Façade Engineering and Soundscape

Tommaso Crippa, Edoardo Dagnini, Gareth Davies and Harry Rees

Façade Engineering and Acoustics, BuroHappold Engineering,

London, U.K., Tommaso.Crippa@BuroHappold.com, Edoardo.Dagnini@BuroHappold.com, Gareth.Davies@BuroHappold.com, Harry.Rees@BuroHappold.com

Abstract

A key parameter for the psychophysical wellbeing in the built environment is perception of a space and the control of the sound levels in relationship to the human activities being performed. Soundscape ecology is the study of acoustic relationships between all living organisms, human and others, and their environment. Research has shown how human behaviour and mental health is significantly affected by the disruption of an acoustic environment, commonly known as noise pollution.

Nowadays, in architectural design, building envelopes are designed to achieve and guarantee optimal levels of indoor comfort for the future occupiers. Hygrothermal analysis and acoustic simulations are consolidated and belong to a typical design process where engineers are required to specify materials and technological systems. How can the buildings that we design, interact with outdoor spaces? The scope of this paper is to explain how certain design choices can create an urban space that is more acoustically inclusive and desirable. Façade engineering can play a vital role, especially in the early design stages, for architects and clients to modify and shape, by the use of appropriate materials, complex surfaces and volumes.

These principles will be applied to an iconic case study, the Central St. Giles square in London, which includes a central public space surrounded by a busy urban environment, to show the possible impact on the acoustic experience of this space and understand the relationship between façade and acoustic engineering.

1. Introduction

It is predicted that the worldwide urban population is to increase by 13% between 2018 and 2050 [1]. This upsurge in urban living demands that the perception of urban environments, including environmental noise, are not detrimental to the physical and mental well-being of its inhabitants.

Urban areas are lively, complex, and sometimes harsh, places where architects, designers, planners and acousticians play a crucial role in establishing pleasant and sustainable sound environments. Certain urban areas (e.g. Bilbao, Berlin, Sheffield, Brighton, Dublin) have already committed to improving the acoustic comfort of their outdoor spaces in order to engender a culture of belonging and identity to their cities. There are numerous other advantages to creating desirable urban areas, which includes improvement in quality of life, well-being and health for residents as well as beneficial economic impacts [2, 3]. Furthermore, it is recognised that areas of tranquillity are desirable where people can enjoy undisturbed recreational and amenity value [2]. This paper explores certain building skin design choices that can be used to create urban soundscapes that are more inclusive and desirable, in the hope that good acoustic design and forward-thinking policy can add to the improvement in well-being of urban dwellers. As such, a case study has been chosen to determine the effect that varying building skin constructions can have on the local noise climate. Due to its location, i.e. encircled by a busy road network and boundaries formed by surrounding buildings, Central St. Giles Piazza offers the opportunity to understand the effects that the acoustic properties of the adjacent building façades have on the local environment. Furthermore, it is possible that courtyards which are formed by high-rise buildings partially screening the dominant environmental noise sources, such as Central St. Giles Piazza, offers a typical example for urban policy makers, designers etc. to create areas of tranquillity which may be improved by the acoustic properties of the building skins.

1.1 Acoustic well-being: impact of noise polluted outdoor spaces on people's health

Recently released guidelines by the World Health Organization (W.H.O.) state that: *"Environmental noise is an important public health issue, featuring among the top environmental risks to health. It has negative impacts on human health and well-being and is a growing concern among both the general public and policy-makers in Europe."* [4]. The World Health Organisation defines health as a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity, and recognises the enjoyment of the highest attainable standard of health as one of the fundamental rights of every human being. A large body of evidence indicates adverse well-being, physical (auditory and non-auditory) and mental health effects are apparent due to long-term noise exposure [5, 6]. In a European wide survey involving nearly 37000 citizens, almost one-third (32%) reported problems with noise and increasing to 49% in cities or city suburbs [7]. A similar earlier survey in 2010 showed that 80% of respondents (26602) believed that noise affects their health, either to some or to a great extent [8]. Furthermore, in another survey, 15% of 28000 respondents stated that noise pollution is one of the top five environmental issues they are worried about [9]. Often, it is suggested that road traffic noise is the dominant source of annoyance [10, 11, 12]. Road traffic noise is the dominant environmental noise source impacting Central St. Giles Piazza. Studies indicate that over 245000 people every year in the European Union are affected by cardiovascular diseases, of which nearly 50000 suffer a lethal heart attack, that can be traced to traffic noise [13]. It is estimated that at least one million healthy years of life are lost every year within western Europe from traffic-related noise [14]. Furthermore, the same report [14] states that the sum of life lost (premature death) and years lived with disability / health conditions (i.e. disability-adjusted life-years - DALYs) caused by environmental noise can be summarised as follows:

- 61000 years for ischaemic heart disease;
- 45000 years for cognitive impairment in children;
- 903000 years for sleep disturbance;
- 22000 years for tinnitus.

As a result, environmental noise is considered to be the second highest cause of disease within the European region [14]. There is therefore an urgent need to address and understand the implications of noise levels on populations for the improvement of physical and mental well-being. It is hoped that areas of tranquillity within urban areas will allow residents to take advantage of sound scapes that allow respite from environmental noise, particularly road traffic noise, and its adverse health consequences.

1.2 Soundscape

A sound scape is defined as an "acoustic environment as perceived or experienced and / or understood by a person or people, in context" [15]. There is an increasing demand to understand and design soundscapes particularly to inform the design of outdoor urban areas. As such, soundscape research is required to determine the factors that make outdoor spaces acoustically desirable. Governmental initiatives such as "European Directive relating to the assessment and management of environmental noise" (European Directive 2002/49/EC) and Noisefutures network have been established to research the successful creation of desirable soundscapes. Most relevant to this research is the European Directive 2002/49/EC that stresses the need to protect and create quiet areas in cities. Design of soundscapes is still a burgeoning area and clarification of design considerations, applications, frameworks and indices are still being sought. Commonly used guidance does attempt to quantify, with the caveat that this is not always possible in city centres, acceptable noise levels as being 55 dB L_{Aeq} or lower in residential outdoor amenity areas intended for relaxation [16]. However, numerous studies [3, 17, 18] indicate that noise levels are not enough on their own to determine desirable sound scapes and / or quiet areas. For instance, one area of research [17] indicates that variation of noise levels when entering quiet areas is fundamental to perceiving change in the environment, as opposed to absolute noise levels. Other factors also include the diversity of sounds including pleasant sounds that are in context with the location and human activities taking place within the space [3, 19]. Central St.Giles Piazza as a case study is considered to be strongly representative of the scenario described in the above sections, being a communal square semi-enclosed by surrounding buildings, and encircled by busy central London roads. Therefore is it expected that the acoustic atmosphere in the square may benefit from exploring potential acoustic treatments and façade build-ups to reduce noise ingress into the space.

2. Case study - Central St. Giles, London

Squares and plazas are designed to offer the urban community a 'break-out' space to relax and socialize, and optimising this experience requires careful design considerations. The geometrical configuration of a plaza is architecturally crucial, and it is usually something that urban planners, cities consultants and architects design in order to merge together retails, facilities, infrastructures, buildings and people. The buildings surrounding a square plays an important role and needs to be visually and geometrically concordant, therefore facades, building heights and proportions have an impact on the perception of a space. This aspect is subjective and depends on gender, age, culture, etc. but can be influenced by some common factors. One of these is represented by the impact that facades, in terms of shape and materials can have on the sound distribution.
Building skin surfaces have acoustic properties related to their capability to absorb, reflect and scatter sounds that are incident upon them. In early design stages, aesthetic features, mitigation of glare issues etc. are commonly taken in to account from architects and designers in parallel to how to achieve typical thermal, shading, security and structural performances of the building envelopes, though acoustics is often overlooked. Based upon the findings within this study, indications are that the acoustic properties of building skins ought to be considered alongside other design considerations to inform the possible effects on noise levels in outdoor spaces. The case study suitable for the analyses was chosen between a range of possible squares, courtyards and plazas in central London. The key parameters adopted to choose the most appropriate site were:

- Selecting a square in a busy and noisy environment, where people can relax and escape from the 'urban jungle' in search of quiet and to interact with other people;
- An urban space surrounded by high rise building clad by glazing and opaque curtain walls and glazing shopfronts at the ground floor;
- The buildings should create a semi-enclosed outdoor space where reflected sound is a considerable percentage of the overall sound environment, due to acoustic absorption inevitably having no effect on direct sound. The following diagram *Figure 1* shows this principle, where, in the square on the right, the receiver is likely to be subject to a higher ratio of reverberant to direct noise than the receiver in the left diagram, which is essential to understand the true impact of acoustic absorption.

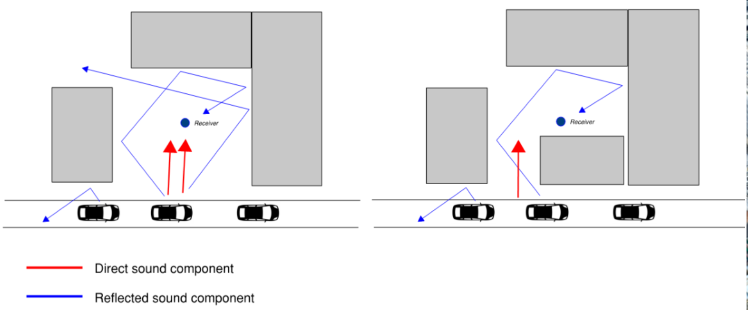


Figure 1: (Left) Diagram of direct and reflected sound components from a traffic road

Figure 2: (Right) St. Giles Central, Google Maps

The case study requirements outlined above are fulfilled by the Central St. Giles Piazza which is situated between Tottenham Court Road underground station, New Oxford Street and High Holborn Street, in central London, and has been chosen as an appropriate case study. The site is nearly equal to 3000 m^2 in plan, where 850 m^2 are represented by the main square which is surrounded by office buildings. The ground floor of the buildings is represented by glazing shopfronts, restaurants with glazing canopies and outdoor dining areas.The mixed use buildings, designed by Renzo Piano (RPBW), are mainly characterised by the iconic coloured glass and tiles facades. The buildings are generally clad with the same repetitive curtain wall system comprising of fully prefabricated units.

2.1 Methodology

The analysis has been carried out through computer aided acoustic prediction software CATT-Acoustic v9.1a. An acoustic prediction is a process where, using geometrical acoustics, octave-band echograms are predicted based on a 3D CAD model. Frequency dependent material properties (absorption, scattering and transmission coefficients) are assigned to model's surfaces and frequency dependent source directivities are assigned to sound sources. From this information, echograms and a great number of numerical measures of e.g. sound pressure level, speech intelligibility, and reverberation times can be estimated. [20] Due to the high amount of iterations to be analysed, it has been necessary to develop a computational modelling approach to export and convert three-dimensional architectural models into structured text data files that can then be imported directly in CATT-A Acoustic software. A total of 20 different simulations were carried out, corresponding to 7 alternative scenarios with variable amounts and locations of absorptive material on the facades, measured for both source A2 and A3; and 6 scenarios with various different geometries and façade material properties for the entrance in front of source A3 only. This computational tool has been used, at the same time, to parametrically control the buildings' geometries and the acoustic properties of the façade materials. In particular, the script subdivides and converts the CAD model's surfaces and planes into geometrical acoustic models, adopting the syntax required by CATT-Acoustic, applying automatically to each of these planes their relative acoustic features (i.e. absorption and scattering coefficients). Moreover, it retrieves from the 3D model both receiver and source locations as spatial coordinates, and specifies the octave band sound pressure levels for the latter. The process workflow has been demonstrated to be an extremely efficient calculation procedure allowing evaluation of numerous different case studies in a short period of time.

2.2 Assumptions

The St.Giles square has been modelled with sound sources and materials that are considered to be representative of a typical real-world scenario, input into 3D acoustic modelling software which simulates the distribution of sound throughout the square as a result of both direct sound and the reverberant field. In software predictions there is an inherent degree of uncertainty, typically taken to be +/- 3 dB for computer modelling software. However, uncertainty has been minimised where practicable by maintaining consistent parameters throughout each case study.

2.2.1 Materials

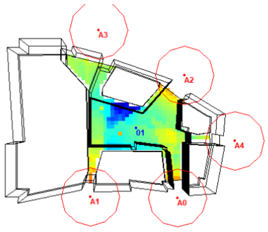
Each material in the space has been modelled with a realistic absorption coefficient, shown in *Table 1* below, where absorption coefficients from 0-100 can roughly be approximated to the percentage of sound that is absorbed on impact – where 100% would indicate that little to no sound is reflected back off the surface.

Absorption coefficients %						
Material	**Frequency [Hz]**					
	125	250	500	1000	2000	4000
Rough Concrete	2	3	3	3	4	7
Smooth unpainted concrete	1	1	2	2	2	5
Double glazed unit	15	5	3	3	2	2
'Class A' acoustic material	60	70	90	90	90	80

Table 1: Material's absorption coefficients [21]

2.2.2 Noise Sources

The first output parameter is a map of sound pressure level throughout the entirety of the square. This has been used to clearly communicate the differences between each scenario in a visual format. By mapping the sound pressure distribution on the square with the coloured map, areas of significant interest have been identified for further analysis with specific receivers, as covered in the following section.



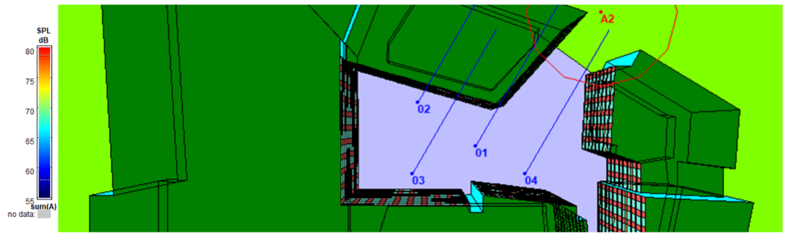


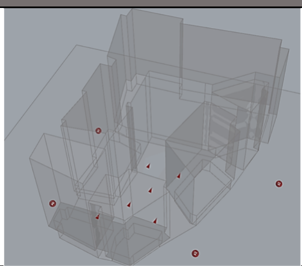
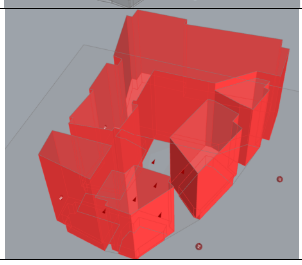
Figure 3:(Left) Typical Sound Pressure Level Map (CATT output)
Figure 4:(Right) Typical setting out for SxR analysis

Following this mapping exercise *Figure 3*, source A2 and A3 were selected to be the 2 noise sources used for the remainder of the analysis, as these sources highlight the significant difference between a predominantly direct sound field (A2) and a predominately reverberant sound field (A3), and the impact this has on the effectiveness of acoustic absorption. Source A3 is also located at the end of a narrow tunnel, whereas source A2 is located at the end of a much wider opening, producing a strong basis for comparison.
The noise sources have been modelled to be representative of typical traffic noise levels, with reference to BS 8233:2014 “Guidance on sound insulation and noise reduction for buildings”. A representative broadband (typically 63 Hz – 8kHz) L_{Aeq} has been identified to be $L_{Aeq,16h}$ 88 dB; a representative value calculated at 1 metre, using the BS 8233 value of $L_{Aeq,16h}$ 68 dB measured at 20 metres for a busy main road through a residential area.

2.2.3 Predict Source – Receiver

To refine the results and quantify differences more accurately, the following analyses concentrate the attention on 4 specific receivers located in the square, relative to source A2 and A3 on the road. The receivers are located in positions with varying levels of exposure to the direct sound, considering that the absorption will only affect the reverberant sound field and thus, in areas where direct sound is dominant, absorption will have little to no effect. From this result, sound pressure level at 4 specific points (*Figure 4*), in the square is measured across the full frequency range, and also given as an A-weighted broadband value. These 4 broadband sound pressure levels will be used to compare the various cases, clearly indicating the impact of each strategy in terms of acoustic amenity in the square.

2.3 Results

CATT analyses – Baseline options			
Case		**Description**	**Main Result**
0		Fully reflective façade Typical real-world scenario. Mixture of glass and concrete throughout.	**Source A2** High sound level experienced in the square due to a strong direct and reverberant sound field. **Source A3** High sound level experienced in the square due to a large build-up in the reverberant sound field.
1		Fully absorptive façade. While unrealistic, Case 1 presents the ultimate limit in SPL reduction achievable by applying acoustic absorption in the square, setting out a benchmark for future scenarios.	**Source A2** 10-15 dB reduction at receiver 02/03 due to screening. Minimal losses at receiver 01/04 as direct sound is dominant. **Source A3** 15-20 dB reduction at all receivers, as absorption reduces the reverberant sound field.
1.1		Absorptive façade from 7 metres and above.	**Source A2** Minimal reductions experienced at all receivers.

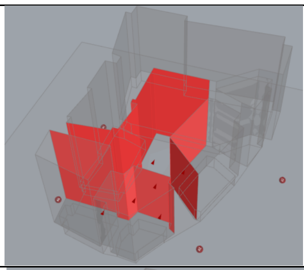
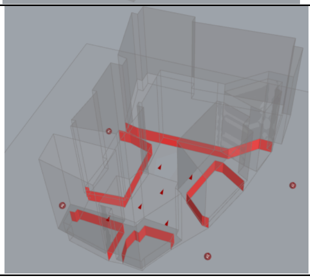
		Absorption at this height was found to be negligible for a ground based noise source – traffic in this case. Findings may be different for, as an example, aircraft noise.	**Source A3** Minimal reductions again, absorption has a low impact at this height.
2		Fully absorptive ground floor, reflective façade elsewhere. Due to findings in 1.1, absorption from Case 2 onwards is limited to ground floor level (7 metres).	**Source A2** 2-8 dB reductions, direct sound is dominant at exposed receivers, but reverberant field is greatly reduced. **Source A3** 4-8 dB reductions as noise ingress into the square is reduced by reduction in the reverberant sound field.

Table 2: CATT analyses – Baseline options

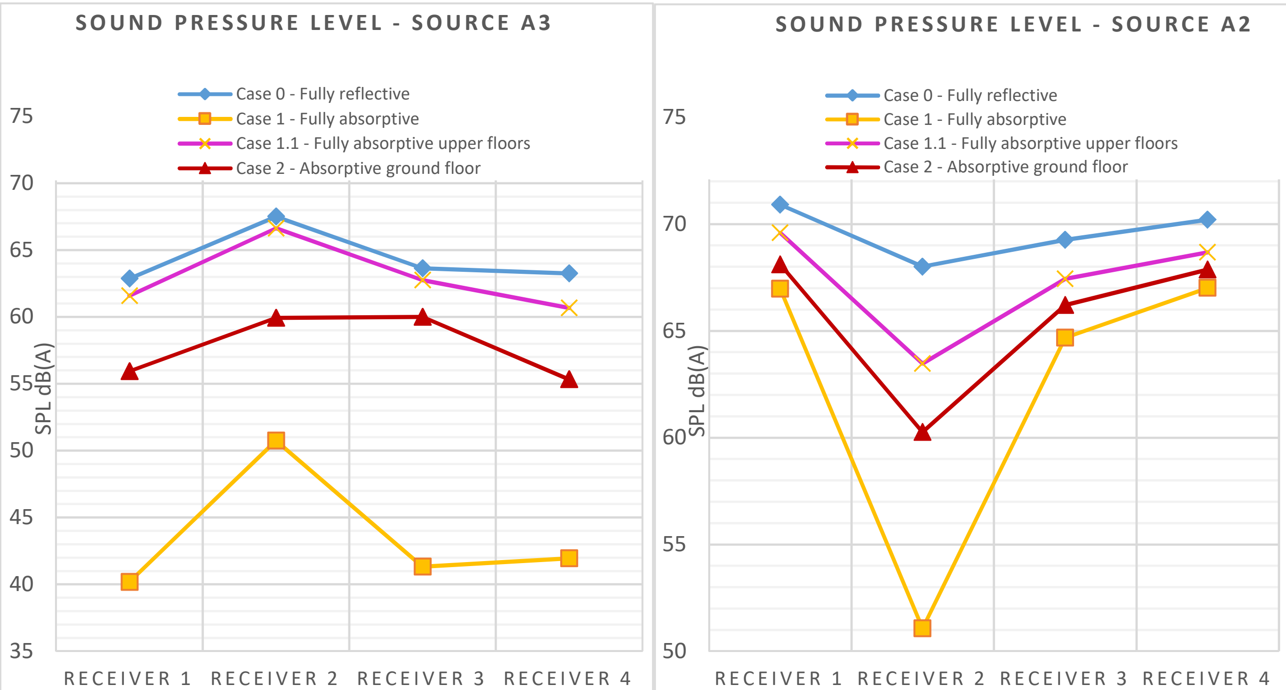
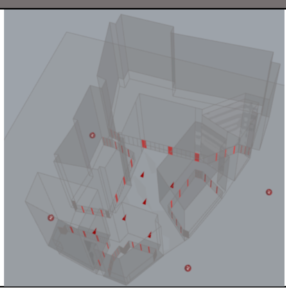


Figure 5: SPL results – Baseline options

CATT analyses – Ground floor absorption variations			
Case		**Description**	**Main Result**
2.1		15% of the ground floor absorptive, randomly distributed.	**Source A2** 0-2 dB reduction due to dominant direct sound field. **Source A3** 3-4 dB reduction in sound level presents a noticeable difference in the square's atmosphere.
2.2		Randomly distributed absorption on the ground floor doubled to 30%.	**Source A2** 0-2 dB reduction in sound level, due to the direct sound remaining dominant.

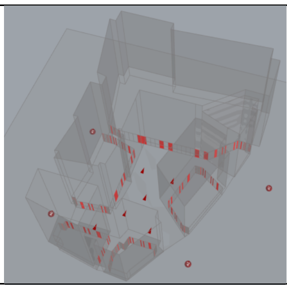
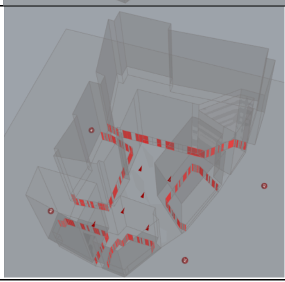
			**Source A3** 6-7 dB fall in sound level, significantly reducing the impact of noise ingress into the square from traffic noise.
2.3		Absorption doubled to 60% coverage on the ground floor.	**Source A2** 1-3 dB reduction in sound level – absorption is making a minor impact, but the direct sound is still dominant. **Source A3** 9-11 dB reduction in sound pressure level, where a loss of 10 dB is said to be perceived as the sound being *half as loud*.

Table 3: CATT analyses – Ground floor absorption variations

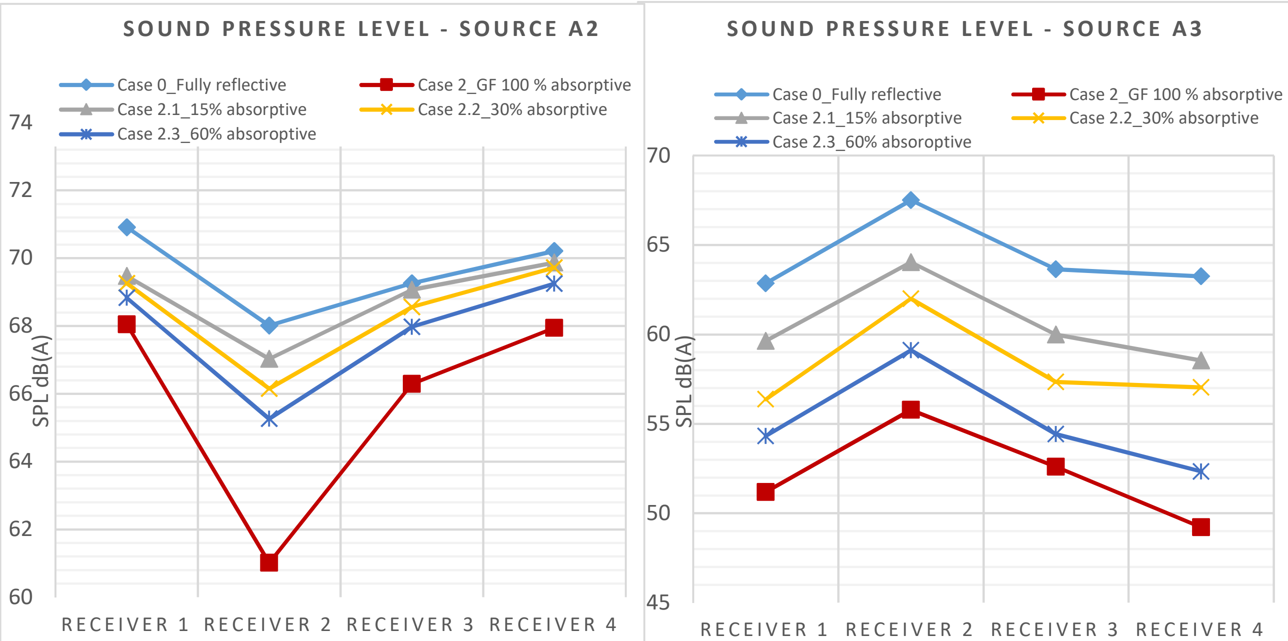
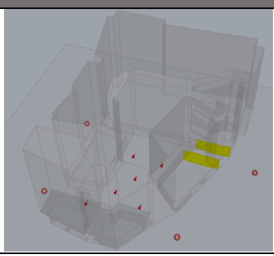


Figure 6: SPL results – Ground floor absorption variation

CATT analyses – Tunnel options			
Case		**Description**	**Main Result**
5		Narrow tunnel option, reflective surfaces. Experiments were undertaken to determine whether narrowing the tunnel entrance would reduce the amount of sound breaking into the square.	**Source A3** 0-7 dB reduction in sound level. 0 was experience at a receiver in direct line of sight, thus the tunnel dimensions had no impact. For other receivers, the reduced area for sound to travel through has a positive impact.

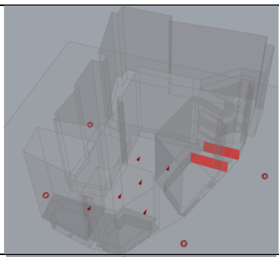
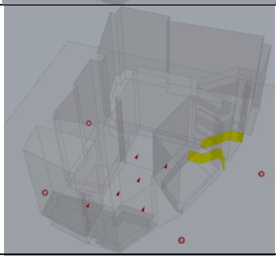
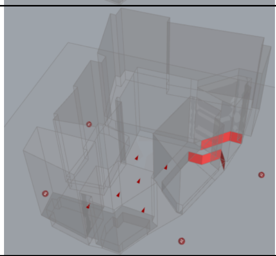
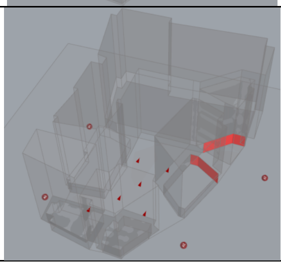
5.1		Narrow tunnel option, fully absorptive surfaces.	**Source A3** 4-9 dB reduction in sound levels, as the total amount of sound breaking through the tunnel is reduced, and the addition of absorption minimises reverberant build-up.
6		Kinked tunnel option, reflective surfaces. By complicating the path the sound has to travel through, inherent losses in sound level can occur. The kink attempts to reduce line of sight and complicate the sound path.	**Source A3** 2-5 dB reduction in sound level. With a wider entrance, more sound is escaping into the square than the narrow option. However, reductions are consistent across all receivers as line of sight is completely nullified.
6.1		Kinked tunnel option, fully absorptive surfaces.	**Source A3** 11-12 dB reduction in sound level. With the lack of direct sound paths, the reverberant reflected sound becomes the dominant transmission path, and thus the addition of absorption has a very strong impact. Perceived sound level is more than halved in the square.
7		Original tunnel layout, fully absorptive. For comparison between the above cases, the tunnel layout from the original model was modelled with Class A absorption.	**Source A3** 6-9 dB reduction in sound level. Absorption has a strong impact on the reverberant field, but the addition of direct sound paths lessens the impact compared to Case 6.1.

Table 4: CATT analyses – Tunnel options

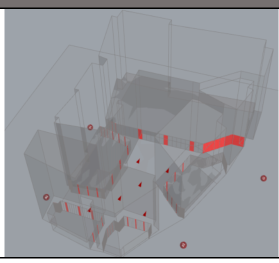
CATT analyses – Ideal proposal			
Case		**Description**	**Main Result**
8		Ideal, realistic scenario. 15% cover randomly distributed absorption on the ground floor. Kinked tunnel, with absorption applied to the right side wall – due to this wall being the primary source of reflections.	**Source A3** 8-11 dB reduction. Reverberant sound field build-up is greatly reduced by the wall of absorption, while the kink helps to reduce direct sound. Performing comparably to a fully absorptive kinked tunnel, and better than a fully absorptive ground floor with the standard tunnel shape.

Table 5: CATT analyses –Ideal proposal

As can be seen from the results table above, in the case that the sound is travelling in from a tunnel. Case 8.1 produces results better than a fully absorptive tunnel and nearly on par with a fully absorptive kinked tunnel, and reduces the sound level by over 10 dB – thus resulting in a perceived halving of sound pressure level in the square. Case 8.1 also performs better than all narrow tunel options. However, Case 8.1 with only 15% of the ground floor covered in Class A absorption, and one wall in the kinked tunnel, this scenario is considerably more realistic and achievable than the other options

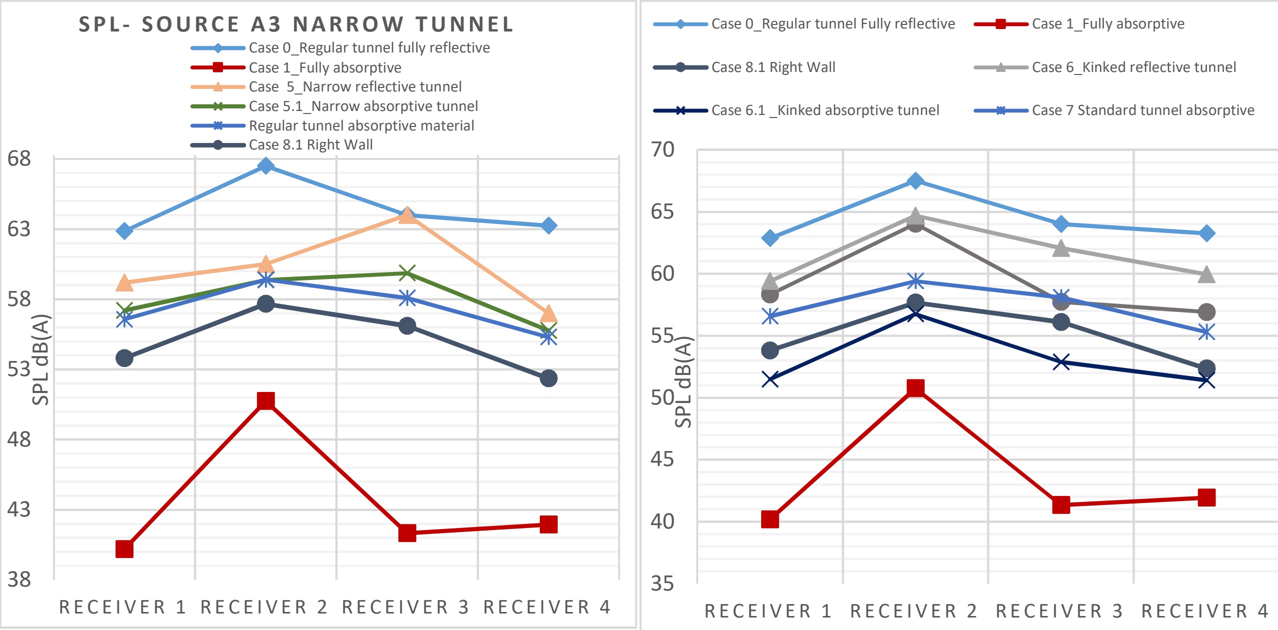


Figure 7: SPL results – Tunnel Options

3. Conclusions

The analyses covered in the previous sections have provided clear, indicative results that translate into practical guidelines that can be adopted by designers. In the following sections, the best performing cases will be considered against typical architectural constraints and material limitations. This section will also consider the inherent limitations in this experiment's methodology, and suggest further development opportunities for future research.

3.1 Interpretation of the results

As shown in the above sections, the acoustic environment in Central St. Giles has been improved by reducing the sound pressure level of traffic noise breaking into the square, achieved by a combination of: adopting a percentage of absorptive material in various quantities on the ground floor surfaces facing the square; and changing the shape of the entrance tunnels in front of the noise source in order to reduce the number of direct sound rays that enter the square and come into contact with an acoustic receiver. These two macro areas have therefore been further investigated, with the purpose of extracting more realistic and feasible design guidelines for possible architectural modifications of the environment, generating the ideal case of:

- Applying absorptive material to just 15 % of the ground floor surfaces facing the piazza;
- Having a kinked tunnel with absorptive material on just one of the vertical side walls.

With this scenario, a reduction of SPL between 3-4 dB has been achieved for source A2 where direct sound dominates, while a reduction of SPL between 10-11 dB; considered to be perceived as a halving of the noise level; has been achieved by remodelling the larger straight tunnel to a kinked alternative and reducing the reverberant noise build-up through applying minimal, yet strategically placed absorption.

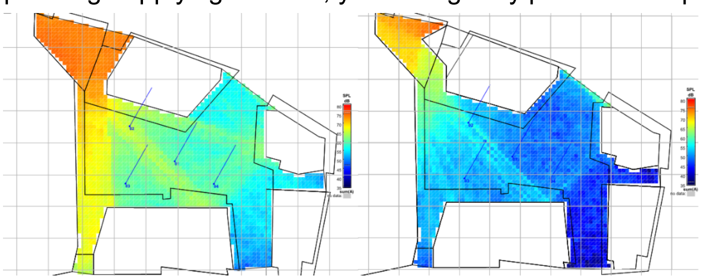


Figure 9: SPL map comparison – Source A3 – Case 0 (left) Case 8.1 (Right)

3.2 Practice guidelines

In a real project, particularly during early design stages, designers can follow simple design steps to consider acoustic wellbeing in an urban built environment such as a square or an enclosed public space. The following flowchart *Figure 10* explains the possible workflow path to determine a feasible, project specific strategy for considering and improving acoustic amenity. The first step is understand the relationship between noise source and receivers and understand if direct sound can be obstructed by building layout. If considerable proportions of the total sound level is from sound waves being reflected into the area (i.e. direct sound is well screened), implementation of acoustic absorption is a viable option. It has been demonstrated that the greatest effect is when absorption is introduced at the lower levels of the buildings, and further direct sound screening can be achieved by shaping the entrance tunnels that connect the plaza to the external environment, that could consist of disturbing noise sources such as a busy street, as per the St. Giles Central.

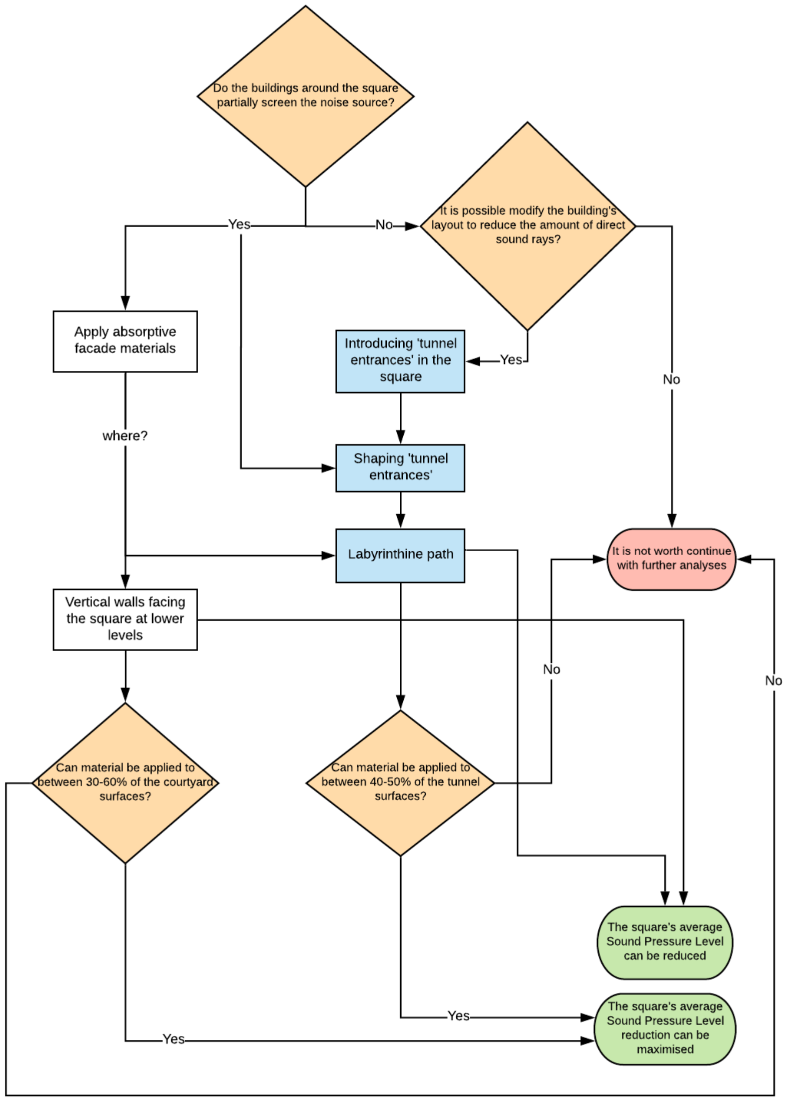


Figure 10: Practice guidelines flowchart

During the acoustic analyses, a high performance 'Class A' absorptive material has been chosen, but in reality, particularly for external applications, what system or material can be used to achieve more or less the same acoustic properties? This ultimately depends on various factors, such as the design intent, exposure to the elements, etc. Architecturally there are many different options to explore, sometimes is however difficult to find a proprietary façade system with acoustic absorptive properties, as acoustic absorption is mainly commercialised for interior surfaces. Usually screens and barriers are used to screen direct sound, rather than employing materials for the purposes of absorption or scattering. Hybrid systems such as green walls and roofs are therefore considered to be the most realistic solutions, as these provide some levels of acoustic performance if placed correctly, while already being attractive from a design point of view thanks to their natural properties of thermal insulation, air filtration and water capture, as well as enhancing the aesthetics of the space. It is also possible to adopt, within traditional curtain walling systems, opaque panels made either of weather louvres or perforated metal sheet, shielding acoustic mineral wool absorption from the elements. It is important note that semi-permeable panels of this natural are inherently less effective than the Class A acoustic panels modelled in this paper, and thus a balance must be met between the quantities of these panels with the required acoustic performance.

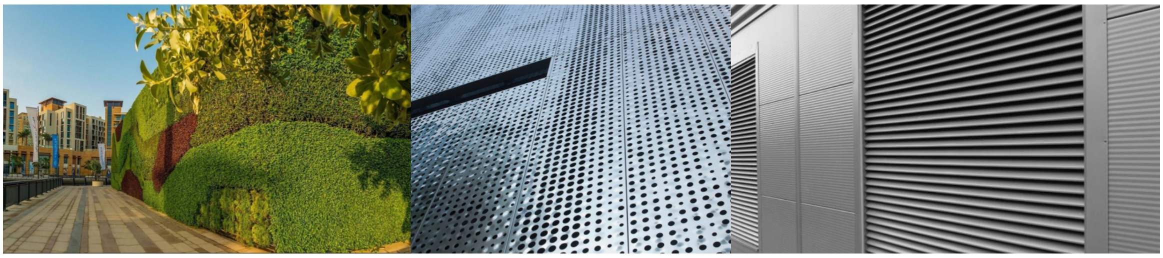


Figure 110: Examples of Absorptive wall systems

3.3 Limitations

The analysis undertaken in the paper uses CATT-A to model an outdoor open space through mathematical ray tracing; CATT-A being a software that is primarily used for indoor acoustics. The extend of the limitations of this methodology are unknown, though it is recognised that in software predictions there is always an inherent degree of uncertainty, typically taken to be +/- 3 dB for computer modelling software. However, uncertainty has been minimised where practicable by maintaining consistent parameters throughout each case study and using real-world data for sources and materials. Additionally, the acoustic performance of each case has not and should not be considered in terms of absolute sound pressure level, and are instead representative in terms of the delta of variation between cases.

3.4 Further development

It is acknowledged that an important next step in this analysis would be to validate the integrity of the results by conducting a series of acoustic tests on site. Due to the massive scale of such a test, it would likely be impractical to test genuine absorptive façade materials on site. Consequently, to reduce cost and resources, it is suggested that thick acoustically significant fabric could be hung at ground level to simulate the impact of absorptive material; comparing measurements before and after the material is installed.

4. References

[1] United Nations, World urbanization prospects: The 2018 revision., New York: United Nations, 2018.

[2] Communities and Local Government, National Planning Policy Framework, London: Department for Communities and Local Government, 2012.

[3] J. L. Bento Coelho, K. Chourmouziadou, O. Axelsson and M. Boubezari, "Soundscape of European Cities and Landscapes - Creating and Designing," COST Action TD0804, Oxford, 2013.

[4] World Health Organization, "Environmental Noise Guidelines for the European Region," WHO Regional Office for Europe, Copenhagen, 2018.

[5] M. Basner, W. Babisch, A. Davis, M. Brink, C. Clark, S. Janssen and S. Stansfeld, "Auditory and non-auditory effects of noise on health," *The Lancet,* vol. 383, no. 9925, pp. 1325-1332, 2014.

[6] C. Eriksson, A. Hilding, A. Pyko, G. Bluhm, G. Pershagen and C.-G. Ostenson, "Long-term aircraft noise exposure and body mass index, waist circumference, and Type 2 Diabetes: A prospective study," *Environmental Health Perspectives,* vol. 122, pp. 687-694, 2014.

[7] Eurofound, "European Quality of Life Survey 2016," Publications Office of the European Union, Luxembourg, 2016.

[8] European Foundation for the Improvement of Living and Working Conditions, "Subjective well-being in Europe," Office for Official Publications of the European Communities, Luxembourg, 2010.

[9] European Commission, "[1] Attitudes of European citizens towards the environment," Office for Official Publications of the European Communities, Luxembourg, 2014.

[10] J. Lambert and C. Philipps-Bertin, "Perception and attitudes to transportation noise in France: A national survey," Bron, 2008.

[11] L. Sobotova, J. Jurkovicova, Z. Stefanikova, L. Sevcikova and L. Aghova, "Community noise annoyance assessment in an urban agglomeration," *Bratisl Lek Listy,* vol. 107, no. 5, pp. 214-216, 2006.

[12] Department for Environment Food and Rural Affairs, "National Noise Attitude Survey 2012 (NNAS2012)," Department for Environment Food and Rural Affairs, London, 2014.

[13] L. den Boer and A. Schroten, "Traffic noise reduction in Europe - Health effects, social costs and technical and policy options to reduce road and rail traffic noise," CE Delft, Brussels, 2007.

[14] World Health Organization, "Burden of disease from environmental noise - Quantification of healthy life years lost in Europe," WHO Regional Office for Europe, Denmark, 2011.

[15] International Organization for Standardization, "ISO 12913-1:2014 Acoustics — Soundscape — Part 1: Definition and conceptual framework," International Organization for Standardization, Brussels, 2014.

[16] British Standards Institution, "BS 8233:2014 Guidance on sound insulation and noise reduction for buildings," BSI Standards Limited 2014, U.K., 2014.

[17] P. Delaitre, C. Lavandier and D. Masson, "Characterization of quiet areas with a new indicator of contrast ," in *AIA-DAGA Euroregio Conference*, Merano, 2013.

[18] I. Aspuru, M. Fernandez, I. Garcia and K. Herranz, "Soundscape within the strategy of Bilbao city to improve Quality of Public Spaces," in *AIA-DAGA Euroregio Conference*, Merano, 2013.

[19] R. Cain, P. Jennings and J. Poxon, "The development and application of the emotional dimensions of a soundscape," *Applied Acoustics,* vol. 74, no. 2, pp. 232-239, 2013.

[20] "CATT-Acoustic™ v9.1," CATT, [Online]. Available: https://www.catt.se/.

[21] 2019. [Online]. Available: http://www.acoustic.ua/st/web_absorption_data_eng.pdf.