Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 45 No. 10
October 2024

A Comprehensive Review of Parameters and Assessment Methods for Auditorium Acoustics

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Abstract
This systematic review consolidates and analyzes significant advancements in the acoustic design of auditoriums, emphasizing the integration of architectural innovation to improve sound quality in built environments. Initially, the review explores traditional and modern acoustic materials, detailing the transition from synthetic to sustainable resources like natural fibers and bio-based composites, which offer environmentally friendly solutions. The review further delves into the empirical research underpinning these materials' effectiveness, supported by ISO standard tests that illustrate their practical benefits in contemporary architectural acoustics. Additionally, the review contextualizes the historical evolution of acoustic design, reflecting on the impact of architectural forms and materials on the acoustic quality of auditoriums, and proposes a forward-looking perspective on the use of advanced materials and technologies. Through a comprehensive analysis, this review highlights the ongoing innovations and challenges in the field, offering a valuable reference for future research and practical applications in auditorium acoustic design.

Keywords: *Acoustics; Sustainable Acoustic Materials; Architectural Acoustic Design; Computational Acoustics; Sound Absorption Technologies.*

Introduction

The section titled "Introduction to Auditoria Acoustics" establishes the foundation for the thorough examination of auditoria acoustics, elucidating its importance in the context of improving performance spaces via sound engineering. The fundamental principles of sound absorption, reflection, sound propagation, and reflection are critical in the design of auditoriums. To attain a comprehensive comprehension and investigation of these fundamental elements, the referenced literature in the document provides a more profound dive into the components and progressions in the domain of auditoria acoustics. He et al. [1] presented a comprehensive historical account of the progression of concert hall acoustics. By providing exhaustive analyzes of the acoustic qualities of concert halls around the world, Beranek [2] advances knowledge regarding sound propagation and audience perception in auditoriums. Barron [3] established a correlation between subjective experiences and objective acoustic measurement programmes implemented in British concert halls. The citations highlight the

intricate and diverse characteristics of auditorium acoustics, encompassing historical developments as well as the incorporation of both subjective and objective evaluations in the planning and assessment of performance areas.

Major objectives of the comprehensive review of parameters and assessment methods for auditorium acoustics are as follows.

- Evaluation of significant advancements in the acoustic design of auditoriums, focusing on how architectural innovation and material science contribute to enhanced sound quality.
- Investigation of the evolution of acoustic materials from traditional to modern options, including the shift from synthetic to sustainable materials such as natural fibers and bio-based composites.
- Examination of the role of innovative fabric-based acoustic solutions and the impact of computational simulations in optimizing the acoustical attributes of auditorium interiors.

- Assessment of the effectiveness of new materials like coal bottom ash concrete and hybrid bio-benzoxazines/epoxy matrices in improving sound absorption and insulation.
- Proposal of a forward-looking perspective on the use of advanced materials and technologies, highlighting ongoing innovations and challenges in auditorium acoustic design.

2. Literature Review

Using a structured scientific approach, the literature review on auditorium acoustics methodically evaluated previous investigations, emphasizing developments in acoustic materials and architectural methods. First, a thorough search was conducted using keywords like "auditorium acoustics," "architectural acoustics," and "sound absorption" across academic databases (Scopus and Web of Science) and specialised publications. To achieve a comprehensive analysis, selection criteria were based on the relevance to auditorium acoustics, and both empirical and theoretical works were considered. The extraction of data was centred on the kinds of acoustic materials that were employed, the assessment of architectural designs, the techniques for measuring acoustic performance, and the efficacy of different designs and materials. After that, data was arranged thematically to facilitate an organised analysis that revealed patterns, gaps, and new themes. The methodological rigour and impact of each study were evaluated to ensure that only high-quality and significant research was included. In the end, the review synthesised the data to create a cohesive story about the condition and developments of auditorium acoustics today, bridging the gap between sustainability and acoustic performance and pointing out areas that require more investigation. This approach guaranteed a thorough review, highlighting effective techniques and prospective avenues for auditorium design innovation.

2.1 Thematic cluster – 1 Architectural Design Building Shape and Form

The acoustical peculiarities of historic curved buildings are rarely seen in modern acoustic design, which instead uses computer models to modify circular and elliptical spaces for a variety of uses[4]. The book "Auditorium Acoustics and Architectural Design" by Michael Barron examines both traditional and contemporary methods of improving auditorium acoustics [5]. A novel approach to design is put forth, utilising statistical analysis of current auditoria to provide insights on designs that go beyond conventional techniques [6]. Problems such as "boomy" noises in speech-oriented environments highlight the importance of careful planning and absorptive remedies, especially for stage towers [7]. Seoul's Grand Theatre has undergone restorations that include material and architectural changes to improve acoustical quality, which have been confirmed by model measurements and simulations [8].

2.2 Thematic cluster – 2 – Acoustic Materials

A variety of environmentally friendly acoustic materials and uses are examined in this collection[9]. Reviews highlight natural fibers—such as jute, kenaf, and coconut coir—as affordable, eco-friendly substitutes for synthetic materials, highlighting their capacity to reduce noise[10]. Studies of a range of fabric-based acoustic devices, including fixed parts and movable panels, show that fabric structure has a major effect on sound absorption at all frequencies [11]. Additional research on hybrid bio-benzoxazines/epoxy matrices and coal bottom ash concrete emphasizes their potential as building insulation, highlighting both their environmental and acoustic benefits [12] Furthermore reviewed are the acoustical, thermophysical, and structural qualities of timber materials, highlighting their crucial role in environmentally friendly building [13].

3. General studies on quantitative criteria and evaluation methods

Donald and Baxa [14] developed a comprehensive set of eight quantitative merit criteria for concert hall design, which are used in an automated computer optimization method. Their approach, which employed a modified image method, sought to identify the best hall configurations and absorption coefficients for each criterion. By comparing the acoustical merits of these optimized designs to an existing hall with well-known acoustical quality, they gained valuable insights into improving specific design objectives and comparing metrics. Bradley [15] emphasized the significance of early-to-late sound ratios and interaural cross-correlation in assessing acoustic performance. He emphasized the significance of early sound on music quality, highlighting the delicate balance required for maximum clarity and richness. Furthermore, correlations were discovered between hall width and acoustic measures, indicating that mean width is an accurate predictor. Lacatis [16] looked into the historical evolution of concert hall acoustic parameters, providing a retrospective analysis of how they have changed over time.

Barron [3] conducted extensive objective acoustic measurements in British concert halls, comparing subjective preferences with various objective measures. Preferences for intimacy and reverberance were discovered, and correlations demonstrated the importance of total sound level and early decay time. Bradley [17] discussed the evolution of newer auditorium acoustics measures other than reverberation time, emphasizing the importance of clarity and definition in addition to reverberation. Carl and Eyring [18] presented a reverberation time equation that accounts for variations in room shape, resulting in a more general formula than Sabine's. Their findings emphasized the importance of taking into account room geometry when predicting sound decay. Bradley [19] conducted detailed measurements of the acoustical conditions in multipurpose halls and renowned concert halls, revealing significant differences. The study sought to emphasize the significance of extensive measurements in accurately assessing auditorium acoustics.

Fergus and Fricke [20] examined existing concert hall acoustic design guidelines and proposed a statistical approach based on existing auditorium shape as an alternative design method. Barron [21] investigated the effects of hall design features on bass frequency attenuation and sound diffusion, highlighting the importance of grazing incidence and ceiling designs in shaping sound spectra. Plenge [22] conducted experiments to assess concert hall acoustic quality, comparing subjective ratings to physical parameters like position, reverberation time, and brilliance. Factor analysis revealed that hall quality is multidimensional. Gerald Marshall [23] discussed indices for measuring speech intelligibility in enclosed spaces, emphasizing the importance of including directional characteristics and directivity factors in speech intelligibility predictions.

John Bradley [24] conducted experiments to evaluate acoustic measures as predictors of subjective judgements, comparing objective measures to subjective parameters to identify reliable predictors. Hidaka and Beranek [25,26] investigated the use of interaural cross-correlation coefficients (IACC) and lateral efficiency to evaluate concert hall quality, focusing on the effects of low and high-frequency sound levels on perceived quality. Beranek [26] documented various acoustical features of concert halls, providing insights based on experiments carried out in several halls. Gade [27] proposed prediction methods for newer acoustical parameters associated with hall shape and dimensions, to assist acoustic consultants during the early stages of design.

Lam [28] talked about partial diffusion and its implications for room acoustics prediction, including models for calculating diffuse reflection coefficients in auditoriums. Rindel [29] discussed sound reflections and computer modelling solutions, emphasizing the importance of accurately simulating diffusion and diffraction effects. Okano [30] investigated the relationship between subjective characteristics of concert hall acoustics and objective measures such as apparent source width and interaural cross-correlation coefficient and found that they can predict subjective rankings. Takayuki et al. [31] presented objective and subjective evaluations of opera houses, identifying key parameters for determining acoustic quality. John and Bradley [32] discussed speech intelligibility metrics about sound reflections and background noise, and they provided analytical formulas for comparing speech intelligibility in different room conditions.

Takayuki Hidaka [33] demonstrated the predictability of occupied reverberation time and other parameters using unoccupied values, emphasizing the importance of fabric covering in hall acoustics. Reinhard [34] proposed a modified formula for calculating reverberation time in unevenly distributed absorptive environments to make more accurate predictions. Chiles and Barron [35] measured in scale models, revealing differences between predicted and observed reflected sound levels, and looked into scatter in reverberation time. Shin-ichi Sato [36] presented a genetic algorithm-based optimization system for theatre design, to produce optimized forms with high subjective sound quality preferences. Beranek [37] described how size, shape, and building materials affect hall acoustics while also introducing new terminology. Bradley [38] investigated the use of ISO 3382 standards to evaluate concert hall acoustics, emphasizing the significance of understanding spatial variations as well as early and late sound levels.

Fergus et al. [39] assessed the information required for concert hall acoustics design while considering the feasibility of calculating objective parameters using neural networks. Jack and Evans [40] discussed the design of circular auditoriums for optimal acoustics, proposing improvements to sound foci, reflection patterns, and reverb. Daniel et al. [41] proposed acoustical parameters for describing sound fields in halls, emphasizing their importance in distinguishing between good and excellent acoustics. Barron [42] investigated clarity values for various music genres and the relationship between clarity and early-to-late sound indices, revealing the optimal hall conditions. Marshall [43] emphasized the superiority of shoebox concert halls in sound quality ratings, implying that a better understanding of their acoustical properties is required to achieve excellence in modern hall design.

Pavel Zahorik [44] investigated the perceptual properties of room acoustic simulation techniques, which have been thoroughly researched and refined in terms of physical aspects. However, the perceptual aspects of these simulations have received relatively little attention. Zahorik developed and tested a method for estimating perceptual similarity between rooms by running 15 small-room simulations based on binaural room impulse responses (BRIRs). These BRIRs were either measured in real rooms or estimated using fundamental geometrical acoustic modelling techniques. The study experimented with room size, surface absorption properties, and virtual simulation features such as the use of personalised head-related transfer function measurements for spatial rendering. While BRIRs differed in several physical parameters, multidimensional scaling analysis revealed that the rooms differed only in two perceptual dimensions: reverberation time (T60) and coherence (IACC). The study found that modelled rooms differed from measured rooms in this perceptual space, but the differences were minor and easily corrected by adjusting T60 and IACC.

Martellotta [45] looked into how reverberation time (T) affects just noticeable difference (JND) values in clarity measurements. While the JND values for the majority of acoustical parameters used in practice have been determined using conditions commonly found in concert halls and speech rooms, Martellotta's research considered longer reverberation times. The study altered measured B-format impulse responses to introduce changes in reverberation time, then conducted listening tests to determine subjective limens. The results showed that JND in the clarity index was nearly independent of T, while JND in the centre time was significantly related to T. Bradley [46] talked about ISO 3382, which defines objective room acoustics parameters for assessing specific aspects of concert hall sound fields. However, little research has been conducted on how to effectively develop and implement these objective measures. Values for measures such as Early Decay Time (EDT) are uncertain, and changes proposed for measures such as energy ratios lack subjective support. Bradley emphasized the importance of having a better understanding of just noticeable differences (JND) for each measure and went over specific issues with measurements in different halls.

Niels Wermer et al. [47] took objective measurements in 20 Danish rock music venues and used a questionnaire to solicit subjective feedback from musicians and sound engineers. The study found that the best-rated halls had reverberation times (RT) ranging from 0.6 to 1.2 seconds, while the worst-rated halls had higher RT in the 63 to

125 Hz range. A standing audience's absorption coefficient was found to have a significant effect on sound absorption in mid/high frequencies when compared to a sitting audience. Magne Skalevik [48] faced the challenge of describing sound differences between rooms with similar RTs. Skalevik proposed five aspects, each with its physical measure, to reduce the number of listener aspects. Despite claims that RT is no longer required, statistical analysis of measurements and computer simulations, combined with Barron's Revised Theory, revealed that RT controls four of the five most important listener characteristics. Skalevik demonstrated that all five aspects could be predicted using RT, volume, and the source-receiver distance.

Krzysztof Leo [49] spoke about speech intelligibility as measured in the Auditorium Novum at the Technical University of Gdansk. Articulation tests were run, and the Speech Transmission Index (STI) and EDT were calculated. The study investigated the effect of negative noise on speech intelligibility and discovered that the majority of seats in the auditorium had high speech intelligibility. Correlations between spatial differences and articulation tests were studied. Tapio Lokki et al. [50] described a concert hall acoustics study using the individual vocabulary profiling method. This method allowed assessors to rate samples recorded in three locations across three concert halls based on individual characteristics. The subjective results revealed that loudness and reverberance were the most important perceptual dimensions, with separate groups of attributes formed for apparent source width, definition, and distance. The study also compared subjective results to objective room acoustic parameters, concluding that ISO 3382-1 parameters could not account for all of the variability in the subjective data.

Michelle Vigeant [51] examined just noticeable differences (JND) in room acoustics parameters, specifically the music clarity index (C_80). Two new studies were conducted to further investigate C_80 JND, and the findings showed a higher JND than previous studies. The studies also compared testing methods and discovered an interaction effect between the test method and the order in which subjects received it. These studies advance our understanding of room acoustics, the perceptual aspects of acoustic simulations, subjective assessments of room quality, and the relationship between objective measures and subjective perception. They emphasize the importance of considering both physical parameters and perceptual attributes when evaluating and optimizing room acoustics for a wide range of applications, including concert halls and rock music venues.

Mike Barron [52] emphasizes the importance of good concert hall acoustics and the value of research in this field. While much effort has gone into better understanding reflection preferences and developing new measurable acoustic quantities, translating acoustic requirements into three-dimensional built form has received less attention. Barron conducted an acoustic survey on existing auditoriums of various types, including concert halls, recital halls, drama theatres, opera houses, and multipurpose rooms. The survey included measurements of physical acoustic characteristics as well as listening tests administered during public performances via questionnaires. The results of this comprehensive survey are presented alongside a thorough examination of the concerns and principles of good acoustic design.

Beranek [53] delves into the parameters necessary for concert hall acoustics design, focusing on sound strength (G) and RT. G, which is closely related to loudness, and RT, which is inversely related to total sound absorption in a hall, are both important acoustic design factors. Beranek discusses how the bass index determines the loudness of bass sounds, as well as architectural features that influence strength (G). He emphasizes the importance of adhering to specific G and RT ranges when designing and evaluating concert halls. Tapio Lokki et al. [54] investigated perceptual differences in simulated concert halls, specifically the role of temporal envelope preservation and lateral reflections in sound perception. Their findings show that preserving a signal's temporal envelope in reflections increases the perceived strength of sound and bass. Furthermore, lateral reflections affect perceptions of envelopment, openness, and sound source distance, with stronger effects at higher frequencies.

Ahmed Ali Elkhateeb [55] investigates architectural details in lecture auditoriums and compares field measurements to predicted values to determine speech intelligibility. Despite the high levels of speech intelligibility attributed to finishing materials, Elkhateeb notices an issue with excessive background noise, most likely caused by natural ventilation. Alicia Gimenez [56] examines audience perceptions of concert hall acoustics by comparing responses from music fans, acousticians, and the general public. The study discovers a shared vocabulary among music enthusiasts and acousticians in rating halls, emphasizing the importance of subjective perceptions in evaluating acoustics. Yann Jurkiewicz [57] investigates the importance of early reflections in producing high acoustic quality in performing arts venues. His research demonstrates the ability to predict early reflected energy across an audience area using solid angles, which has implications for acoustic design. Marina et al. [58] conducted an acoustic analysis of a rectangular auditorium, focusing on parameters such as RT and diffusion. Their study evaluates room acoustics through measurements and simulations, emphasizing the importance of factors such as diffusion in achieving optimal acoustics.

Abdelouahab [59] measures acoustic comfort in classrooms using variables such as background noise and RT. The study identifies problems with impulse decay and background noise in classrooms and makes recommendations for acoustic rehabilitation. Colin Campbell [60] discusses the use of reverberation time to set acoustic conditions in classrooms, emphasizing the limitations of relying solely on RT to explain human perception differences. He emphasizes the importance of measuring additional room acoustic parameters to achieve acceptable acoustic comfort levels. Peisheng Zhu [61] investigates speech intelligibility metrics such as the STI and the Speech Intelligibility Index, concluding that both can be used to objectively rate speech intelligibility. Alicia Gimenez [62] investigates objective room acoustics in performance spaces and compares the findings to subjective survey results. The study uses factor analysis to identify independent parameters for describing acoustic quality, which shows correlations with traditional parameters like impression of space and strength. Salvador Cerda [63] assesses Ando-Beranek's sound quality model for symphony orchestra concert halls and combines it with Barron's theory to determine the optimal design regions for classical music venues. Czerwinski and Dziechciowski [64] compare measurement results for auditorium acoustic properties, with a focus on speech intelligibility and uniform sound distribution. They notice issues with EDT and sound level variation with distance from the source.

Tapio Lokki [65] discusses the challenges of explaining the success of specific concert halls, despite extensive research on measured and simulated impulse responses. Patynen [66] describes experiments that show how concert hall acoustics affect emotional responses, emphasizing the importance of near-orchestra positions and shoebox-shaped hall designs in increasing musical impact. Chrissanth Mourti [67] investigates the relationship between technological principles and architecture in rock auditoriums, emphasizing the challenges of developing successful designs due to limited acoustic knowledge. Tansu Yilmaz [68] investigates the acoustic quality of a multipurpose hall and proposes volume resonator-based low-frequency noise control solutions. Artur Nowoswiat [69] discusses RT models and their application in describing acoustic parameters in enclosed rooms. Cheung and Tanga [70] present a framework for predicting early IACCs and show that geometrical regression models outperform neural network approaches. Gimenez [71] uses factor analysis to identify independent parameters for describing musical performance halls that correlate with traditional parameters like impression of space and strength. Laurent and Galbrun [72] look at the accuracy of predicting the STI with RT and signal-to-noise ratio, highlighting differences between measured and predicted STIs. Kwangbok Jeong et al. [73] look into the acoustic design of a classical concert hall and evaluate its performance using metrics like RT, clarity, and lateral fraction. Hochgraf [74] discusses the acoustic design elements of concert and vineyard halls, focusing on the importance of wall surfaces, reflections, and reverberation in achieving optimal sound quality.

4. Simulation studies

The evolution and refinement of room acoustical models and simulation techniques have made significant contributions to our understanding and improvement of sound quality in a variety of settings, particularly concert halls and auditoriums. This comprehensive overview examines the contributions and findings of several key researchers over the years, highlighting the evolution from basic models to sophisticated hybrid and real-time simulation techniques. Beginning with Claus Lynge Christensen in 1999 [75], a room acoustical model capable of handling point, line, and surface sources was established, with a special ray-tracing algorithm for line and surface sources and Image Source Modelling for point sources. This method enabled the modelling of complex sound sources in workrooms, laying the groundwork for future advances in acoustic simulation. Rindel's work [76] advanced the field by emphasizing the benefits of hybrid models, which combine the best features of image source models and ray-tracing methods to shorten calculation times and improve results. The importance of accurately modelling sound scattering from surfaces was emphasized, indicating a need for more data on material scattering properties. Jens Holger Rindel's [77] comparison of measured room acoustical parameters with those obtained from computer simulations using the ODEON programme shed light on the accuracy of these models in non-rectangular spaces, such as concert halls, demonstrating the potential of these tools in real-world applications. In 2002, Sanmartin [78] compared two acoustic simulation software, highlighting ODEON's efficiency over Ray noise in terms of processing time and frequency accuracy, emphasizing the importance of modelling accuracy in simulation outcomes. Michael Vorländer's [79] contributions in 2005, and later in 2010 [80] and 2011 [81], shed light on the uncertainties inherent in room acoustical computer simulations, as well as the importance of real-time modelling, emphasizing the ongoing need for verification and improvement in simulation algorithms and software reliability. Graham Naylor's 1992 [82] prediction of room acoustical behaviour highlighted the discrepancies that can result from geometrical simplifications, advocating for simpler room models to make more reliable predictions in certain situations. In 2007, Hiroyoshi Shiokawa [83] assessed the capabilities of computer simulations by comparing measured and simulated room acoustical parameters in concert halls, emphasizing the importance of high geometrical fidelity in models. David and Bradley [84] and Carolina Reich and Marcon Passero [85] investigated specific applications of ODEON software in evaluating concert hall acoustics and classroom RTs, demonstrating the utility of simulation software in real-world settings. Jens Holger Rindel's 2010 [86] paper examined the strengths and weaknesses of various modelling techniques, emphasizing the differences that can arise due to differences in material absorption characteristics and the approximation of wave phenomena such as scattering and diffraction in simulations. In 2010, Kaminski [87] and Cameron M. Hough [88] investigated the acoustics of concert halls using various simulation software and methods, addressing specific issues such as acoustic defects and the effectiveness of acoustic immersion indices in evaluating hall acoustics. Tapio Lokki's [89] studied concert hall acoustics employed descriptive sensory analysis to generate sensory profiles of concert halls, presenting a novel approach to evaluating acoustic qualities.

Jens Holger Rindel reiterated in 2013 [91] the close agreement between measured and simulated room acoustical parameters, while Emma Linnea Gjers in 2014 [92] and Lukas Aspöck in 2016 [93] investigated correlations between measurements, simulations, and subjective opinions, as well as the impact of boundary conditions on simulation results. Amit Kr. Singh Chauhan et al. [94] discussed solutions for improving room acoustics through material selection and placement, emphasizing the potential of new materials and treatments in improving acoustical properties. Finally, Soha Eldakdoky's 2017 study on auditoria [95], which used experimental and digital simulation techniques, highlighted the importance of absorptive materials and ceiling shapes in achieving optimal reverberation and speech intelligibility, demonstrating the practical applications of simulation techniques in architectural acoustics. This journey through the evolution of room acoustics modelling and simulation shows how the field progressed from simple geometric and statistical methods to complex hybrid models and real-time simulations. Researchers have worked tirelessly to improve the accuracy, efficiency, and applicability of these models, tackling challenges such as material properties, geometrical fidelity, and wave simulation. These scholars' collective work emphasizes the importance of acoustical simulations in space design and evaluation, ensuring that sound quality and listener experience meet desired standards.

5. Artificial neural network

The advancement of room acoustical modelling and simulation techniques in recent decades has had a significant impact on the field of architectural acoustics, particularly in the design and evaluation of concert halls and auditoriums. This condensed review focuses on key contributions and findings from several researchers who influenced the development and application of these models. Claus Lynge Christensen [75] introduced a comprehensive model for room acoustics that can handle point, line, and surface sources while also utilising a unique ray-tracing algorithm and Image Source Modelling. This methodology enabled the simulation of complex sound sources in work environments, which was a watershed moment in acoustical modelling. Jens Holger Rindel's work in 2000 and subsequent years [77,85,89] focused on the effectiveness of hybrid models, which combine the best aspects of image source models and ray-tracing methods to improve accuracy and reduce computation times. Rindel's comparisons of measured and simulated room acoustical parameters using the ODEON programme demonstrated the ability of these tools to accurately reflect real-world acoustics, particularly in non-standard spaces such as concert halls.

Sanmartin [78] compared acoustic simulation software and found that ODEON outperformed Ray noise in processing time and accuracy, emphasizing the importance of modelling accuracy in simulation outcomes. Michael Vorländer [79-81] provided critical insights into the uncertainties of room acoustic computer simulations and the significance of real-time modelling. His work emphasized the importance of continuous verification and refinement of simulation algorithms to improve their reliability and applicability in architectural acoustics. Graham Naylor [82] and Hiroyoshi Shiokawa [83] discussed the discrepancies that can result from geometrical simplifications in models, advocating for simpler, more reliable room models and emphasizing the importance of geometrical fidelity in simulations.

David and Bradley [84], along with Carolina Reich and Marcon Passero [85], used ODEON software in real-world settings to evaluate concert hall and classroom acoustics. These studies demonstrated the software's accuracy in predicting acoustic parameters as well as its potential for real-world applications. Kaminski [87] and Cameron M. Hough [88] investigated the acoustics of concert halls using various simulation methods, addressing issues such as acoustic defects and the usefulness of acoustic immersion indices. Their findings shed light on specific issues in hall acoustics and proposed solutions to improve auditory experiences. Tapio Lokki [89] used a novel approach to evaluate concert hall acoustics, resulting in sensory profiles that provided unique insights into the perceptual aspects of acoustic quality.

Lukas Aspöck [95], Amit Kr. Singh Chauhan et al. [94], and Soha Eldakdoky [95] broadened the scope of acoustical simulations by investigating the effects of boundary conditions, material selection, and architectural changes on simulation accuracy and room acoustics. Their research emphasized the importance of detailed input data, novel material applications, and design changes in achieving optimal acoustic properties. Together, these researchers have improved our understanding and capabilities in room acoustics modelling and simulation. Their efforts have resulted in significant improvements in the accuracy, efficiency, and practical application of these models, addressing challenges such as material properties, geometrical fidelity, and wave simulation. Their findings highlight the critical role of acoustical simulations in ensuring that sound quality and listener experience in architectural spaces meet high expectations.

6. Subjective studies

The evaluation of acoustic quality in concert halls and educational spaces has evolved significantly over the years, with various methodologies used to collect subjective assessments from a diverse range of respondents. This review chronicles researchers' pioneering efforts and methodologies for assessing the acoustical quality of spaces, highlighting the variety of approaches and insights gained from these studies. Parkin et al. [96] conducted what is thought to be the first known use of questionnaires to numerically rate the overall acoustics of British concert halls in 1952. They used a three-point scale to survey music critics, academics, and composers and received a 25% response rate, laying the groundwork for future subjective acoustical assessments. A decade later, Beranek [2] expanded on this approach by interviewing 50 distinguished musicians and music critics to assess 54 world-renowned concert halls. His method of categorising halls into five levels of acoustical quality and identifying key attributes of successful spaces demonstrated the value of interviews for detailed feedback, despite the higher cost when compared to questionnaires. Hawkes and Douglas [97] developed a more nuanced questionnaire with 16 bipolar rating scales that were distributed to attendees at four London concert halls. Their findings highlighted the multidimensional nature of acoustic assessments, revealing differences depending on the type of music and the venue.

Gade [98] interviewed 32 musicians to determine 12 critical attributes of room acoustic quality from the standpoint of the stage. This study emphasized the significance of performer-audience acoustic dynamics in spatial perception. Barron [3] improved questionnaire techniques by administering continuous semantic differential scales to 27 acoustics specialists during live concerts in British halls. His research demonstrated the validity of expert opinions in live settings when determining design characteristics for good acoustics. In the late 1990s, Haan and Fricke [6] broadened the scope by surveying musicians and conductors from the Sydney Symphony Orchestra, evaluating the acoustics of 60 concert halls on a three-point scale and receiving a 32% response rate. This study validated the questionnaire approach to assessing concert hall acoustics on a global scale. Cox and Shield [99] and Richardson and Shield [100] examined the general audience's perception of live concerts at the Royal Festival Hall and four other British venues, respectively. Their research highlighted the difficulties of engaging non-expert listeners, as evidenced by the relatively low response rates of 25% and 17%. Nonetheless, these studies were a significant step towards understanding the lay audience's acoustic experiences.

Satya Pancharatnam and Ramachandraiah [101] investigated the subjective responses of regular attendees to South Indian classical music concerts. Their in-depth survey of seven live vocal concerts sought to capture listeners' acoustic preferences and rankings of 22 concert halls, providing valuable insights into cultural and genre-specific acoustic requirements. Arianna Astolfi [102] shifted the focus to educational spaces, conducting a subjective survey of the perceived environmental quality of 51 secondary school classrooms, including acoustically renovated ones. Astolfi's study, which included responses from 1006 students, found significant correlations between acoustic quality, speech comprehension, and academic performance. The study highlighted the effect of acoustic conditions on concentration and the disturbance caused by intermittent noise versus constant noise. These studies cover a wide range of methodologies and respondent groups used to assess the acoustic quality of various spaces. Subjective acoustic assessment has evolved from the use of simple numerical scales to detailed semantic differential scales, and from focusing solely on concert halls to including educational settings, reflecting a growing understanding of the complex interplay between architectural acoustics and human perception. The varying response rates, as well as the shift from expert opinions to general audience feedback, highlight the challenges and opportunities associated with capturing the subjective acoustic experience. These pioneering efforts have laid the groundwork for current and future research aimed at improving acoustic design to meet the diverse needs of users in various settings.

7. Indian studies

Ramakrishna [103], Bhandari [104], Pancharatnam and Ramachandraiah [105,106], and Paulraj et al. [107] investigate various aspects of acoustical design and testing in a variety of auditoriums and classroom settings. Ramakrishna [103] focuses on the acoustic design and testing of a multipurpose auditorium with a seating capacity of 3250 people. The study focuses on the optimal RT for a hall with a sound reinforcement system, as well as the system's design and performance. The key parameters are hall volume, RT, bass ratio, sound level variation, and noise level. Bhandari [104] emphasizes the importance of taking into account a variety of factors that influence sound quality when designing acoustics for multipurpose halls. The interaction of various aspects of sound and the internal physical environment of the room is investigated to ensure good acoustics.

Pancharatnam and Ramachandraiah [105] use simulation software to investigate the acoustics of an image auditorium in Chennai. The parameters examined include RT, EDT, C_80, G, and clarity. The study shows a more reverberant hall at higher frequencies, emphasizing the importance of shape in achieving optimal acoustics for South Indian classical music. Satya Pancharatnam and Ramachandraiah [106] compare two South Indian classical music halls in Chennai, analyzing parameters such as RT, C_80, and G using simulation and field measurements. The study emphasizes the importance of hall shape, resonance, and clarity for various types of music. Paulraj [107] focuses on creating a system for predicting speech intelligibility in the classroom. The study includes data collection from various classrooms, statistical analysis, and the creation of an Elman network-based prediction system. The study concludes that network performance is influenced by the normalisation method employed. In conclusion, these studies offer useful insights into acoustical design considerations for auditoriums and classrooms, including RT, clarity, sound reinforcement systems, and speech intelligibility prediction.

8. Discussion and Conclusion

The comprehensive review of auditorium acoustics reveals that each auditorium worldwide possesses distinct acoustical characteristics. Literature highlights that various researchers have studied individual auditoriums, often comparing their acoustical properties over time. Despite similarities in volume, shape, and other design features, auditoriums can exhibit subtle variations in their acoustical behavior. Some factors contributing to these differences have been identified, resulting in a matrix of objective parameters such as clarity, strength, lateral efficiency, definition, and Speech Transmission Index (STI).

The increasing importance of simulation studies in architectural acoustics, which often replace physical scale model studies, underscores the need for a deeper focus on various acoustical aspects of interior spaces. Computational simulations have advanced, but they require further refinement to accurately address the complexities of acoustical behavior.

In the context of Indian architecture, while there has been research focused on single-purpose auditoria relevant to local needs, there is a noticeable gap in studies related to multipurpose auditoria. The lack of indices for objective parameters in these settings indicates a need for more targeted research. Future investigations should address this gap, focusing on the development of standardized indices and further exploration of acoustical characteristics specific to multipurpose halls. This research is essential for advancing our understanding and improving acoustic design practices in diverse architectural contexts.

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