Journal of Applied Automation Technologies

Review Paper

Intelligent Algorithm-Based Methods and Applications for Optimizing Architectural Acoustic Environments: A Reivew

Roman Piotr Kotowski[1, *]

[1] Faculty of Electrical Engineering and Automatics, Wroclaw University of Science and Technology, Wroclaw, 50-371, Poland
*Corresponding author: roman.pk@pwr.edu.pl

Abstract. In the field of architectural acoustics design, traditional optimization methods exhibit significant limitations when addressing complex acoustic challenges. Consequently, intelligent algorithm-based approaches for optimizing architectural acoustic environments have emerged, pioneering new pathways for architectural acoustics design. This paper thoroughly examines the research background and significance of this field, elucidating the practical relevance and potential value of the research topic. Through a comprehensive analysis of the current research landscape, it reveals the primary research content, existing issues, and future research directions. The core contribution of this paper lies in systematically organizing and summarizing the theoretical foundations, application cases, and future development trends of intelligent algorithm-based architectural acoustic environment optimization methods. It provides valuable references and insights for subsequent research, helping to advance the further development and practical application of architectural acoustic environment optimization technologies, thereby enhancing the demand for high-quality architectural acoustic environments.

Keywords: *Building Acoustics Environment, Intelligent Algorithms, Optimization Methods*

Received on 29 September 2023, Accepted on 23 February 2024, Published on 18 March 2024

Introduction

The acoustic environment of buildings, as a key element in architectural design, exerts a significant influence on people's physical and mental health as well as their quality of life [1-2]. A favorable acoustic environment not only enhances speech intelligibility and enriches musical enjoyment but also effectively reduces noise interference and harm, thereby improving work efficiency and learning outcomes [3]. However, traditional architectural acoustics design methods primarily rely on empirical formulas and simplified models, making it challenging to accurately address complex acoustic issues such as sound field distribution in large architectural spaces and the sound absorption effects of multiple material combinations[4-5].

With the rapid advancement of intelligent algorithms, their application in optimizing architectural acoustic environments has garnered increasing attention [6]. Leveraging their robust global search capabilities and adaptability to complex problems, intelligent algorithms can effectively address architectural acoustic optimization challenges that prove difficult for traditional methods, thereby providing novel approaches and tools for architectural acoustic design [7].

Currently, research on optimizing architectural acoustic environments using intelligent algorithms primarily focuses on the following areas: First, integrating acoustic modeling with intelligent algorithms to guide optimization design through accurate simulation of acoustic environments [8]. Second, developing optimization methods targeting key acoustic metrics such as noise control and reverberation time [9]. Third, implementing comprehensive optimization strategies that integrate acoustic design with architectural design [10]. Numerous scholars have proposed various optimization methods combining intelligent algorithms with acoustic models, exploring their application in acoustic optimization for different building types. These studies provide new approaches and tools for architectural acoustic design, with some research outcomes already applied in practical engineering projects, yielding significant economic and social benefits [11].

However, despite some achievements, several challenges remain to be addressed. The computational efficiency of intelligent algorithms for large-scale acoustic problems needs improvement, data acquisition and model validation in practical engineering applications pose significant difficulties, and achieving a balance in multi-objective optimization remains challenging [12].

This paper aims to systematically review intelligent algorithm-based methods and applications for optimizing architectural acoustic environments. It organizes current research findings, analyzes existing challenges, and outlines future development trends to provide reference for researchers and engineering practitioners. Specific contributions include: (1) A comprehensive overview of architectural acoustic environment elements and optimization objectives, laying a foundation for subsequent research; (2) It delves into intelligent algorithm-based optimization methods for architectural acoustic environments, detailing the principles, advantages, disadvantages, and application cases of each approach; (3) By analyzing acoustic optimization case studies in public buildings, residential structures, and specialized facilities, it demonstrates the practical effectiveness and advantages of intelligent algorithms in engineering applications; (4) It summarizes the current research landscape and challenges, while projecting future development trends to guide subsequent research directions.

Overview of Architectural Acoustics

The architectural acoustic environment is a critical aspect of building design that cannot be overlooked, as it profoundly impacts auditory comfort, work efficiency, learning effectiveness, and physical and mental well-being [12]. A well-designed acoustic environment not only enhances speech intelligibility and enriches musical enjoyment but also effectively reduces noise interference and harm to occupants [13]. This section will delve into the constituent elements and optimization objectives of architectural acoustic environments, providing a solid theoretical foundation for subsequent research.

Environmental Factors in Architectural Acoustics

The architectural acoustic environment is fundamentally shaped by a combination of critical factors, including noise levels, reverberation time, sound field distribution, and the characteristics of sound propagation [14]. These elements collectively determine the overall acoustic quality and functionality of a space, influencing both the auditory comfort and the effectiveness of sound transmission within the environment. A detailed analysis of the impact of these factors is summarized and presented in Table 1.

Table 1. Environmental Factors in Building Acoustics and Their Effects

Element	Impact Description	Key Control Points
Noise Levels	Interferes with people's lives and work damages the auditory system	Control of external noise sources internal noise isolation
Reverberation Time	Affects speech intelligibility and musical enjoyment	Arrangement of sound-absorbing materials spatial design
Sound Field Distribution	Causes localized areas of excessive or insufficient sound	Design of reflective surfaces optimization of sound source position
Sound Propagation Characteristics	Affects acoustic design and noise control effectiveness	Material selection spatial layout

The analysis presented in Table 1 illustrates the critical role of various environmental factors in shaping the acoustic quality of buildings. Noise levels, reverberation time, sound field distribution, and sound propagation characteristics are interdependent elements that must be carefully considered to achieve optimal acoustic performance. For instance, controlling noise levels requires not only sound insulation but also strategic spatial design to minimize the intrusion of external noise. Similarly, managing reverberation time involves balancing material selection and spatial configuration to ensure that speech intelligibility and musical enjoyment are not compromised. These interrelations underscore the need for a systematic approach to architectural acoustic design, where each factor is addressed comprehensively to create a balanced and functional acoustic environment.

To better understand the interactions among key environmental factors in architectural acoustics, a schematic diagram (Figure 1) is provided. It visually illustrates how noise levels, reverberation time, sound field distribution, and sound propagation characteristics influence each other. This diagram serves as a foundation for designing optimized acoustic environments.

Added Content with Formula: Generalized Reverberation Time Calculation
In architectural acoustics, accurately predicting reverberation time (RT) in complex environments requires consideration of multiple materials, geometries, and sound wave interactions. To address this, the generalized reverberation time formula can be expressed as:

$$RT = \frac{0.161 \cdot V}{\sum_{i=1}^{n} S_i \cdot \alpha_i \cdot \beta_i} \tag{1}$$

Here:V is the volume of the space in cubic meters (m^3).S_i represents the surface area of the i-th material in square meters (m^2). α_i is the absorption coefficient of the i-th material, accounting for its frequency response.β_i is a correction factor to account for irregular geometry and the angle of sound wave incidence.

This formula extends the classical Sabine equation by introducing the correction factor β_i, which adjusts for the real-world complexities of non-planar surfaces and oblique sound wave incidence. Such adjustments are crucial for spaces like concert halls or atriums, where irregular geometries and diverse material properties influence sound behavior. By integrating β_i, the formula ensures a more realistic approximation of reverberation time, enabling precise optimization of acoustic environments.

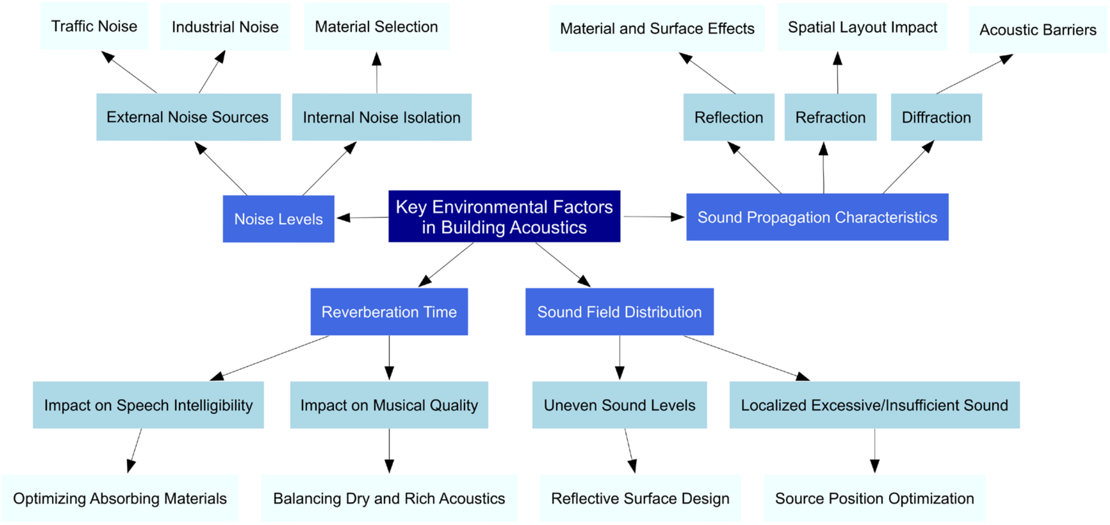

Figure 1 Schematic diagram of key environmental factors in building acoustics and their interactions.

This diagram illustrates the complex interplay between noise levels, reverberation time, sound field distribution, and sound propagation characteristics. Each factor plays a crucial role in shaping the overall acoustic environment of a building. For example, high noise levels can negatively impact reverberation time, leading to reduced speech intelligibility and discomfort. Similarly, uneven sound field distribution and improper sound propagation control can result in acoustic dead zones or excessive sound reflections. By understanding these interactions, designers can adopt a more holistic approach to optimize architectural acoustics, ensuring that each factor is adequately addressed to enhance auditory comfort and functionality.

Noise levels encompass external traffic noise, industrial noise, and human-generated noise within buildings [15-17]. Excessively high noise levels can damage the human auditory system and disrupt normal daily life and work. Different building functions have varying noise level requirements; for instance, hospitals require quiet environments, while schools also need low noise levels to ensure effective teaching [18].

Reverberation time refers to the duration required for sound within a room to decay to a specified intensity level[19]. Excessively long reverberation times cause sound to trail off, impairing speech intelligibility; conversely, too short a time makes sound dry and harsh. Different building types demand varying reverberation durations: concert halls require longer times to preserve musical richness and reverberation, while conference rooms need shorter times to ensure clear speech transmission[20].

Sound field distribution describes the propagation and distribution of sound within architectural spaces [21]. Uneven sound field distribution can result in excessively loud or soft sound levels in localized areas, compromising the overall quality of the acoustic environment. In large auditoriums, uneven sound field distribution may cause portions of the audience to experience difficulty hearing speeches or music clearly [22].

The characteristics of sound propagation involve the speed of sound transmission through different media, its attenuation patterns, and phenomena such as reflection, refraction, and diffraction [23]. Understanding these characteristics facilitates the implementation of appropriate acoustic measures for control and optimization, such as installing sound-absorbing materials or reflective surfaces to improve the acoustic environment.

Building Acoustics Environmental Optimization Objectives

Building acoustic environment optimization aims to enhance indoor acoustic quality through scientific design and appropriate material selection to meet the functional requirements of different buildings. Key optimization objectives include reducing noise interference, improving speech intelligibility, creating high-quality musical environments, and fulfilling specialized acoustic needs, as analyzed in Table 2.

Table 2. Acoustic Optimization Targets for Different Building Types

Building Type	Optimization Objectives	Key Design Considerations
Public Buildings	Improve speech intelligibility create high-quality music environment	Control of reverberation time sound field uniformity
Residential Buildings	Reduce noise interference provide a quiet and comfortable living environment	External sound insulation internal sound absorption
Special Buildings	Meet specific acoustic needs	Sound insulation performance sound field control

As shown in Table 2, the optimization objectives for different building types reflect the varying functional requirements and usage scenarios of these spaces. Public buildings, such as theaters and conference halls, prioritize speech intelligibility and sound field uniformity, while residential buildings focus on reducing noise interference to provide a quiet and comfortable living environment. Special buildings, like recording studios and hospitals, demand precise acoustic control to meet their specific functional needs. These objectives highlight the importance of tailoring acoustic optimization strategies to the unique characteristics of each building type. Achieving these goals often requires the integration of advanced simulation tools and acoustic modeling techniques to accurately predict and address the acoustic challenges specific to each scenario.

Figure 2 presents a comparative analysis of acoustic optimization objectives for different types of buildings, including public, residential, and special buildings. This comparison highlights the varying requirements for noise reduction, speech intelligibility, and musical quality across building types, further showcasing the importance of tailored acoustic optimization strategies.

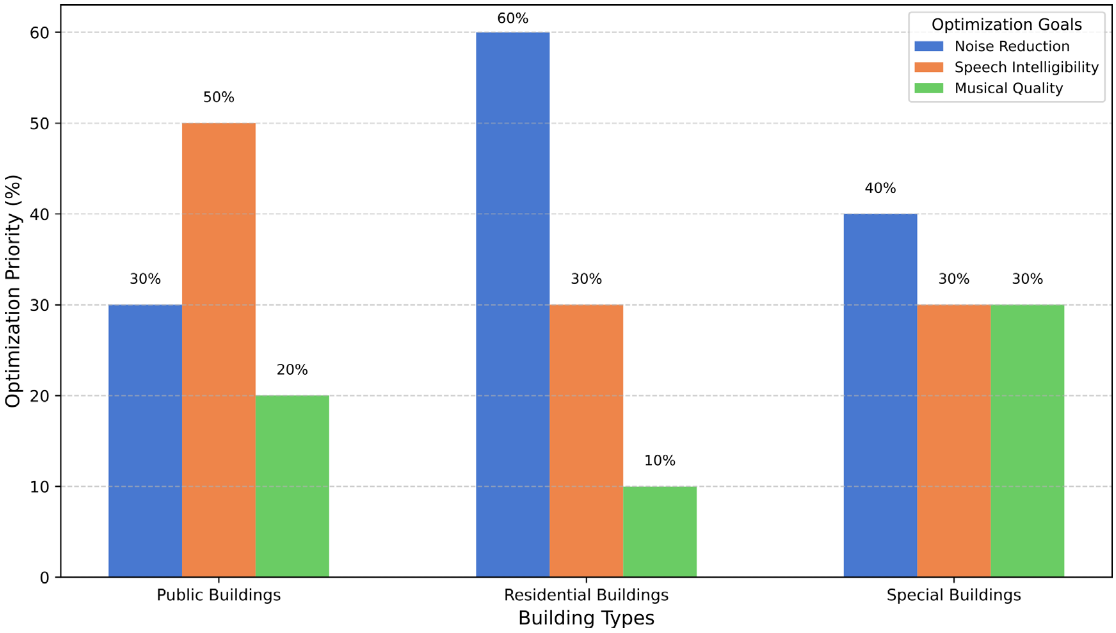

Figure 2 Comparison of acoustic optimization objectives for different building types.

This comparison highlights the varying acoustic requirements for public, residential, and specialized buildings, emphasizing the need for tailored optimization strategies. Public buildings such as theaters and conference halls prioritize speech intelligibility and sound field uniformity, whereas residential spaces focus on minimizing noise interference to create a quiet, comfortable environment. Specialized buildings, like recording studios and hospitals, demand precise acoustic control to meet specific functional needs. These differences underline the importance of context-aware acoustic design, ensuring that optimization efforts align with the intended purpose of the building while maintaining cost efficiency and practical feasibility.

As shown in Table 2, reducing noise interference involves implementing measures such as sound insulation and sound absorption to minimize the impact of external and internal noise on building interiors, thereby enhancing indoor quietness and comfort [24-26]. Specific acoustic material analyses are detailed in Table 3. Improving speech intelligibility entails optimizing reverberation time and sound field distribution to make speech signals clearer and more discernible, making it suitable for venues like conference rooms, classrooms, and theaters. Creating an optimal musical environment involves adjusting acoustic parameters—such as reverberation time and frequency response—according to the requirements of different music genres to achieve ideal listening experiences [27]. Specific analyses are detailed in Table 4. Scenarios with specialized acoustic demands include recording studios and hospitals. Recording studios require rooms with excellent sound insulation, uniform sound field distribution, and appropriate reverberation time to ensure recording quality [28]. Hospital wards, meanwhile, necessitate quiet environments through sound insulation and absorption measures to facilitate patient rest and recovery [29].

Table 3. Acoustic Material Performance Comparison

Material Type	Sound Absorption Coefficient	Sound Insulation Level	Applicable Scenarios
Porous Sound-Absorbing Materials	High-frequency sound absorption good absorption coefficient up to 0.8-1.0	Relatively low sound insulation about 20-30dB	Wall sound absorption in conference rooms and concert halls
Sound Insulation Materials	Low sound absorption coefficient	High sound insulation up to 40-60dB or more	Sound insulation for partition walls and exterior windows

The data in Table 3 highlights the distinct performance characteristics of various acoustic materials and their applications in different scenarios. Porous, sound-absorbing materials are highly effective in reducing high-frequency noise, making them ideal for spaces like conference rooms and concert halls. In contrast, materials with superior sound insulation properties are better suited for partition walls and exterior windows, where blocking noise transmission is critical. The careful selection and combination of these materials play a pivotal role in achieving the desired acoustic outcomes. Furthermore, understanding the trade-offs between sound absorption and insulation performance is essential for designing environments that balance quietness and acoustic clarity without compromising aesthetic or functional requirements.

Table 4. Acoustic Design Parameter Range

Parameter	Value Range	Optimization Recommendations
Reverberation Time (Living Room)	0.3-0.5 seconds	Adjust using sound-absorbing materials
Reverberation Time (Theater)	1.5-2.0 seconds	Combine spatial design and material selection
Noise Level (Bedroom)	≤30dB	Enhance sound insulation measures
Noise Level (Office)	≤40dB	Reasonable layout to reduce internal noise

Table 4 provides valuable insights into the recommended ranges of key acoustic design parameters for various building types. For example, the suggested reverberation time for theaters ensures that musical performances retain their richness, while the shorter reverberation time for living rooms prioritizes clear speech communication. Similarly, noise level thresholds for bedrooms and offices emphasize the importance of creating environments conducive to relaxation and productivity, respectively. These parameters serve as benchmarks for designers, enabling them to make informed decisions when selecting materials and designing spaces. By adhering to these guidelines, it is possible to create acoustic environments that meet functional requirements while enhancing user comfort and satisfaction.

Key Considerations in Acoustic Design

In architectural acoustic design, beyond the aforementioned core elements and optimization objectives, multiple factors must be comprehensively considered to ensure the optimized acoustic environment meets practical usage requirements. These include: 1) Building Function and Purpose. Buildings with different functions exhibit significant variations in acoustic environment requirements. At the outset of acoustic design, clearly defining the building's function and purpose is a prerequisite for establishing acoustic objectives and selecting appropriate acoustic measures [30]; 2) Spatial layout and form. The spatial arrangement and architectural form directly influence sound wave propagation and reflection characteristics. A well-designed spatial layout and form can provide favorable conditions for acoustic optimization, reducing the difficulty and cost of subsequent acoustic treatments [31]; 3) Material Selection and Application. The performance characteristics of acoustic materials play a crucial role in optimizing the acoustic environment. When selecting acoustic materials, comprehensive consideration must be given to factors such as sound absorption coefficient, sound insulation rating, fire resistance, and environmental performance. This ensures the material properties align with acoustic design requirements while meeting building safety and environmental standards [32-34]. 4) Economic Costs and Budgeting. Optimizing acoustic environments typically involves significant economic investment, including procurement and installation of acoustic materials, as well as design and consulting fees. Practical projects must balance acoustic performance with economic costs by ensuring optimal results while maintaining reasonable expenditure [35].

For analyzing noise propagation and attenuation in enclosed architectural spaces, a complex model incorporating frequency-dependent absorption and diffraction effects is given as:

$$L_p(f) = L_w - 20 \cdot \log_{10}(r) - \frac{1}{2} \cdot \ln\left(\frac{\omega \cdot \eta}{\rho \cdot c^2}\right) - \sum_{i=1}^{n} \frac{\alpha_i(f) \cdot S_i}{A_{eq}} \tag{2}$$

The frequency-dependent sound pressure level at the receiver point, denoted as $L_p(f)$, is influenced by multiple factors, including the sound power level of the source (L_w) and the distance between the source and the receiver (r). The angular frequency of the sound wave, defined as $\omega = 2\pi f$, also plays a critical role, where f is the frequency of the sound. Additionally, the viscosity of air (η) contributes to sound energy dissipation, while the air density (ρ) and the speed of sound in air (c) further affect the propagation dynamics. The frequencydependent absorption coefficient of the i-th material ($\alpha_i(f)$) and the surface area of the i-th material (S_i) also interact with the equivalent absorption area (A_{eq}), collectively determining the attenuation and distribution of sound pressure across the environment. This comprehensive relationship highlights the complex interplay of physical, material, and environmental factors in shaping acoustic behavior.

This extended formula captures the intricate interactions of sound waves with architectural surfaces by explicitly modeling frequency-dependent absorption and air viscosity effects. The logarithmic term accounts for geometric spreading losses, while the summation term models the cumulative effect of multiple materials' absorption. This formula is particularly valuable for spaces like industrial plants or airports, where high-frequency noise and large spatial dimensions require advanced acoustic optimization.

Practical Strategies for Acoustic Environment Optimization

To effectively optimize the architectural acoustic environment, designers and engineers can adopt the following practical strategies:

First, acoustic design should be integrated into the overall planning during the early stages of architectural design, coordinated with other specialized disciplines. Through close collaboration with other fields such as architecture, structural engineering, and HVAC, the acoustic design solutions must be harmonized with the building's overall design to avoid extensive modifications and rework later due to acoustic issues [36].

Secondly, professional acoustic simulation software is employed to simulate and analyze the building's acoustic environment. By establishing acoustic models and inputting architectural design parameters along with acoustic material performance data, the acoustic performance within the building can be predicted, including noise levels, reverberation time, and sound field distribution [37]. Based on the simulation results, the acoustic design scheme is promptly adjusted to optimize acoustic measures, thereby enhancing the accuracy and reliability of the acoustic design.

Following the completion of construction, conducting on-site acoustic testing is a critical step in verifying the effectiveness of the acoustic design. By utilizing specialized acoustic testing equipment, in-situ measurements of indoor acoustic parameters—such as noise levels, reverberation time, and sound insulation—are taken and compared against the acoustic design objectives for analysis [38].

Finally, as demands for acoustic environmental quality continue to rise and acoustic technologies advance, the optimization of architectural acoustic environments also requires ongoing refinement and innovation [39]. Keeping abreast of the latest research findings and cutting-edge technologies in the field of acoustics—such as the development of novel acoustic materials and the application of intelligent acoustic control systems [40]—and integrating these appropriately into acoustic design will continuously elevate the level of acoustic environment optimization.

Intelligent Algorithm-Based Method for Optimizing Architectural Acoustic Environments

Acoustic Model Construction and Algorithm Integration

The construction of acoustic models forms the foundation for optimizing architectural acoustic environments. Common acoustic models include geometric acoustic models [41], wave acoustic models [42], and statistical acoustic models [43]. Geometric acoustic models are suitable for high-frequency sound field simulations, treating sound as rays propagating and reflecting within a space. Wave acoustic models, based on wave equations, account for sound wave diffraction and interference phenomena, making them appropriate for low-frequency sound field simulations. Statistical acoustic models, such as reverberation theory models, are primarily used to estimate parameters like the average reverberation time within a room.

In practical applications, after selecting an appropriate acoustic model based on the specific problem, it must be integrated with intelligent algorithms. The integration process is as follows: 1) Identify optimization variables: Based on acoustic design objectives, determine adjustable design variables such as the position and thickness of sound-absorbing materials, the sound insulation performance of walls, and the shape and dimensions of the room; 2) Establish an interface between the acoustic model and the intelligent algorithm, mapping the acoustic model's inputs to the algorithm's parameters and using the acoustic model's outputs as the fitness function values for the intelligent algorithm; 3) Execute the intelligent algorithm, which evaluates the quality of different design variable combinations based on fitness function values and iteratively optimizes the design variables to achieve optimal acoustic performance [44].

To provide a clearer understanding of the integration process between acoustic modeling and intelligent algorithms, Figure 3 illustrates the workflow. It highlights key steps such as identifying optimization variables, establishing interfaces, and executing intelligent algorithms for iterative optimization.

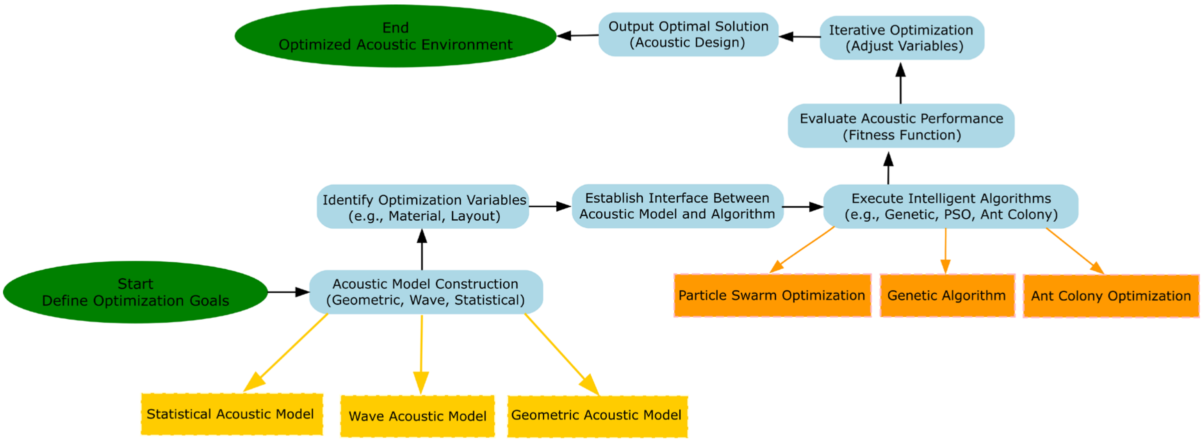

Figure 3 Workflow of architectural acoustic environment optimization integrating acoustic modeling and intelligent algorithms.

This workflow demonstrates the systematic integration of acoustic modeling with intelligent algorithms, offering a structured approach to optimizing building acoustics. The process begins with identifying key optimization variables, such as material properties and room dimensions, followed by establishing a seamless interface between the acoustic model and the intelligent algorithm. This enables iterative optimization to achieve desired acoustic outcomes. By leveraging intelligent algorithms like genetic algorithms or particle swarm optimization, this method provides more accurate and efficient solutions compared to traditional trial-and-error approaches, particularly for complex, multi-variable acoustic challenges.

Noise Control Optimization Methods

Optimization methods for noise control based on intelligent algorithms primarily address three aspects: noise sources, propagation paths, and reception points [45-47], as detailed below:

Noise source control involves reducing the intensity of noise sources through methods such as optimizing equipment selection and adjusting equipment layout [45]. In industrial plant design, [48] employs intelligent algorithms to select low-noise equipment and determine optimal placement locations, thereby lowering noise levels within the facility.

Transmission path control employs measures such as sound absorption, sound insulation, and noise reduction to block noise propagation [46]. Intelligent algorithms can optimize the placement and area of sound-absorbing materials, as well as design parameters for sound-insulating structures, such as wall thickness and material combinations [49]. Reference [50] employs intelligent algorithms to determine optimal sound insulation material combinations and wall structures in building partition wall design, enhancing sound insulation effectiveness.

To optimize the placement and performance of acoustic barriers, a more comprehensive model for sound diffraction and barrier attenuation is proposed as:

$$\Delta L(f) = 10 \cdot \log_{10}\left(1+\frac{\lambda^2}{4\cdot h^2}\right)+\frac{\gamma\cdot\cos(\theta)}{1+(r/h)^2} \tag{3}$$

The frequency-dependent attenuation provided by the barrier, denoted as $\Delta L(f)$, is determined by several interrelated factors. The wavelength of the sound wave, expressed as $\lambda = c/f$, where c is the speed of sound and f is the sound frequency, plays a crucial role in defining diffraction behavior. The effective height of the barrier (h) significantly influences its ability to block or diffract sound waves, while the material-dependent reflection coefficient (γ) characterizes how much of the incident sound energy is reflected by the barrier surface. Additionally, the angle of incidence of the sound wave relative to the barrier (θ), measured in radians, affects the efficiency of sound redirection and attenuation. Finally, the distance from the sound source to the barrier (r) contributes to the geometric spreading and diffraction effects, collectively shaping the overall attenuation performance of the barrier across different frequencies.

This formula accounts for both diffraction effects around the barrier and the reflection effects due to the material properties. The inclusion of γ and θ enables the precise calculation of barrier performance under varying sound wave orientations and material characteristics. This approach is essential for noise control in urban environments or along highways, where barriers are used to minimize noise exposure for surrounding residential areas.

Reception point protection involves implementing measures near noise receptors to reduce impact, such as installing sound enclosures or soundproof rooms [47]. Intelligent algorithms can optimize enclosure shape and material selection based on receptor location and noise propagation characteristics to achieve optimal noise reduction [51].

Methods for Optimizing Reverberation Time

Reverberation time is a critical and widely studied metric in the field of architectural acoustics, as it plays a significant role in determining the auditory experience and acoustic performance of a space. The optimization of reverberation time involves various methods, which primarily focus on the careful selection and strategic arrangement of materials with specific acoustic properties, adjustments to the spatial configuration to better control sound reflections, and the implementation of other targeted approaches to achieve desired acoustic outcomes [52-54]. To provide a deeper understanding of these strategies, specific case studies detailing the methods and results of reverberation time optimization are comprehensively presented in Table 5.

Table 5. Reverberation Time Optimization Case Study

Case	Optimization Method	Optimization Effect
Concert Hall Reverberation Time Optimization	Using ant colony algorithm to optimize sound-absorbing material layout and spatial design	Reverberation time optimized from 1.8 seconds to 1.6 seconds significant improvement in sound quality
Conference Room Reverberation Time Optimization	Using genetic algorithm to select suitable sound-absorbing materials and layout positions	Reverberation time optimized from 0.6 seconds to 0.4 seconds speech intelligibility improved

The examples in Table 5 demonstrate how intelligent algorithms can optimize reverberation time for different building types. In concert halls, the use of ant colony algorithms to optimize the layout of sound-absorbing materials and spatial design led to a significant improvement in sound quality. Similarly, genetic algorithms applied to conference rooms enhanced speech intelligibility by reducing reverberation time. These case studies underscore the practical benefits of integrating intelligent algorithms with acoustic design, allowing for precise and efficient optimization of complex acoustic parameters. Such approaches not only improve the auditory experience but also provide valuable insights for future projects aiming to enhance acoustic performance in similar settings.

Material selection and placement involve choosing appropriate sound-absorbing materials and strategically positioning them on interior walls, ceilings, and floors. Intelligent algorithms can optimize the type, thickness, and placement of these materials based on specific target reverberation times. In theater design, as documented in [52], intelligent algorithms determine the optimal layout of sound-absorbing materials across different zones, achieving reverberation times within the desired range.

To calculate the energy decay profile of a room, a differential equation describing the sound energy loss over time is introduced:

$$\frac{dE(t)}{dt} = -\frac{c \cdot A}{4V} \cdot E(t) \tag{4}$$

The sound energy density at a given time, denoted as $E(t)$ and measured in joules per cubic meter (J/m^3), is governed by the dynamic relationship between the physical and acoustic properties of the space. The speed of sound in air (c, measured in meters per second) determines the rate at which sound energy propagates, while the total absorption area (A, in square meters of absorption units) quantifies the capacity of the room's surfaces to absorb sound energy and reduce reflections. Additionally, the volume of the room (V, in cubic meters) plays a critical role, as larger spaces allow sound energy to disperse more widely, reducing its density over time. Together, these factors interact to define the temporal decay of sound energy within the space, influencing the acoustic experience and the reverberation characteristics of the environment.

This equation can be solved to give the exponential decay of sound energy:

$$E(t)=E_0\cdot\exp\left(-\frac{c\cdot A}{4V}\cdot t\right) \tag{5}$$

Where E_0 is the initial sound energy density.

This model provides a time-domain representation of sound decay, enabling the calculation of reverberation time as the time required for $E(t)$ to drop to a defined threshold (e.g., -60 dB). This equation is critical for designing spaces such as auditoriums, where precise control of sound energy decay ensures optimal auditory experiences.

Spatial configuration adjustments alter a room's shape and dimensions, influencing sound wave reflections and propagation paths to modify reverberation time [53]. Intelligent algorithms can optimize spatial parameters such as adjusting room aspect ratios and installing diffusers to enhance reverberation effects [54].

To better demonstrate the effectiveness of intelligent algorithm-based methods in optimizing reverberation time, Figure 4 provides case study results. It shows the improvement in reverberation time for specific building types, such as concert halls and conference rooms, before and after optimization.

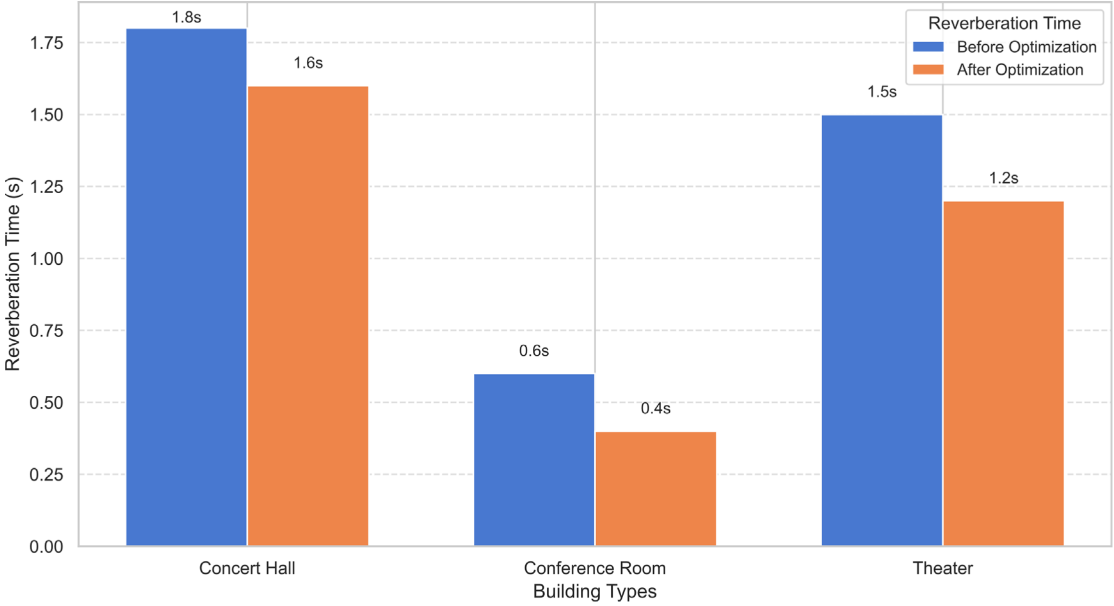

Figure 4 Case study results of reverberation time optimization in different buildings.

The results depicted in this figure demonstrate the effectiveness of intelligent algorithm-based methods in optimizing reverberation time across various building types. For instance, in concert halls, fine-tuning the placement of sound-absorbing materials and adjusting spatial configurations significantly enhances sound quality, preserving musical richness. Similarly, conference rooms benefit from reduced reverberation times, improving speech intelligibility for listeners. These case studies underscore the practical value of intelligent algorithms in achieving precise acoustic control, ensuring that optimization efforts align with the unique requirements of each architectural space.

Integrated Optimization Method for Acoustic Design

Integrated acoustic design optimization methods combine architectural acoustics with other disciplines such as architectural design and structural engineering, comprehensively considering factors including acoustic performance, spatial utilization, and economic efficiency. Intelligent algorithms play a crucial role in solving these multi-objective optimization problems.

During the architectural design phase, acoustic designers collaborate with architects, structural engineers, and other professionals to jointly determine the building's spatial layout, structural form, and material selection to meet acoustic and other disciplinary requirements [55]. Intelligent algorithms can comprehensively optimize parameters across multiple disciplines to identify optimal design solutions that satisfy multidisciplinary constraints.

From the perspective of the entire life cycle—spanning architectural planning and design, construction, operation, and eventual demolition and recycling—consider optimizing the acoustic environment [56]. Intelligent algorithms can assist in evaluating the acoustic performance and economic costs of different design options throughout the entire life cycle, enabling the selection of the optimal design solution.

Application Analysis of Building Acoustic Environment Optimization Based on Intelligent Algorithms

Acoustic Optimization for Public Buildings

Public buildings, due to their diverse functions and complex spatial configurations, impose special requirements on acoustic environments. The application of intelligent algorithms in acoustic optimization for public buildings can effectively enhance their acoustic quality and improve the auditory experience for occupants [57-59].

In theater acoustic optimization, intelligent algorithms enhance speech intelligibility and musical richness by optimizing seating arrangements, the placement of sound-absorbing materials on walls and ceilings, and stage acoustic design [57]. Following the application of genetic algorithms to optimize acoustic design schemes in [60], speech clarity in the audience area improved, and acoustic performance during musical performances was significantly enhanced.

In concert hall acoustic optimization, intelligent algorithms are employed to adjust acoustic parameters such as reverberation time and sound field distribution, creating an acoustic environment suitable for various types of musical performances [58]. Following optimization via the particle swarm optimization algorithm in [61], the distribution of reverberation time across different frequencies became more uniform, resulting in more consistent acoustic effects throughout the audience seating areas.

In conference hall acoustic optimization, the primary focus is on speech intelligibility and sound field uniformity [59]. By employing intelligent algorithms to optimize the placement of sound-absorbing materials and the hall's geometry, clear audibility of presentations is ensured from every seat. Following optimization with intelligent algorithms as described in [62], speech intelligibility significantly improved, eliminating the need for amplification equipment during meetings.

To evaluate the spatial uniformity of sound fields in public buildings, the concept of spatial energy distribution variance is introduced:

$$\text{Variance} = \frac{1}{N}\sum_{i=1}^{N} \left(L_p(i) - \bar{L}_p\right)^2 \tag{6}$$

The number of measurement points in the space is denoted as N, where each point has a corresponding sound pressure level $L_p(i)$ (in dB) at the $\mathbf{i}$-th point. The mean sound pressure level across all points is represented as $\bar{L}_p$ (in dB), calculated as the average of the individual sound pressure levels measured at all N points.

This formula quantifies the variance in sound pressure levels across a space, with lower variance indicating a more uniform sound field. By minimizing this variance during design, public buildings such as theaters or concert halls can achieve consistent auditory experiences for audiences seated at different locations.

The above analysis highlights key aspects of acoustic optimization in architectural design, particularly in public buildings where acoustic performance is essential for functionality and user comfort. To provide a more detailed and practical understanding, a comparative case study focusing on various acoustic optimization strategies and their outcomes in different types of public buildings has been conducted. The findings, which illustrate the effectiveness of these strategies in real-world applications, are comprehensively presented in Table 6.

Table 6. Case Studies of Acoustic Optimization in Public Buildings

Building Type	Acoustic Issues Before Optimization	Improvement Effects After Optimization
Theater	Poor speech intelligibility sound noisy in some areas	Speech intelligibility improved acoustic performance significantly enhanced
Concert Hall	Uneven reverberation time uneven sound field distribution	Reverberation time distribution uniform sound field consistency improved
Conference Hall	Insufficient speech intelligibility and sound field uniformity	Speech intelligibility significantly improved

As presented in Table 6, the optimization of acoustic environments in public buildings demonstrates the transformative impact of intelligent algorithm-based methods. In theaters, improvements in speech intelligibility and sound field distribution significantly enhanced the audience experience. Similarly, optimizing reverberation time and sound field consistency in concert halls ensured that musical performances were delivered with clarity and richness. In conference halls, enhanced speech intelligibility eliminated the need for additional amplification, creating a more natural auditory environment. These examples highlight the importance of precise acoustic design tailored to the unique requirements of each public space, ensuring functional and aesthetic harmony.

Figure 5 compares the sound field distribution in a theater before and after acoustic optimization. The optimized design significantly improves sound field uniformity, enhancing both speech intelligibility and musical richness for the audience.

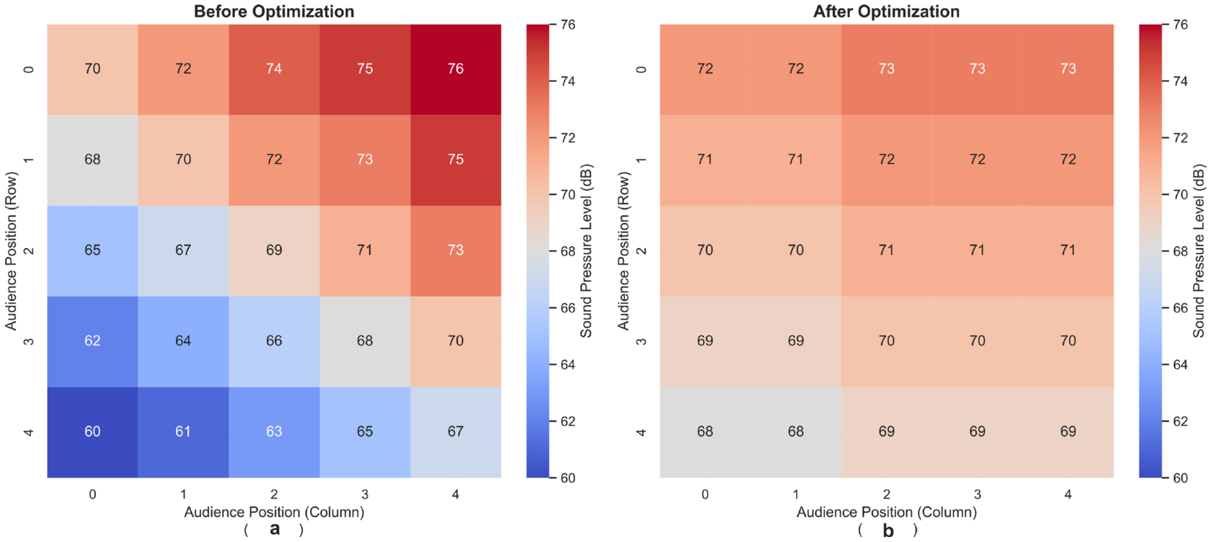

Figure 5 Comparison of sound field distribution in a theater before and after acoustic optimization.

This figure highlights the transformative impact of acoustic optimization on sound field distribution in a theater setting. Prior to optimization, the sound field exhibited uneven distribution, with certain areas experiencing excessive loudness or inadequate sound levels. After optimization, the sound field became more uniform, enhancing auditory experiences for all audience members, regardless of their seating location. This improvement demonstrates the capability of intelligent algorithms to analyze and address complex sound propagation issues, ensuring high-quality acoustic performance tailored to the specific needs of performance spaces.

Acoustic Optimization of Residential Buildings

A favorable acoustic environment is crucial for residential buildings, directly impacting residents' quality of life and physical and mental well-being. The application of intelligent algorithms in acoustic optimization for residential buildings can create a quiet and comfortable living environment for residents. Acoustic optimization analysis for residential buildings is shown in Table 7.

Table 7. Acoustic Optimization Analysis for Residential Buildings

Building Type	Acoustic Issues Before Optimization	Improvement Effects After Optimization
Residential Buildings	Severe interference from external traffic noise noisy indoors	Indoor noise reduced quietness and comfort improved
Apartments	Severe sound reflections long reverberation time	Reverberation time shortened speech clarity improved

Table 7 indicates that residential acoustic optimization primarily addresses disturbances caused by external traffic noise and neighborhood noise within living spaces [63]. By employing intelligent algorithms to optimize the sound insulation performance of exterior windows and partition walls, along with the placement of indoor sound-absorbing materials, the quietness and comfort of indoor environments are enhanced. Following acoustic optimization design based on intelligent algorithms as described in [64], indoor noise levels decreased, and residents' satisfaction with their living environment significantly improved. Apartment acoustic optimization involves enhancing the indoor acoustic environment within limited spaces through methods such as rational furniture arrangement and selection of appropriate acoustic decorative materials [65]. Intelligent algorithms can help determine optimal material layout schemes and furniture placement to achieve the best acoustic effects [66-68].

Special Building Acoustic Optimization

Special buildings, such as recording studios, hospitals, and schools, impose extremely stringent requirements on their acoustic environments due to their highly specialized functions and unique operational needs. Achieving optimal acoustic performance in these spaces is critical, as it directly impacts the quality of the activities conducted within them. For instance, recording studios require precise control over background noise, frequency response, and reverberation to ensure high-quality audio recordings. Similarly, hospital environments necessitate quiet and restful conditions to aid in patient recovery, while schools rely on effective acoustic design to enhance speech intelligibility and improve teaching outcomes.

The application of intelligent algorithms in the acoustic optimization of special buildings has proven to be an effective approach to addressing these complex demands [69-70]. By leveraging the computational power and adaptability of intelligent algorithms, designers can precisely model acoustic environments, optimize material selection, and adjust spatial configurations to meet specific performance criteria. These methods not only enhance the acoustic quality of these spaces but also provide cost-effective and efficient solutions that align with the functional requirements of each building type. A detailed acoustic optimization analysis for special buildings is presented in Table 8, showcasing practical examples and their corresponding improvements in acoustic performance.

Table 8. Acoustic Optimization Analysis for Special Buildings in Shenzhen

Building Type	Acoustic Issues Before Optimization	Improvement Effects After Optimization
Recording Studio	High background noise uneven frequency response	Background noise reduced frequency response fluctuations controlled
Hospital Ward	Severe noise interference affecting patient recovery	Noise in patient rooms reduced recovery environment improved
School Classroom	Low speech intelligibility affecting teaching effectiveness	Speech intelligibility improved student listening efficiency significantly enhanced

Table 8 indicates that acoustic optimization for recording studios demands exceptionally stringent acoustic environmental requirements, necessitating a noise-free, echo-free acoustic space with flat frequency response [71]. Intelligent algorithms can precisely optimize studio dimensions, selection and placement of sound-absorbing materials, and design of acoustic diffusers to ensure high-quality recording outcomes [72]. Following optimization with intelligent algorithms as described in [73], background noise levels decreased, and fluctuations in the frequency response curve were controlled within specified limits. Hospital acoustic optimization employs intelligent algorithms to optimize the design of soundproof doors and windows in hospital wards, along with the placement of interior sound-absorbing materials. This reduces noise levels within patient rooms while minimizing external noise interference [74]. School acoustic optimization employs intelligent algorithms to enhance classroom acoustic design, improving speech intelligibility and ensuring students clearly hear instructional content [75]. Literature [76] reports significantly increased student listening efficiency following classroom acoustic environment optimization using intelligent algorithms.

Challenges

Although research on optimizing architectural acoustic environments using intelligent algorithms has achieved certain results, several issues remain to be addressed, including computational efficiency, data acquisition and model validation, and balancing multi-objective optimization [77].

Computational Efficiency Issues

Intelligent algorithms often involve substantial computational demands and extended processing times when addressing large-scale architectural acoustics optimization problems, thereby compromising their practical application efficiency. In the acoustic design of large building complexes, the involvement of numerous acoustic parameters and complex acoustic models can result in computational times for intelligent algorithms reaching several hours or even days, significantly hindering practical design work [77].

Data Acquisition and Model Validation

Accurately obtaining relevant data on architectural acoustic environments is challenging, and there exists a certain degree of error between established acoustic models and actual acoustic conditions, making model validation complex [78]. In practical engineering, acquiring acoustic data requires extensive on-site measurements and experiments. This process is not only time-consuming and labor-intensive but also yields potentially inaccurate results due to limitations in measurement environments and conditions [79]. Furthermore, the complexity of architectural acoustic environments often prevents established acoustic models from fully and accurately reflecting reality. Validating these models demands substantial experimental data and sophisticated analytical methods [80].

Multi-Objective Optimization Balancing

In integrated acoustic design optimization, balancing acoustic performance with other design objectives presents a challenging problem [81]. In architectural design, enhancing acoustic performance may require increasing the use of sound-absorbing materials or altering spatial layouts, which could lead to higher construction costs or reduced space utilization [82]. Therefore, achieving maximum economic efficiency and spatial utilization while meeting acoustic performance requirements remains a critical issue requiring resolution in current research.

Conclusions and Outlook

Intelligent algorithm-based methods for optimizing architectural acoustic environments demonstrate significant potential and value in both theory and practice. By integrating optimized acoustic models with intelligent algorithms, these approaches effectively address challenges such as noise control and reverberation time optimization within architectural acoustic environments, thereby enhancing the acoustic quality of buildings. Practical case studies indicate that these methods can provide customized acoustic optimization solutions for diverse building types, improving auditory experiences and overall quality of life.

To enhance the computational efficiency and solution accuracy of building acoustic environment optimization methods, future research will focus on improving and innovating intelligent algorithms, promoting multidisciplinary integration, and expanding practical engineering applications. To further develop more efficient intelligent algorithms and improve their computational efficiency and solution accuracy for large-scale building acoustic optimization problems, new hybrid intelligent algorithms will be explored by integrating emerging technologies such as deep learning. Strengthen interdisciplinary research integrating architectural acoustics with building physics, computer science, materials science, and other fields to broaden the scope and depth of intelligent algorithm-based architectural acoustic optimization applications. Establish a more robust acoustic model validation and data acquisition system to promote the adoption and dissemination of intelligent algorithm-based architectural acoustic optimization methods in a wider range of practical engineering projects.

Author Contributions

Roman Piotr Kotowski contributes to conceptualization, methodology, software, validation, analysis, investigation, data collection, draft preparation, manuscript editing, visualization, supervision. All authors have read and agreed with the manuscript before its submission and publication.

Funding

This research received no specific financial support from any funding agency.

Institutional Review Board Statement

Not applicable.

References

[1] Xiao, J., Aletta, F., & Ali-Maclachlan, I. (2022). On the Opportunities of the Soundscape Approach to Revitalise Acoustics Training in Undergraduate Architectural Courses. Sustainability (Switzerland), 14(4). DOI:10.3390/su14041957

[2] Edamenko, A. S., Yastrebinskaya, A. V., & Semeykin, A. Y. (2021). Research of acoustic discomfort and pollution environment by increased flow motor transportation in the south district of Belgorod. Technology of Technosphere Safety, 91, 85–94. DOI:10.25257/tts.2021.1.91.85-94

[3] Wang, Q., Hongwei, W., Cai, J., & Zhang, L. (2022). The multi-dimensional perceptions of office staff and non-office staff about metro noise in commercial spaces. Acta Acustica, 6. DOI:10.1051/aacus/2022014

[4] Bray, W. R. (2021). A general overview: The appearance and evolution of spatial electroacoustic systems for ambient and other applications in the restaurant environment. The Journal of the Acoustical Society of America, 150(4_Supplement), A162–A162. DOI:10.1121/10.0007990

[5] Huang, Z., Chen, M., Wang, T., Cui, H., & Dong, W. (2023). Numerical Investigation of Background Noise in a Circulating Water Tunnel. Machines, 11(8). DOI:10.3390/machines11080839

[6] Mostafavi, A., & Cha, Y. J. (2023). Construction Noise Cancellation with Feedback Active Control Using Machine Learning. Conference Proceedings of the Society for Experimental Mechanics Series, 5–10. DOI:10.1007/978-3-031-34946-1_2

[7] Palaniappan, E., Mohammed, R., Lewis, E., & Balaji, K. V. (2023). The Influence of the Material Construction of Leatherette in Squeak Noise Control. SAE Technical Papers, 000(4), 5. DOI:10.4271/2023-01-0075

[8] Ferrante, T., & Villani, T. (2021). Environmental Physical and Perceived Quality in Hospice. Health Environments Research and Design Journal, 14(4), 324–338. DOI:10.1177/19375867211028160

[9] Xie, H., Peng, Z., Kang, J., Liu, C., & Wu, H. (2022). Soundscape Evaluation Outside a Taoist Temple: A Case Study of Laojundong Temple in Chongqing, China. International Journal of Environmental Research and Public Health, 19(8). DOI:10.3390/ijerph19084571

[10] Boren, B. (2021). Word and Mystery: The Acoustics of Cultural Transmission During the Protestant Reformation. Frontiers in Psychology, 12(March), 564542. DOI:10.3389/fpsyg.2021.564542

[11] Yang, W., & Jeon, J. Y. (2020). Design strategies and elements of building envelope for urban acoustic environment. Building and Environment, 182. DOI:10.1016/j.buildenv.2020.107121

[12] Liu, X., Kang, J., Ma, H., & Wang, C. (2021). Comparison between architects and non-architects on perceptions of architectural acoustic environments. Applied Acoustics, 184, 108313-. DOI:10.1016/j.apacoust.2021.108313

[13] Dance, S. (2020). Masters course in environmental and architectural acoustics in London: A route on to our Ph.D. programme. The Journal of the Acoustical Society of America, 148(4_Supplement), 2747–2747. DOI:10.1121/1.5147634

[14] Lu, S., Cabrera, D., Holmes, J., & Ferraro, R. (2023). Cube-corner retroreflectors for acoustic support outdoors: A comparison of simple and optimised designs. Building and Environment, 236(May), 236. DOI:10.1016/j.buildenv.2023.110268

[15] Winroth, J., Ögren, M., Glebe, D., & Persson Waye, K. (2023). Child-Centred Room Acoustic Parameters of Public Preschools in Sweden. Buildings, 13(11). DOI:10.3390/buildings13112777

[16] Sert, F. Y., & Karaman, Ö. Y. (2021). An Investigation on the Effects of Architectural Features on Acoustical Environment of Historical Mosques. Acoustics, 3(3), 559–580. DOI:10.3390/acoustics3030036

[17] Cabrera, D., Yadav, M., Holmes, J., Fong, O., & Caldwell, H. (2020). Incidental acoustic retroreflection from building façades: Three instances in Berkeley, Sydney and Hong Kong. Building and Environment, 172, 106733-. DOI:10.1016/j.buildenv.2020.106733

[18] Mustafa, S. A., & Muhealdeen, B. N. (2023). Acoustic Comfort Evaluation in Traditional Houses and its Impact on Inhabitant Satisfaction in the City of Sulaimani. UHD Journal of Science and Technology, 7(2), 50–68. DOI:10.21928/uhdjst.v7n2y2023.pp50-68

[19] Arai, M., & Ueno, K. (2022). Study on Sound Environment and Operational Measures in Temporary School Building. AIJ Journal of Technology and Design, 28(69), 708–714. DOI:10.3130/aijt.28.709

[20] Eggenschwiler, K., Heutschi, K., Taghipour, A., Pieren, R., Gisladottir, A., & Schäffer, B. (2022). Urban design of inner courtyards and road traffic noise: Influence of façade characteristics and building orientation on perceived noise annoyance. Building and Environment, 224. DOI:10.1016/j.buildenv.2022.109526

[21] Bergerot, L., Blaise, J. Y., Pamart, A., & Dudek, I. (2022). Visual Cross-Examination of Architectural and Acoustic Data: the 3D Integrator Experiment. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 46(2/W1-2022), 81–88. DOI:10.5194/isprs-archives-XLVI-2-W1-2022-81-2022

[22] Razali, A. W., Din, N. C., & Hamdan, S. (2023). Investigation of the Acoustics Performance of the University's Lecture Rooms by using Economical and Feasible Design Improvement Strategies. Journal of Design and Built Environment, 23(3), 1–25. DOI:10.22452/jdbe.vol23no3.1

[23] Morgan, M. M., & Braasch, J. (2021). Long-term deep learning-facilitated environmental acoustic monitoring in the Capital Region of New York State. Ecological Informatics, 61(1). DOI:10.1016/j.ecoinf.2021.101242

[24] Bismor, D. (2023). 51st Winter School on Wave and Quantum Acoustics Lth Winter School on Environmental Acoustics and Vibroacoustics Szczyrk, Poland, February 27 – March 3, 2023. Archives of Acoustics, 48(3). DOI:10.24425/aoa.2023.145237

[25] Alambeigi, P., Burry, J., Zhao, S., & Cheng, E. (2020). A study of human vocal effort in response to the architectural auditory environment. Architectural Science Review, 63(3–4), 262–274. DOI:10.1080/00038628.2019.1708259

[26] Álvarez-Morales, L., Lopez, M., & Álvarez-Corbacho, Á. (2020). The Acoustic Environment of York Minster's Chapter House. Acoustics, 2(1), 13–36. DOI:10.3390/acoustics2010003

[27] Kuri, A. B., & Pérez R., S. J. (2022). Acoustic study and architectural proposals to improve acoustic comfort in a university campus of Mexico City. Applied Acoustics, 185, 108416-. DOI:10.1016/j.apacoust.2021.108416

[28] Imene, B., Aissa, D. M., & Rafik, D. B. (2022). Impact of Architectural Changes in Housing Estates on Urban and Environmental Quality in Constantine. International Journal of Innovative Studies in Sociology and Humanities, 7(4), 15–27. DOI:10.20431/2456-4931.0704002

[29] Montoya-Belmonte, J., & Navarro, J. M. (2020). Long-term temporal analysis of psychoacoustic parameters of the acoustic environment in a university campus using a wireless acoustic sensor network. Sustainability (Switzerland), 12(18). DOI:10.3390/SU12187406

[30] Algargoosh, A., & Soleimani, B. (2019). The impact of the acoustic environments on the emotional experience of worship spaces. The Journal of the Acoustical Society of America, 146(4_Supplement), 3022–3023. DOI:10.1121/1.5137477

[31] Sakagami, K., & Hanyu, T. (2023). Advances in Room Acoustics of Non-Performing Public Spaces. Applied Sciences (Switzerland), 13(1). DOI:10.3390/app13010188

[32] Qin, C., Yu, Q., & Zou, W. (2023). Simulation Evaluation of Outdoor Noise Environment in Buildings. Journal of Architectural Research and Development, 7(6), 55–60. DOI:10.26689/jard.v7i6.5553

[33] Khan, N. A., & Bhattacharjee, B. (2021). Methodology for Simultaneous Optimization of the Thermal, Visual, and Acoustic Performance of Building Envelope. Journal of Architectural Engineering, 27(3), 27. DOI:10.1061/(asce)ae.1943-5568.0000474

[34] Hong, X., Xia, D., & Zhu, W. (2023). An efficient calculation method of large-region dynamic traffic noise maps based on hybrid modeling. Environmental Pollution, 331(Aug. Pt.2), 121842.1-121842.9. DOI:10.1016/j.envpol.2023.121842

[35] Iasiello, L., & Colombelli-Négrel, D. (2023). Noisy neighbours: effects of construction noises on nesting seabirds. Marine and Freshwater Research, 74(7), 573–585. DOI:10.1071/MF22138

[36] Mostafavi, A., & Cha, Y. J. (2023). Deep learning-based active noise control on construction sites. Automation in Construction, 151(000), 15. DOI:10.1016/j.autcon.2023.104885

[37] Tang, R., Lu, T., Pan, C., & Zheng, W. (2023). Vibrational loss analysis of a new type of phononic crystal with a tungsten block embedded inside a rubber matrix. Journal of Low Frequency Noise Vibration and Active Control, 42(4), 1765–1774. DOI:10.1177/14613484231185473

[38] Cao, X. N., Ding, K. M., Shi, M., Liu, Q., & Guo, J. Y. (2020). Exploration of the exotic structure in Ce isotopes by the relativistic point-coupling model combined with complex momentum representation. Physical Review C, 102(4), 262011. DOI:10.1103/PhysRevC.102.044313

[39] Noguchi, S., Yoshizawa, H., Sato, M., & Konishi, T. (2019). The sound environment of German preschools and preschool teachers’ thoughts about sound generated by children. Proceedings of the International Congress on Acoustics, 2019-September, 5918–5925. DOI:10.18154/RWTH-CONV-239560

[40] Matheou, M., Couvelas, A., & Phocas, M. C. (2020). Transformable building envelope design in architectural education. Procedia Manufacturing, 44, 116–123. DOI:10.1016/j.promfg.2020.02.212

[41] Huaquín, M. (2019). Acoustic planning of urban space. Akustika, 32, 316–324. DOI:10.36336/akustika201932316

[42] Iannace, G., Ciaburro, G., Guerriero, L., & Trematerra, A. (2020). Use of cork sheets for room acoustic correction. Journal of Green Building, 15(2), 45–55. DOI:10.3992/1943-4618.15.2.45

[43] Jablonska, J. (2021). Architectural acoustics and speech legibility in university environment – Case study. Applied Acoustics, 177(June 2021). DOI:10.1016/j.apacoust.2021.107917

[44] Milo, A. (2020). The acoustic designer: Joining soundscape and architectural acoustics in architectural design education. Building Acoustics, 27(2), 83–112. DOI:10.1177/1351010X19893593

[45] Burfoot, M., Ghaffarianhoseini, A., Naismith, N., & GhaffarianHoseini, A. (2023). The birth of intelligent passive room acoustic technology: a qualitative review. Smart and Sustainable Built Environment, 12(1), 60–83. DOI:10.1108/SASBE-06-2021-0096

[46] Campbell, M., Aisner-Williams, R., Akpulat, T., Estrada, J., Kittridge, M., Pavlovic, M., & Pryporov, M. (2022). Integrated Facies Modeling for Unconventional and Tight Reservoirs. SPE/AAPG/SEG Unconventional Resources Technology Conference, URTC 2022, 000(2-22URTC), 11. DOI:10.15530/urtec-2022-3722978

[47] Zhu, R., Boukerche, A., Huang, X., & Yang, Q. (2023). DESLR: Energy-efficient and secure layered routing based on channel-aware trust model for UASNs. Computer Networks, 234(Oct.), 1.1-1.11. DOI:10.1016/j.comnet.2023.109939

[48] Guo, Q., Zhao, H., Zhou, T., Wang, Z., Xu, S., & Cui, H. L. (2023). Non-iterative constrained compressive beamforming. Measurement: Journal of the International Measurement Confederation, 214. DOI:10.1016/j.measurement.2023.112730

[49] Zhang, Z., Tian, S., & Yang, Y. (2023). Node Depth Adjustment Based Target Tracking in Sparse Underwater Sensor Networks. Journal of Marine Science and Engineering, 11(2), 23. DOI:10.3390/jmse11020372

[50] Somaan, N., Bhardwaj, A., & Sabra, K. G. (2023). Passive underwater Acoustic IDentification (AID) tags for enhancing Autonomous Underwater Vehicle (AUV) navigation during docking or homing operations. The Journal of the Acoustical Society of America, 153(3_supplement), A345–A345. DOI:10.1121/10.0019102

[51] Guo, X., Guo, Y., Wang, J., Xiao, B., Cao, Y., & Wu, C. (2022). Thermodynamic analysis and optimization of a novel hybrid system using thermoacoustic cycle to harvest waste heat of high temperature PEMFC. Energy Conversion and Management, 260(May), 260. DOI:10.1016/j.enconman.2022.115572

[52] Avramov, I. D., & Ivanov, G. R. (2022). Layer by Layer Optimization of Langmuir–Blodgett Films for Surface Acoustic Wave (SAW) Based Sensors for Volatile Organic Compounds (VOC) Detection. Coatings, 12(5). DOI:10.3390/coatings12050669

[53] Li, D., Liu, F., Shen, T., Chen, L., Yang, X., & Zhao, D. (2022). Generalizable Underwater Acoustic Target Recognition Using Feature Extraction Module of Neural Network. Applied Sciences (Switzerland), 12(21). DOI:10.3390/app122110804

[54] Ali, W. R., & Prasad, M. (2022). Design and Fabrication of Piezoelectric MEMS Sensor for Acoustic Measurements. Silicon, 14(12), 6737–6747. DOI:10.1007/s12633-021-01437-1

[55] Ding, Z., Zou, N., Zhang, C., Chen, Y., Tong, S., Wang, F., Xiong, F., Zhang, Y., & Zhang, X. (2022). Self-Optimized Vibration Localization Based on Distributed Acoustic Sensing and Existing Underground Optical Cables. Journal of Lightwave Technology, 40(3), 844–854. DOI:10.1109/JLT.2021.3122738

[56] Pradeep, S., & Tapas Bapu, B. R. (2022). An efficient energy consumption and delay aware autonomous data gathering routing protocol scheme using a deep learning mobile edge model and beetle antennae search algorithm for underwater wireless sensor network. Concurrency and Computation: Practice and Experience, 34(15). DOI:10.1002/cpe.6946

[57] Giliberti, C., Lo Castro, F., Patrizia Orlando, M., Mariconte, R., & Diano, M. (2022). Use of hearing aids at work: results of a questionnaire for the analysis of comfort and perceived benefit. Human Factors in Accessibility and Assistive Technology, 37. DOI:10.54941/ahfe1001640

[58] Zhang, Y., Su, Y., Shen, X., Wang, A., Wang, B., Liu, Y., & Bai, W. (2022). Reinforcement Learning Based Relay Selection for Underwater Acoustic Cooperative Networks. Remote Sensing, 14(6), 27. DOI:10.3390/rs14061417

[59] Chao, Y., Wang, B., Li, H., Xia, M., Zhao, Q., Wang, H., Li, R., Chen, J., & Gan, Z. (2022). A two-stage thermally-coupled pulse tube cryocooler working at 35 K for space application. Acta Astronautica, 191(Feb.), 193–203. DOI:10.1016/j.actaastro.2021.11.007

[60] Yang, L., Wang, H., Fan, Y., Luo, F., & Feng, W. (2022). Reinforcement Learning for Distributed Energy Efficiency Optimization in Underwater Acoustic Communication Networks. Wireless Communications and Mobile Computing, 2022. DOI:10.1155/2022/5042833

[61] Zhu, J., Gao, H., Dai, S., Qu, Y., & Meng, G. (2023). Multilayer structures for high-intensity sound energy absorption in low-frequency range. International Journal of Mechanical Sciences, 247. DOI:10.1016/j.ijmecsci.2023.108197

[62] Jiang, B., Liu, X., & Wu, X. (2023). Sound power estimation method based on dual arrays sound intensity scaling and sound pressure superposition. Noise Control Engineering Journal, 71(1), 24–33. DOI:10.3397/1/37713

[63] Kim, J., Sands, M., & Hayes, E. (2023). Adaptive unsaturated stochastic resonance in parallel array and its application to acoustic emission signal denoising. Proceedings of SPIE, 12488(000), 72. DOI:10.1117/12.2658611

[64] Yin, Y., Ji, N., Wang, X., Shen, W., Dai, B., Kou, S., & Liang, C. (2023). An investigation of fusion strategies for boosting pig cough sound recognition. Computers and Electronics in Agriculture, 205, 107645. DOI:10.1016/j.compag.2023.107645

[65] Bhingare, N. H., & Subramaniam, P. (2023). Optimization of sound absorbing material by using Taguchi and ANOVA. Noise and Vibration Worldwide, 54(4–5), 162–171. DOI:10.1177/09574565231161646

[66] Africa, A. D. M., Mercado, J. A., & Sim, J. K. (2023). Development of an adaptive finite impulse response filter optimization algorithm using rough set theory. Indonesian Journal of Electrical Engineering and Computer Science, 31(1), 238–247. DOI:10.11591/ijeecs.v31.i1.pp238-247

[67] Li, G., Bu, W., & Yang, H. (2023). Research on noise reduction method for ship radiate noise based on secondary decomposition. Ocean Engineering, 268, 113412-. DOI:10.1016/j.oceaneng.2022.113412

[68] Wang, J., Feng, Q., Ma, J., & Feng, Y. (2023). FL-SDUAN: A Fuzzy Logic-Based Routing Scheme for Software-Defined Underwater Acoustic Networks. Applied Sciences (Switzerland), 13(2), 18. DOI:10.3390/app13020944

[69] Xiang, S., Fei, X., Long, X., & Jidong, C. (2023). Research on Transformer Voiceprint Feature Extraction Oriented to Complex Noise Environment. International Journal of Acoustics and Vibrations, 28(2), 193–199. DOI:10.20855/ijav.2023.28.21933

[70] Chaitanya, S. K., Sriraman, S., Srinivasan, S., & Srinivasan, K. (2022). Equivalent source method based near-field acoustic holography using machine learning. Internoise 2022 - 51st International Congress and Exposition on Noise Control Engineering. DOI:10.3397/in_2022_0213

[71] Bozcu, L., Söğütlü, I. E., Öztürk, S., & Erol, H. (2023). On optimum speaker placement with a model-based approach for indoor local active noise control applications. Noise Control Engineering Journal, 71(2), 109–120. DOI:10.3397/1/377110

[72] Fan, Q., Yu, Y., An, L., Cao, H., & Zhu, C. (2023). Fast and accurate wideband sparse spatial spectrum estimation in an underwater strong interference environment. The Journal of the Acoustical Society of America, 154(6), 3810–3820. DOI:10.1121/10.0023934

[73] Lombard, J., Biben, T., & Merabia, S. (2022). Electron-phonon effects on the photoacoustic response of gold core-silica shell nanoparticles: From the linear regime to nanocavitation. Journal of Chemical Physics, 156(8), 84701. DOI:10.1063/5.0078457

[74] Siddiqui, S. H., & Langde, A. (2023). Performance analysis in the design of thermoacoustic refrigeration system: review. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 45(3), 7705–7731. DOI:10.1080/15567036.2023.2223148

[75] Wei, W., Shang, Y., Peng, Y., & Cong, R. (2022). Research Progress of Noise in High-Speed Cutting Machining. Sensors, 22(10). DOI:10.3390/s22103851

[76] Zhang, H., Wang, B., Gao, C., Zhu, T., Xiong, M., & Ren, H. (2022). Effective degradation of hydrolyzed polyacryamide (HPAM) in a simultaneous combination of acoustic cavitation and microbubbles ozonation: Process optimization and degradation mechanism. Process Safety and Environmental Protection, 159, 465–476. DOI:10.1016/j.psep.2022.01.007

[77] Wei, J., Yang, H., & Ning, F. (2022). Acoustic scene classification based on joint optimization of NMF and CNN. Xi Tong Gong Cheng Yu Dian Zi Ji Shu/Systems Engineering and Electronics, 44(5), 1433–1438. DOI:10.12305/j.issn.1001-506X.2022.05.01

[78] Li, Y., & Nandakumar, R. (2023). A Cognitive Scaling Mixer for Concurrent Ultrasound Sensing and Music Playback in Smart Devices. ACM International Conference Proceeding Series, 260–265. DOI:10.1145/3576914.3589559

[79] Zhou, M., Han, J., Rachh, M., & Borges, C. (2023). A neural network warm-start approach for the inverse acoustic obstacle scattering problem. Journal of Computational Physics, 490, 490. DOI:10.1016/j.jcp.2023.112341

[80] Chaitanya, S. K., Sriraman, S., Srinivasan, S., & Srinivasan, K. (2023). Machine learning aided near-field acoustic holography based on equivalent source method. The Journal of the Acoustical Society of America, 153(2), 940–951. DOI:10.1121/10.0017115

[81] Choi, J., Hong, J., Kang, H., Hong, T., Park, H. S., & Lee, D. E. (2022). An automatic decision model for optimal noise barrier plan in terms of health impact, productivity, and cost aspects. Building and Environment, 216, 109033-. DOI:10.1016/j.buildenv.2022.109033

[82] Kim, T., An, I., & Yoon, S. eui. (2023). Inexpensive indoor acoustic material estimation for realistic sound propagation. Computer Animation and Virtual Worlds, 34(5). DOI:10.1002/cav.2131