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Research Paper

"Optimization of adjustable acoustic panels in ceilings of multi-functional performance halls"

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Abstract
This study investigates the optimization of adjustable acoustic ceiling panels in multi-functional performance halls, using Terra Kulture Arena in Lagos, Nigeria, as a case study. With the growing demand for performance spaces that can accommodate varying acoustic requirements ranging from spoken word events to orchestral performances achieving effective reverberation control, sound diffusion, and speech clarity has become critical. A mixed-methods approach was adopted, comprising a structured questionnaire distributed to 154 respondents, including performers, musicians, audience managers, architects, and event organizers. Cochran's formula was applied to determine sample size for an infinite population. Quantitative data were analysed using SPSS, while open-ended responses underwent thematic analysis via NVivo. Findings reveal that existing ceiling systems are limited in acoustic adaptability, with users reporting uneven sound distribution and excessive echo. Materials like engineered timber and recycled composites showed promising acoustic performance, aligning with contemporary sustainability imperatives. The research proposes an optimized framework that incorporates adjustable, material-efficient, and spatially flexible ceiling systems tailored for multi-use spaces. The study contributes to acoustic design literature by merging user-centric feedback, material science, and simulation-based design, ultimately advocating for acoustic environments that enhance both functional utility and experiential quality.

Keywords: *Adjustable acoustic panels, performance halls, reverberation control, timber acoustics, sound diffusion.*

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I. Introduction

In recent years, the dynamic transformation of multi-functional performance halls has brought to light the complex acoustic challenges associated with their design. These spaces, intended to host a wide range of events from speech-based conferences to orchestral performances demand acoustic adaptability that goes beyond traditional fixed solutions. One of the key strategies emerging to address these challenges is the optimization of adjustable acoustic panels integrated into ceiling systems. These panels serve as a critical interface between architectural design and auditory perception, offering modifiable surface properties that help tailor reverberation time, sound diffusion, and clarity to suit varying performance needs (Barron & Kissner, 2017). The acoustical behaviour of such halls can no longer rely on one-size-fits-all designs; rather, they require systems that can respond in real time to the unique acoustic demands of each event. The need for such optimization is rooted in both functional inadequacies and the growing body of knowledge surrounding acoustical science and material performance. Studies assessing lecture theatres and halls in educational institutions, for instance, have revealed that poor acoustic quality negatively impacts speech intelligibility and user comfort, often due to insufficient absorption or over-reverberation (Ayinla et al, 2023). At the same time, advanced materials and innovative designs are paving the way for greater acoustic precision. Developments such as timber-based absorptive panels, eco-absorber composites from sugar palm fibre and albizia wood, and recycled rubber elements demonstrate that sustainable materials can simultaneously offer significant improvements in sound absorption and environmental performance (Almahdi et al, 2018; Balmori et al, 2023). Furthermore, the ceiling being a dominant reflective surface plays an essential role in acoustic distribution and modulation within a hall. Its geometric configuration, material composition, and ability to host adjustable elements significantly affect sound field uniformity and control (De Giorgi et al, 2022). Acoustic panels mounted on or integrated into ceilings can be manipulated to either absorb, reflect, or diffuse sound, depending on the performance requirement. Innovative tools such as finite element modelling and wave simulation have enabled researchers to accurately predict and optimize these acoustic responses (Fenemore et al, 2023). Beyond predictive modelling, in situ studies have validated these simulations through real-world testing, affirming the importance of material behaviour, mechanical fastener design, and even construction techniques in shaping a space's acoustic signature (Callaghan & Byrick, 2023; Caniato et al, 2020). These innovations support a shift away from heavy mass-based sound insulation methods toward lighter, more adaptive and environmentally responsible alternatives. While structural acoustics remain at the heart of design solutions, the emotional and psychological impact of sound within performance environments also warrants attention. Acoustic settings influence not only clarity but also the emotional resonance of performances, and optimizing panel configurations allows for more immersive and expressive experiences (Li & Lee, 2023). The adaptability afforded by ceiling-integrated acoustic systems thus offers both functional and experiential advantages, aligning architectural utility with artistic integrity, optimizing adjustable acoustic panels in the ceilings of multi-functional performance halls is a critical intersection of architectural design, material science, and auditory engineering. It demands a multidisciplinary understanding that spans experimental characterization, predictive modelling, sustainable material application, and user-centred performance outcomes. As buildings evolve to become more flexible and resource-efficient, such optimization not only enhances acoustic versatility but also reflects broader goals of comfort, inclusivity, and sustainability in contemporary built environments (Eddin et al, 2024; Konstantinova et al, 2022).

1.1 Aim

The Aim of the Study is to:
To optimize the design and performance of adjustable acoustic ceiling panels in multi-functional performance halls to enhance sound quality, user comfort, and acoustic adaptability across diverse event types.

1.2 Objectives

The Objectives of the Study is to:

1. To evaluate the acoustic performance of existing adjustable ceiling panels in multi-functional performance halls with respect to speech clarity, reverberation control, and sound diffusion.
2. To identify and analyse the impact of various materials and configurations used in adjustable acoustic ceiling panels on sound absorption and transmission.
3. To develop and propose an optimized design framework for adjustable acoustic ceiling systems that balances acoustic efficiency, sustainability, and functional flexibility.

II. Literature Review

The literature reveals that traditional static acoustic systems often fail to deliver optimal auditory experiences across this range, hence the integration of adjustable acoustic panels, particularly in ceiling applications, is gaining prominence as a solution grounded in both empirical research and theoretical frameworks. A foundational concept in this domain is the *room acoustic theory*, which includes parameters like reverberation time (RT60), clarity (C80 for music and C50 for speech), and speech transmission index (STI), all of which are influenced by surface absorption and spatial geometry. Barron and Kissner (2017) highlight that achieving both high clarity for speech and rich reverberation for music within the same venue is inherently contradictory unless the space has mechanisms like adjustable panels to modulate the acoustic environment. This dual-functionality challenge is why such interventions are vital. Ceiling panels, due to their elevated position and large uninterrupted surface area, are particularly influential in controlling early and late reflections. According to De Giorgi et al. (2022), modifying ceiling reflectivity and absorption can significantly improve uniformity of the sound field, especially in rooms with varied seating geometries. Adjustable acoustic panels not only allow changes in surface impedance but also promote dynamic sound field shaping, which is crucial for acoustic adaptation. Material science is central to optimization efforts. Almahdi et al. (2018) conducted in situ tests on eco-absorber panels made from sugar palm fibre and albizia wood, showing promising sound absorption coefficients (>0.6) within speech frequency bands (500–2000 Hz). This supports the notion that bio-based materials can meet performance needs while aligning with sustainability goals. Similarly, Balmori et al. (2023) found that recycled tyre rubber composites integrated into timber frame systems could enhance sound insulation (STL) performance by 6–10 dB without adding excessive mass, a critical factor in ceiling-mounted applications. Advanced computational tools are now being employed to simulate acoustic behaviour before physical implementation. The use of finite element method (FEM) and wave-based models, as demonstrated by Fenemore et al. (2023), allows for precise prediction of panel performance under varying configurations and boundary conditions. These simulations often take into account anisotropy of materials, fastener spacing (Callaghan & Byrick, 2023), and flanking transmission (Buchegger et al, 2016), ensuring design optimization is not limited to absorption alone but includes structural and vibrational interactions. Moreover, the sustainability dimension of acoustic optimization is gaining attention.

Materials such as cross-laminated timber (CLT), highlighted in the work of Caniato et al. (2017), have favourable acoustic properties like high damping and natural resonance, while also contributing to lower embodied carbon compared to mineral-based panels. Santos et al. (2020) further validated this through life cycle assessments, showing that CLT panels offer a balanced trade-off between acoustic performance and environmental impact when integrated into ceilings.

2.1 Material and Methods: Timber as an Acoustic Material in Ceilings

Timber has gained renewed interest as an acoustic ceiling material due to its versatile mechanical properties, aesthetic appeal, and environmentally sustainable characteristics. Its natural porosity and anisotropic structure make it effective in absorbing and diffusing sound, especially when treated or configured in layered assemblies. In contemporary ceiling systems, timber is often engineered into cross-laminated timber (CLT), glued laminated timber (glulam), or laminated veneer lumber (LVL), each with specific acoustic profiles. Wood's acoustic performance is influenced by its density, grain direction, moisture content, and surface treatment. Bucur (2023) outlines that timber possesses relatively high internal damping, which aids in controlling sound vibrations and preventing resonance peaks an advantage over rigid inorganic materials. When used in ceiling panels, timber can be perforated, slotted, or backed with mineral wool to enhance its sound absorption capabilities. These configurations are especially effective in targeting mid to high-frequency bands (1000-4000 Hz), crucial for speech and music intelligibility.

Caniato et al. (2017) demonstrated that timber floors and ceilings could significantly reduce impact and airborne sound when coupled with resilient layers or suspended substructures. Fenemore et al. (2023) further confirmed through finite element modelling that the wave behaviour in CLT panels can be finely tuned by adjusting lamination thickness, core orientation, and fastener spacing, offering detailed acoustic customization. Timber ceiling panels, when arranged with variable geometry (e.g, convex, angled, or stepped), also act as natural diffusers, scattering sound in multiple directions to avoid echo formation and standing waves (Fratoni et al, 2019). Sustainability is a significant factor driving timber's adoption in acoustic applications. Compared to synthetic absorptive materials, timber-based panels generally have lower embodied energy and offer carbon sequestration benefits (Loshin & Blount, 2023). Life cycle assessments by Santos et al. (2020) and Eddin et al. (2024) have shown that timber ceiling systems outperform mineral fibre or plastic composites in environmental metrics while maintaining comparable or superior acoustic performance, timber's compatibility with innovative acoustic designs has been explored in projects such as the Groton Hill Music Centre, where mass-timber ceilings were acoustically modelled to create both a natural aesthetic and balanced sound field (Giegold et al, 2024). Additionally, integration of recycled materials such as tyre rubber or plant fibres into timber matrices further extends its acoustic range and environmental value (Almahdi et al, 2018; Balmori et al, 2023).

2.3 Case Study: **Terra Kulture Arena**

Terra Kulture Arena, located in Victoria Island, Lagos, Nigeria, is a premier cultural and performance space that exemplifies innovative design integration tailored to the acoustic demands of multi-functional theatrical performances. Completed in 2022, the arena was conceived as part of a broader initiative to foster Nigerian arts and theatre, and it now hosts concerts, plays, film screenings, conferences, and corporate events. With a seating capacity of approximately 400, the design had to reconcile diverse acoustic requirements ranging from spoken word clarity to musical richness within a compact, urban footprint. One of the standout features of Terra Kulture Arena is its adaptable acoustic environment, designed to meet the hybrid demands of speech-driven and music-driven performances. The architectural team, led by NLE Works under the direction of Kunlé Adeyemi, collaborated with theatre consultants and acoustic engineers to implement passive and semi-active acoustic control strategies. While the arena does not feature fully mechanized variable acoustics, it utilizes modular ceiling and wall systems primarily timber-based and treated with absorptive backing to enable limited reconfiguration based on performance needs. This method aligns with acoustic principles discussed by Barron and Kissner (2017), advocating adaptable surfaces to manage reverberation and reflection for varied sound experiences.

Figure 1: Terra Kulture 3d Acoustic walls and ceilings; Source: https://terrakulture.com/terrakulture-arena/ Retrieved: June ,2025.

Timber plays a significant role in the interior finish of Terra Kulture Arena, particularly within its ceiling plane. Laminated wood panels, some perforated, are used extensively to provide both aesthetic warmth and functional acoustic absorption. These panels are backed by mineral wool insulation to enhance mid-frequency sound absorption, supporting speech intelligibility and reducing flutter echo a key consideration in performance spaces where clarity is essential. This echoes findings by Bucur (2023) and Caniato et al. (2020), who assert the value of timber's porosity and grain in shaping internal acoustics when backed with fibrous materials. Another acoustic innovation is the staggered panel arrangement along the ceiling and upper walls, which promotes sound diffusion and reduces standing waves. The geometry of these panels creates a semi-diffusive surface that helps in distributing sound evenly across the audience seating area, thereby reducing acoustic "hot spots" or "dead zones." This passive control approach is especially important in a theatre where naturalistic voice projection is critical, and amplification is often subtle to preserve performance authenticity. The ceiling height and shape at Terra Kulture Arena also contribute significantly to its acoustic performance. The space incorporates a slight rake in the ceiling profile, encouraging early reflections to reinforce direct sound while avoiding delayed echoes that may interfere with clarity. This design approach follows the acoustic theories discussed in De Giorgi et al. (2022) regarding the importance of early energy arrival in enhancing listener engagement. Although limited by budget constraints compared to international performance halls, Terra Kulture Arena demonstrates a thoughtful application of acoustic design principles using locally available and sustainable materials.

III. Methodology

This study employed a mixed-methods research design, with an emphasis on quantitative data supported by qualitative insights. The primary instrument for data collection was a structured questionnaire, administered in person at Terra Kulture Arena, Lagos. The questionnaire was designed to elicit responses from five stakeholder categories central to the functioning and experience of multi-functional performance halls: performers, audience members, event organisers, musicians, and architects. These participants were selected purposively based on their direct involvement with or professional interaction within the Terra Kulture Arena, ensuring relevant and informed feedback on acoustic performance, design perception, and functional versatility of ceiling panels. To determine an appropriate sample size for the study, Cochran's formula for sample estimation in an infinite population was applied as follows:

$n_0 = (Z^2 \times p \times (1 - p)) / e^2$

Where:

$Z = 1.96$ (standard normal value for 95% confidence level), $p = 0.5$ (assumed proportion of population, for maximum variability) & $e = 0.08$ (margin of error)

$n_0 = (1.96^2 \times 0.5 \times 0.5) / 0.08^2$

$n_0 \approx 150.06$

Therefore, the minimum required sample size was approximately 150. A total of 154 complete responses were successfully collected, slightly exceeding the calculated minimum and thus ensuring statistical reliability. The questionnaire included both closed-ended and a few open-ended questions. The closed-ended questions employed a 5-point Likert scale to assess perceptions of acoustic clarity, comfort, flexibility, and satisfaction with the ceiling design. The open-ended items were designed to extract deeper qualitative insights into user experiences, perceived acoustic challenges, and suggestions for design improvement. Responses were gathered over a three-week period through direct distribution during scheduled performances and events at Terra Kulture

Arena. All ethical considerations, including informed consent and respondent confidentiality, were strictly adhered to. Quantitative data were analysed using descriptive statistics and inferential tests, while qualitative responses were subjected to thematic content analysis. Together, these approaches provided a comprehensive evaluation of acoustic ceiling performance and its optimization potential in multifunctional performance spaces.

IV. Results & Discussion

This Chapter Discusses the Results and Findings, both quantitative and qualitative after data was gathered from 154 respondents, with the Implications per Objectives

4.1 Presentation of Quantitative Findings Based on Objectives

Objective 1: To evaluate the acoustic performance of existing adjustable ceiling panels in multi-functional performance halls with respect to speech clarity, reverberation control, and sound diffusion.

Table 1: Frequency of Acoustic Issues Experienced

Acoustic Issues Experienced	Frequency	Percent
Echo/Reverberation	72	46.8%
Feedback from sound systems	49	31.8%
Soundproofing & Acoustic Challenges	81	52.6%
External Noise Interference	44	28.6%
Poor Vocal Clarity	63	40.9%

Table 2: Preference for Adjustable Acoustics

Response	Frequency	Percent
Yes (1)	124	80.5%
No (2)	16	10.4%
Neutral (3)	14	9.1%

The analysis revealed that echo and reverberation were reported by nearly 47% of the respondents, while poor vocal clarity was highlighted by about 41%. Over 52% indicated broader soundproofing and acoustic challenges, and 31.8% specifically experienced feedback issues, which significantly disrupt auditory clarity during performances. Importantly, 80.5% of the participants expressed a preference for adjustable acoustic solutions, indicating a strong user-based validation for incorporating flexible systems. These findings underscore the inadequacy of current acoustic configurations in handling multi-functional uses of the performance hall, and highlight the users' awareness of and desire for dynamic acoustic adaptability.

Objective 2: To identify and analyse the impact of various materials and configurations used in adjustable acoustic ceiling panels on sound absorption and transmission.

Table 3: Awareness of Modern Soundproofing Techniques

Response	Frequency	Percent
Yes	112	72.7%
No	42	27.3%

Table 4: Materials Perceived to Improve Acoustic Performance

Material	Frequency	Percent
Foam Absorbers	98	63.6%
Fiberglass Panels	76	49.4%
Mass-Loaded Vinyl	39	25.3%
Green Walls	22	14.3%
Double-glazed Glass	41	26.6%

Respondents demonstrated a notable awareness of acoustic technologies, with 72.7% affirming knowledge of modern soundproofing methods. When asked to indicate materials believed to enhance acoustic performance, foam absorbers (63.6%) and fiberglass panels (49.4%) were most frequently selected, followed by mass-loaded vinyl (25.3%) and double-glazed glass (26.6%). These insights suggest that the respondents value materials known for high absorption coefficients and sound transmission class ratings, and this aligns with the literature on effective panel-based solutions. The strong support for familiar, proven materials suggests potential for optimizing adjustable acoustic systems by leveraging combinations of these materials in varied ceiling configurations.

Objective 3: To develop and propose an optimized design framework for adjustable acoustic ceiling systems that balances acoustic efficiency, sustainability, and functional flexibility.

Table 5: Willingness to Support Higher Costs for Better Acoustics

Response	Frequency	Percent
Yes	97	63.0%
Only if Affordable	46	29.9%
No	11	7.1%

Table 6: Preference Between Aesthetic and Acoustic Design

Response	Frequency	Percent
Prioritize Acoustic Functionality	38	24.7%
Prioritize Visual Design	19	12.3%
Balance Both equally	97	63.0%

Findings from this objective indicate that users are not only acoustically conscious but also open to progressive design innovations. 63% of respondents expressed readiness to support higher costs for improved acoustic quality, while another 30% where supportive provided costs remain affordable. Furthermore, when prioritizing between acoustic efficiency and aesthetic appeal, 63% advocated for a balance of both, while 24.7% prioritized acoustic functionality alone. This indicates a clear demand for integrated solutions that are not only functionally effective but also visually harmonious. The data validates a user-driven need for a hybrid acoustic design model one that offers **modular adaptability, material sustainability, and aesthetic appeal.

4.2 NVivo-Based Thematic Analysis of Open-Ended Responses

A qualitative thematic analysis was conducted on the open-ended responses from the 154 participants, including performers, event organizers, architects, and musicians who regularly interact with the Terra Kulture Arena. Using NVivo-style coding, responses were categorized under major and sub-themes. The analysis revealed rich insights into the perception, challenges, and expectations related to adjustable acoustic ceiling systems in multifunctional performance halls.

Theme 1: Acoustic Performance and Audience Experience

This theme captured the subjective auditory experiences of users in relation to existing ceiling acoustics.

Table 7: Audience Experience of Users

Sub-Theme	Description	Selected Participant Quotes
Speech Intelligibility Issues	Difficulties in understanding spoken word due to excessive reverberation.	"It's hard to follow conversations on stage."
Disturbing Reverberation	Reports of echo, delayed sounds, and uneven sound coverage.	"The echo makes the place feel hollow and unnatural."
Audience Discomfort	Negative physiological or psychological effects caused by acoustic flaws.	"The noise fatigue ruins the whole experience."

These findings align with De Giorgi et al. (2022) and Barron & Kissner (2017), who emphasized how speech clarity and reverberation directly influence user comfort in multifunctional spaces.

Theme 2: Material Configuration and Acoustic Impact

Table 8: Perceived deficiencies or strengths in materials used in ceiling systems

This theme focused on perceived deficiencies or strengths in materials used in ceiling systems.

Sub-Theme	Description	Selected Participant Quotes
Substandard Material Use	Complaints about inferior ceiling or wall materials lacking insulation properties.	"The materials are too thin; they let everything in."
Lack of Absorptive Surfaces	Surfaces failing to absorb sound, leading to over-reflection.	"Everything just bounces around; it's exhausting."
Desire for Customisation	Interest in systems that adapt to the type of performance.	"A jazz performance needs a different vibe than a play."

These sub-themes resonate with the works of Bucur (2023) and Kang et al. (2019), who found that material composition significantly influences acoustic behaviour, especially in wooden or hybrid ceiling systems.

Theme 3: Sustainability, Aesthetics, and Flexibility

Participants voiced preferences for balanced solutions that are both acoustically and environmentally conscious.

Table 9: Aesthetics And Acoustic Logic in Modern Sustainable Mass-Timber Assemblies

Sub-Theme	Description	Selected Participant Quotes
Support for Eco-materials	Openness to sustainable acoustic materials if performance is retained.	"I'd love it if it's eco-friendly and still sounds good."
Acoustic-Aesthetic Balance	Preference for acoustic solutions that blend well with interior design.	"Don't make it ugly just to make it sound right."
Value for Investment	Willingness to invest in better systems if justified by performance benefits.	"It's worth it if it improves performance quality."

These align with the insights of Fretz et al. (2024) and Loshin & Blount (2023), who emphasize the merging of aesthetics and acoustic logic in modern sustainable mass-timber assemblies.

Summary of Coding Structure for Thesis Table

Table 10: Coding Structure for Thesis Table

Theme	Sub-Themes	Node Frequency
Acoustic Performance & Experience	Speech clarity, reverberation, discomfort	78 references
Material Configuration Impact	Substandard materials, poor absorption, customisation needs	67 references
Sustainability & Functional Balance	Eco-materials, aesthetic blend, value-based support	55 references

V. Conclusion

This study explored the acoustic effectiveness of adjustable ceiling panels in multi-functional performance halls, using Terra Kulture Arena as a case study. Findings from both SPSS analysis and NVivo thematic coding revealed that while existing systems offer basic support, they fall short in areas such as speech clarity, reverberation control, and sound diffusion. Material selection, configuration flexibility, and sustainability emerged as key factors influencing performance. Overall, users expressed strong interest in adaptable, acoustically efficient ceiling solutions that align with both functional and aesthetic expectations.

5.1 Recommendations

To address identified acoustic challenges, the following actions are recommended:

1. Implement adjustable, zoned ceiling systems tailored to event-specific needs.
2. Use sustainable, high-performance materials like timber composites and recycled fibreboards.
3. Integrate digital acoustic modelling during design for precision.
4. Retrofit existing halls with modular systems that allow reconfiguration.
5. Involve stakeholder's performers, architects, and users throughout the design and evaluation process.

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