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A critical review of acoustic modeling and research on building façade

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Abstract

Noise pollution has been impacting negatively on living comfort and working environment for a long time. Acoustic treatment on building façade is one of the effective means to tackle this issue. Numerous articles were published over the past decades to address the acoustic related problems of building façade. However, a systematic review of the research development on façade acoustic technology is lacking. Therefore, this paper examines the published research articles from seven selected journals, in terms of the annual number of articles, citation counts, co-authorships, research locations, and keywords. The analyses show that interest in façade acoustics increased during the last two decades. Researchers from Europe and areas with a high density of tall buildings made significant contributions to this development. Based on keyword analysis, articles are categorized into three groups. These include sound insulation studies, studies on the effect of façade on street noise, and noise reduction techniques. The surveyed research topics comprise numerical modeling, experimental studies, ISO standard development, and analyses on annoyance level. Potential future directions are presented based on a summary of the limitations of the existing research. This paper offers researchers and engineers an in-depth understanding of the state-of-the-art of the current façade acoustic research. Additionally, potential future directions are identified based on the findings and limitations of the previous studies.

Keywords

Research review, building façade, façade acoustics, research trend, sound insulation, noise reduction

Introduction

A façade is the exterior side, especially the face, of a building. The building façade system generally includes two parts: the structural elements to resist movements and the envelope elements to separate the inside and the outside environments. The functions of a façade are multifaceted. It

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minimizes the influence of rain and wind, helps in controlling light levels from the outside, and controls air permeability, thermal and acoustic insulations, etc. Because building facades are expected to sustain wind actions and transfer them to the main building structure, connections are mounted on each floor so that the building frame supports the weight of the building façade of the floor above it. The façade may either be bottom-fixed or suspended from the floor above. For office use buildings, large areas of glazing from floor to ceiling are required to provide a sufficient level of natural light. A greater expanse of glazing can enhance the penetration of direct sunlight into a building, which leads to solar gain and glare. A good design of the building façade should guarantee that all these functions are at an acceptable level.[1]

Recent advances in building façade focused more on the incentive of sustainable development.[2–6] A typical example is the Double Skin Façade (DSF) system, which was innovated and widely deployed in European countries. Considerable thermal performance was achieved in both cold and warm seasons when the ventilation strategies of the DSF system were optimized. However, the realization of acoustic insulation becomes more difficult when a complex ventilation system was deployed. This could lead to an increased sound transmission through the internal structures among different floors. A similar challenge could be encountered when a larger glazing is used for the solar gain purpose.

The environmental noise problem is becoming increasingly serious. Environmental indicator report by the European Environment Agency[7] indicated that efforts to control environmental noise appeared to be offset by an increase in the number of people exposed to a high noise level. Therefore, researchers paid significant attention to the effect of a building façade due to its key role in the transmission and reflection of environmental noise.

Relevant studies began in the 1970s. Examples include prediction of the level of sound pressure transmitted through a balcony façade into a room[8] and investigation of sound propagation in a street of façade boundaries.[9] Since then, numerous works were also published to investigate the sound insulation performance and surface reflection characteristics of the building facade. The research objectives ranged from acoustic modeling to the improvement of noise reduction ability, and many other relevant topics. According to the analyses of the existing literature, academic interest in this area is growing fast. A systematic classification and review of the previous publications will considerably benefit future researches in this area.

It is widely accepted by the research community that a good literature review plays an active part in examining the extent of research on a specific subject. A study showed that a systematical review can not only assist researchers in developing insights into a topic but also inspire them on new directions to avoid duplicating past efforts.[10]

Despite the significance of a research review, no such work has been directed at façade acoustics. Therefore, this paper conducts a systematic analysis and review of the articles published in the façade acoustic area. The objectives of this paper are (1) to adopt a bibliometric study to identify the latest and popular research topics in façade acoustics; (2) to present an overview of each research topic pertinent to façade acoustics; (3) to reveal the current limitations in façade acoustics with the aim of providing suggestions for future research.

Research methodology

The review methods used in some previous researches,[11–13] which belonged to either construction engineering or acoustics, offered valuable guidance for the work in this paper. In this paper, the Scopus search engine is used to identify the relevant articles. The keywords used in this search engine are *façade* and *acoustic*. Articles containing these terms in the title, abstract, or keywords

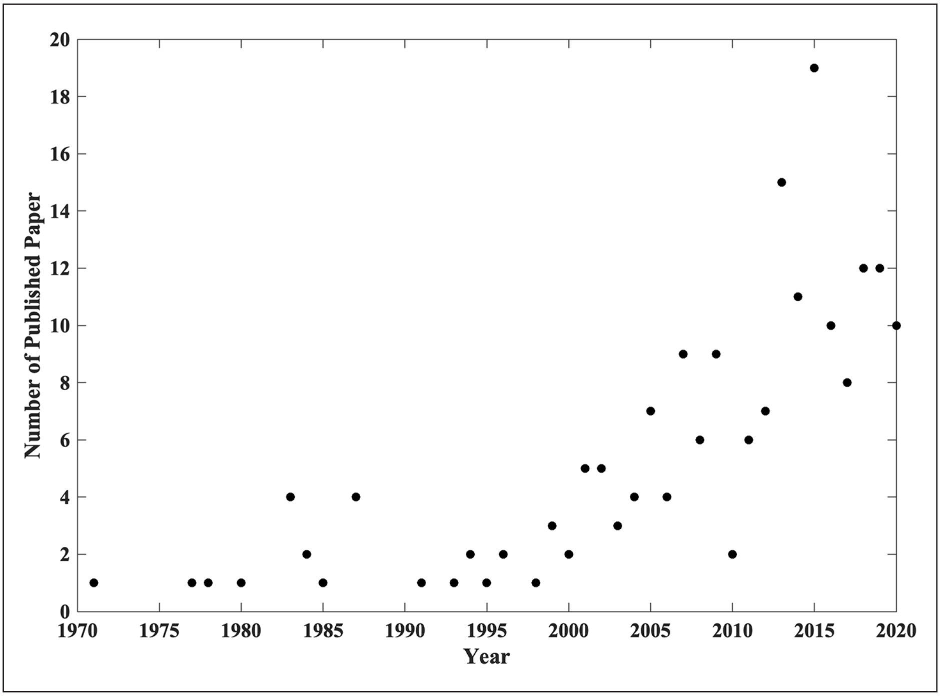

Figure 1. Number of published papers per year in the selected journals.

are selected for this review. The search is further narrowed to cover only English publications including those published in journals and conference proceedings.

It was found that seven journals, namely, Applied Acoustics (APAC), Journal of the Acoustical Society of America (JASA), Building and Environment (BaE), Building Acoustics (BUA), Journal of Sound and Vibration (JSV), Noise Control Engineering Journal (NCEJ), and Acta Acustica United with Acustica (AAuA) published at least 10 façade acoustic related articles. Therefore, a total of seven academic journals were used in the review analysis of façade acoustics. Following the selection criteria above, 199 articles published in the seven selected journals between 1990 and 2020 were retrieved for the review.

Data analyses and discussions

Qualitative analyses

Figure 1 shows the number of papers published per year on façade acoustics. Interest in the discipline of façade acoustics becomes pronounced from the 1990s and it has continued to increase significantly. Nineteen articles were published in 2015. The data of year 2020 is cut-off in August. This trend indicates the increasing amount of attention that the façade acoustics receive from researchers. To better analyze the variation trend in the two decades, the number of papers published per year in each journal is shown in Table 1. A significant increase can be observed in the last few years for acoustic engineering applications (APAC and BaE) and building applications (BaE).

Table 1. Number of papers published per year in the selected journal (2010–2020).

Year	APAC	JASA	BaE	JSV	AAuA	BUA	NCEJ
2010	1	0	0	1	0	0	0
2011	1	1	0	0	1	0	3
2012	2	1	2	0	0	2	0
2013	5	5	1	0	1	0	2
2014	6	0	1	0	1	0	3
2015	5	2	5	0	1	4	2
2016	4	0	2	0	0	4	0
2017	3	2	1	0	0	2	0
2018	7	1	1	1	0	2	0
2019	3	2	5	0	1	1	0
2020	6	1	2	0	0	2	0
In total	43	15	20	2	5	17	10

Table 2. Top 10 frequently cited papers.

Article title	Citation times
Reducing the acoustical façade load from road traffic with green roofs	128
Parameter study of sound propagation between city canyons with a coupled FDTD-PE model	96
The potential of building envelope greening to achieve quietness	91
Numerical modeling of the sound fields in urban streets with diffusely reflecting boundaries	89
Noise control strategies for naturally ventilated buildings	89
Numerical modeling of the sound field near a tall building with balconies near a road	80
Numerical modeling of the sound fields in urban squares	69
Multipurpose characterization of glazing systems with silica aerogel: in-field experimental analysis of thermal-energy, lighting and acoustic performance	65
Road traffic noise—The relationship between noise exposure and noise annoyance in Norway	65
Noise screening effects of balconies on a building facade	63

Table 2 lists the highly cited top 10 papers for reference. Notice that the effect of publication year on the citation number is not considered. The list shows that the most cited papers fall into the noise abatement category. This category explores the potentials of green roofs in reducing sound transmission over the façade surface. In Table 2, four articles focus on noise control techniques and five on acoustic modeling. These two topics are intensely investigated by scholars of façade acoustics.

Table 3 lists the number of citations of the selected journals in terms of façade acoustics. It is found that AA is the most-cited journal. However, in terms of the number of times an article is cited, JASA, BE, and JSV score more than AA. Particular attention should be paid to JSV, which has the most cited times per article out of the seven selected journals. However, the number of articles on façade acoustics in JSV is the second lowest among the selected journals. The good performance of JSV can be attributed to the scopes of JSV, which emphasizes fundamental works with the potential for practical applications. Basically, within the area of façade acoustic, fundamental research has a larger chance to be cited by other related works.

Table 3. Number of citations of the selected journals (façade paper only).

Journal	Total citations	Cites per article
Applied Acoustics	1322	16.53
Journal of the Acoustical Society of America	706	24.34
Building and Environment	668	23.86
Journal of Sound and Vibration	386	27.57
Acta Acustica united with Acustica	165	13.75
Building Acoustics	112	4.83
Noise Control Engineering Journal	47	3.92

Science mapping analyses

The above filtered 199 articles are analyzed with *VOSviewer*, which is a software tool for constructing and visualizing bibliometric networks. The research co-authorship, research country locations, and co-occurrence of keywords are studied.

Awareness of the existing scientific collaboration networks in any field of research facilitates access to funds, specialties, and expertise. It also enhances productivity and assists investigators to reduce isolation.[14] Here, the minimum number of publications and the minimum number of citations are set to 2 and 10, respectively to extract information on authorship. As a result, 71 out of a total of 376 authors are identified from the co-authorship analysis. The first two clusters among these collaborations in façade acoustics are shown in Figure 2(a). The second group mainly focuses on the performance and characterization of vegetation as a noise control device and the effect of traffic noise in a street canyon with building façade.

Countries are also analyzed for their contributions to façade acoustics. Figure 2(b) shows the mapping of façade acoustics studies in terms of the country locations of the scholars. The minimum number of publications and citations are set to 5 and 20 respectively in *VOSviewer*, resulting in 18 out of a total of 42 countries being selected. It can be seen in Figure 2(b) that most countries active in façade acoustics are in Europe. Particularly, the five countries in the core of co-authorship, France, Italy, the United Kingdom, Netherland, and Belgium, are all European countries. Additionally, they are more likely to cite each other's work as shown by the line thickness. Another characteristic of the façade acoustic study location is the high density of tall buildings in places like Hong Kong, which is constantly suffering from street traffic noise.

Keywords play an important role in a research article because they represent the essential contents of an article and summarize the topics studied within a given discipline.[15] The co-occurrence of keywords is analyzed. Among the 199 selected articles, "Author Keywords" and "Fractional Counting" were set in *VOSviewer*, as suggested by Hosseini et al.[14] The software initially outputted 24 out of 323 keywords. Next, the inclusion and exclusion of keywords were manually conducted based on the following rules: (1) minimum number of occurrences of a keyword was set to 3; (2) general keywords, such as "façade," "acoustic," and "building" were removed; and (3) keywords with essentially consistent meaning were combined, for example, "sound insulation" and "acoustic insulation". Finally, the co-occurrence of the remaining 15 keywords are shown in Figure 2(c).

It is found that "environmental noise" is the most mentioned keyword. This is because it is the most prevalent source of noise in façade acoustic studies. There are several other major keywords, that is, topics, which are closely linked to "environmental noise". Sound insulation refers to the acoustic transmissibility of the façade. It is worth noting that there is a keyword that is strongly connected to sound insulation, the "ISO 140-5". Although ISO 140-5 has been updated to ISO 16283-3 since 2014, existing researches towards ISO 140-5 can still provide a valuable guidance for the new comers in this area. This keyword represents the field measurements of airborne sound insulation of façades. This series of ISO standards play a significant role in evaluating and examining the acoustic performance of a designed façade.

"Noise reduction" is another major topic in façade acoustics. It indicates that façades are not only being used for increasing insulation to control the indoor noise, but also for reducing the noise level in the street. Particular attention should be paid to keywords, like "noise mapping," "reflection," and "sound propagation," with which most works study the effect of façade on street canyon noise. These keywords are not well reflected in Figure 2(c) because they do not tend to be listed as a keywords by the authors. Another misunderstood or underestimated keyword is "numerical

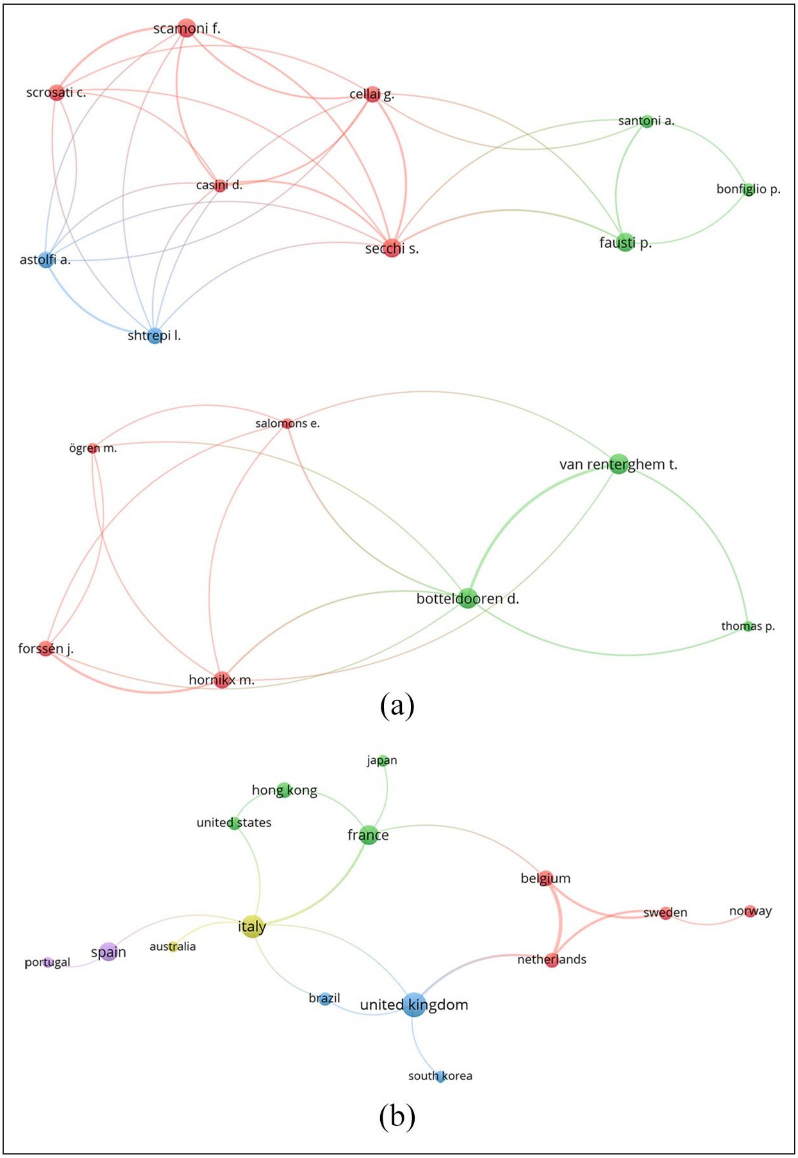

Figure 2. *(Continued)*

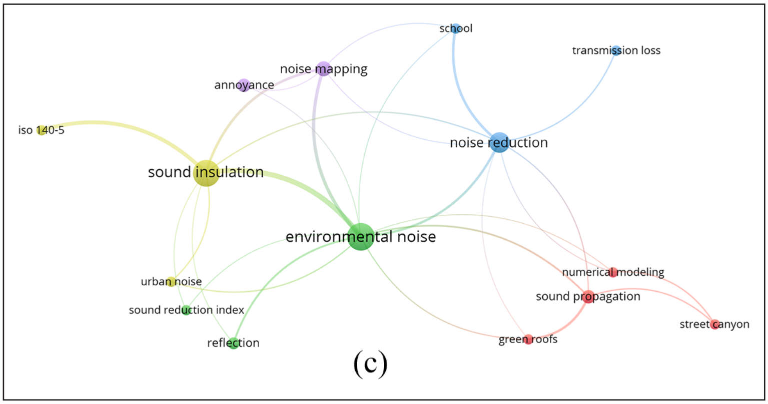

Figure 2. (a) Co-authorship analysis in façade acoustics, (b) mapping of countries where façade acoustic scholars were located, and (c) co-occurrence of keywords in the research of façade acoustics.

modeling," which is of significant importance in façade acoustic studies. It is applied in the predictions of sound insulation ability, noise reduction performance and sound propagation in urban space, etc.

Following the analysis shown in Figure 2(c), the technical review part in this paper will be categorized into three sections. The first part is on sound insulation and acoustic characteristic of the façade itself. It also includes the effect of a building façade on the indoor sound environment and subjective annoyance level. Next is the effect of building façade on the outdoor environment, which refers to the sound propagation and street canyon noise. Lastly, noise reduction, either aimed at an indoor or outdoor environment, will be summarized as an individual section.

Studies on sound insulation of building façade

The studies on the sound insulation properties of building façade mainly focus on the prediction and evaluation of the sound insulation ability. One way is to find a specific approach, either numerical or experimental, to predict or assess the acoustic characteristic of a given façade structure. The other is to follow the ISO standard to measure the sound reduction index of a façade. Efforts have been devoted to the improvement and future development of the corresponding ISO standard. In addition to the prediction and measurement of the Sound Reduction Index (SRI) of a façade, the effect of the façade on the resident annoyance level is also an attractive research direction.

Evaluation of acoustic characteristics

Evaluating the acoustic characteristics of a building façade is of great importance in terms of design and other practical applications. The evaluations can be conducted either numerically[16–36] or experimentally.[37–63]

Numerical methods. To study the acoustic characteristics of a given facade, numerical tools, such as the Finite Element Method (FEM), used in traditional vibroacoustics are generally applied. For example, Arjunan et al.[16] develop a 2D FEM to predict the SRI of a stud-based double leaf wall of a finite size. Despite the insightful analyses, it is recognized that the extension of the method to 3D analyses is difficult due to the large number of elements needed. In fact, the rule of thumb stipulates that at least 8–10 elements per wavelength are usually required to obtain converged and reliable results.[16] This reflects the difficulty in modeling a building façade due to the large dimensions and complex components in different façade layers.

However, traditional numerical modeling approaches usually require enormous computational resources. To overcome these challenges, researchers choose to adapt the existing vibroacoustic models, such as the Transfer Matrix Method (TMM) and Finite-Difference Time-Domain (FDTD) analysis. These are used to target the structures or develop specific models based on a general framework, such as the Artificial Neural Network (ANN). For example, the External Thermal Insulation Composite System (ETICS)[17] is commonly used nowadays to increase both thermal and acoustic performance of a façade. However, traditional sound transmission models are not accurate enough to analyze the partitions in ETICS. For example, the TMM is usually employed in predicting the acoustic transmission of a multilayer structure, which is a multilayer façade in the present case, as shown in Figure 3(a). The general formulation of the system in Figure 3(a) can be described by

$$\mathbf{V}^{S1} = [\mathbf{T}]\mathbf{V}^{S2}, \tag{1}$$

where V^{S1} and V^{S2} are the vectors to define the acoustic field on surface S1 and S2, respectively, and **T** is the transfer matrix whose size depends on the nature of each layer as solid or poroelastic. The basic assumption of this method is that the dimension of each layer is infinite in the lateral direction, that is, *y*-axis in Figure 3(a). Therefore, the error of TMM is significant, especially within the low-frequency range due to the structure modes of the finite size layers. Santoni et al.[17] developed a numerical model based on the TMM, which adds correction factors to address these assumptions. The ratio between the average velocity on surfaces S_1 and S_2, as marked in Figure 3(a), were calculated by the TMM. The results are shown in Figure 3(b). It can be observed that the model shows good agreement with the experimental data in the low-frequency range, while the results in higher frequencies are overestimated. This can be attributed to the influence of uncertainties. Also with the TMM, Attal et al.[32] simulated the absorption coefficient and effective acoustic properties of a multi-layer green façade. The effects of the plant, soil, and air gap thickness were also taken into account to improve the absorption bandwidth. Asakura and Sakamoto[33] presented a numerical method to predict the sound insulation performance of a façade wall system using the FDTD analysis. The sound transmission loss of glass plates and plasterboard walls was obtained with the proposed model. The energy loss at the boundary part of the plates and the internal damping of the plates were taken into account in the prediction model. Later on, this model was applied to predict the sound from passing vehicles transmitting through a building façade.[24] As a further application of this model, a 2-D to 3-D Fourier-like transformation technique has been developed to improve the modeling efficiency.[18] With the improved method, more elements can be included in the model. Eaves and louvers attached to the building façade were found to be effective for noise reduction. Based on a previously developed piecewise modeling scheme,[64] Hu et al.[36] present a tool for systematical design and analysis of building façade in mid-to-high frequency range. It is shown that besides the prediction of sound insulation characteristics, the proposed piecewise scheme can be more comprehensive when compared with traditional modeling tools to achieve complex functions like sound intensity mapping and boundary absorption evaluation in a shorter period.

Other research efforts include the application of the ray theory. Li and Tang[29] developed a ray model to study the sound reflections between the barriers in front of a tall building and the façade surfaces. The predictions of the model were proven to agree well with the in-door measurement over a broad frequency band. Hossam El Dien and Woloszyn[26] conducted a pyramid ray-tracing simulation to study the effect of the balcony depth on the noise protection level of a façade. A total of 0.5 – 8 dB(A) noise reduction could be achieved, throughout the investigated configurations. Prediction results showed a good agreement with the measured one.

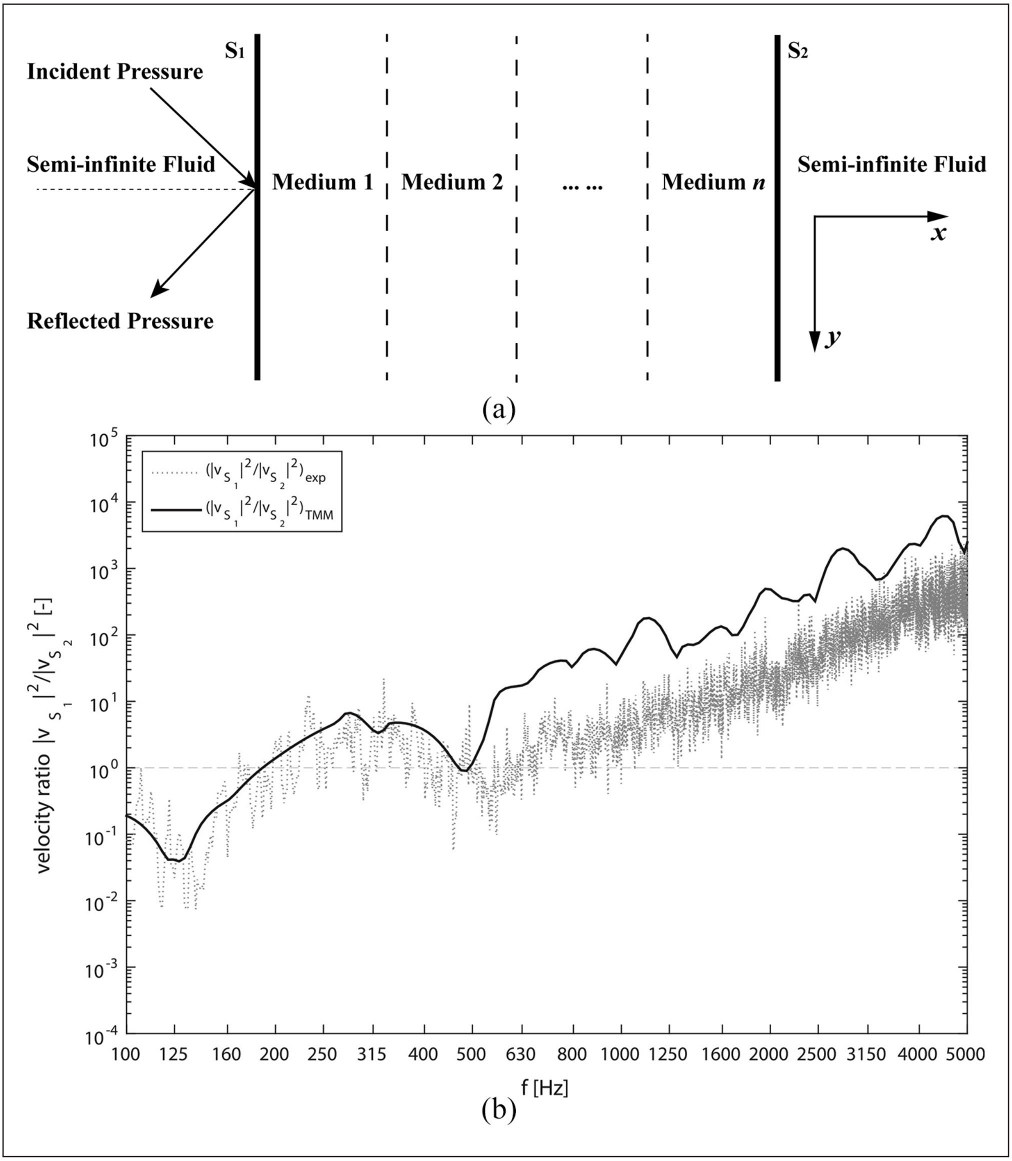

Figure 3. (a) An illustration for an acoustic wave impinging on a multilayer façade structure with semi-infinite fluid on both sides and (b) ratio between the mean square velocities on the external surfaces of the multilayer structure. Reprinted from "Sound transmission loss of ETICS cladding systems considering the structure-borne transmission via the mechanical fixings: Numerical prediction model and experimental evaluation," by A. Santoni, P. Bonfiglio, J.L. Davy, P. Fausti, F. Pompoli, and L. Pagnoncelli, 2017, Applied Acoustics, 122, p. 95. Copyright 2017 by Elsevier Ltd. Reprinted with permission.

Besides the traditional modeling methods in vibroacoustics, ANN has also been employed by researchers. Buratti et al.[23] developed an ANN-based model to evaluate the sound insulation performance of a wooden window façade. The system had five main parameters as network inputs, which are window topology, frame and shutters thickness, number of gaskets, and sound insulation

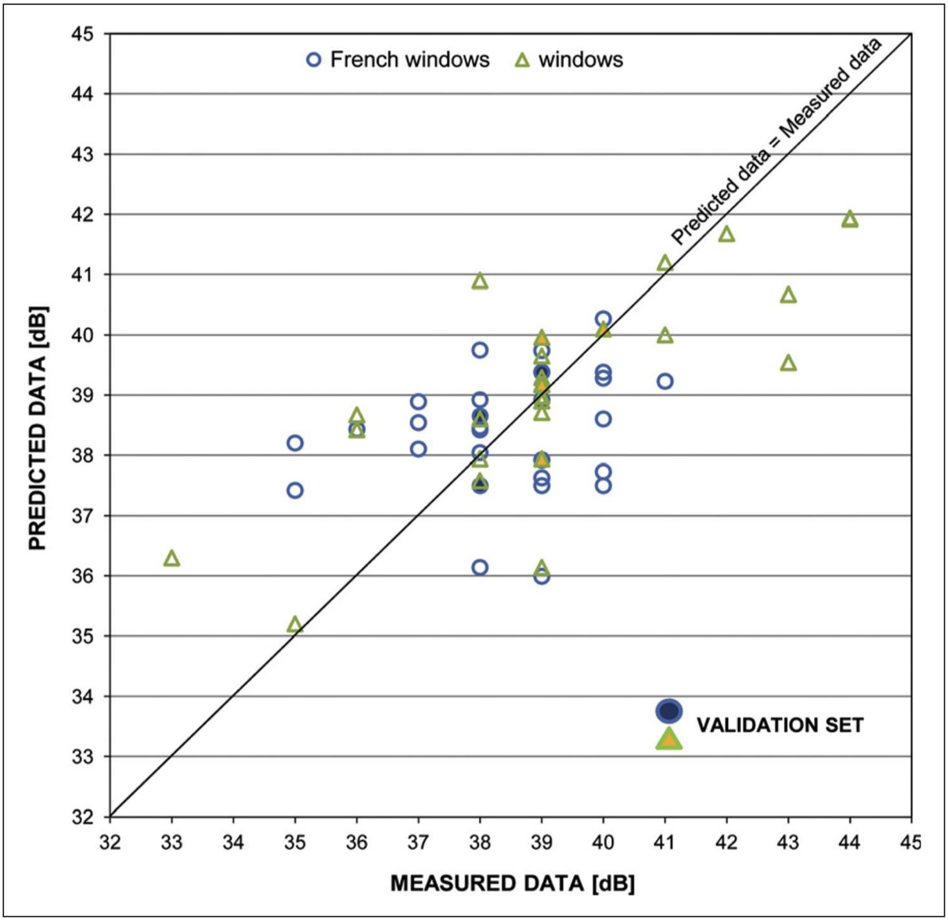

Figure 4. R_w predicted data obtained from the ANN model versus R_w measured data. Reprinted from "Wooden windows: Sound insulation evaluation by means of artificial neural networks," by C. Buratti, L. Barelli, and E. Moretti, 2013, Applied Acoustics, 74, p. 744. Copyright 2012 by Elsevier Ltd. Reprinted with permission.

index of glazing. The sound insulation index R_w of the window, according to EN ISO 717-1,[65] was the output of the system. The networks were trained under different configurations and a root-mean-square error of less than 3% was obtained. The results are shown in Figure 4. A good agreement can be observed for both windows and French windows. These results show that the system can be very useful for the acoustic design and optimization of new products.

Experimental methods. Experimental methods are friendly to solving problems with a strong practical background like a building façade. Because the reliability of numerical methods is limited by numerous uncertainties, experimental methods can be used to improve the modeling performance. Some researches opted to study the acoustic characteristics of a façade in laboratories.[37–52] Díaz and Pedrero[37] and Díaz et al.[38] experimentally investigated the effect of rolling shutters and shutter boxes on the sound insulation properties of a façade window. The study contained a summary of sound insulation from airborne noise in several types of windows with a built-in shutter and prefabricated box. The effects of different shutter arrangement, shutter box material, and noise spectrum on the sound insulation ability were given.

Some other experimental studies were aimed at summarizing an empirical formula to describe the complex acoustic characteristics with a few parameters. Urbán et al.[39] experimentally analyzed the sound insulation ability of 18 different DSF with the test configuration shown in Figure 5(a) and conducted parametric studies on cavity thickness, absorptivity of the cavity, effect of the size of ventilation slots, etc. Then, the authors compared the laboratory test results with different prediction models[66–71] and integrated these models into one simplified formula to estimate the sound insulation ability of the DSF, as

$$D_{2m,nT} = R + 10\lg\frac{0.32V}{S}, \tag{2}$$

in which $D_{2m,nT}$ is the standardized level difference, V is the volume of the receiving room, S is the area of the examined façade sample, and R is a piecewise function of frequencies including three frequency ranges. For each frequency range, the dominant contribution in R is different: (1) Sound insulation behavior dominated by transmission enhancement due to cavity resonances (below cavity resonance frequency f_0); (2) Sound insulation behavior dominated by transmission of sound via the ventilation slots (between f_0 and the coincidence frequency f_{cr} of the exterior glass panel); (3) The frequency range above f_{cr}. Detailed expressions of R will not be expanded in this paper. Finally, the predicted results were verified by the measured ones, as shown in Figure 5(b). It can be seen that the proposed model generally outperforms its predecessor proposed by Blasco and Crispin.[72]

On the other hand, owing to the large dimensions of the façade structure, some researchers have chosen to use scaled configurations to facilitate the tests. Tang et al.[40] experimentally studied the insertion loss of asymmetrical balconies on a building façade with a 1:3 scaled-down model. It was shown that the position of the sound source relative to the full-height sidewall significantly affects the balcony insertion loss. For short side-wall structures, the insertion loss spectral pattern was determined, where coupled modes can be observed so that sounds are amplified at these frequencies regardless of balcony form and elevation angle.

To take the actual noise environment into account, some studies directly measure the acoustic performance of a façade on-site to make the results more reliable.[53–62] For example, field measurements have been carried out to investigate the façade sound insulation ability of balcony windows.[53] The measurements were taken with the guidance in ISO 140-5 and the Single Number Quantities (SNQ) was analyzed accordingly. It was shown that the SNQ for sound insulation varies as the test methods, noise sources, or changes in the angles of incidence, even if the tested façade configuration is identical. Therefore, it was suggested that the field test results of a product should be given together with the method and environment of measurement. School is a typical site which has a rigorous requirement in terms of the acoustic environment. Secchi et al.[54] investigated the effect of traffic noise and façade insulation on the indoor acoustic environment with a sample of 103 facades from 54 different school buildings. Measurements were conducted both before and after adding acoustic treatments to the façade. The obtained results showed that the indoor sound pressure level was significantly attenuated after improving the façade insulation ability.

Researchers have also tried to improve the testing technologies to obtain improved results. To study the infrasound insulation ability of a façade, Keränen et al.[63] designed a special infrasound loudspeaker. The frequency range of the loudspeaker was as low as 5 Hz and it was exploited to measure the outdoor-indoor level difference of 26 different façades. Other standard methods to measure the sound reduction index (SRI) of a façade were down to 50 Hz only.

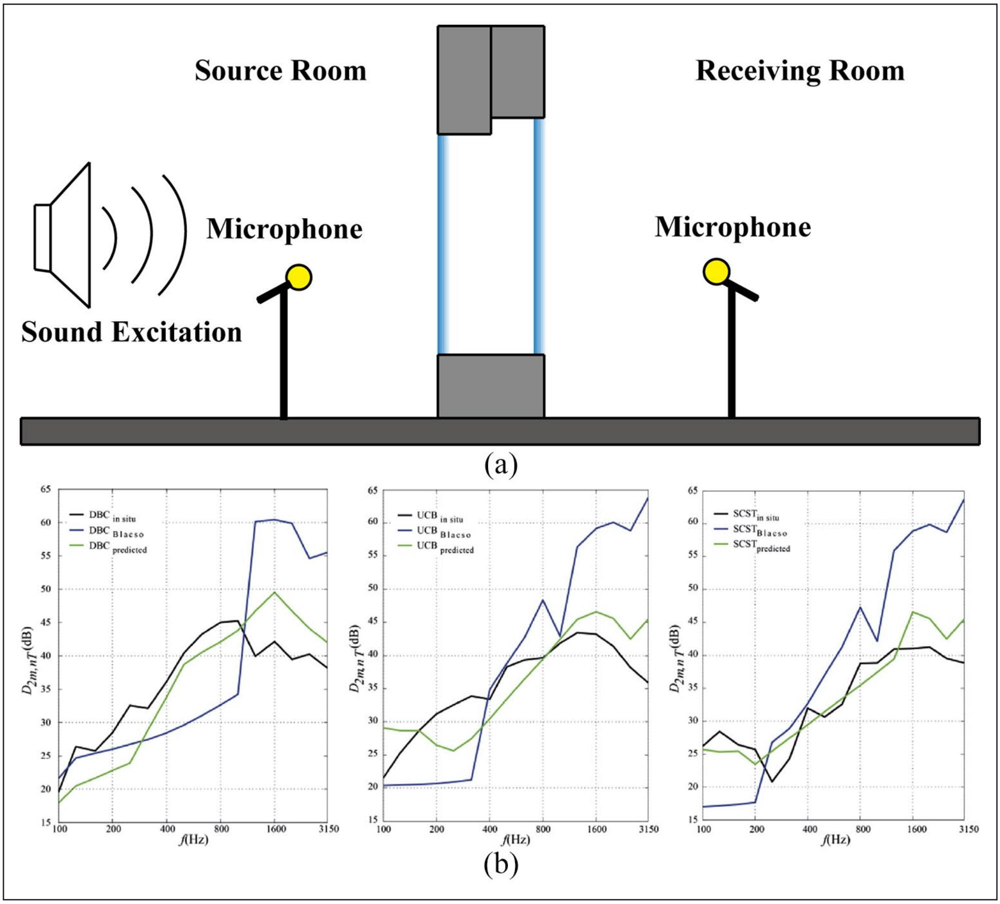

Figure 5. (a) Experiment setup to measure the sound insulation of a double glass structure and (b) comparison between predicted and in situ measured sound insulation spectra for three different DSFs: (i) Slotted DSF; (ii) Corridor DSF ventilated by grills; (iii) Corridor DSF ventilated by slots. Reprinted from "Assessment of sound insulation of naturally ventilated double skin facades," by D. Urbán, N.B. Roozen, P. Zaťko, M. Rychtáriková, P. Tomašovič, and C. Glorieux, 2016, Building and Environment, 110, p.158. Copyright 2016 by Elsevier Ltd. Reprinted with permission.

Studies on ISO standards

ISO standards play an important role in the engineering field since they ensure the quality of designed products. As for the acoustic design of building façades, the ISO standards are applied to guarantee the insulation ability, reliability of measurement, etc. Studies have been conducted to improve or assist in the future development of the ISO standards.[73–83] An interesting point is although some papers are targeted to the withdrawn standard ISO 140-5, which has been replaced by ISO 16283-3, their conclusions are still valid. Revisions made in the new standard can be referred to in Berardi's[73] work. A study investigated the influence of the front microphone mounting condition towards improving ISO 1996-2:2008 standard.[74] Results indicated that the traditional correction factor may lead to significant errors in the results collected over a long duration, such as monthly based. The study proposed that the correction factor should be determined case-by-case.

Besides, it further advised that in situ studies are necessary when precision measurements are needed.

Some evaluations have also been conducted with respect to the development of future standards regulating road-traffic noise. In this regard, Hongisto et al.[83] evaluated 25 different SNQs correlated with subjective ratings of road-traffic noise transmitting through a façade. Five spectrally different traffic noise and 12 façade structures, that is, 60 combinations, have been evaluated in a psychoacoustic laboratory in total. The study suggested the most suitable SNQ for the standard road-traffic spectrum of ISO 717-1, which can benefit the development of future standards.

Another factor that has a significant influence on the performance of modeling and measurement is the uncertainty effect. Berardi studied the low-frequency uncertainties with the method proposed in ISO 16283-3, regarding the instrument positions in the measurement of sound insulation.[73] It was shown that an average among different measurements is necessary to reduce the interference effect. Navacerrada et al.[78] conducted a series of analyses on the uncertainty values mentioned in the standard ISO 12999-1. These values were summarized from interlaboratory activities and individual calculations. The comparisons were based on around 1000 in situ measurements for sound insulation. It is also suggested that if the reader tends to calculate individual uncertainty with Monte Carlo simulation rather than the method proposed in ISO 12999, further studies of sound insulation are needed in the low-frequency range as a supplement. Also regarding ISO 12999, Scrosati et al.[84] pointed out that it is too difficult to address the uncertainties in different quantities in building acoustics. As a consequence, the uncertainty must be calculated from reproducibility data from interlaboratory comparisons. Particularly, it was reported that, in ISO 12999-1, the standard deviation σ_{R95} related to reproducibility may cause an overcoverage in the confidence interval. Thus, σ_{R95} has been removed in the latest version ISO 12999-1:2020. It should be noticed that this piece of work is not targeting at façade so it is not included in the quantitative analyses in Section 2. Another considerable research regarding ISO 12999-1 is the frequency analysis conducted by Wittstock,[85] who compared various deviations from a set of interlaboratory tests. It was found that, by extending the frequency range, the standard deviation of reproducibility is little affected while a small increase and a relatively larger increase has been observed in the in situ standard deviation and the standard deviation of repeatability, respectively.

Studies on annoyance level

Researches on annoyance evaluation have been conducted.[86–95] Some study the effect of building façade on the noise annoyance level in general. In a laboratory, Ryu and Song[86] experimentally investigated the effect of building façade on traffic noise annoyance in terms of frequencies and sound insulation ability. The relationship between the subjective annoyance level and the noise spectrum was studied. It was shown that the proper use of a building façade can considerably reduce the annoyance level. The on-site survey questionnaire is also an effective way to study the noise annoyance level in a certain area. A survey investigation,[87] which features 18 areas from two cities in Norway and a total of near 4000 respondents, reported that a single glazing window with poor insulation ability can lead to a higher noise annoyance level.

Studies on street canyon noise

Similar to the studies on sound insulation properties, researches on the effect of building façade on street canyon noise can also be divided into numerical studies[96–120] and experimental studies.[121–125]

Numerical studies

There are two major objectives when investigating the effect of building façade on street canyon noise; one is the sound propagation process and the other is the noise mapping.

Modeling of sound propagations. The effect of building façades on street canyon noise is another hot topic in the façade acoustic area. One of the most representative methods is the Boundary Element Method (BEM). This technique is friendly to large-space acoustic simulations with given boundaries,[96–98] although such a low-frequency method usually requires tremendous computational resources and time when the dimensions of the modeling target become larger.

A BEM based model[98] was proposed by Salomons et al. to study the multiple reflections by building façades in street canyons. The method was supported by a room-acoustical analysis of the reverberant sound fields in the source and receiver canyons. Noise maps and exposure distributions of the city of Amsterdam were generated. The model helped to redistribute traffic flows to reduce the percentage of highly annoyed inhabitants from 23% to 18%. Montes González et al.[96] have also numerically studied the effect of vehicle parking lines on the noise over a building façade with BEM. A screen effect was observed with the presence of the parking line, which was suggested to be considered in the future noise mapping projects.

Owing to the development of the Perfectly Matched Layer (PML), the Finite Element Method (FEM) can also deal with an infinite domain by truncating it into a finite processible one. Pelat et al.[104] proposed a coupled modal-finite element method to model wave propagation in a street canyon. The multiple reflections of the acoustic waves on the building façades were taken into account. This allowed the acoustic field to be modeled as an irregular open waveguide. Although the model revealed the acoustic wave propagation mechanisms along a street, the obtained result was rough in terms of boundary conditions.

To take more boundary details into account, Echevarria Sanchez et al.[100] numerically studied the sound pressure level distribution with a full-wave FDTD analysis. They demonstrated in detail the strong effect of building shape, street geometry, and the presence of street furniture on people's noise exposure. Finally, the immission levels (L_p) are obtained for different octave bands as

$$L_p = L_w + relSPL - Aff, \tag{3}$$

where *relSPL* is the acoustic energy expressed relative to the free field, *Aff* is the attenuation observed in the free field, and L_w is obtained from the CNOSSOS (Common Noise Assessment Methods in Europe) Equivalent source model.[126] It was found that a proper façade design could reduce the average noise exposure at windows by 12.9 dB(A). Also based on the FDTD analysis, Van Renterghem et al.[105] proposed an FDTD-PE (Parabolic Equation) method to increase the modeling efficiency and to reduce the required computational cost. The FDTD-PE model explored the symmetry of the source and the receiver canyon. With the proposed calculation method, simulations are only necessary for half of the sound propagation domain.

Sound field and noise mapping. Geometrical acoustic-based ray theory is another popular tool used in large-space acoustic modeling.[114–120] A typical example is the sound field prediction and noise mapping in urban space. A radiosity-based numerical model has been proposed by Kang,[114] as shown in Figure 6(a). The model studies the fundamental characteristics of the acoustic field in an urban street resulting from diffusely reflecting boundaries. The model divides the boundaries of a street into a set of patches. Then, the sound energy response at receiver $R(R_x, R_y, R_z)$ is given as a function of time and represented as

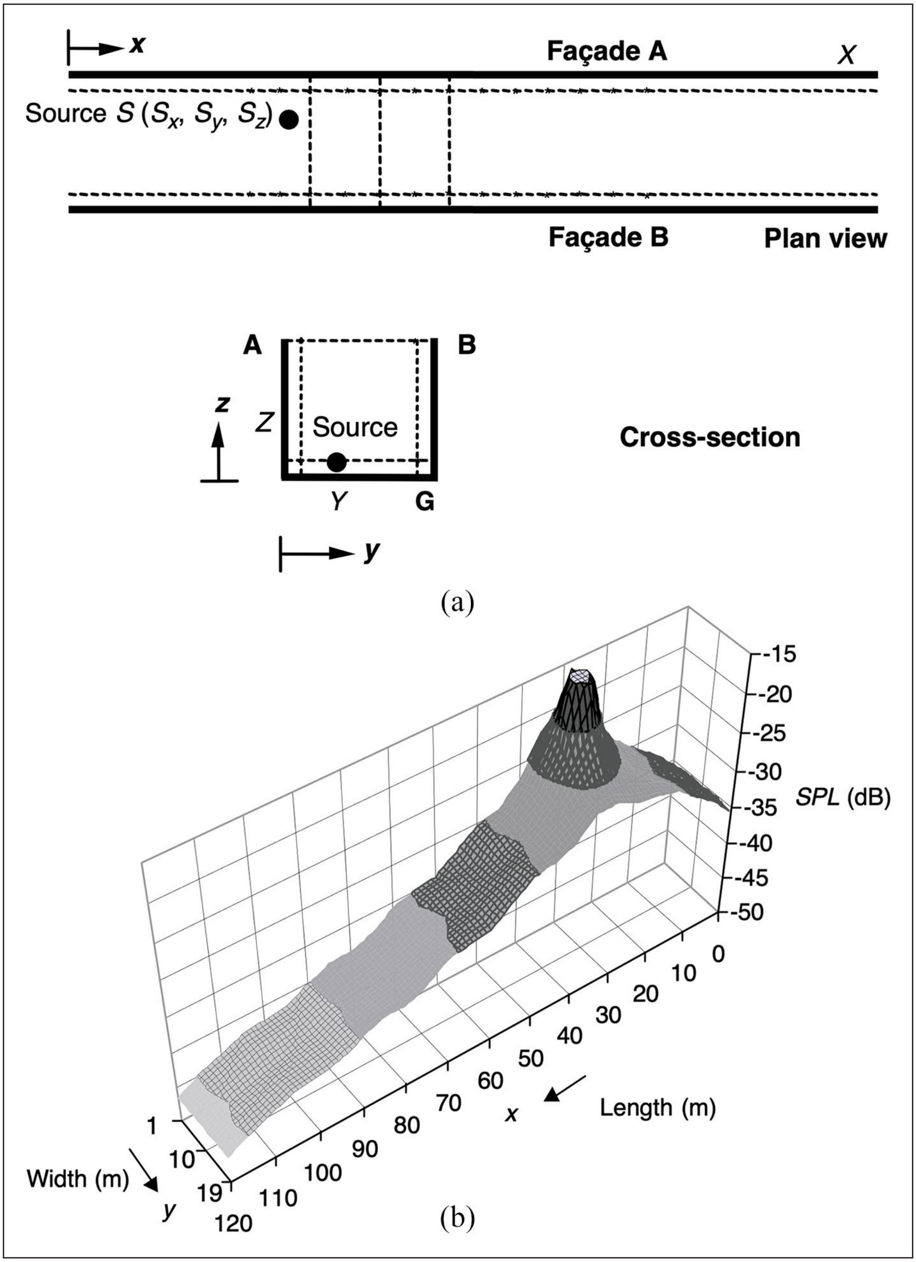

Figure 6. (a) Overlook and cross-section illustration of an idealized rectangular street and (b) SPL distribution on a horizontal plane in a typical street, 1m above the ground. Reprinted from "Numerical modeling of the sound fields in urban streets with diffusely reflecting boundaries," by J. Kang, 2002, Journal of Sound and Vibration, 258, p. 794 and p. 802. Copyright 2002 by Elsevier Science Ltd. Reprinted with permission.

$$L(t) = 10\lg\left\{E_d(t) + \sum_{k=1}^{\infty}\left[E_k(t)_G + E_k(t)_A + E_k(t)_B\right]\right\} - L_{ref}, \tag{4}$$

where $E_d(t)$ is the direct sound, L_{ref} is the reference level, $E_k(t)_G$ is the energy contribution from each patch source being considered, and $E_k(t)_A$ and $E_k(t)_b$ are the energy contributions from the patches on façade A and B, respectively. A set of calculations of the SPL distribution is shown in Figure 6(b). It can be observed that SPL variation along a street can be well described by the proposed model. The work emphasizes the effect of the reflective property of the street ground on a diffusively reflective façade. In other words, if building façades are diffusely reflective, the reflective property (diffusely or geometrically) of the street ground has no significant effect on the sound field distribution within the street. Another application of this model is investigating the acoustic characteristics in urban squares surrounded by a reflective building façade.[115] After adapting the model, the effects of façade design on reverberation time and sound pressure level reduction were investigated. These investigations include the reflection pattern, height, aspect ratio, boundary absorptions, etc. However, when modeling the façade reflections and the corresponding fittings, the required computational resource and time significantly increase. To save modeling cost, Can et al.[116] ran 32,175 simulations to quantify the errors of neglecting acoustic diffusion by the façade. Thereafter, the authors applied regressions to evaluate the impact of diffusive reflections and street fittings on sound propagation. These regressions can be used to refine sound levels predictions when using classical outdoor sound propagation models without considering the effect of façade reflections. Some other researchers also focused on noise sources other than traffic noise. Riegel and Sparrow[117] proposed a combined ray tracing/radiosity method to model the sound field of sonic booms around buildings. The influences of façade features, absorption coefficients, and scattering coefficients were investigated. The calculated results were in good agreement with the measured ones.

Experimental studies

Scaled-down models are often used to study road traffic noise due to the on-site measurement difficulties.[121–124] Compared to a full-scale on-site test, most parameters can be optionally controlled and studied, and the uncertainties level can be reduced.[122] With a 1:50 scaled-down model, Picaut and Simon[121] studied the effect of multiple reflections and diffuse-scattering by façade irregularities on sound propagation in a street. The results of the scaled model were compared with the on-site measured ones. It was found that the attenuation effect can be well predicted with the scaled model. However, the sound level in the scaled model was found to be generally lower when the receiver is away from the source. It was then suggested that a larger scale factor should be used. In the model of Hornikx and Forssén,[122] facades of acoustically rigid, absorptive, and diffusive surfaces were investigated. The analyses included sound pressure level, decay time, and 3-D geometrical effect in a street canyon. Besides, a wavelet-based method was applied to correct the air attenuation effect.

On the other hand, on-site experimental studies usually involve more complexities so that more dedicated techniques are required. For instance, Bjelić et al.[125] designed a microphone array system to analyze the characteristics of traffic noise. Notably, the system contains a lower number of microphones compared to existing solutions. The designed system was dedicated to the analysis of the angular distribution of incident sound energy impeding a facade in the urban environment.

Noise reduction techniques

The noise reduction method is also a hot topic. The ultimate objective of investigating façade acoustics is to improve the indoor and outdoor acoustic environment. Generally, noise reduction techniques in façade acoustics include using absorptive materials,[127–134] adding control components,[135–137] applying new designs,[134,138–142] etc.

To reduce the noise level close to a building façade, one straight forward way is to add a layer of absorption material over the façade surface. For instance, Wang et al.[127] numerically investigated the effect of the phase gradient of the façade ceiling surface on screening exterior noise with a ray-based model. It was shown that, with impedance inhomogeneity being used on the ceiling surface, the sound reflections were considerably reduced, particularly in the high-frequency range. However, the absorption material has a durability problem when exposed to the environment on a building façade surface in a long-lasting application scenario.

To tackle this issue, Ishizuka and Fujiwara[130,131] proposed a ceiling-mounted noise reflector to achieve the noise-shielding effect. The performance was experimentally assessed for balconies with ceiling-mounted reflectors on a high-rise building façade. The sound pressure reduction, provided by the reflectors, on a window surface adjacent to the balcony was evaluated at intermediate floor levels. The design was examined in a full-scale balcony for practical use.

Active control is another popular technique in the noise control society.[133,135] Aiming at reducing the noise of an aircraft fly-over, Pàmies et al.[135] designed an active control system for sound transmission through a restricted opening bottom-hinged window. A 3dB of transmission loss increase was achieved in the low-frequency range.

Applying a new design is also a preferable selection. Hossam El Dien and Woloszyn[26] modified the angle of the ceiling surface within the balcony. An additional 0.5–6 dB noise reduction was achieved according to the proposed numerical model. Jessop et al.[136] also investigated the effect of adding non-periodic stiffening elements to windows for impaired sound transmission. The results show that the low-frequency sound transmission loss below 150 Hz can be increased by several dB. Santoni et al.[141] investigated the possibility of using Wood Plastic Composite (WPC) as a façade cladding or sound barrier. The proposed configuration showed good potential in roadside buildings.

In addition, Yu[137] proposed a new design of acoustic metasurface to improve the sound insulation of a building façade structure. The parameters were tuned based on FEM, while in situ measurements were taken to test the performance. The design was shown to outperform the traditional casement window by 7 dB in terms of SNQ noise rating. Badino et al.[138] also investigated the effect of façade shape and acoustic cladding on the reduction of noise levels in a street canyon. It was shown that the noise reductions achieved were much higher than those by increasing the sound absorption of the street paving. This study highlights the role of façade design in environmental noise mitigation. Also based on a metastructure, Fusaro et al.[143] developed a metacage to simultaneously achieve noise control and ventilation in a window system. The acoustic performance was studied and optimized with FEM. In general, a minimum of 8 dB and a mean of 30 dB can be obtained in terms of transmission loss, within the frequency between 350 and 5000 Hz.

Among existing noise control techniques in building façade, the utilization of vegetation has become popular in the last decade.[144–151] Such a disposition can simultaneously improve the thermal and acoustical performance environmentally. Van Renterghem and Botteldooren[148] explored the potential of green roofs as a control device to reduce the effect of road traffic noise loading on a façade. The effects of traffic speed and vehicle types on the performance of the green roof were parametrically studied. One of the analyzed sets is shown in Figure 7. For a detailed parametric arrangement, readers can refer to Ref.[148] It can be observed that most of the green roofs can achieve an approximately 5 dB reduction on the sound pressure level at the relatively low height region. It

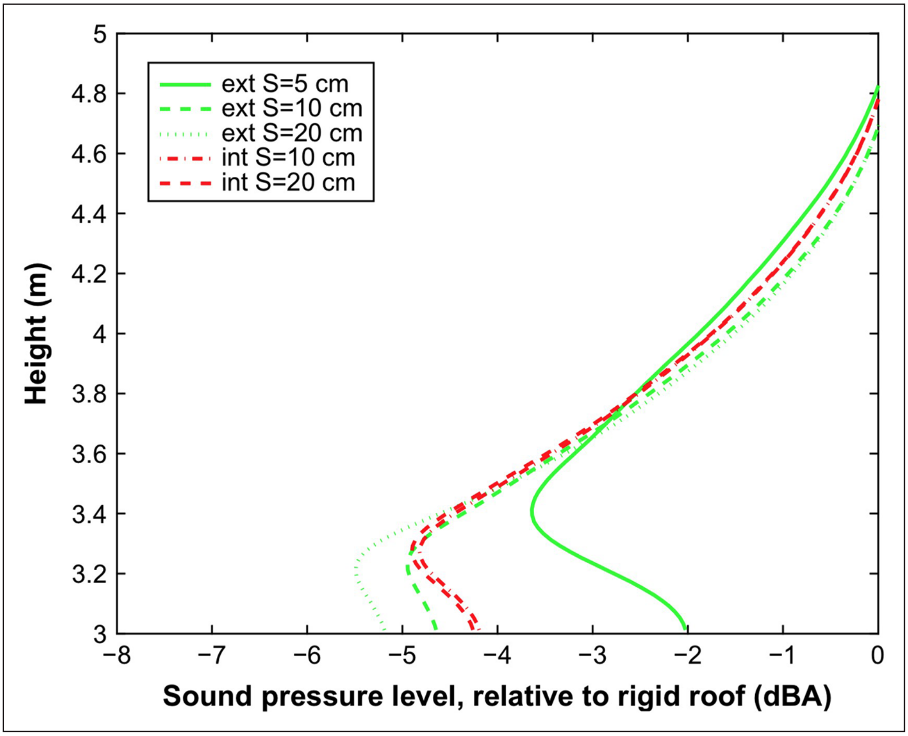

Figure 7. Sound pressure level, relative to a rigid roof, over the full height of the window at a facade. Extensive green roofs with substrate thicknesses S of 5, 10, and 20 cm, and intensive green roofs of 10 and 20 cm are shown. Reprinted from "Reducing the acoustical façade load from road traffic with green roofs," by T. Van Renterghem and D. Botteldooren, 2009, Building and Environment, 44, p.1084. Copyright 2008 by Elsevier Ltd. Reprinted with permission.

is also shown that the shielding of a green roof can be achieved when its parameters can be properly tuned.

Pérez et al.[144] experimentally examined the acoustic insulation of two Vertical Greenery Systems (VGS) in situ. It was found that a thin layer of vegetation can introduce sound insulation between 1 and 3 dB, according to the subjected excitations. It was also suggested that the influence of other factors, such as mass related factors, type of modular unit, and support structures, should be considered in future design processes. Yang et al.[150] measured the random incidence absorption and scattering coefficients of vegetation. They considered various factors, such as soil depth, soil moisture content, and the level of vegetation coverage. It was shown that at higher frequencies, sound absorption and scattering become stronger as the vegetation coverage increases. Davis et al.[146] also measured the sound absorption properties of a vertical garden system in a building façade. Their study suggested a design by which the configurations of a vertical garden can be optimized to suit the target noise frequency spectrum.

Research gaps and limitations

Despite the significant progress made in the study of the acoustics of a building façade as reviewed in previous sections, there are still limitations and space for future studies. Figure 8 lists some of these topics.

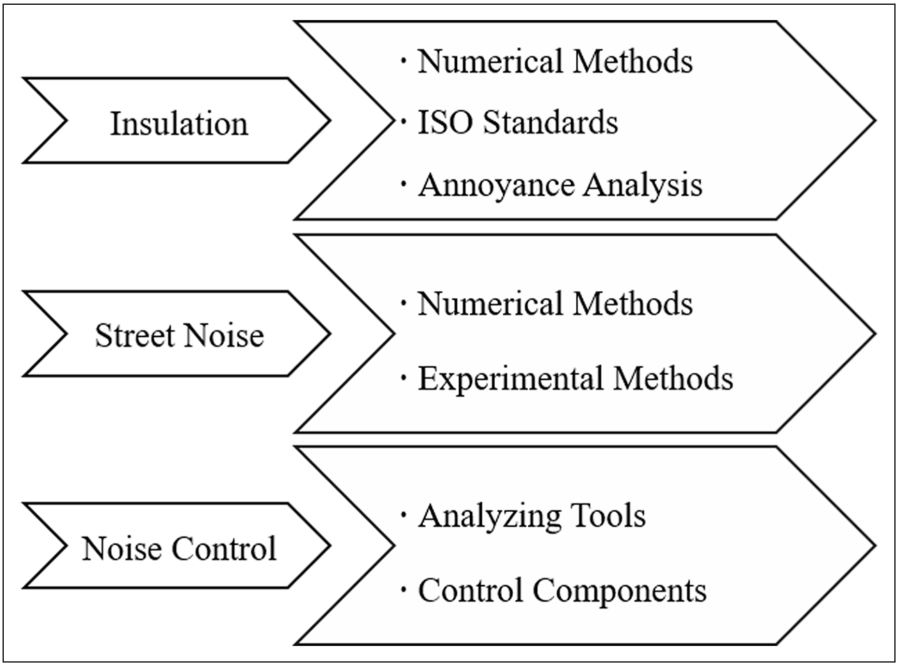

Figure 8. Summarized points for existing research limitations.

Firstly, some numerical studies aimed at predicting the acoustic characteristics of the building façade suffered from obvious inadequacy. These models have been developed based on empirical formulas, which are efficient and user-friendly. However, these models are too rough when compared with the actual experimental data. Furthermore, they can hardly address the need for allowing parameter variations at the design stage. On the other hand, although more accurate modeling tools such as BEM and FEM exist, they are extremely and computationally cost-demanding. Therefore, they can hardly be used for optimization purposes. Potential solutions may be sought from the mid-to-high frequency methods in vibroacoustic analyses, which aim at balancing the result accuracy and calculation efficiency. Basically, the mid-to-high frequency methods can be categorized into the enhanced low-frequency methods,[64,152–154] the enhanced high-frequency methods,[155–157] and the hybrid methods.[158,159] In general, the enhanced low-frequency methods and hybrid methods are more suitable for the prediction of sound insulation predictions while the enhanced high-frequency methods are more friendly to street canyon noise mapping.

The use of ISO standards for the measurement of the performance of a façade also suffers from similar drawbacks. Although several ISO standards have been formulated to address the uncertainty issue, relevant laboratory tests would increase the cost of design. On the other hand, the reproducibility requirement of the test also brings extra cost. Thus, further development of existing vibroacoustic models, particularly for those involving system uncertainty, could benefit the design and optimization of the acoustic characteristics of the building façade. Actually, most of the above mentioned mid-to-high frequency methods are still at conceptual stage or have only been applied to extremely simple structures such as a plate-beam or a plate-cavity system. With the development of calculation ability and performance, these models are of great potential in façade acoustic analysis.

The effect of building façades on the annoyance level is important as a civil structure. Albeit the effect of building façade on noise annoyance level is still not completely understood, it would be better to address the annoyance consideration at the design stage based on the existing knowledge.

The limitations of numerical methods in street canyon noise studies are similar to those in sound insulation studies. It is difficult to balance the efficiency and the fineness of a method. Specific methods are needed to address this issue. The authors believe that turning to traditional vibroacoustic models for help could be a reasonable solution as well as in the sound insulation predictions. For the experimental methods, scaled-down tests offer flexibility in terms of geometry size, reflection, and absorption. However, considerable discrepancies can still be observed when estimating high-frequency noise, where the atmosphere attenuation cannot be well apprehended in the scaled model. If the scaled ratio is large (e.g. more than 50), the acoustic similarity process becomes complex due to the use of ultrasonic sound sources, adapted receivers. For the on-site test, besides those less competitive compared with the scaled-down model, legal authorizations from city administrations and limitations in measurement duration exist. Uncertainties like abrupt noise and weather changes also bring additional challenges to the reliability of field measurement results.

Noise reduction is an attractive topic not only in façade acoustics but in many other acoustic branches, like structure acoustics and room acoustics. It is widely accepted that exploring its mechanisms and making parametric analysis can significantly benefit the optimization of control devices. Therefore, dedicated analyzing tools should be developed to increase the control performance of a typical device. A representative example is the Micro-Perforated Panel (MPP). As shown in the existing literature,[160–162] the measured absorption coefficient of MPP cannot completely reflect its in situ performance. This can result in false predictions in the induced noise reduction benefit. The MPP should be analyzed together with the façade structure as an integral part. Recent findings of the relationship between the glazing flow and the acoustic impedance could also improve the applicability of MPP in building façade.[163] As a reference, the investigations on vegetation walls and green roofs provide a good example, as reviewed in Section 5. Such a methodology should be advocated and promoted in the development of other noise control devices. Additionally, with an analyzing tool, the control efficiency could be further improved by especially considering the frequency spectrum obtained from the annoyance analysis. Another research trend of focus is the acoustic metamaterial. As reviewed in previous sections, it is a rising star in terms of noise reduction in the last few years. While the performance of metamaterial largely depends on the quality of optimization, the complex function and configuration of a building façade add difficulties to the design process. To tackle the design efficiency issue, recent works which employ machine learning have provided valuable references.[164–166]

As a final remark, the authors summarize the potential directions for future researches in façade acoustics in the following. Firstly, there is a need for the development of an integrated tool that can facilitate the acoustic design and optimization of different façade configurations. Additionally, parametric studies with such a tool can take the annoyance analysis results into account. Not only can the design period be shortened, but the performance of the noise control devices be improved at the same time, which could benefit both the improvement of sound insulation and street noise reduction. In the end, more attention should be paid to the latest research topics such as metamaterial and machine learning aided design.

For experimental studies, uncertainties should be better apprehended in the scaled-down tests to better mimic the practical environment, which can considerably strengthen the reliability of the results. Finally, although many investigations and surveys are conducted on the effect of a building façade on the annoyance level, most of them focus on sound insulation performance. Studies on the annoyance level in terms of street noise in urban spaces are scarce in the open literature. Such topics deserve more attention to benefit the research on building façade and street noise.

Conclusions

A comprehensive review of the studies on the acoustic effect of a building façade is presented. The review is conducted on research articles published in seven selected journals, namely, APAC, JASA, BaE, JSV, AAuA, BUA, and NCEJ. It is found that the popularity of research on façade acoustics has been persistently increasing in the last two decades. Most researches are in Europe due to the wide application of façade technology. The central topic in façade acoustics is environmental noise, around which sound insulation and noise reduction are the two most attractive directions. Most of the other topics can be classified into studies on the effect of building façades on street canyon noise. A systematic review of façade acoustics is presented based on the above three categories. Research limitations and existing gaps are identified and summarized following the reviews.

Generally, this study provides a reference for both academia and noise control engineers in buildings. It is relevant to note that, despite the effort in collecting the most representative articles to reflect the current statues of façade acoustic research, the cited references are in no way exclusive and it is an insurmountable task to include all existing papers. Readers are advised to read the paper in this context.

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References

1. CWCT (Centre for Window and Cladding Technology). Standard for Systemised Building Envelopes. CWCT, University of Bath, Bath, UK, 2005.
2. Davis MM and Hirmer S. The potential for vertical gardens as evaporative coolers: an adaptation of the 'Penman Monteith Equation'. *Build Environ* 2015; 92: 135–141.
3. Stec W, Van Paassen A and Maziarz A. Modelling the double skin façade with plants. *Energy Build* 2005; 37(5): 419–427.
4. Mingotti N, Chenvidyakarn T and Woods AW. The fluid mechanics of the natural ventilation of a narrow-cavity double-skin facade. *Build Environ* 2011; 46(4): 807–823.
5. Nore K, Blocken B and Thue J. On CFD simulation of wind-induced airflow in narrow ventilated facade cavities: coupled and decoupled simulations and modelling limitations. *Build Environ* 2010; 45(8): 1834–1846.
6. Kim S, Lee J-H and Moon JW. Performance evaluation of artificial neural network-based variable control logic for double skin enveloped buildings during the heating season. *Build Environ* 2014; 82: 328–338.
7. European Environmental Agency. Environmental indicator report 2018 - In support to the monitoring of the Seventh Environment Action Programme. EEA Report, European Environmental Agency, 2018.
8. Mohsen EA and Oldham DJ. Traffic noise reduction due to the screening effect of balconies on a building façade. *Appl Acoust* 1977; 10(4): 243–257.

9. Delany ME, Rennie AJ and Collins KM. A scale model technique for investigating traffic noise propagation. *J Sound Vib* 1978; 56(3): 325–340.
10. Tsai CC and Lydia Wen M. Research and trends in science education from 1998 to 2002: A content analysis of publication in selected journals. *Int J Sci Educ* 2005; 27(1): 3–14.
11. Ke Y, Wang S, Chan AP, et al. Research trend of public-private partnership in construction journals. *J Constr Eng Manag* 2009; 135(10): 1076–1086.
12. Li Z, Shen GQ and Xue X. Critical review of the research on the management of prefabricated construction. *Habitat Int* 2014; 43: 240–249.
13. Mak CM and Wang Z. Recent advances in building acoustics: an overview of prediction methods and their applications. *Build Environ* 2015; 91: 118–126.
14. Hosseini MR, Martek I, Zavadskas EK, et al. Critical evaluation of off-site construction research: a Scientometric analysis. *Autom Constr* 2018; 87: 235–247.
15. Su H-N and Lee P-C. Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in Technology Foresight. *Scientometrics* 2010; 85(1): 65–79.
16. Arjunan A, Wang CJ, Yahiaoui K, et al. Development of a 3D finite element acoustic model to predict the sound reduction index of stud based double-leaf walls. *J Sound Vib* 2014; 333(23): 6140–6155.
17. Santoni A, Bonfiglio P, Davy JL, et al. Sound transmission loss of ETICS cladding systems considering the structure-borne transmission via the mechanical fixings: numerical prediction model and experimental evaluation. *Appl Acoust* 2017; 122: 88–97.
18. Sakamoto S and Aoki A. Numerical and experimental study on noise shielding effect of eaves/louvers attached on building façade. *Build Environ* 2015; 94: 773–784.
19. Yu X, Lau S-K, Cheng L, et al. A numerical investigation on the sound insulation of ventilation windows. *Appl Acoust* 2017; 117: 113–121.
20. Naish DA, Tan ACC and Demirbilek FN. Simulating the effect of acoustic treatment types for residential balconies with road traffic noise. *Appl Acoust* 2014; 79: 131–140.
21. Garg N, Saxena TK, Kumar A, et al. Uncertainty evaluation and implications of spectrum adaptation terms in determining the airborne sound insulation in building elements. *Noise Control Eng J* 2014; 62(5): 333–343.
22. Garg N, Kumar A and Maji S. Parametric sensitivity analysis of factors affecting sound insulation of double glazing using Taguchi method. *Appl Acoust* 2013; 74(12): 1406–1413.
23. Buratti C, Barelli L and Moretti E. Wooden windows: sound insulation evaluation by means of artificial neural networks. *Appl Acoust* 2013; 74(5): 740–745.
24. Asakura T, Miyajima T and Sakamoto S. Prediction method for sound from passing vehicle transmitted through building facade. *Appl Acoust* 2013; 74(5): 758–769.
25. Barclay M, Kang J and Sharples S. Combining noise mapping and ventilation performance for non-domestic buildings in an urban area. *Build Environ* 2012; 52: 68–76.
26. Hossam El Dien H and Woloszyn P. Prediction of the sound field into high-rise building facades due to its balcony ceiling form. *Appl Acoust* 2004; 65(4): 431–440.
27. ElDien HH and Woloszyn P. The acoustical influence of balcony depth and parapet form: experiments and simulations. *Appl Acoust* 2005; 66(5): 533–551.
28. Cheng WF, Ng CF and Fung KC. Theoretical model to optimize noise barrier performance at the window of a high-rise building. *J Sound Vib* 2000; 238(1): 51–63.
29. Li KM and Tang SH. The predicted barrier effects in the proximity of tall buildings. *J Acoust Soc Am* 2003; 114(2): 821–832.
30. Tadeu A, António J, Mendes PA, et al. Sound pressure level attenuation provided by thin rigid screens coupled to tall buildings. *J Sound Vib* 2007; 304(3-5): 479–496.
31. Oldham DJ, Kang J and Brocklesby MW. Modelling the acoustical and airflow performance of simple lined ventilation apertures. *Build Acoust* 2005; 12(4): 277–292.
32. Attal E, Côté N, Shimizu T, et al. Sound absorption by green walls at normal incidence: physical analysis and optimization. *Acta Acust United Acust* 2019; 105(2): 301–312.
33. Asakura T and Sakamoto S. Finite-difference time-domain analysis of sound insulation performance of wall systems. *Build Acoust* 2009; 16(3): 267–281.

34. Caniato M. Sound insulation of complex façades: a complete study combining different numerical approaches. *Appl Acoust* 2020; 169: 107484.
35. Caniato M, Bettarello F, Bonfiglio P, et al. Extensive investigation of multiphysics approaches in simulation of complex periodic structures. *Appl Acoust* 2020; 166: 107356.
36. Hu Z, Maxit L and Cheng L. Acoustic design and analyses of a double Skin Façade system. *Appl Acoust* 2021; 173: 107727.
37. Díaz C and Pedrero A. An experimental study on the effect of rolling shutters and shutter boxes on the airborne sound insulation of windows. *Appl Acoust* 2009; 70(2): 369–377.
38. Díaz C, Díaz A and Navacerrada MA. An experimental study on the effect of rolling shutters on the field measurements of airborne sound insulation of façades. *Appl Acoust* 2013; 74(1): 134–140.
39. Urbán D, Roozen NB, Zaťko P, et al. Assessment of sound insulation of naturally ventilated double skin facades. *Build Environ* 2016; 110: 148–160.
40. Tang SK, Ho CY and Chan WY. Insertion loss of asymmetrical balconies on a building facąde. *J Acoust Soc Am* 2019; 146(3): 1580–1594.
41. Demirkale SY and Ascigil-Dincer M. Retrofitting masonry and cavity brick façades for different noise zones using laboratory measurements. *Build Acoust* 2017; 24(2): 77–100.
42. Cabrera D, Ashmore N and Kocer C. Airborne sound insulation of vacuum insulating glazing: general observations from measurements. *Build Acoust* 2016; 23(3-4): 193–206.
43. Bajraktari E, Lechleitner J and Mahdavi A. The sound insulation of double facades with openings for natural ventilation. *Build Acoust* 2015; 22(3-4): 163–176.
44. Secchi S, Cellai G, Fausti P, et al. Sound transmission between rooms with curtain wall Façades: a case study. *Build Acoust* 2015; 22(3-4): 193–208.
45. Ruggeri P, Peron F, Granzotto N, et al. A combined experimental and analytical approach for the simulation of the sound transmission loss of multilayer glazing systems. *Build Acoust* 2015; 22(3–4): 177–192.
46. Olafsen S, Bard D, Strand MK, et al. Methods of field measurements of facade sound insulation. *Noise Control Eng J* 2015; 63(5): 467–477.
47. Miskinis K, Dikavicius V, Bliudzius R, et al. Comparison of sound insulation of windows with double glass units. *Appl Acoust* 2015; 92: 42–46.
48. Cotana F, Pisello AL, Moretti E, et al. Multipurpose characterization of glazing systems with silica aerogel: in-field experimental analysis of thermal-energy, lighting and acoustic performance. *Build Environ* 2014; 81: 92–102.
49. Mateus D, Pereira A and Tadeu A. Acoustic behavior of high acoustic performance window glazing. *Noise Control Eng J* 2013; 61(3): 320–329.
50. Tong YG and Tang SK. Plenum window insertion loss in the presence of a line source—a scale model study. *J Acoust Soc Am* 2013; 133(3): 1458–1467.
51. Tang SK. Scale model study of balcony insertion losses on a building façade with non-parallel line sources. *Appl Acoust* 2010; 71(10): 947–954.
52. Guillen I, Uris A, Estelles H, et al. On the sound insulation of masonry wall façades. *Build Environ* 2008; 43(4): 523–529.
53. Kim MJ and Kim HG. Field measurements of façade sound insulation in residential buildings with balcony windows. *Build Environ* 2007; 42(2): 1026–1035.
54. Secchi S, Astolfi A, Calosso G, et al. Effect of outdoor noise and façade sound insulation on indoor acoustic environment of Italian schools. *Appl Acoust* 2017; 126: 120–130.
55. Buratti C, Belloni E and Moretti E. Façade noise abatement prediction: new spectrum adaptation terms measured in field in different road and railway traffic conditions. *Appl Acoust* 2014; 76: 238–248.
56. Cabrera D, Holmes J, Caldwell H, et al. An unusual instance of acoustic retroreflection in architecture – Ports 1961 Shanghai flagship store façade. *Appl Acoust* 2018; 138: 133–146.
57. Pinho PG, Pinto M, Almeida RMSF, et al. Aspects concerning the acoustical performance of school buildings in Portugal. *Appl Acoust* 2016; 106: 129–134.
58. Torchia F, Ricciardi P, Scrosati C, et al. Improvement of façades' sound insulation of schools near the Bergamo - Orio al Serio International Airport: case study. *Build Acoust* 2015; 22(2): 123–142.

59. Jagniatinskis A and Fiks B. Assessment of environmental noise from long-term window microphone measurements. *Appl Acoust* 2014; 76: 377–385.
60. Dintrans A and Préndez M. A method of assessing measures to reduce road traffic noise: a case study in Santiago, Chile. *Appl Acoust* 2013; 74(12): 1486–1491.
61. Guigou-Carter C, Foret R, Wetta R, et al. Comparison of measured and predicted sound insulation for a thermal retrofitted building. *Noise Control Eng J* 2011; 59(3): 278–289.
62. Yang HS, Cho HM and Kim MJ. On-site measurements for noise reduction through open windows of classrooms with different building dispositions. *Appl Acoust* 2018; 139: 165–173.
63. Keränen J, Hakala J and Hongisto V. The sound insulation of façades at frequencies 5–5000 Hz. *Build Environ* 2019; 156: 12–20.
64. Hu ZY, Maxit L and Cheng L. Piecewise convergence behavior of the condensed transfer function approach for mid-to-high frequency modelling of a panel-cavity system. *J Sound Vib* 2018; 435: 119–134.
65. ISO 717-1:2020. Acoustics — Rating of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation. https://www.iso.org/standard/77435.html
66. Fahy FJ and Gardonio P. *Sound and structural vibration: radiation, transmission and response*. Academic Press, 2007.
67. London A. Transmission of reverberant sound through double walls. *J Acoust Soc Am* 1950; 22(2): 270–279.
68. Čechura J. Stavební fyzika 10: akustika stavebních konstrukcí, Praha, 1. vydání, ČVUT Praha, 1997.
69. Brekke A. *Sound transmission through single and double-leaf partitions (Norwegian)*. Inst. for Husbyggingsteknikk, NTH, Trondheim, Norway, 1979.
70. Rindel J. Transmission of traffic noise through windows. Report No. 9, Acoustics Laboratory, Technical University of Denmark, 1975.
71. Sharp BH. Prediction methods for the sound transmission of building elements. *Noise Control Eng J* 1978, 11(2), 53–63.
72. Blasco M and Crispin C. Geventileerde Dubbele Gevels Akoestische Evaluatie In situ en labo metingen, modelisatie en evaluatie van de toepasbaarheid van de bestaande normalisatie, Wetenschappelijk en Technisch Centrum voor het Bouwbedrijf, 2004.
73. Berardi U. The position of the instruments for the sound insulation measurement of building façades: from ISO 140-5 to ISO 16283-3. *Noise Control Eng J* 2013; 61(1): 70–80.
74. Mateus M, Dias Carrilho J and Gameiro Da Silva M. An experimental analysis of the correction factors adopted on environmental noise measurements performed with window-mounted microphones. *Appl Acoust* 2015; 87: 212–218.
75. Flores R, Asensio C, Gagliardi P, et al. Study of the correction factors for aircraft noise façade measurements. *Appl Acoust* 2019; 145: 399–407.
76. Sánchez Bote JL. Procedures to smooth the coverage of dodecahedron loudspeakers on façades according to ISO 16283-3 standard. *Appl Acoust* 2018; 131: 210–219.
77. Asensio C, Trujillo JA and Arcas G. Analysis of the effects of uneven sound coverage over a facade during a sound insulation test according to the international standard ISO 16283-3. *Appl Acoust* 2018; 130: 52–62.
78. Navacerrada MA, Pedrero A and 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.
79. Hopkins C. Revision of international standards on field measurements of airborne, impact and facade sound insulation to form the ISO 16283 series. *Build Environ* 2015; 92: 703–712.
80. Scrosati C, Scamoni F and Zambon G. Uncertainty of façade sound insulation in buildings by a Round Robin Test. *Appl Acoust* 2015; 96: 27–38.
81. Berardi U. A comparison of measurement standard methods for the sound insulation of building façades. *Build Acoust* 2012; 19(4): 267–282.
82. Sánchez Bote JL, Pedrero González A and Gómez Alfageme JJ. Procedure for verification of sound source coverage over façades according to the International Standard ISO 140-5. *Appl Acoust* 2012; 73(9): 977–985.

83. Hongisto V, Oliva D and Rekola L. Subjective and objective rating of the sound insulation of residential building façades against road traffic noise. *J Acoust Soc Am* 2018; 144(2): 1100–1112.
84. Scrosati C, Pievatolo A and Garai M. The uncertainty declaration of building acoustics measurements: how to select the uncertainty of reproducibility from inter-laboratory tests. *Acta Acust United Acust* 2018; 104(2): 295–303.
85. Wittstock V. Determination of measurement uncertainties in building acoustics by interlaboratory tests. Part 1: Airborne sound insulation. *Acta Acust United Acust* 2015; 101(1): 88–98.
86. Ryu J and Song H. Effect of building façade on indoor transportation noise annoyance in terms of frequency spectrum and expectation for sound insulation. *Appl Acoust* 2019; 152: 21–30.
87. Klæboe R, Amundsen AH, Fyhri A, et al. Road traffic noise: the relationship between noise exposure and noise annoyance in Norway. *Appl Acoust* 2004; 65(9): 893–912.
88. Attia S, Garat S and Cools M. Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades. *Build Environ* 2019; 157: 268–276.
89. Zuhaib S, Manton R, Griffin C, et al. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building. *Build Environ* 2018; 139: 69–85.
90. Asensio C, Recuero M and Pavón I. Citizens' perception of the efficacy of airport noise insulation programmes in Spain. *Appl Acoust* 2014; 84: 107–115.
91. Amundsen AH, Klæboe R and Aasvang GM. Long-term effects of noise reduction measures on noise annoyance and sleep disturbance: the Norwegian facade insulation study. *J Acoust Soc Am* 2013; 133(6): 3921–3928.
92. Jik Lee P and Griffin MJ. Combined effect of noise and vibration produced by high-speed trains on annoyance in buildings. *J Acoust Soc Am* 2013; 133(4): 2126–2135.
93. Berardi U, Cirillo E and Martellotta F. Interference effects in field measurements of airborne sound insulation of building facades. *Noise Control Eng J* 2011; 59(2): 165–176.
94. Vos J. A- and C-weighted sound levels as predictors of the annoyance caused by shooting sounds, for various façade attenuation types. *J Acoust Soc Am* 2003; 113(1): 336–347.
95. Salomons EM, Janssen SA and Verhagen HLM. Local impact assessment of urban traffic noise. *Noise Control Eng J* 2014; 62(6): 449–466.
96. Montes González D, Barrigón Morillas JM, Godinho L, et al. Acoustic screening effect on building façades due to parking lines in urban environments. Effects in noise mapping. *Appl Acoust* 2018; 130: 1–14.
97. Hothersall DC, Horoshenkov KV and Mercy SE. Numerical modelling of the sound field near a tall building with balconies near a road. *J Sound Vib* 1996; 198(4): 507–515.
98. Salomons EM, Polinder H, Lohman WJA, et al. Engineering modeling of traffic noise in shielded areas in cities. *J Acoust Soc Am* 2009; 126(5): 2340–2349.
99. Magrini A and Lisot A. A simplified model to evaluate noise reduction interventions in the urban environment. *Build Acoust* 2016; 23(1): 36–46.
100. Echevarria Sanchez GM, Van Renterghem T, Thomas P, et al. The effect of street canyon design on traffic noise exposure along roads. *Build Environ* 2016; 97: 96–110.
101. Hao Y, Kang J, Krijnders D, et al. On the relationship between traffic noise resistance and urban morphology in low-density residential areas. *Acta Acust United Acust* 2015; 101(3): 510–519.
102. Wei W, Botteldooren D, Renterghem TV, et al. Urban background noise mapping: the general model. *Acta Acust United Acust* 2014; 100(6): 1098–1111.
103. Pelat A and Lihoreau B. On the approximation of total absorption of the street open ceiling at low frequencies. *Appl Acoust* 2012; 73(8): 734–740.
104. Pelat A, Felix S and Pagneux V. A coupled modal-finite element method for the wave propagation modeling in irregular open waveguides. *J Acoust Soc Am* 2011; 129(3): 1240–1249.
105. Van Renterghem T, Salomons E and Botteldooren D. Parameter study of sound propagation between city canyons with a coupled FDTD-PE model. *Appl Acoust* 2006; 67(6): 487–510.
106. Le Pollès T, Picaut J, Bérengier M, et al. Sound field modeling in a street canyon with partially diffusely reflecting boundaries by the transport theory. *J Acoust Soc Am* 2004; 116(5): 2969–2983.
107. Picaut J, Simon L and Hardy J. Sound field modeling in streets with a diffusion equation. *J Acoust Soc Am* 1999; 106(5): 2638–2645.

108. Hornikx M and Forssén J. The 2.5-dimensional equivalent sources method for directly exposed and shielded urban canyons. *J Acoust Soc Am* 2007; 122(5): 2532–2541.
109. Heimann D. Three-dimensional linearised Euler model simulations of sound propagation in idealised urban situations with wind effects. *Appl Acoust* 2007; 68(2): 217–237.
110. Tong YG, Tang SK and Yeung MKL. Full scale model investigation on the acoustical protection of a balcony-like facade device (L). *J Acoust Soc Am* 2011; 130(2): 673–676.
111. Onaga H and Rindel JH. Acoustic characteristics of urban streets in relation to scattering caused by building facades. *Appl Acoust* 2007; 68(3): 310–325.
112. Heutschi K. Calculation of reflections in an urban environment. *Acta Acust United Acust* 2009; 95(4): 644–652.
113. Janczur R, Walerian E and Czechowicz M. Sound levels forecasting for city-centers Part III: a road lane structure influence on sound level within urban canyon. *Appl Acoust* 2001; 62(5): 493–512.
114. Kang J. Numerical modelling of the sound fields in urban streets with diffusely reflecting boundaries. *J Sound Vib* 2002; 258(5): 793–813.
115. Kang J. Numerical modeling of the sound fields in urban squares. *J Acoust Soc Am* 2005; 117(6): 3695–3706.
116. Can A, Fortin N and Picaut J. Accounting for the effect of diffuse reflections and fittings within street canyons, on the sound propagation predicted by ray tracing codes. *Appl Acoust* 2015; 96: 83–93.
117. Riegel KA and Sparrow VW. Sonic boom propagation around a large building using a combined ray tracing/radiosity method. *J Acoust Soc Am* 2019; 145(4): 2317–2327.
118. Li KM, Law MK and Kwok MP. Absorbent parallel noise barriers in urban environments. *J Sound Vib* 2008; 315(1–2): 239–257.
119. Thorsson PJ and Ögren M. Macroscopic modeling of urban traffic noise – influence of absorption and vehicle flow distribution. *Appl Acoust* 2005; 66(2): 195–209.
120. Iu KK and Li KM. The propagation of sound in narrow street canyons. *J Acoust Soc Am* 2002; 112(2): 537–550.
121. Picaut J and Simon L. A scale model experiment for the study of sound propagation in urban areas. *Appl Acoust* 2001; 62(3): 327–340.
122. Hornikx M and Forssén J. A scale model study of parallel urban canyons. *Acta Acust United Acust* 2008; 94(2): 265–281.
123. Mulholland KA. The prediction of traffic noise using a scale model. *Appl Acoust* 1979; 12(6): 459–478.
124. Jones HW, Stredulinsky DC and Vermeulen PJ. An experimental and theoretical study of the modelling of road traffic noise and its transmission in the urban environment. *Appl Acoust* 1980; 13(4): 251–265.
125. Bjelić M, Stanojević M, Šumarac Pavlović D, et al. Microphone array geometry optimization for traffic noise analysis. *J Acoust Soc Am* 2017; 141(5): 3101–3104.
126. Kephalopoulos S, Paviotti M and Anfosso-Lédée F. JRC Reference report on common noise assessment methods in EU (CNOSSOS-EU). Luxembourg: Publications Office of the European Union 978-92-79-25281-5, 2012.
127. Wang X, Mao D, Yu W, et al. Acoustic performance of balconies having inhomogeneous ceiling surfaces on a roadside building facade. *Build Environ* 2015; 93(P2): 1–8.
128. Wang X, Yu W, Zhu X, et al. Effects of ceiling phase gradients on the acoustic environment on roadside balconies. *J Acoust Soc Am* 2017; 141(2): EL146–EL152.
129. de Araújo BCD and Bistafa SR. Façade elements for natural ventilation and sound insulation. *Build Acoust* 2012; 19(1): 25–43.
130. Ishizuka T and Fujiwara K. Full-scale tests of reflective noise-reducing devices for balconies on high-rise buildings. *J Acoust Soc Am* 2013; 134(2): EL185–EL190.
131. Ishizuka T and Fujiwara K. Traffic noise reduction at balconies on a high-rise building façade. *J Acoust Soc Am* 2012; 131(3): 2110–2117.
132. De Salis MH, Oldham DJ and Sharples S. Noise control strategies for naturally ventilated buildings. *Build Environ* 2002; 37(5): 471–484.
133. Naticchia B and Carbonari A. Feasibility analysis of an active technology to improve acoustic comfort in buildings. *Build Environ* 2007; 42(7): 2785–2796.

134. Fausti P, Secchi S and Zuccherini Martello N. The use of façade sun shading systems for the reduction of indoor and outdoor sound pressure levels. *Build Acoust* 2019; 26(3): 181–206.
135. Pàmies T, Romeu J, Genescà M, et al. Active control of aircraft fly-over sound transmission through an open window. *Appl Acoust* 2014; 84: 116–121.
136. Jessop AM, Li KM and Bolton J. Reduction of low frequency noise transmitted through a single-pane window. *Acta Acust United Acust* 2011; 97(3): 382–390.
137. Yu X. Design and in-situ measurement of the acoustic performance of a metasurface ventilation window. *Appl Acoust* 2019; 152: 127–132.
138. Badino E, Manca R, Shtrepi L, et al. Effect of façade shape and acoustic cladding on reduction of leisure noise levels in a street canyon. *Build Environ* 2019; 157: 242–256.
139. Van Renterghem T and Botteldooren D. The importance of roof shape for road traffic noise shielding in the urban environment. *J Sound Vib* 2010; 329(9): 1422–1434.
140. Hornikx M and Forssén J. Noise abatement schemes for shielded canyons. *Appl Acoust* 2009; 70(2): 267–283.
141. Santoni A, Bonfiglio P, Mollica F, et al. Vibro-acoustic optimisation of wood plastic composite systems. *Constr Build Mater* 2018; 174: 730–740.
142. Ibrahim M, Nocentini K, Stipetic M, et al. Multi-field and multi-scale characterization of novel super insulating panels/systems based on silica aerogels: thermal, hydric, mechanical, acoustic, and fire performance. *Build Environ* 2019; 151: 30–42.
143. Fusaro G, Yu X, Kang J, et al. Development of metacage for noise control and natural ventilation in a window system. *Appl Acoust* 2020; 170: 107510.
144. Pérez G, Coma J, Barreneche C, et al. Acoustic insulation capacity of Vertical Greenery Systems for buildings. *Appl Acoust* 2016; 110: 218–226.
145. Van Renterghem T. Improving the noise reduction by green roofs due to solar panels and substrate shaping. *Build Acoust* 2018; 25(3): 219–232.
146. Davis MJ, Tenpierik MJ, Ramírez FR, et al. More than just a Green Facade: the sound absorption properties of a vertical garden with and without plants. *Build Environ* 2017; 116: 64–72.
147. Van Renterghem T, Hornikx M, Forssen J, et al. The potential of building envelope greening to achieve quietness. *Build Environ* 2013; 61: 34–44.
148. Van Renterghem T and Botteldooren D. Reducing the acoustical façade load from road traffic with green roofs. *Build Environ* 2009; 44(5): 1081–1087.
149. Jang HS, Lee SC, Jeon JY, et al. Evaluation of road traffic noise abatement by vegetation treatment in a 1:10 urban scale model. *J Acoust Soc Am* 2015; 138(6): 3884–3895.
150. Yang HS, Kang J and Cheal C. Random-incidence absorption and scattering coefficients of vegetation. *Acta Acust United Acust* 2013; 99(3): 379–388.
151. Jang HS, Kim HJ and Jeon JY. Scale-model method for measuring noise reduction in residential buildings by vegetation. *Build Environ* 2015; 86: 81–88.
152. Zhao XI and Vlahopoulos N. A hybrid finite element formulation for mid-frequency analysis of systems with excitation applied on short members. *J Sound Vib* 2000; 237(2): 181–202.
153. van Hal B, Desmet W and Vandepitte D. Hybrid finite element—wave-based method for steady-state interior structural–acoustic problems. *Comput Struct* 2005; 83(2-3): 167–180.
154. Hu Z, Maxit L and Cheng L. Mid-to-high frequency piecewise modelling of an acoustic system with varying coupling strength. *Mech Syst Signal Process* 2019; 134: 106312.
155. Maxit L and Guyader JL. Estimation of sea coupling loss factors using a dual formulation and fem modal information, part I: theory. *J Sound Vib* 2001; 239(5): 907–930.
156. Maxit L and Guyader JL. Estimation of sea coupling loss factors using a dual formulation and fem modal information, part II: numerical applications. *J Sound Vib* 2001; 239(5): 931–948.
157. Bernhard RJ and Huff JE. Structural-Acoustic Design at high frequency using the energy finite element method. *J Vib Acoust* 1999; 121(3): 295–301.
158. Cotoni V, Shorter P and Langley R. Numerical and experimental validation of a hybrid finite element-statistical energy analysis method. *J Acoust Soc Am* 2007; 122(1): 259–270.

159. Vergote K, Van Genechten B, Vandepitte D, et al. On the analysis of vibro-acoustic systems in the mid-frequency range using a hybrid deterministic-statistical approach. *Comput Struct* 2011; 89(11-12): 868–877.
160. Yang C, Cheng L and Hu Z. Reducing interior noise in a cylinder using micro-perforated panels. *Appl Acoust* 2015; 95: 50–56.
161. Yang C and Cheng L. Sound absorption of microperforated panels inside compact acoustic enclosures. *J Sound Vib* 2016; 360: 140–155.
162. Yu X, Cheng L and Guyader JL. Modeling vibroacoustic systems involving cascade open cavities and micro-perforated panels. *J Acoust Soc Am* 2014; 136(2): 659–670.
163. Zhang X and Cheng L. Acoustic impedance of micro-perforated panels in a grazing flow. *J Acoust Soc Am* 2019; 145(4): 2461–2469.
164. Bacigalupo A, Gnecco G, Lepidi M, et al. Machine-learning techniques for the optimal design of acoustic metamaterials. *J Optim Theory Appl* 2019; 1–24.
165. Zheng B, Yang J, Liang B, et al. Inverse design of acoustic metamaterials based on machine learning using a Gauss–Bayesian model. *J Appl Phys* 2020; 128(13): 134902.
166. Zhao T, Li Y, Zuo L, et al. Machine-learning optimized method for regional control of sound fields. *Extreme Mech Lett* 2021; 45: 101297.