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Seeking the Nexus Between Building Acoustics and Urban Form: A Systematic Review

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Abstract

Purpose of Review Noise is penetrating urban life pervasively and is imperative for demonstrating the factors behind it regarding built environment, aka buildings and urban form. So, this review aims to provide a better understanding of the association between building acoustics and urban form characteristics.

Recent Findings There is a growing attention for building acoustics, including materials and simulation aspects with various increasing urban form attributes, i.e., the built and natural environment and transportation.

Summary Building acoustics is a key aspect of urban life and falls within the interface of various urban form characteristics. While these two main attributes are not sufficiently addressed, they may adversely affect individuals; thus, all the more reason to explore this nexus. This study has evaluated 67 peer-reviewed journal articles after systematically reviewing the triple resources in assessing building acoustics and urban form between 2016 and 2022. This review separates the indoor and outdoor categories within the simulation, theory, building materials, facade, and the built environment sub-categories. The study does not only review the overall scope of present studies but also direct future directions of their associations.

Keywords Building · Acoustics · Urban form · Noise · Sound

Introduction

More than half of the world's population will reside in cities by 2050. While this pattern increases the urbanization rate, unemployment, food security, public health, and migration concerns, it will expectedly yield intended and unintended consequences, including impacts on air and noise. More than half of the individuals will be inevitably exposed to higher noise levels in urbanized areas, causing with multiple socio-psychological and physiological consequences.

People residing both indoors and outdoors within various urban forms, remain vulnerable and exposed to noise regardless of location and time of day. Various sampling techniques and applications help understand the impacts of noise exposure. As a subsidiary of physics, acoustics and other core sciences can help measure various parameters of noise including in-situ measurements, simulations, experiments, and modeling for data collection. Yet seen differently and associated with human preferences and perception, individuals comprise the research subjects who constitute 'preferred' acoustic environments with varying individual differences.

Different urban forms, also affect human life with noise-related parameters/variables. Urban forms comprise characteristics such as streets, roads, buildings, land uses, and so on, where each attribute impacts noise levels. These features range from road lengths and widths, speed limit, construction sites, building type –commercial, residential etc.-, building geometry, height, façade design, indoor and outdoor materials to single or mixed land use. All these features are associated with building acoustics. However, no study has systematically assessed the nexus between building acoustics and urban form characteristics.

This paper aims to fill this gap in the literature by reviewing building acoustics in various contexts, as the concept mainly pertains to indoor and outdoor urban characteristics.

This article is part of the Topical Collection on *Noise Pollution*

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Methods

Study Protocol

The study has conducted a systematic overview of the literature.

Search Principle

Since the study includes most recent narratives, it covers the 2016–2022 period. The study started off on January 1st, 2016, and lasted until April 30th, 2022. The initial search started within various electronic databases, including Scopus, ScienceDirect, and Google Scholar, and only covered published journal articles and excluded conference papers, proceedings, as well as magazines, and project reports. The study aimed to explore the linkage between building acoustics and urban form contexts utilizing the following search words in the aforementioned databases: 'building acoustics', 'acoustics and urban', 'building acoustics and urban form', 'sound and urban form', 'noise and urban', 'noise and urban form'. These words were extracted in title and abstract of studies initially and all researchers involved this process.

Search Extraction

The initial search result identified 149 published journal articles, after removing duplicates ($N = 127$), and assessing the keywords within the titles or abstracts. The next stage included 107 full-text articles 34 of which were excluded from further consideration due to lack of information on building and urban form-related variables. In the final process, three articles turned out to fall outside the scope of the study as the body of the literature did not include building and particularly urban form variables even though the title and/or the abstract affirmed such contexts. At the final stage, three more studies were excluded from indoor-related categories. Eventually, 67 journal articles made the cut out of which 10 covered the indoor-related categories and 57 outdoor-related articles. All researchers assessed the abstracts and complete versions of the articles while removing some sub-categories for reaching consensus.

The assessment criteria included the publication year, indoor vs. outdoor relevancy, research method, both indoors and outdoors sub-categories, and specific additional variables. Eventually, the study included two main categories and eight specific sub-categories of building acoustics. The sub-categories of indoor building acoustics included: building materials, simulation/VR, and theory while outdoor building acoustics included: building material/geometry, facade, built environment (this is the only category with sub-categories), simulation/VR, and theory.

Results

At a Glance

Table 1 shows all 67 articles included in this study in chronological order. Indoor attributes of building acoustics within the search protocol gradually decreased over the last six years, while showing an increase in 2020. Looking at the outdoor-related building acoustic publications, there has been somehow consistency over the last six years.

Indoor-Related Factors in Building Acoustics

10 studies out of 67 were included within the indoor-related category for the last six years of building acoustic studies.

Simulation, Estimation, and Virtual Reality

Three studies examined indoor-related simulations and virtual reality. In one of the earlier studies, Chetoni et al. [1] created a web-oriented application for collecting noise data among schools by increasing the school stakeholders' (i.e., students, parents, teachers, and administrators) awareness. The app simply gathers acoustic information from classrooms to assess various parameters that might be helpful in designing better educational facilities. To create such app, the authors used building –related attributes, i.e., façades and wall as well as urban structures surrounding education facilities, i.e., locating urban/suburban and different types of roads. In another study, Hou et al. [2] modeled a 3D ray tracing method to understand the reflections of the traffic noise. The study also assessed several parameters and found the method's validity about 1.68 dB for indoors. Finally, the study reported that vehicle speed, vehicle size, and traffic signal phase have impacts on the model. Particularly, the traffic during the red light causes 20 dB quieter urban areas. Jeon and Jo [3] performed research on noise propagation of virtual reality by using head-related transfer function (HRTF) and head-mounted display (HMD) to examine indoor residential buildings by using four combinations: with HRTF and HMD and without HRTF or HMD, and both techniques combined. Identifying the traffic noise turns out to be the highest with HRTF, while the space shows the highest level with HMD. So, the study contributes to urban-related factors of specific noise characteristics.

Theory

Other studies theorized some aspects of indoor acoustics. Schiavi et al. [4] conducted a literature review of the comfort context inside the buildings. To do this, they proceeded with theoretical and empirical literature assessments and

Table 1 Summary of studies for building acoustics and urban form

I/O	Category	Reference	Research design	Location	Key aspect(s)
Indoor	Simulation	Chetoni et al. [1]	App-based (GIOCONDA)	Italy	■ Acoustic performans of education facilities ■ A new noise index was proposed ■ Noise is a critical issue in schools ■ Urban/Suburban and road matters for noise
	Simulation	Hou et al. [2]	3D ray tracing	China	■ The method is effective with almost 2 dBA error ■ Speed limit, heavy vehicle, and signal duration are significant factor for noise levels ■ Traffic during red light causes 20 dB noise reduction
	Simulation	Jeon and Jo [3]	Virtual reality	N/A	■ Traffic noise identification is better with HRTF ■ Place identification is better with HMD ■ Urban-related factors define noise specifics
	Theory	Schiavi et al. [4]	Literature review	N/A	■ Comfort and discomfort on historical buildings over decades
	Theory	Yilmazer and Acun [5]	Mixed-method	Turkey	■ Theory application on individuals for indoor sound assessment ■ Outdoor noise affects and mixes indoor sounds
	Theory	Aburawis and Dokmeci Yorukoglu [6]	Literature review	N/A	■ Proposing a post-occupancy evaluation framework ■ Architectural features i.e., form and circulation were included
	Theory	Torresin et al. [7]	Structured interview	N/A	■ Identified well-being and QoL ■ Provacative soundscape directions ■ Facade, ventilation, building structure and amenities are related to healthy building design
	Building mat/shape/geo	Zhao et al. [8]	SPL and reverberation time (T_{30})	China	■ Length, height, skylight and slope has effects on SPL and T_{30} in atria of shopping centers ■ An increase in length and height particularly decreases SPLs
	Building mat/shape/geo	Wang and Du [9]	SPL	N/A	■ Acoustic performance of different materials on floor ■ Thickness, density, loading status, percantage of insulation materials significant on acoustic performance

Table 1 (continued)

I/O	Category	Reference	Research design	Location	Key aspect(s)
	Building mat/shape/geo	Sentop Dumen and Tamer Bayazit [10]	Mixed-method (Various SPL and survey)	Turkey	■ Higher SPL values show association with the residents' annoyance
	Simulation	Hornikx [11]	Literature review (10 questions)	N/A	■ Pros and cons of computational methods and modeling on acoustics
Outdoor	Simulation	Lesieur et al. [12]	Noise modeling software	France	■ The model showed a small error with faster computation time
	Simulation	Hong et al. [13]	Construction noise prediction model	South Korea	■ The model has 35% better prediction than general model
	Theory	Luzzi et al. [14]	Overview	N/A	■ Sustainability and smart city aspects of acoustics
	Theory	Morillas et al. [15]	Literature review	N/A	■ Urban planning and particularly traffic noise
	Theory	Jablonska [16]	Case study	Japan	■ Noise policy and design aspects
	Building mat/shape/geo	Han et al. [17•]	Noise sampling	China	■ Spatial distribution of building density
	Building mat/shape/geo	Paszkowski and Sobiech [18]	Noise sampling (Noise mapping)	Poland	■ Floor space index, number of buildings and building proportions showed negative correlations with noise data
	Building mat/shape/geo	Verma et al. [19]	Aural and visual data collection	India	■ Auditory and visual data may result in better urban representations
	Building mat/shape/geo	Verma et al. [20]	Mixed-method (Deep learning and survey)	India	■ Spatioperceptual understanding between individuals and auditory/visual clips
	Building mat/shape/geo	Margaritis et al. [21]	Mixed-method (Noise mapping and survey)	The U.K	■ Building density increases the noise levels
	Building mat/shape/geo	Zytoon [22]	Noise sampling and modeling	The Kingdom of Saudi Arabia	■ Building height, type, and geometry has association with noise levels
	Building mat/shape/geo	Sanchez et al. [23]	Finite-difference-time domain calculation method	N/A	■ Building shape may cause 7 dBA noise level difference ■ Facade design may cause 12 dBA
	Building mat/shape/geo	Huang et al. [24]	Noise sampling both horizontally and vertically	China	■ High-rise buildings are affected at different scale from traffic noise levels
	Building mat/shape/geo	Flores et al. [25]	Noise sampling (Single event level)	Spain	■ Line of sight angle and facade have significant effects on aircraft noise levels
	Building mat/shape/geo	Wang et al. [26]	Noise exposure model	China	■ One third of POIs are exposed to higher noise ■ Traffic is liason for 5 dBA noise level difference

Table 1 (continued)

I/O	Category	Reference	Research design	Location	Key aspect(s)
	Building mat/shape/geo	Yuan et al. [27]	Noise sampling and statistical analyses	China	■ Forest areas are more effective on noise reduction than grassland ■ Building areas are more effective than building lands
	Building mat/shape/geo	Fan et al. [28]	Noise complaint assessments	Singapore	■ Building age and number of floors did not show any association with noise complaints
	Building mat/shape/geo	Gevú et al. [29]	Noise measurement and mapping	Brazil	■ Building height reduces the noise levels
	Building mat/shape/geo	Galindo et al. [30]	Experiment	Spain	■ Temporal, energy, and spatial acoustic performance of historic places ■ All parameters of acoustics indicate normal patterns
	Building mat/shape/geo	Sukaj et al. [31]	Noise sampling (Impulse response)	Albania	■ The geometry of buildings may cause speech understanding concern
	Building mat/shape/geo	Van Renterghem [32]	Finite-difference time domain modeling	N/A	■ Green roof results in 3 dBA noise level reduction ■ With solar panel of different materials it may reduce 5 dBA noise level
	Building mat/shape/geo	Paull et al. [33]	Noise sampling	Australia	■ Green walls decrease noise levels while there was not significant difference statistically
	Facade	Zhou et al. [34]	Noise sampling	China	■ The facade of high-rise and small plan buildings include the highest noise levels
	Facade	Qu and Kang [35]	Noise sampling	The UK	■ Distance to wind turbine affects the façade noise levels
	Facade	González et al. [36]	Noise modeling (Boundary element method)	N/A	■ There is significant difference for facade noise level over 4 m building height
	Facade	Sotiropoulou et al. [37]	Noise modeling	Greece	■ High-rise buildings increase façade noise levels
	Facade	De Bort and Beckers [38]	Noise modeling	N/A	■ Facade noise levels are highly related to building geometry
	Facade	Meza et al. [39]	Noise sampling	Chile	■ Opening and closing windows may cause facade noise level increase
	Facade	Fausti et al. [40]	Noise sampling	N/A	■ Shading materials affect facade noise levels
	Facade	Cabrera et al. [41]	Noise sampling	USA, Australia, Hong Kong	■ Cross-national study shows that geometry of buildings is significant on façade acoustics

Table 1 (continued)

I/O	Category	Reference	Research design	Location	Key aspect(s)
	Facade	Forssén et al. [42]	Noise sampling	Sweden	■ Single side and U-shape buildings show better facade performance in terms of acoustics
	Facade	Akdag et al. [43]	Noise sampling	Turkey	■ Linear type blocks increase the facade noise
	Facade	Gramez et al. [44]	Noise sampling	Algeria	■ Acoustic insulation of facade is not enough for Algeria's policy and regulation
	Facade	Calleri et al. [45]	Noise modeling software	Italy	■ Positioning of individuals highly affects the facade noise perception
	Facade	Camara et al. [46]	Noise sampling and Survey	Mali	■ The window and door openings increase the aircraft noise
	Built environment	Micheli and Farne [47]	Noise modeling and survey	Italy	■ Individuals tend to trade-off 15 dbA for noise reduction
	Built environment	Gozalo et al. [48]	Noise mapping	Spain	■ The model showed high accuracy with low error
	Built environment	Magrini and Lisot [49]	Noise modeling	N/A	■ Simpler building geometry with narrow road structure reduces noise levels
	Built environment	Hupeng et al. [50••]	Noise modeling	China	■ C-shaped building and narrow road reduces noise levels
	Built environment	Margaritis and Kang [51]	Noise modeling	Various European cities	■ Porosity and green space decrease noise levels
	Built environment	Ryu et al. [52]	Noise sampling	South Korea	■ GSI, FSI, traffic and density affect noise levels
	Built environment	Silva et al. [53]	Mixed-method	Portugal	■ Road traffic noise affects the perception of students
	Built environment	Bilasco et al. [54]	Noise mapping	Romania	■ Land use and DEM particularly significant for noise levels
	Built environment	Yu and Kang [55]	Noise mapping	China	■ Landscape-matrix is more significant among other parameters on noise levels
	Built environment	Guo et al. [56]	Noise modeling	Hong Kong	■ High-rise cities increase noise levels
	Built environment	Park et al. [57]	Noise modeling	South Korea	■ GSI, FSI, and street typologies increase noise levels
	Built environment	Wang et al. [58]	Noise modeling	N/A	■ Positioning building affects the noise levels
	Built environment	Yildirim and Arefi [59]	Noise sampling	USA	■ Land use and building density increase noise levels
	Built environment	Ascigil-Dincer and Demirkale [60]	Noise modeling	Turkey	■ A complex model is important to model noise levels

Table 1 (continued)

I/O	Category	Reference	Research design	Location	Key aspect(s)
	Built environment	Li and Xie [61]	Noise modeling	China	▪ Rectangle shape reduces and slope increases noise levels
	Built environment	Kim et al. [62]	Noise modeling	South Korea	▪ Traffic volume and road density increases noise levels
	Built environment	Hong and Jeon [63••]	Noise sampling and survey	South Korea	▪ Soundscapes –water,green space- of urban life are important to consider
	Built environment	Yu and Kang [64]	Noise modeling	China	▪ Street geometry is the most important feature for noise levels
	Built environment	Lee et al. [65]	Noise modeling	Singapore	▪ Vibration is significant for construction sites
	Built environment	Silva et al. [66]	Noise modeling	Portugal	▪ Sky view factor increases the noise levels
	Built environment	Alvares-Sanches et al. [67]	Noise modeling	The UK	▪ Machine learning method might be used for noise levels

identified individuals' reactions, such as disturbance and behavioral changes. The study obtained the key vibration sources of buildings caused by the industrial and transportation-related factors. Yilmazer and Acun [5] used the grounded theory as a framework for assessing the indoor acoustics of a historical mosque and gathered participants' responses on the surrounding acoustic environment and found that indoor and outdoor sounds are mixed with noise from streets and vendors. Thus, this condition does not offer unique indoor and outdoor acoustic environments. Aburawis and Dokmeci Yorukoglu [6] created a theory-based framework for applying post-occupancy evaluation (POE) of sounds by conducting a systematic review. Based on this, six sound typologies emerged within five key experiential characteristics. The study matched these typologies and characteristics to understand the key stages of the POE context and included architectural features i.e., form, circulation, and proportion in the proposed framework. From another angle, Torresin et al. [7] addressed the association between indoor acoustics and residents' health and well-being by posing thematic discussion with experts in the context of health-related sound. The study puts forward arguments on healthy building design strategies as well as the harmony between anticipated and actual indoor experience. Based on experts, facade design, ventilation, building configuration, and amenities play key roles on health buildings. Eventually, the study directs the importance of noise control applications and strategies.

Building Material/Shape/Geometry

Indoor-related building acoustics were mainly assessed in the building materials and shapes in regards to the urban form context., Zhao et al. [8] assessed the atria of various commercial areas by examining the geometric parameters, i.e., length, height, the proportion of length to width, skylight portion, and slope. The authors ran several computer-based simulations including sound pressure levels and reverberation times, and found that an increase in length and/or height decreases the SPL and mix effects on reverberation time. Furthermore, an increase in length to width proportion decreases the SPL with reverberation time decreasing. Another study identified acoustic absorption. Wang and Du [9] conducted a theory-based study on reinforced residential buildings to understand the performance of sound insulation on several key variables, including floor type, thickness, density, elasticity, and so on.. 40 mm thickness along with denser materials shows greater sound insulation. Furthermore, theoretical application of the study area shows up to 5 dBA difference compare to the experimental version. The study also contributed to building acoustics in terms of sound and insulation performance.

Only one study used a mixed-methods approach by defining residents' indoor acoustic preferences. Sentop Dumen and Tamer Bayazit [10] examined the acoustic performance of residential units by both sound level sampling in six buildings and surveying 136 residents. The study incorporated noise concerns regulations for building acoustics in particular with façade design and building insulation.

Outdoor-Related Factors in Building Acoustics

Simulation

Three studies examined the simulation of outdoor-related building acoustics. In an earlier study, Hornikx [11] highlighted the computational model options for building acoustics in an urban environment by using the pros and cons of different ideas including noise mapping and other simulation and modeling solutions. The study also forecasted the future of the buildings' acoustic modeling by pointing out the importance of virtual reality (VR) and incorporating auditory sense with other senses. That study offers key engineering aspects with themes from'10 questions' surrounding the importance of sound predictions and computations. Lesieur et al. [12] created noise maps with the Noise Modelling software and obtained statistical output in Lorient, France, using the Kriging method. That study found the method considerably faster than the other models by testing physical modeling, with a 1.58 dB mean error. In other words, the study required 2,000 simulations for making such conclusions while it turns out much faster than the other noise map modeling techniques. In the latest and more specific prediction study, Hong et al. [13] showed how to control noise during building construction acoustics, and performed a promising aspect in terms of accuracy with the general model (at about 35% improvement), by including construction noise data and the residents' exposure to noise. By doing so, the study called attention to construction companies and the individuals involved.

Theory

To understand the sustainability context relative to building acoustics for smart cities, Luzzi et al. [14] examined acoustics and assessed the individuals' preferences and awareness in a participatory approach. However, it did not perform any qualitative or quantitative research design to relay its core message. Rather, it remained at the policy and regulation suggestion level. In the same year, Morillas et al. [15] expanded the noise and acoustics in urban planning by focusing on a broad range of issues from trafficand urban land use, to street typologies, and so on, and reviewed dozens of studies. Furthermore, urban noise has been examined within various scales ranging from small sampling points to modeling the whole city. The study also offers a snapshot of new fields, i.e., urban morphology, green spaces, parking lanes, car parking areas, traffic signals etc. [15]. Jablonska [16] highlighted noise as a negative anomaly that needs to be addressed in policy and design aspects, and specifically concentrated on Tokyo, Japan, compared to other regions for the public and private sector solutions.

Building Material/Shape/Geometry

Outdoor-related features of this context might be included within three categories; density, type-shape-geometry, and specific units of buildings.

Some studies concentrate on density in terms of the number of buildings. Han et al. [17•], for instance, examined China's urban morphological configurations based on noise levels. The study incorporated different factors, including nighttime light density, land surface temporal conditions, traffic features, and so on, and found positive associations between building density and environmental noise levels. On top of that, the authors found negative association between building density and noise level in spatial distribution compared to spatially concentrated settings. The study reported some key associations both for environmental and transportation-related noise factors. In another study, Paszkowski and Sobiech [18] calculated urban noise factors by using GIS. Operationalizing entropy, diversity, and transport data, the study mainly used building factors, such as floor space index, number of buildings, land cover, and building proportions, by using the neural network technique. Based on the study, building variables showed negative correlations with noise data. Perhaps using hexagonal fields to assess the noise indicators in different categories became one of its primary feature.

Zooming out on both the auditory and visual aspects, Verma et al. [19] compiled the visual and auditory information from the streets in Mumbai, India and used time-related data from streets with smartphone camera and audio recorders. Calculating several variables and algorithms, it used the number of buildings on streets, and found that buildings play key roles in relation to higher noise levels. The same authors also conducted a research a year later on individual perceptions of visual and auditory environments [20]. Using a method similar to their previous study, they recruited 73 participants and evaluated their perceptions on several audio and video clips. Based on the participants' perception, audio clips were identified as significantly related to the following factors: pleasant, calm, vibrant, chaotic, and eventful. On the other hand, transportation-related attributes showed no significance. While these two studies offer promising planning tools for visual and aural data collection and interpretations, they still need multi-disciplinary platform to generation a comprehensive understanding.

In the last study in this category, Margaritis et al. [21] assessed the land use-related factors on noise by having a mixed-methods approach. They performed a noise sampling as well as surveyed 20 participants. Then, statistical analyses were performed and found density to have key roles on building-related attributes. As expected, the results showed that residential land uses include lower noise level compared to industrial and commercial ones.

Beyond density, other studies examined building types, shapes, and geometry specifics. Many studies fit in this building material/shape/geometry category. Using transportation and built environment data along with building information, i.e., building geometry, number of floors, and building type (residential or commercial), Zytoon [22] studied environmental noise by considering several urban characteristics in Saudi Arabia, and created noise maps of three-day times. The study found building height, complex geometry, and commercial type of use positively affecting the noise levels. The results recommend using noise modeling application and computation for noise mitigation purposes. Sanchez et al. [23] investigated the street and building geometries on road traffic noise. Using CNOSSOS spectra parameters for a two-lane road with more than forty cases, they showed how building shape may result in 7 dBA variations on noise exposure and by designing building facades and other building attributes, showed an almost 13 dBA difference. So, building geometry and facade design should be specifically considered for streetscape design and planning.

Huang et al. [24] specifically assessed China's noise levels and building height, where the key aim was modeling and understanding noise patterns for high-rise apartments adjacent to highways. To do this, by sampling noise on different floors, they identified the factors affecting it, and eventually, created a noise estimation pattern based on the neural network technique. While the model was confirmed in terms of statistics, the study results highlighted that building heights between 12–24 m and over 54 m show better acoustics environments than other height variations. These findings shed light on the traffic-related factors on high-rise building construction regarding noise propagation. From the aviation noise point of view, Flores et al. [25] addressed the nexus between aircraft noise and urban form, and examined street features, building positioning, facade details, and the combination thereof in Madrid, Spain. Their findings showed that a higher line of sight for buildings correlates with noise level. So, the study results call specific attention on the building locationing and other factors regarding aircraft activities.

On a more general level, Wang et al. [26] examined the association between points of interest (POIs) and noise exposure in Guangzhou, China. Having several building criteria including type, use, distribution as well as interrogating with traffic factors, they found almost one-third of such buildings exposed to higher noise levels. As an interesting finding, the study demonstrates that the majority of people, as expected, do not consider urban form-related traffic noise as annoyance.Yuan et al. [27] examined the land cover, land use, urban form factors, and noise by performing various statistical analyses, including correlations and multiple linear regressions. Based on this, grassland use impacts noise less than forest areas. Also, high density and high-rise buildings impact noise levels most, while residential buildings are more effective for decreasing noise levels. Finally, while the study found the generic aspects of denser building areas creating more noise, specific results show that larger building footprints and multiplex shapes seem more effective in noise reduction.

Fan et al. [28] explored whether a proposed bus direction affects noise complaints in Singapore and included factors such as building age and number of floors. However, none of those variables showed significance on the impacts of the bus route on noise complaints. The findings call attentions on massive noise exposure near transportation-related communities. Gevú et al. [29] compared noise level in pre- and during the COVID-19 pandemic and related comparative factors in Rio de Janeiro, Brazil, and compromised several noise maps based on the noise datasets and related variables. The study found a ten dBA reduction during the COVID-19 period, with the building height as a variable in noise level reduction. It also demonstrated that half reduction on traffic density caused 3–5 dBA lesser noise.

Some other studies examined this category in historic places. Galindo et al. [30] assessed the historical Roman theaters in Spain for building acoustic performance to understand how several acoustic parameters operate in terms of temporal and spatial aspects. Sukaj et al. [31] examined five Byzantine churches in Albania in terms of acoustic performance by having building variables, including roof material and morphology as well as building features. They found that slight concerns about individuals' conversations and building shape and height significantly affect acoustic environments. Both studies show how historical places were designed and planned by factoring in the sound attributes in different geographies.

This last category in this section examined studies that focused on building components, i.e., roof and wall. Van Renterghem [32] assessed the noise absorption effects of green roofs, and found that green roofs reduce noise levels up to three dBA compared to non-green traditional roofs. They also examined the solar panel effects, and provided up to 5 dBA reduction on noise as some materials in solar panels show sufficient absorption capability. Paull et al. [33] investigated the buildings with green walls on noise levels along with other parameters, including particulate matter and temporal circumstances. The study performed analyses on twelve green walls over a half-year period. While other parameters did not significantly differ, noise levels were significantly lower in those buildings. The study proposed pre-installed green wall ideas on buildings for better acoustic performance. So, green materials show significant performance on noise reduction no matter where they are used, including roofs, facades, or walls.

Facade

To gain a better understanding, facade and building acoustics are divided into three key categories: facade noise prediction, on-site measurements, and mix methods.

As regards noise prediction, Zhou et al. [34] generated noise maps for traffic noise in several types of buildings in China, and found that buildings with high-rise and small footprints have the highest noise levels in facades. Also, the parking lot area showed a negative association with the noise from building facades, while the floor space index shows a positive relationship. The study findings highlight how architectural form and traffic noise considerations affects building façades particularly in small buildings with novel and effective urban planning methods. Using statistical analysis, Qu and Kang [35] investigated the wind turbine noise on building facades in the UK. They assessed how various distances in the wind turbines better explaned the noise associated with particular façade conditions. The study demonstrated that a quiet façade with various urban configurations, i.e., building orientation, length, and shape might reduce noise to about 13 dBA. González et al. [36] assessed the effects of street noise in building facades with the Boundary Element Method (BEM), and distinguished the screen effects of various heights of materials in parking spaces. The study findings associated urban street patterns with building traffic noise regarding noise levels on facades. In another study, Sotiropoulou et al. [37] explored the interface between high-rise buildings, road noise, and estimation technique in Athens, Greece. To do this, they included the vertical aspects of building facades as tools for creating noise mapping and predictions. The vertical noise mapping prediction showed 2.2 dBA lower than the actual noise sampling, and therefore the study concludes that this method might be useful for measuring the noise effect of facades on high-rise buildings. Finally, De Bort and Beckers [38] assessed the noise effects on walls by using the ray tracing method for three scenarios. The study found about 6 to 11 dB difference on various facades and referred to understanding street and facade ratios for noise levels. Eventually, the study results identified that noise reflections are highly related to geometry and such method may offer both auditory and visual representations.

Considering on-site measurements, Meza et al. [39] experimented building acoustics insulation of facades in Santiago, Chile. By using international ISO 140–5 standards, theyused several cases, including opening/closing positions of windows as well as the type of glass and found that insulation curtails the noise levels at about 2.4 dBA. The study findings place emphasis on how building materials affect noise reduction. Fausti et al. [40] examined shading equipment effects on indoor and outdoor acoustic environments. To perform the study, the shading equipment included some sound absorption textures and was attached to building façade. The material proved effective up to 20 m adjacent to the building. The study demonstrated that attaching additional materials to façade improves noise insulation on buildings.

From a different geographical perspective, Cabrera et al. [41] performed a cross-national study in the USA, Australia, and Hong Kong and measured the effects of corner cube materials on building façade acoustics. The authors used more than four hundred materials within three study areas. Having acoustic measurements of each site, the study found that sound reflection is higher than geometric estimations. The study findings made interesting points on how reflections on façades might prove useful in building acoustics. Finally, Forssén et al. [42] examined 31 urban configurations, including vegetation surfaces on various facades and roofs. The study measured facade noise levels at L_{den} and L_{night} parameters, where single-sided flats showed better acoustic performance as well as U-shaped structures. Vegetation as expected proved to dramatically reduce the noise levels on both facades and roofs.

Some studies conducted a mixed-methods approach on the last category (facade and building acoustics). Akdag et al. [43] evaluated 25 mass housing structures and their facades within different road types. They both used simulation and on-situ sound sampling techniques on linear type blocks facades and reported the highest noise levels while open spaces showing the lowest. The study proposed using noise barriers in required and sensitive locations around public housing and warned about the nexus between noise barriers and building heightsSimilarly, Gramez et al. [44] examined the multiplex social housing and acoustic performance using on-site noise measurements in Algeria, and identified the noise insulation on facades and proposed some noise regulations in the specific case of Algeria where housing options do not provide suitable acoustic building environments. The results represent facade and noise policies in developing countries.

Calleri et al. [45] also conducted a mixed-method approach to understanding the facade design of building acoustics by creating simulation models with ODEON software and the perception and preference of the individuals in Turin, Italy. Various absorption and reflection circumstances, i.e., materials for objective and subjective approaches were applied to facades. The study concluded that individual positioning for facade assessment affects noise parameters and perceptions. Last but not least, Camara et al. [46] studied the airport noise exposure on the surrounding buildings by conducting an experiment on building units in Mali, and measured the inhabitants' perceptions in them. The study found that opening outdoor, including windows and doors, has significant impacts on noise along with the noise insulation materials and techniques. So, perhaps building construction should take advantage from the results of the study.

Built Environment/Tranportation/Land Use

Most studies on building acoustics and urban form pertain to built environment features. This category, in turn, involves three key sub-categories: transportation and traffic, street geometry, and others.

Transportation and Traffic

Micheli and Farne [47] analyzed the railway traffic noise implications on community well-being where their primary purpose was to identify the trade-off value between annoyance and cost of interaction. The authors conducted a case study approach in Milan, Italy, by considering different parameters, i.e., building variables, rail traffic, and the production cost of noise barriers. They showed that having 15 to 25 dBA is ideal for community trade-offs and innovative materials and approaches for noise mitigation purposes are imperative for the railway sector. In another study, Gozalo et al. [48] examined various streets in Spain by including more than a hundred variables initially and fifty for the entire study after performing multicollinearity tests. Among them, traffic noise explained63% with eight variables, and noise mapping showed no more than a two dBA difference. The study included more than a hundred urban-related variables and found more than fifty of those associated with noise. Therefore, the results included the key planning components.

Magrini and Lisot [49] examined the various traffic and building-related attributes and whether they had impacts on noise propagation or not. As such, the authors performed a model for understanding building facade effects (absorption and green materials) as well as geometries (road factors, building heights, balconies), and found that simpler building shapes and narrower road typologies tend to reduce noise propagation. Similarly, Hupeng et al. [50••] conducted a study on street characteristics for noise implications a year later. Having almost hundred fifty cases with thirteen parameters, noise levels show reduction pattern with the cross-sectional enclosure degree, plan enclosure degree of buildings, and reduced vehicle road width.

Margaritis and Kang [51] explored the association between the progressive effects of green spaces on traffic noise within the urban context, and used areas with 25 configurations, 6 of which were examined in-depth. While they found no difference within urban configurations, porosity and green space showed greater effects on low noise levels. The study also used statistical analysis for correlating green space and traffic noise and found that higher land cover areas covered with green space combinations include lower noise levels. The findings underlined that green space evidently reduces noise, but at different magnitudes and with different green coverage.

Ryu et al. [52] performed a study to estimate the association between noise and transportation in South Korea within a 250 m grid square. The study considered urban form factors by performing statistical analyses, i.e., spatial autoregression and ordinary least squares. Based on this analysis, green space index, floor space index, traffic speed, and density, as well as industrial building uses, significantly affectnoise. Silva et al. [53] examined noise levels in three primary school surroundings within nine classes using a mixed-methods study approach. While they surveyed students and teachers qualitatively, they explored the role noise plays in ergonomics, and found that road and schoolyard affect indoor and outdoor building acoustics. While the school operates during active semester-times, indoor noise rises compared to the outside. Regarding outdoors, in particular, school facades are exposed to the highest noise levels among other areas in the schoolyard. So, the study calls a specific attention on both indoor and outdoor noise sources in educational facilities. Bilasco et al. [54] examined the noise levels affected by road and other built environment factors. To do this, the authors created GIS-based noise maps by considering several buildings, land use types, transportation factors, DEM, and temporal changes and found that all those characteristics impact noise levels. The results sought to contribute to local authorities and policy makers to tap into benefits of GIS-oriented tools in the decision making proces. Yu and Kang [55] assessed the reduced elevated roads and various urban form parameters on noise barriers for road and building acoustics. Examining six urban form parameters and applying noise maps for sixty sites, they suggested to keep the road 1 km distance and 20 raising the road height as the most successful approach for lowering the noise level. Regarding noise barriers, 600 m seems ideal for both sides of the road in a parallel configuration. So, based on the study, the landscape-related factors have the highest impact on noise levels for urban forms. Guo et al. [56] examined the road traffic noise by considering building and street characteristics in Hong Kong. Having road noise database in high-rise city-based, the study examined the effects of such variables on noise, and modeled more than eight thousand buildings with noise exposure information using CadNaA software. Findings showed 3 out of 4 buildings exposed to high noise levels. The study results show that all types of roads as well as other urban form indicators affect noise levels and public health aspects should be considered regarding noise mitigation. Park et al. [57] assessed the road-traffic noise and urban form features, including ground space index, floor space index, traffic density, and street length in 125 square shape grids in South Korea, and offered some fundamental noise-related policy approaches for urban design and urban planning, such as redevelopment of dense communities. Wang et al. [58] simulated traffic noise by combining the geometry of both indoor and outdoor attributes on noise levels. After running various models, the study found that indoor and outdoor have impacted at about 1.50 dB. Furthermore, positioning the building, i.e., front portions include the highest and the taller the building means the higher noise levels, and finally, bedrooms are exposed to higher noise levels [58].

Irrespective of any differences reported, more recently, Yildirim and Arefi [59] examined the sound levels around transit-oriented developments (TODs) and non-TODs, by performing hierarchical linear modeling. They found that TODs generate nine dBA higher noise levels as TOD features, including mixed-use land as well as dense building and transportation attributes. Ascigil-Dincer and Demirkale [60] created a local model for noise indicators with noise mapping in Istanbul, Turkey. To do this, they included various key characteristics, i.e., traffic data, sociodemographics, built environment, topography etc., and established a road-related traffic estimation model for local officials. Li and Xie [61] assessed the road traffic noise levels within hilly cities to understand the impacts of topography, population, and compact urban configurations in Chongqing. After examining three sets of housing types, they found that daytime and nighttime noise did not differ while roadside or non-roadside differs for noise levels. Moreover, the rectangle shape of buildings includes lower noise levels while the slope has positive association with the noise levels. Kim et al. [62] performed road-related noise maps to understand urban form factors that do not include urbanized buildings and road structures. Instead, the study aimed to observe a quiet city environment by using artificial neural network and ordinary least squares methods. As many other studies identified, the study found that road characteristics, including traffic volume and road density, have greater impacts on noise levels. Also, the statistical methods show under and over estimation compared to noise maps.

Street Geometry

Hong and Jeon [63••] assessed the soundscapes and urban morphological patterns in Seoul, Korea, by using three different sound sampling times, and used building, street, open space, and water elements as essential morphological attributes. They found significant correlations between those attributes and soundscapes. Furthermore, the research model explained how pleasantness while eventfulness had slight forecasting roles. From a more diverse variable investigation, Yu and Kang [64] assessed the urban form parameters on noise levels in China by considering six factors –complete aspect ratio (CAR), building shape, patch coverage, street length, street intersection, street shapes. Having sixty study areas indicated that building and street geometries are the most significant factors in traffic noise levels.

Other Studies

Lee et al. [65] explored the noise exposure of construction sites adjacent to subway routes, and using a sound level meter and acoustic camera, conducted multiple noise measurements. Both dBA and dBC measurements showed excessive noise levels, and vibration even resulted in more challenging circumstances. Silva et al. [66] analyzed Braga, Portugal's nexus between urban form geometry and noise implications. The key factor of urban geometry was the sky view factor of buildings and its effects on noise levels. The study found that lower sky view includes higher noise levels in urban areas. Finally, Alvares-Sanches et al. [67] collected over 50,000 sound samples within more than 700 km of Southampton to estimate the urban form-based sound maps of the entire city using machine-learning techniques. The study results showed that A-weighted sound mapping is more appropriate for building and health and machine learning is useful for city-related data collection.

Discussion and Conclusions

Indoor-Related Building Acoustics

Indoor-related studies that use on-site measurements are mainly conducted in education facilities, residential, and historic buildings. Also, studies on simulation context tried out some state-of-the-art applications and VR technologies. Theory-based studies sought to contribute to individuals' behavior, grounded theory, post-occupancy evaluation framework, and individuals' well-being. Indoor-related building acoustic studies, however, examined the following variables: wood floor, length, height, surface, floor thickness, and density. On the other hand, only two studies performed a mixed-method approach by getting residential apartments' and historic building's indoor acoustic preferences [5, 10].

Outdoor-Related Building Acoustics

Simulating outdoor-related acoustic studies, like the indoor ones used the VR technology as well as noise mapping techniques with similar mean errors of almost two dBA. As a different pattern from indoor-related studies, the outdoor studies simulated construction noise with more than 30% better modeling. Theory-related studies showed a different pattern than indoor-related studies by contributing sustainability, smart city, urban planning context of built environment studies, and policy and regulation aspects of noise as an adverse implication.

Building-related features in outdoor studies showed a combination of findings while some found building density raising the noise level [17•, 21], some others indicated that the number of buildings, floor space index include negative correlations with noise level [18]. On the other hand, building geometry shows more consensus on findings, where complex building geometry, height, length, number of floors, and commercial type of building include positive correlations with noise levels. As for the "green" material use on building surface or wall, green roofs and walls absorb noise levels up to 5 dBA.

Noise prediction models for the façade effects showed up to 13 dBA difference by including urban morphologies. Using different techniques, i.e., BEM, ray tracing, and noise mapping, within several study locations, including China, the U.K., and Greece, complex building geometry as well as building heights have positive interaction with noise levels on the façade, balcony, vegetation, special insulation materials include negative interaction noise levels. Mixed-methods research relied on residents' preference for façade effects and showed that absorption and reverberation effects are affected by participants' positioning, and window and door impact individuals' understanding.

The built environment, particularly transport-related characteristics, seems to be the driving force behind the association between building acoustics and urban form, and as several studies worldwide showed, road traffic-related factors highly affect noise levels.

While road length, width, road geometry, sky view coefficient, building density, traffic density, reduced speed limit, mixed-land use, and hilly topography and slope show positive association with the noise levels in buildings; simpler shape (rectangle) buildings, narrow road, C-type formation, green space, water soundscapes, and single land use include negative association with the noise levels.

Urban form is a complex phenomenon with various factors that also affect noise. This paper provides a systematic review of the nexus between building acoustics and urban form. Distinguishing between two general indoor and outdoor categories for building acoustics are the key factors and related studies generally performed quantitative analyses worldwide by either running various computer-based applications or in-situ measurements. Very few studies included the qualitative aspects of the urban form. Perhaps, future studies may concentrate on individuals' perception as they reside in those urban and urban-related dynamics.

This study presented the key findings based on other scholars' contributions, demonstrating that building shape, density, geometry, façade, road, and street morphologies, such as width, length, geometry, as well as traffic factors, i.e., density, speed limit, land use type, green space, water feature, etc. all have implications on noise levels. On the other hand, changing building structure science trends, technological improvements, and urban form features may also alter such patterns.

Since authors have used various techniques in these reviewed studies, they may show different accuracy details, which fall outside the scope of this paper. Nonetheless, a consistent pattern of studies emerges in building acoustics and urban form interface. Perhaps, innovative and state-of-the-art materials and techniques may delve deeper into building acoustic context with more studies in the pipeline for future reference. Another takeaway from the study is that building acoustics seem excluded from a multi-disciplinary context. So, further studies may include various disciplines for better understanding and vast implications on individuals and societies.

Data Availability Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Compliance with Ethical Standards

Conflict of Interest The authors declare that there is no conflict of interest for this study.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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