Institution: University of Salford		
Unit of Assessment: 13		
Title of case study: Reducing noise and improving the sound of the built environment		
Period when the underpinning research was undertaken: January 2000 – August 2017		
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:**
Prof. Jamie Angus	Professor of Audio Technology	February 2001 – April 2019
Prof. Trevor Cox	Professor of Acoustic Engineering	September 1995 – Present
Dr Andrew Elliot	Reader in Vibro-Acoustics & Experimental Methods	July 2009 – Present
Prof. Yiu Lam	Professor of Acoustics	July 1998 – October 2018
Prof. Andy Moorhouse	Professor of Engineering Acoustics and Vibration	January 2004 – Present
Dr Olga Umnova	Reader in Theoretical Acoustics	October 2004 – Present
Prof. David Waddington	Professor in Environmental Acoustics	May 2000 – Present
Period when the claimed impact occurred: August 2013 - December 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

Environmental noise and poor acoustics in the built environment are known to create numerous short- and long-term health problems, including cardiovascular disease, sleep disturbance and poorer work performance (World Health Organisation). University of Salford research has addressed poor acoustics through better ISO standards and guidance used in buildings, product design and noise assessment. These methods have been adopted as standard practice by government bodies, test houses and manufacturers, particularly in construction and transportation (automotive and aerospace sectors). Direct commercial exploitation of our research by companies (e.g. Audi, **[text removed for publication]** and Siemens) have impacts including reduced noise, improved music and speech communication in buildings and lower weight of vehicles to lessen energy consumption. For example, **[text removed for publication]** cites Salford's research as being pivotal to them gaining **[text removed for publication]**.

2. Underpinning research

There are five strands of research that have improved the sound in the built environment by tackling problems at the noise source (A & E), during transmission through structures (A & B), during transmission within rooms (C) and understanding how humans respond to sound (D).

A) Structure-borne sound

Characterising vibration sources is difficult because their motion is influenced by the structure they are connected to, and so experimental data is only representative of the specific installation for which it is measured. Moorhouse, Elliott et al developed an in-situ blocked force method that, for the first time, allowed sources to be independently characterised by measurement on a test rig **[3.1]**. Salford's method provides vital input data that allows vibration through buildings and products such as cars to be simulated, the subsequent noise to be estimated and mitigation measures designed. Salford had a KTP with Farrat Isolevel applying the methods to building (KTP0010582) and other key projects include EPSRC grants **[3]**.

B) Building envelope

Metal cladding constructions must meet high specifications for thermal and sound insulation. This requires multiple layers, including corrugated sheets with fasteners at regular intervals. Acoustic modelling for this combination of features is highly challenging. In 2017, an improved method for predicting the noise transmission was developed by Salford and validated on measurements of complex roof structures **[3.2]**. The novel contributions in **[3.2]** are: (i) It combines the well-established transfer matrix method with a new approach for handling regular point fixings; (ii) It provides a method for deriving properties of panels in the form needed for the prediction model. The implementation of the models was funded by the industry trade association (Metal Cladding and Roofing Manufacturers Association) for the value of GBP67,860 **[3]**.

C) Room acoustic diffusers

These are used to make a space fit-for-purpose, for example enhancing the quality of music in theatres and studios or improving speech intelligibility in churches. Cox, Lam et al proposed a new approach to measure and characterise the performance of diffusers **[3.3]**. In addition, Angus and Cox proposed methods that significantly improve performance through the way diffusers are grouped together **[e.g. 3.4, pp. 345-351, 400-403]** and these were protected in two patents **[e.g. 3.5]**. Both the performance characterisation method and the novel way of grouping diffusers led to new designs being installed worldwide during the census period.

D) Low frequency noise

This causes extreme distress to those who are sensitive to it – the estimated prevalence of such sensitivity is about 10% of the population. It causes annoyance, often accompanied by effects such as headaches, concentration difficulties, palpitations and sleep problems. Moorhouse, Waddington et al developed a procedure for the assessment of low frequency noise complaints. The research included: (i) Laboratory tests addressing low frequency hearing threshold and acceptability; (ii) Field measurements that complemented interview-based questionnaires **[3.6]**. Environmental health departments then tested the Salford procedure in trials with genuine low frequency noise complaints.

E) Multiscale porous materials

Materials that have sorption, such as activated carbon, can provide extraordinary acoustic absorption and change compliances of cavities **[3.7]**. Umnova and Cox pioneered investigation into the acoustic behaviour of such materials. The theory of how sound propagates in multi-scale materials was extended to account for physical processes specific to very small pores **[3.7]**. This allowed the sound interaction with such materials to be better understood. This research was supported by an EPSRC grant worth GBP147,000 **[3]**. These properties allow for devices (e.g. air springs in vehicle suspensions) that are smaller and lighter **[3.8]**.

3. References to the research

3.1. Moorhouse A T, **Elliott, A S**, Evans T A, 2009. In situ measurement of the blocked force of structure-borne sound sources, *Journal of Sound and Vibration*, 325:4-5, pp. 679-685. https://doi.org/10.1016/j.jsv.2009.04.035

3.2. Massaglia, J. and **Moorhouse, A.**, 2018, December. An extended transfer matrix model for the sound insulation of dual leaf structures with corrugated panels and structural connections. In

INTER-NOISE and NOISE-CON Congress and Conference Proceedings, 257:1, pp. 660-671. *Institute of Noise Control Engineering*. https://www.ingentaconnect.com/content/ince/incecp/2018/00000257/00000001/art00066

3.3. Hargreaves, Tristan J and **Cox, Trevor J** and **Lam, YW** and D'Antonio, P, 2000, Surface diffusion coefficients for room acoustics: Free-field measures, *The Journal of the Acoustical Society of America*, 108, p. 1710. https://doi.org/10.1121/1.1310192

3.4. Cox, T. and D'Antonio, P., 2004 (1st edition), 2009 (2nd), 2016 (3rd). Acoustic absorbers and diffusers: theory, design and application. CRC Press. pp. 355-358, 400-403, 415-440. ISBN 9781315352220. **(REF2)**

3.5. D'Antonio, P. and **Cox, T.J.**, RPG Diffusor Systems Inc, 2004. Embodiments of aperiodic tiling of a single asymmetric diffusive base shape, US Patent US6772859B2

3.6. Moorhouse, A. T., **Waddington, D. C.** and Adams M. D., 2005. Proposed criteria for the assessment of low frequency noise disturbance, Contract no NANR45, Defra London

3.7. Venegas, R., Boutin, C. and **Umnova, O.**, 2017. Acoustics of multiscale sorptive porous materials, *Physics of Fluids*, 29(8), p. 082006. https://doi.org/10.1063/1.4999053 **(REF2)**

3.8. Coakley, J. and **Elliott, A.S.**, 2010. An air spring, Patent EP3489041

Key grants

Structure-borne sound source model as a pre-processor for statistical energy analysis: SuBSS-SEA Pre-processor. EPSRC (EP/D002109/1) 2006 – 2009 for GBP96,000.
IMP&CTS - in situ measurement method for prediction & characterisation and diagnostic testing of structure-borne sound. EPSRC (EP/G066582/1) 2009 – 2012 for GBP253,000.
Time domain modelling of sound attenuation by porous materials. EPSRC (EP/E016529/1), 2007 – 2010 for GBP147,000.
Embedding measured data within a computational framework for vibro-acoustic design. EPSRC (EP/P005489/1), 2016 – 2019 for GBP496,000.
KTP0010582, Farrat Isolevel Ltd. 2017 – 2020 for GBP209,000.
Research contract: Sound reduction index prediction tool, Metal Cladding and Roofing Association, 2013 – 2017 for GBP68,000.

4. Details of the impact

Impacts in the built environment come from better measurement and design tools to reduce noise and so improve environmental quality in the built environment **(A, B, C)**, better guidance for evaluating noise problems and so addressing health and wellbeing **(D)** and innovative materials to attenuate noise to improve environmental quality and reduce resource use to address sustainability **(E)**.

A) Structure-borne sound

This is of immense importance in vehicles, domestic products and buildings, because what users hear can be important to usability, brand value as well as health and wellbeing. Designers need to replace physical prototypes with computer models to speed prototyping and improve design. Salford's blocked force method **[3.1]** was **adopted in ISO 20270:2019** and is considered to be a *'game changer'* **[5.1]** because it allows sources to be independently characterised for computer models. This **enables prototyping of not-yet-existing products** and also allows the **proper specification of components**, solving contractual difficulties between suppliers and installers of components.

For these reasons, Siemens' Simcenter Testlab data acquisition and analysis software implements Salford's blocked force method. They expect this to help **drive an increase in the Transfer Path Analysis (TPA) measurement market**, **[text removed for publication] [5.2]**.

This then feeds into even bigger product markets that use the TPA measurement method. For example, **[text removed for publication]** confirms that **a major factor in being awarded a contract [text removed for publication]** was their *'unique capability to perform all noise and vibration testing according to the in-situ blocked force method'*, based on Salford's research **[5.3]**. The method is used by many engineering companies whose products create noise that shapes the built environment soundscape, including Alstom, Bentley, Dyson, Volvo, General Motors and Scania.

B) Building envelope

Better prediction models of sound insulation can speed up design work, reduce over-design and save resources. Salford's new prediction model **[3.2]** was funded by the Metal Cladding and Roofing Manufacturers Association (MCRMA). The MCRMA members supply and manufacture approximately half of the GBP675,000 UK metal cladding and roofing market. **Approximately 80%** of the leading metal roll formers, **66%** of the leading rooflight manufacturers and **20%** of the leading independent roofing and cladding consultants nationally have been **trained to use Salford's new prediction models** since 2014. After 2 years, **75% of them renewed the license** to continue using the product **[5.4]**.

C) Room acoustic diffusers

These diffusers are used to improve speech intelligibility and the quality of musical sound. Salford's research **[3.3] led to international measurement standard ISO 17497-2** (2012), which continues to be the **standard method that underpins diffuser design and specification** in this census period **[5.5, 5.6]**. Salford's research has led to diffuser designs that can be found in hundreds of rooms worldwide. Examples of completed high-profile constructions from this census period include The Academy Museum of Motion Pictures, Apple, Google, Facebook, NY University, UCLA, Juilliard, MIT and Harvard **[5.6]**.

D) Low frequency noise

This type of noise can affect health and wellbeing. Salford's guidelines for assessment of low frequency noise have been **adopted as a standard approach for low frequency noise complaints by local authority environmental health officers** within the UK. The guidelines are also the method of choice for the Environment Agency **[5.7]**. Furthermore, they are **widely used in planning enquiries** via BS4142. BS4142 is used in all UK planning enquiries to address noise issues. The procedures in BS4142 exclude low frequency noise, instead deferring to Salford's assessment method **[5.7]**. **The guidelines are also being adopted abroad**, for example for wind farm assessment in Ireland **[5.8]**.

E) Multi-scale sorptive porous materials

Salford's research led to two patents **[e.g. 3.8]** and **formation of the spin-out company** Carbon Air Ltd. in 2012, which has received multiple rounds of venture capital funding totalling GBP2,054,000 (GBP 1,200,000 since 1 August 2013) and now has 8 employees (headcount: 8; FTEs: 6.5) **[5.9]**. The company has filed a further **5 patent families** (2014 – 2015) since formation and **secured several licence contracts**, including with a specialist manufacturer of acoustic materials for buildings. **A 12-year license agreement was also signed** with a German Tier 1 supplier to exploit the materials in transportation, as air springs in car suspensions **[5.9, 5.10]**.

Over 100,000 carbon air springs are now in Audi A6 and A6 Allroad cars. **All major automotive original equipment manufacturers** are trialling the technology. Production of novel air-augmenting inserts for mountain bike forks began in 2019. Research to develop other novel microporous polymer materials for use in small-scale audio applications is ongoing in collaboration with one of the world's largest smartphone manufacturers **[5.9]**.

5. Sources to corroborate the impact

A) Structure-borne sound

5.1. Adverts: Siemens Component TPA (October 2018), referring to Salford's blocked force method as being a 'game changer'
5.2. Testimonial: Siemens Industry Software NV (December 2020), on driving an increase in the Transfer Path Analysis (TPA) measurement market
5.3. Testimonial: **[text removed for publication]** (July 2020), on use of Salford's blocked force method to obtain a major contract

B) Building envelope

5.4. Testimonial: Metal Cladding and Roofing Manufacturers Association Ltd. (MCRMA) (January 2021), on training in the use of Salford's new prediction models

C) Room acoustic diffusers

5.5. Product Datasheets and Example Projects, available at https://www.rpgacoustic.com/ (August 2013 onwards), using [3.3] (within ISO 17497-2) and [3.4] - [3.5], confirming that Salford's standard method underpins diffuser design and specification
5.6. Testimonial: RPG Acoustical Systems LLC (January 2021), on Salford's standard method that underpins diffuser design and specification and examples of completed high-profile constructions

D) Low frequency noise

5.7. Testimonial: Environment Agency (January 2021), on use of Salford's guidelines for assessment of low frequency noise adopted as a standard approach
5.8. Revised Wind Energy Development Guidelines, Government of Ireland (December 2019), with research cited on p. 174

E) Multi-scale sorptive porous materials

5.9. Testimonial: CarbonAir Ltd. (January 2021), on formation of the spin-out, licence agreement with Tier 1 supplier and use of air suspension technology in vehicles and trials with other manufacturers
5.10. Article: Vehicle Dynamics International (7 January 2021), on use of air suspension technology in vehicles