Institution: University of Liverpool

Unit of Assessment: 13 Architecture

Title of case study: Establishing International and European Standards in building acoustics

Period when the underpinning research was undertaken: 2007-2019

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Carl Hopkins	Professor	2007 – Present
Barry Gibbs	Professor	1977 – Present
Pyoung Jik Lee	Senior Lecturer	2014 – Present

Period when the claimed impact occurred: 2013-2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Protecting the health, welfare and privacy of building occupants against noise requires an assessment of the acoustic performance of buildings, particularly dwellings, hotels, schools and hospitals. Our research on sound transmission has led to new developments and improvements in Standards on building acoustics that prescribe measurement methods, prediction models and evaluation. It has provided the scientific basis and experimental validation needed to establish new approaches in 8 International and European Standards. These Standards are adopted in over 34 countries where they are used by accredited test laboratories, consultants, manufacturers and government regulators for buildings, ships and offshore structures.

2. Underpinning research

The Acoustics Research Unit (ARU) has strong links with industry and consultancies. Our research on sound transmission in buildings is driven by the needs of industry, regulators, and acousticians that require (a) standardised measurement procedures with suitable accuracy, (b) links between objective and subjective assessment, (c) validated prediction models for sound insulation, and (d) laboratory methods to predict noise from machinery in buildings.

For increasingly mechanised buildings, 2 concepts to quantify machinery noise have been developed to the point of knowledge transfer and take-up by industry. These allow the vibration of machines to be described in terms of a single equivalent value by measuring their vibrational output when attached to a well-defined structure [3.1]. This significantly reduces the complexity of measurements and prediction models and is therefore favoured by manufacturers, engineers and designers. The first concept is the reception plate developed by Gibbs and co-workers. This is well-suited to machinery installed in heavyweight buildings, but also to equipment inside airplanes. The focus has been on quantifying and improving the accuracy of reception plate measurements. Gibbs carried out collaborative research with Boeing Commercial Airplanes which confirmed that it gave nominally the same result as more complex measurement procedures. For practical implementation by test laboratories, Hopkins demonstrated that the accuracy relies on the reception plate being isolated from any other structure. This isolation must be provided by resilient materials; hence Hopkins and co-workers developed experimentally-validated finite element models that would allow laboratories to predict the structural damping of reception plates before they are built. As an alternative approach when an isolated reception plate is not available, Gibbs developed an approach for a coupled reception plate using a calibrated source [3.2]. The second concept has been the development of a two-stage reception plate method by Gibbs which allows the vibrational output to be quantified as input data for all types of building constructions, including lightweight and heavyweight buildings.

For sound and structure-borne sound transmission in buildings, Hopkins has developed measurement procedures for the laboratory and field as well as improving prediction models. Due to interest from practitioners in using hand-held sound level meters to simplify sound insulation measurements on building sites, Hopkins developed theory to estimate the efficacy of manual sampling of sound fields [3.3]. To predict structure-borne sound transmission with impulsive sources, Hopkins and co-workers developed models using transient statistical energy analysis to predict structural reverberation times. These models showed that the connection of walls/floors to the rest of the building, caused distinct curvature in the measured decay curves due to energy returning from other walls/floors. This allowed identification of optimal evaluation ranges for decay curves and led to a new evaluation procedure to minimise measurement errors [3.4]. Subsequent research by Hopkins on the prediction of sound insulation in heavyweight buildings identified errors in both laboratory and field measurements of the vibration reduction index that had been used by other researchers as input data in prediction models. This led Hopkins to determine new empirical relationships to calculate the vibration reduction index which, in turn, led to a collaboration with European researchers to broaden the application of these relationships to low-frequencies and increase their accuracy [3.5]. To enable the prediction of machinery noise in modern lightweight buildings, Hopkins and colleagues in Germany defined a new measurement approach by defining a calibrated structure-borne sound source. This allowed measurement of a new parameter, a transmission function, to determine sound pressure levels due to vibrating machinery in another part of the building [3.6].

Lee joined the ARU in 2014 to broaden the research activity into human perception of noise. Lee and co-workers used subjective evaluation studies to investigate the rating of impact sound insulation measured with a heavy impact source. This assessment of the link between different single-number ratings and annoyance identified the most effective single-number rating.

3. References to the research

3.1 Mayr AR, **Gibbs** BM. (2012) Single equivalent approximation for multiple contact structure-borne sound sources in buildings. Acta Acustica United with Acustica, 98, 402-410. doi:10.3813/AAA.918525

3.2 Holler C, **Gibbs** BM. (2018) Source substitution method for obtaining the power transmission from vibrating sources in buildings. Applied Acoustics, 141, 240-249. doi:10.1016/j.apacoust.2018.07.014

3.3 **Hopkins** C. (2011) On the efficacy of spatial sampling using manual scanning paths to determine the spatial average sound pressure level in rooms. Journal of the Acoustical Society of America, 129(5), 3027- 3034. doi:10.1121/1.3573986

3.4 **Hopkins** C, Robinson M. (2013) On the evaluation of decay curves to determine structural reverberation times for building elements. Acta Acustica United with Acustica, 99(2), 226-244. doi:10.3813/aaa.918606

3.5 **Hopkins** C, Crispin C, Poblet-Puig J, Guigou-Carter C. (2016) Regression curves for vibration transmission across junctions of heavyweight walls and floors based on finite element methods and wave theory. Applied Acoustics, 113, 7-21. doi:10.1016/j.apacoust.2016.06.002

3.6 Schöpfer F, **Hopkins** C, Mayr A, Schanda U. (2017) Measurement of transmission functions in lightweight buildings for the prediction of structure-borne sound transmission from machinery. Acta Acustica United with Acustica, 103, 451-464. doi:10.3813/AAA.919075

3.7 Jeong JH, Park SH, **Lee** P. (2019) Single-number quantities of heavyweight impact sound insulation. Acta Acustica United with Acustica, 105(1), 5-8. doi:10.3813/AAA.919280

In the bibliographies of the 8 Standards there are references to 14 different pieces of underpinning research; these are listed for each Standard in Source 5.1.

4. Details of the impact

Our research provides scientific underpinning for the creation of new and revised Standards on building acoustics at a European and International level. These Standards are used to ensure the protection of health, welfare and privacy for the occupants, and a fair and accurate comparison of buildings and building products for construction companies and manufacturers. The main beneficiaries are test laboratories, consultants, manufacturers and government regulators that assess and regulate the acoustic performance of buildings such as dwellings, hotels, schools and hospitals. Our publications are referenced in the bibliographies of these Standards [5.1]. Our input is confirmed by the Chairperson for European Standardisation on building acoustics: "*In CEN TC126, standards are improved and developed by building consensus between technical experts, industry and manufacturers. At the committee stage, this often relies on the availability of validated procedures/approaches from rigorous research such as that which is provided by the ARU at Liverpool.*" [5.2].

In terms of reach, the Standards are adopted by Standardization bodies from 34 European countries and 164 countries worldwide. Our active participation in Standards committees and Working Groups ensures our research addresses the needs of industry and government stakeholders. The Convenor for International Standardisation on building acoustics confirms our influence: "*The work by the Acoustics Research Unit plays a significant role in shaping and improving Standards on building acoustics, and I look forward to this continuing in the future.*" [5.3].

Hopkins is Chair of the British Standards committee on building acoustics (2009–Present). Due to his research on sound transmission in buildings, he was appointed as Convenor of European and International Standards groups on the measurement of flanking transmission (2009–Present), and Convenor of 3 International Standards project groups on field measurement of sound insulation (2009–Present). Currently there are 10 International/European Standards which reference his sole-author research monograph 'Sound insulation' (2007) as a key text with 5 of these Standards being published during this REF period [5.1]. Due to his extensive research on the topic, Gibbs is the main contributor to the working group on the measurement of structure-borne sound power input from machinery into building structures (2013–Present).

Increasing the accuracy and practicality of field sound insulation measurements
Sound insulation testing is carried out according to European/International Standards to ensure traceability. The UK construction industry carries out approximately 35,000 field sound insulation tests per annum, providing a direct income of approximately GBP10,000,000 per annum for acoustic consultants. This is in addition to income of approximately GBP53,000,000 that UK acoustic consultants earn using these Standards in consultancy work on building acoustics.

An important driver for the revision of Standards on the measurement of sound insulation in the field (EN ISO 16283 Part 1 (2014), Part 2 (2018) and Part 3 (2016)) came from consultants and test laboratories who wanted to be inside the receiving room to (a) monitor background noise on construction sites due to high intermittent levels of noise and (b) reduce the amount of measurement equipment and cabling. The main driver from regulators and the building industry was the need for improved accuracy because 24 European countries use these tests to confirm compliance with National building regulations with mandatory testing in 7 of these countries. In addition, 11 countries have acoustic classification schemes for dwellings which require accurate field tests to ensure that dwellings are reported in the correct quality class because this affects house prices. To address these competing demands for practicality and accuracy, Hopkins used theory he had developed on the efficacy of manual scanning [3.3] to identify 4 manual scanning patterns that gave accurate estimates of the spatial-average sound pressure level and minimised body movement that might generate noise (particularly walking). These were incorporated in the revised Standards to allow hand-held microphones or sound level meters to be used to sample the sound field with the measurer inside the room.

The reach of these Standards outside the building industry is evidenced by ISO 16283 (Parts 1 and 2) being used by the world's largest maritime classification society, DNVGL, to measure sound insulation between technical rooms, work rooms and cabins on ships and offshore oil platforms [5.4]. This is a requirement to obtain a class certificate for their classified fleet of over 11,000 vessels and mobile offshore units.

Introducing new measurement methods to quantify the vibrational output of machinery
Until 2009 there was no generally accepted procedure to measure the vibrational power output of building machinery. This changed when the reception plate method developed by Gibbs was used as the basis for EN 15657-1. However, this was limited to machinery installed in heavyweight buildings. To extend the application of the reception plate approach to any building (including lightweight timber-frame), our research led to it being superseded by a new Standard, EN 15657 in 2017, which applies to all types of building. This was achieved by incorporating the two-stage reception plate method that was developed and validated by Gibbs. This new Standard allows manufacturers of heating, ventilation, domestic appliances etc. to measure their products in laboratories and estimate if they will comply with noise limits after installation.

The reception plate was originally required to be resiliently isolated. To help test laboratories design the isolation for their reception plate, EN 15657 refers to research from Hopkins on using finite element modelling to predict the effect of different resilient materials. However, some test laboratories wanted to reduce costs by using an existing concrete floor that was bonded to other walls and floors. Research by Hopkins showed that this would give unacceptable errors. To circumvent this problem, Gibbs [3.2] developed an alternative approach using a calibrated structure-borne sound source; this was also implemented in EN 15657.

Through the adoption of our research, and its inclusion in EN 15657, at least 10 laboratories and manufacturers across Europe now have reception plates for product development. One of these is the globally operating Geberit Group, a European leader in the field of sanitary products who state: "*The ARU research to develop the reception plate method that led to EN 15657 has significantly improved our acoustical measurement and prediction capability for Geberit products.*" and "*For Geberit's building physics laboratory, the improved experimental and prediction capabilities that result from the reception plate approach will give us an extra competitive advantage in the market.*" [5.5].

Extending measurement methods to give input data for prediction models
At the design stage, consultants and industry need accurate prediction models to assess whether a building is likely to comply with the sound insulation requirements. These models often require input data that is determined from acoustic measurements on a wide range of constructions. In 2015, Hopkins started revising EN ISO 10848 Parts 1–4 to (a) extend their application to field measurements of flanking transmission, lightweight buildings, machinery noise and low-frequencies and (b) improve the accuracy of measurement procedures in the laboratory and the field; these Standards were published in 2017. For heavyweight walls and floors these Standards required accurate measurement of the structural reverberation time to quantify the vibration reduction index that is needed to predict the overall sound insulation. Research by Hopkins [3.4] defined a new procedure to evaluate these reverberation times which reduced the errors; this was included in Part 1. Hopkins' research predicting the errors in the vibration reduction index with different laboratory and field situations formed additional guidance in Part 4. To extend the standard to lightweight buildings, a calibrated structure-borne sound source and the new concept of a transmission function [3.6] were incorporated into Part 1 to give industry a simpler model for the prediction of machinery noise, particularly in lightweight buildings.

Improving the accuracy of prediction models for heavyweight buildings
The original prediction model for sound transmission in heavyweight buildings in EN ISO 12354 Part 1 used empirical relationships for the vibration reduction index. Hopkins (2014) identified 2 significant errors in these relationships. These were caused by (a) not considering all types of structure-borne sound waves and (b) the empirical relationships being based on experimental data which had bias errors due to the situations in which they were measured. To remedy this, Hopkins

and co-workers in Belgium, Spain and France collaborated to develop more accurate relationships using numerical models that extended down to low-frequencies [3.5]. This was needed because previous changes to European and International Standards on field sound insulation measurements introduced more repeatable and reproducible low-frequency measurement procedures. The revised version of EN ISO 12354 Part 1 with these new relationships was published in 2017. This improved the accuracy of sound insulation predictions and reduced the risk of overestimating the actual sound insulation in the field at the design stage [3.5]. The main beneficiaries of these changes are acoustic consultants worldwide who use the model in the acoustic design of heavyweight buildings. The prediction model is implemented in commercial software and sold by 8 International companies [5.6].

Developing a new rating procedure for impact sound insulation

Korea and Japan currently assess impact sound insulation using measurements with a heavy impact source, and there was interest from test laboratories in using this source in Europe. Although the measurement procedures were included in International Standards, there was no internationally agreed method to calculate a single-number rating that could be used to assess annoyance. This rating was needed to identify acceptable levels of impact sound insulation for building regulations. Research using subjective evaluation studies by Lee assessed different ratings developed in Korea and Japan to identify the most suitable rating method. This rating is now included in the draft EN ISO 717-2 which has been approved by international vote.

5. Sources to corroborate the impact

5.1 List of Standards with references to the underpinning research in their bibliographies.

5.2 Letter from the Chairperson for European Standardisation on building acoustics (CEN TC126) ‘Acoustic properties of building elements and of buildings’ to corroborate the impact of our research on European Standardisation activity.

5.3 Letter from the Chair of International Organisation for Standardisation (ISO) Technical Committee 43 Sub-committee 2 ‘Building Acoustics’ which deals with all ISO standards on building acoustics to corroborate the impact of our research on International Standardisation activity.

5.4 Evidence that DNVGL use ISO 16283 for maritime classification.

5.5 Letter from the Head of Building Physics at Geberit International AG evidencing the use of the reception plate on sanitary product development in industry.

5.6 List of commercial software implementing EN ISO 12354.