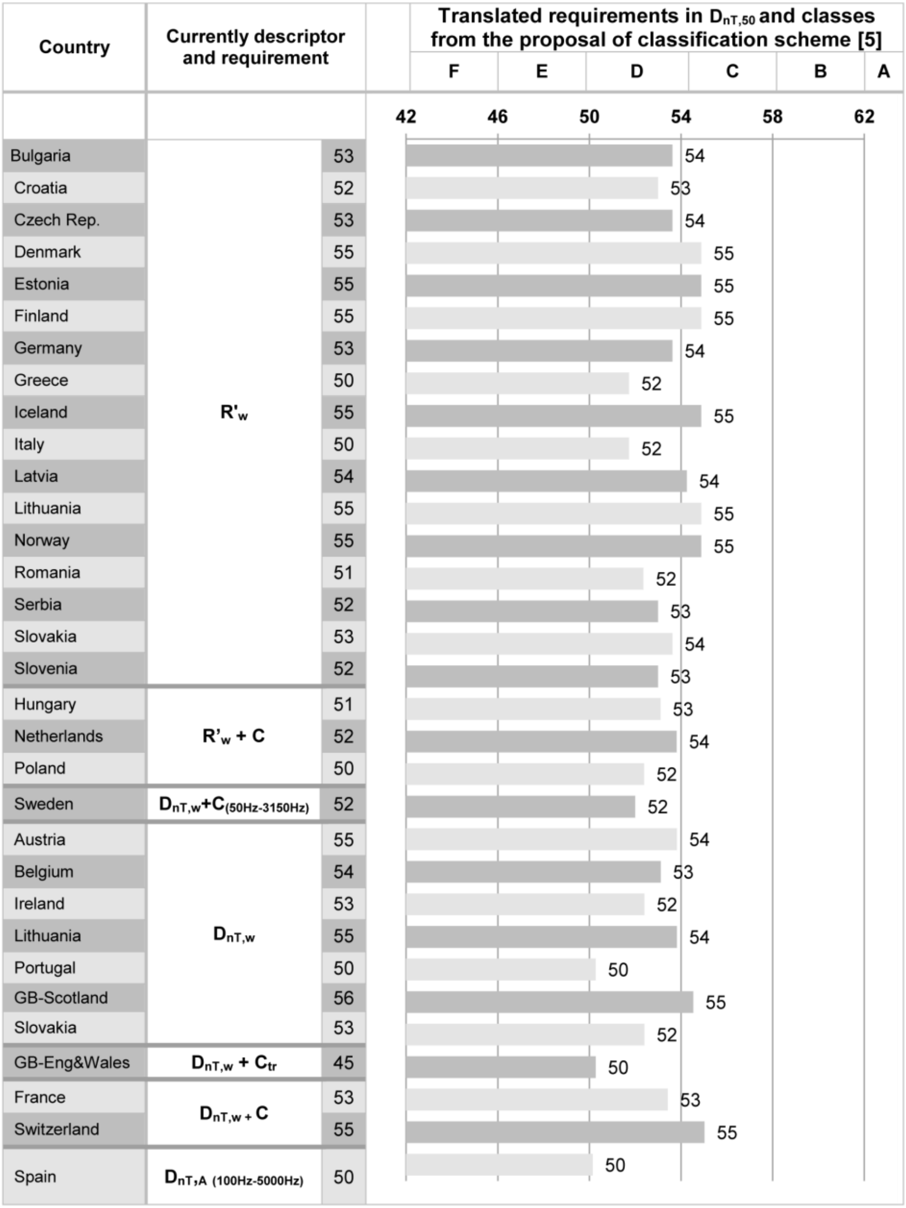
In Gerretsen's proposal, a compromise value for the receiving room volume V=52,5m^3 and the volume/area ratio V/S=2,5m was used. In the present study, a large data set of in-situ measurements was used to obtain the translation, including different construction types. For the 1 099 in-situ tests, the typical volume average was V=35,3m^3 and the typical volume/area ratio was V/S =3,8m. These values correspond better with common spaces found in actual buildings. (e.g.: a room with V=35m^3 could measure 3,8m x 3,7m x 2,5m approximately. And for a V/S =3,8m in the same room, the common partition area should be of 9,2m^2, measuring 3,7m x 2,5m approximately).

6. Evaluation and influence of translated airborne sound insulation requirements within a proposed acoustic classification scheme

Adopting a common acoustic classification scheme based on harmonized descriptors is a policy decision which can have influence on future design and specifications leading to economic impacts. Legislators in each country need to evaluate the effects of the potential change and this cannot be assessed without a proper translation of existing sound insulation requirements into to the new harmonized descriptors. It is also important for legislators to evaluate which sound classification the translated requirement will align to and if this represents a change from the existing situation. In countries having an acoustic classification scheme for buildings, the sound insulation requirements often have lower classification grades or levels for older or renovated existing buildings and higher classes for superior quality new buildings. This should remain unchanged in the potential new scenario. This is an important factor considering that sound insulation is often widely adopted within overall sustainability requirements or guidance of recent building standards in some European countries.

In this section the existing airborne sound insulation requirements in thirty-two countries have been translated to the new suggested descriptor $D_{nT,50}$ and then placed within the proposed acoustic classification scheme for dwellings shown in Figure 1.

The translation has been performed based on the equations obtained in Table 9 (that is, using the full data set). The results are shown in Figure 10. As might be expected, most countries' requirements are located in the centre of the classification scheme (classes C and D) although there are important differences between countries. For example, some countries like Portugal and Spain would have an equivalent requirement $D_{nT,50}$ > 50, whereas others like Denmark or Switzerland require $D_{nT,50}$ > 55.



Country	Currently descriptor and requirement		Translated requirements in $D_{nT,50}$
Bulgaria	R'_w	53	54
Croatia		52	53
Czech Rep.		53	54
Denmark		55	55
Estonia		55	55
Finland		55	55
Germany		53	54
Greece		50	52
Iceland		55	55
Italy		50	52
Latvia		54	54
Lithuania		55	55
Norway		55	55
Romania		51	52
Serbia		52	53
Slovakia		53	54
Slovenia		52	53
Hungary	$R'_w + C$	51	53
Netherlands		52	54
Poland		50	52
Sweden	$D_{nT,w}+C_{(50Hz-3150Hz)}$	52	52
Austria	$D_{nT,w}$	55	54
Belgium		54	53
Ireland		53	52
Lithuania		55	54
Portugal		50	50
GB-Scotland		56	55
Slovakia		53	52
GB-Eng&Wales	$D_{nT,w} + C_{tr}$	45	50
France	$D_{nT,w} + C$	53	53
Switzerland		55	55
Spain	$D_{nT,A\ (100Hz-5000Hz)}$	50	50

Note: As the translated requirements were rounded to be presented in this Figure, some of them have the same number but not exactly the same bar size.

Figure 10: Countries' airborne sound insulation requirements for multi-storey housing, corresponding $D_{nT,50}$ translation and alignment within the common acoustic classification scheme proposal

From the results in Figure 10, it is possible to estimate what would be the effect of adopting $D_{nT,50}$ as airborne sound insulation descriptor in all the countries illustrated. It is worth mentioning that a common sound classification scheme may help improving sound insulation of dwellings as it enables an international comparative and interchange of knowledge about the performance of acoustic conditions around different countries. This assists multi-national operating companies and also SME businesses exporting to different countries.

7. Conclusions

All the results presented in this paper contribute to the ongoing research on the effect on adopting new harmonized sound insulation descriptors, how to find solid translations between existing and proposed descriptors and the potential effect of using different frequency range assessment in the new proposed descriptor.

- Considering the translation between R and D_{nT} according to equation 1, it has been proved that the mathematical translation is in agreement with the field data values. It has also been shown that it is not reliable to predict 50 Hz descriptors by data starting from 100 Hz.

- The obtained empirical translation equations between existing airborne sound insulation descriptors and proposed ones $D_{nT,50}$ and $D_{nT,100}$; are more dependent on the building type when the original and the translated descriptor consider different assessment frequency ranges.

- The obtained empirical translation equations are in good agreement with those proposed by Gerretsen in [27,28] only for translations between the same type of descriptor (level difference to level difference) and same frequency range. The translations between D_{nT} and R based upon empirical data can be done although it is a fact that the relation is geometry dependent.

- Also in agreement with Gerretsen and Dunbavin results, it was observed that a spread around the average translation occurred when the statistical method was employed. It is interesting to point out that the spread obtained from the translation using a large data set, as done in this study, is larger than the spread with a smaller sample. The spread of the values need to be considered as they might incur in several practical consequences.

- The existing airborne sound insulation national requirements in thirty-two countries have been translated to $D_{nT,50;}$ using the translation equations obtained using the full data set. When the translated requirement have been placed in the acoustic classification scheme proposed by COST Action TU0901 it has been observed that if this classification scheme was adopted many countries would find their national requirement falling into class D. This shows that, either the classification scheme C class requirement is it too high, or those countries should increase their national requirement so as to place it under class C, since class D is originally intended for existing or refurbished dwellings.

The obtained outcomes give input to stakeholders to estimate the consequences of adopting an alternative airborne sound insulation descriptor that therefore would be adopted in a common acoustic classification scheme. It also enables acousticians, manufacturers and policy makers from different countries to compare their requirements with other countries and can give support for future improvements of national regulations and development of new building systems.

It is highly recommended that a similar study is undertaken with more data and with in situ airborne sound insulation data from a variety of different countries' typical constructions. It is also necessary to perform a more thorough investigation in order to identify in which cases a single translation equation could be used independently of the building system.

If this is not achieved then it will be necessary to use different translation equations depending on the building system. This is a pathway that regulators and policy makers would wish to avoid in order for all build systems to be treated fairly.

Acknowledgements

The authors would like to thank all members of COST Action TU0901 and Robust Details Ltd for inspiring and supporting this research.

Funding

The author Carolina Monteiro, PhD Candidate at Universidad de Valladolid, Spain, is sponsored by the program GDE/CSF from CNPq – Brazil.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Hänninen O, Knol AB, Jantunen M, Lim T-A, Conrad A, Rappolder M, et al. Environmental Burden of Disease in Europe: Assessing Nine Risk Factors in Six Countries. Environ Health Perspect 2014;122:439–46.

[2] Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S, et al. Auditory and non-auditory effects of noise on health. Lancet 2014;383:1325–32.

[3] Basner M, Brink M, Bristow A, de Kluizenaar Y, Finegold L, Hong J, et al. ICBEN review of research on the biological effects of noise 2011-2014. Noise Health 2015;17:57–82.

[4] Berardi U, Rasmussen B. A Comparison Between National Scheme for the Acoustic Classification of Dwellings in Europe and in the U.S. Int J Acoust Vib 2015;20:63–8.

[5] Rasmussen B, Machimbarrena M, Fausti P, TU0901 C. Building acoustics throughout Europe. Volume 1: Towards a common framework in building acoustics throughout Europe. 2014.

[6] Rasmussen B. Sound insulation between dwellings – Requirements in building regulations in Europe. Appl Acoust 2010;71:373–85. doi:10.1016/j.apacoust.2009.08.011.

[7] Rasmussen B, Rindel JH. Sound insulation between dwellings – Descriptors applied in building regulations in Europe. Appl Acoust 2010;71:171–80. doi:10.1016/j.apacoust.2009.05.002.

[8] Rasmussen B. International proposal for an acoustic classification scheme for dwellings. Inter-Noise 2014 43rd Int. Congr. Noise Control Eng., Australian Acoustical Society; 2014.

[9] ISO 717-1: 2013 Acoustics -- Rating of sound insulation in buildings and of building elements -- Part 1: Airborne sound insulation. International Organization for Standardization; 2013.

[10] ISO 717-2: 2013 Acoustics -- Rating of sound insulation in buildings and of building elements -- Part 2: Impact sound insulation. International Organization for Standardization; 2013.

[11] Yaniv SL, Flynn DR. Noise criteria for buildings: a critical review. Washington: U.S. Dept. of Commerce, National Bureau of Standards; 1978.

[12] Scholl W, Lang J, Wittstockh V. Rating of Sound Insulation at Present and in Future. The Revision of ISO 717. Acta Acust United with Acust 2011;97:686–98.

[13] ISO 16283-1:2014 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation. Geneva, Switzerland: International Organization for Standardization; 2014.

[14] ISO 16283-2: 2015 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 2: Impact sound insulation. International Organization for Standardization; 2015.

[15] ISO 16283-3:2016 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 3: Façade sound insulation. International Organization for Standardization; 2016.

[16] Deželak F, Čurović L, Čudina M. Determination of the sound energy level of a gunshot and its applications in room acoustics. Appl Acoust 2016;105:99–109. doi:10.1016/j.apacoust.2015.12.001.

[17] Hongisto V, Keränen J. Reproducibility of the present and the proposed single-number quantities of airborne sound insulation. Acta Acust United with Acust 2012;98:811–9.

[18] Mahn J, Pearse J. The Uncertainty of the Proposed Single Number Ratings for Airborne Sound Insulation. Build Acoust 2012;19:145–72. doi:10.1260/1351-010X.19.3.145.

[19] Wittstock V. Determination of Measurement Uncertainties in Building Acoustics by Interlaboratory Tests. Part 1: Airborne Sound Insulation. Acta Acust United with Acust 2015;101:88–98. doi:10.3813/AAA.918807.

[20] Ljunggren F, Simmons C, Hagberg K. Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound. Appl Acoust 2014;85:57–68. doi:Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound.

[21] Monteiro C, Machimbarrena M, de la Prida D, Rychtarikova M. Subjective and objective acoustic performance ranking of heavy and light weight walls. Appl Acoust 2016;110:268–79. doi:10.1016/j.apacoust.2016.03.008.

[22] Bailhache S, Jagla J, Guigou C. Effet des basses fréquences sur le confort acoustique - tests psychoacoustiques, Rapport USC-EA-D1_A2.1.4_2. Centre Scientifique et Technique du Bâtiment CSTB 2014.

[23] Rychtáriková M, Muellner H, Chmelík V, Roozen NB, Urbán D, Garcia DP, et al. Perceived Loudness of Neighbour Sounds Heard Through Heavy and Light-Weight Walls with Equal Rw + C50-5000. Acta Acust United with Acust 2016;102:58–66. doi:10.3813/AAA.918924.

[24] ISO/CD 19488:2016 -- Acoustic classification scheme for dwellings. International Organization for Standardization; 2016.

[25] Monteiro CRA, Marino CM, Torchia F, Robertson N, Smith RS, Machimbarrena M. Comparative analysis of airborne sound insulation field measurements using different ISO 717-1 performance descriptors - Heavyweight separating walls and floors. Euronoise 2012, Prague: 2012.

[26] Monteiro CRA, Marino CM, Torchia F, Robertson N, Smith RS, Machimbarrena M. Comparative analysis of airborne sound insulation field measurements using different ISO 717-1 performance descriptors - Lightweight separating walls and floors. Euronoise 2012, 2012.

[27] Gerretsen E. European variety of descriptors for building acoustic performance and translation into proposed harmonized descriptors. 42nd Int. Congr. Expo. Noise Control Eng. 2013, INTER-NOISE 2013 Noise Control Qual. Life, vol. 2, OAL-Osterreichischer Arbeitsring fur Larmbekampfung; 2013, p. 1459–66.

[28] Gerretsen E, Dunbavin PR. Chapter 4: How to translate sound insulation descriptors and requirements. Build. Acoust. throughout Eur. Vol. 1 Towar. a common Framew. Build. Acoust. throughout Eur., 2014.

[29] Robust Details Ltd. Robust details handbook. Part E: Resistance to the passage of sound. 3rd ed. Milton Keynes, UK: 2013.

[30] Smith S, Macdonald R, Lurcock D, Mackenzie R. Airborne sound transmission, ISO 140 and influence of ISO 717-1 spectrum adaptation terms. 19th Int. Congr. Acoust., Madrid: 2007.

8. Trabajos relacionados al desarrollo de la Tesis Doctoral

8.1 Trabajos presentados durante el desarrollo de la Tesis

8.1.1 Capítulos de libros

1. Carrascal, Teresa; Machimbarrena, María; Monteiro, Carolina Rodrigues A. Spain en: Building acoustics throughout Europe Volume 2: Housing and construction types country by country. Madrid: DiScript S.L., 2014, v.2, p. 1-570.

Referencias adicionales: http://www.costtu0901.eu/tu0901-e-books, ISBN: 9788469701591

2. Fausti, Patrizio; Carrascal, Teresa; Ingelaere, Bart; Monteiro, Carolina Rodrigues Alves et al. Design and Acoustic performance of building constructions for multi-storey housing: compendium en: Towards a common framework in building acoustics throughout Europe. Madrid: DiScript S.L., 2013, v.1, p. 1-196.

Referencias adicionales: http://www.costtu0901.eu/tu0901-e-books, ISBN: 9788461671243

8.1.2 Principales artículos presentados en congresos

1. Machimbarrena, Maria; del Val, Lara; Monteiro, Carolina; Herráez, Marta; Johansson, Reine. Translation of existing impact sound insulation descriptors into new proposed ones, based on a large set of in-situ measurements. 22nd International Congress on Acoustics, 2016, Buenos Aires.

2. Monteiro, Carolina; Machimbarrena, María et al. How to translate existing airborne sound insulation descriptors to future proposals. Euroregio 2016, 2016, Porto.

3. Machimbarrena, María; Monteiro, Carolina et al. Determinación de la incertidumbre en medidas de aislamiento acústico a ruido aéreo: Ejemplo de aplicación a un gran número de datos, 2015.
4. Monteiro, Carolina; Prida, Daniel de la; Machimbarrena, María. Contribution to a methodology for perception assessment in building acoustics. Forum Acusticum 2014, 2014, Cracóvia.
5. Monteiro, Carolina; Machimbarrena, María; Pedersoli, S. et al. Contribution to uncertainty of in situ airborne sound insulation measurements. Internoise 2013 - International Congress and Exposition on Noise Control Engineering, 2013, Innsbruck.
6. Monteiro, Carolina; Zamarrón, A. Environmental noise perception assessment: the citizen as a sensor. Tecniacústica 2013, 2013, Valladolid.
7. Monteiro, Carolina; Mondaca, Cristian; Machimbarrena, María et al. Typical heavyweight walls performance: variability and density function distribution of airborne sound insulation single number quantities. AIA-DAGA 2013 International Conference on Acoustics, 2013, Merano.
8. Monteiro, Carolina; Mondaca, Cristian; Torchia, Francesca et al. Comparative analysis of airborne sound insulation field measurements using different ISO 717-1 performance descriptors - Heavyweight separating walls and floors. Euronoise 2012, 2012, Praga.
9. Monteiro, Carolina Rodrigues Alves; Mondaca, Cristian; Torchia, Francesca et al. Comparative analysis of airborne sound insulation field measurements using different ISO 717-1 performance descriptors - Lightweight separating walls and floors. Euronoise 2012, 2012, Praga.
10. Machimbarrena, María; Mondaca, Cristian; Monteiro, Carolina. Comparison of some global indices to adequately assess airborne sound insulation. Euronoise 2012, 2012, Praga.

8.2 Artículos en desarrollo

1. Machimbarrena, Maria; del Val, Lara; Monteiro, Carolina; Herráez, Marta; Johansson, Reine.; Translation between existing and proposed harmonized impact sound level descriptors: A statistical approach based on in-situ measurements.

8.3 Estancias investigadoras y Cursos Cortos

1. 2013, 21-25 de Enero. Training school TU 0901"Integrating Psychoacoustic Methodologies in Building Acoustic Research", curso coordinado por la COST Action TU0901 en el Belgium Building Research Institute (WTCB-CSTC) en Bruselas, Bélgica.
2. 2013, 15-17 de Marzo. EAA Winter School "Synergies between Environmental Noise Control and Soundscape approach", curso coordinaddo por la COST Action TD0804 en el Euroregio 2013 en Merano, Italia.
3. 2013, Agosto y Noviembre. Estancia en el Institute for Sustainable Construction de la Edinburgh Napier University en Edimburgo,Escocia.
4. 2015, 21-25 de Septiembre. Estancia para el desarrollo del trabajo "Acoustic Performance of an insulated fabric structure" en la Newcastle University, Newcastle, Inglaterra.