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Acoustic Modeling and Simulation of an Adjustable Concert Hall with Variable Reverberation Time for Classical and Angklung Music

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ABSTRACT

The acoustic environment of a concert hall is acoustically specially designed for musical performances, typically in a single configuration for general use. While this may be effective for certain genres, it can be less suitable for others. Since traditional music is usually performed with no standardized acoustic, large-capacity halls specifically designed for traditional music, particularly angklung, remain scarce, let alone one capable of accommodating both classical and traditional music in a multipurpose setting. This study explores adjustable design capable of accommodating multiple genres through variable reverberation times. Through modeling and simulation using the room mapping module in EASE 5 software, four hall configurations were developed for angklung and three classical music periods by achieving their respective target RT at 1 kHz. Additional parameters evaluated were C_{80}, T_s, LF, SPL, and G. Adjustability was achieved by varying the ceiling height and materials of the ceiling and rear wall. All four configurations successfully fulfilled the acoustic criteria for their respective genre: 2.0 s for Romantic, 1.7 s for Classical, 1.6 s for Opera, and 1.3 s for angklung. The results of this study confirm that an adjustable concert hall design with variable geometry and surface materials is a versatile solution that can effectively accommodate a wide range of musical genres, from classical to Indonesian traditional music.

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INTRODUCTION

Western classical music and angklung music are music genres with distinct musical and acoustic characteristics commonly performed by Indonesian musicians. Western classical music itself encompasses several historical periods, such as Baroque, Classical, Opera, Romantic, and Contemporary; each with distinctive features and, consequently, varying acoustical requirements (Table 1). These differences, both within and between the two genres, include variations in instrument types and materials, sound characteristics and timbral qualities, musical structure, and the number of performers involved. As a result, the acoustic requirements for their performances differ significantly. Classical music is typically performed in concert halls specifically designed to meet its acoustic requirements. In contrast, angklung, as a folk instrument, has traditionally been performed in informal settings with no standardized acoustic considerations. Currently, there are no large-capacity concert halls in Indonesia with acoustics specifically designed to meet the requirements of traditional music, particularly angklung, let alone one capable of accommodating both classical and traditional music in a multipurpose setting. Designing a dedicated concert hall to support the acoustic qualities of angklung music would enhance performance quality. Furthermore, introducing an adjustable performance space with variable acoustics would enable flexibility to achieve optimal acoustic conditions for both classical and angklung music. This would serve as a multifunctional venue capable of accommodating a variety of musical genres. In this study, three genres from different periods in classical music are evaluated: Romantic, Classical, and Opera, in addition to the traditional angklung music.

Table 1. Characteristics and acoustic requirements of various periods in western classical music

Period	Description	Optimum reverberation time at 1 kHz [1]–[3]
Baroque (1600 – 1750)	Features clearly articulated, discrete notes, with frequent use of polyphony and ornamental figures	1.4 – 1.5 s
Classical (1750 – 1820)	Prominent main melody supported by harmonic accompaniment marked by contrasts and variety in dynamics	1.6 – 1.8 s
Opera (Classical)	Features a vocalist, requires clarity to ensure clear and intelligible articulation of lyrics	1.3 – 1.6 s
Romantic (1820 – 1920)	Expressive and passionate, frequent modulation and greater variation in pitch, dynamics, and harmonic progression	1.9 – 2.1 s
20th century	Broad dynamic contrasts, frequent use of atonal passages, a wide spectrum of stylistic diversity	Variative
Angklung	Bright, percussive timbre with a uniform tonal color across a wide pitch range forming both melody and harmony	1.0 – 1.4 s [4]

In this study, acoustic simulations were performed on geometrical models of several concert hall configurations. Several acoustic parameters were evaluated, including reverberation time (RT30), clarity (C80), center time (Ts), lateral fraction (LF), sound pressure level (SPL), and sound strength (G). RT30 represents the time needed for sound to decay by 60 dB (extrapolated from 30 dB). C80 measures sound clarity, defined as the ratio of early sound energy (including direct sound and early reflections within the first 80 ms) to late reflections (after 80 ms). Ts indicates the temporal center of gravity which represents the balance between direct sound and reflections, which describes the point where sound is concentrated in the echogram [5]. LF relates to spatial impression or perceived spaciousness that describes the ratio of early reflections to the total sound energy within the first 80 ms [5], [6].

METHODOLOGY

This study is divided into two main parts: geometrical modelling (room acoustics design) and acoustic simulation. The geometrical design includes the development of the general hall configuration and its variations to produce four distinct configurations.

Concert Hall Design

The concert hall design was developed based on considerations from existing halls and established conventions. The design process began with determining key architectural elements, including the basic hall shape, primary dimensions, and the dimensions of internal features such as seating, stage, stairs, audience area, and ceiling reflectors. Acoustic simulations were then conducted to evaluate acoustic parameters, namely RT15, C80, LF, Ts, SPL, and G. The design was iteratively refined until the acoustic parameters fulfilled the requirements for each configuration. Adjustments involved modifying geometrical aspects, such as surface areas (walls, reflectors, audience areas), terraced seating step height, ceiling height, angles (walls, ceiling, reflectors), material properties (absorptivity and diffusivity), while maintaining a seating capacity of 1,600. The hall adopts a shoebox shape, which is commonly used in traditional concert halls [7]. It offers more consistent sound distribution throughout the space [8] and better performance in terms of sound intensity, reverberation, tone, and definition compared to fan-shaped and vineyard halls [7].

The concert hall design variations were achieved by modifying the hall dimensions, specifically by varying the ceiling height, and adjusting the surface materials based on their assigned absorption coefficients. Certain elements of the hall are kept consistent across all configurations, such as the materials used for the lateral walls, reflectors, balcony sides, upholstery, and stage walls and floors. Reflectors, as its name implies, as well as parts of the stage, including the floor and walls, are also constructed with reflective materials to help project and distribute the sound created by the musicians as effectively as possible towards the audience area. The main lateral walls and balcony sides of the hall are made up of the same reflective material to enhance lateral reflections, which contributes to sound envelopment, and help sustain reverberation. Seating upholstery plays a significant role in the hall’s reverberation time due to its large surface area. Lightly upholstered seats were selected to minimize sound absorption, which supports achieving a longer reverberation time [9]. To closely replicate actual performance conditions, audience areas are set to be fully occupied in the simulation.

Acoustic simulations were conducted in EASE 5 Third Edition software. The concert hall geometry was created in a separate computer-aided design (CAD) software which was then exported as a DWG file and imported into EASE for surface material assignment and acoustic simulation. Alternatively, the design process could have been done directly in the drawing function of EASE. However, using CAD software allows greater precision and flexibility in modelling complex geometries. The imported geometry was then assigned specific surface materials based on the required absorption depending on the target reverberation time for each configuration. The materials were selected from the database available in EASE, which includes both generic and specific data from the AFMG (EASE developer company) Database.

Design Configuration Variation

Four concert hall configurations were designed to accommodate four distinct music genres: three from different periods of the western classical music—Classical, Opera, and Romantic—and one Indonesian traditional genre, angklung music. Each design aimed to achieve a specific reverberation time as the primary acoustic parameter, with supporting parameters adjusted accordingly to complement the specific performance requirements of each genre.

The target reverberation time for each concert hall configuration was determined based on the ideal values for the corresponding music genres, as mentioned in Table 1. The first design (Design I), intended for Romantic music, requires the longest reverberation time. According to Sabine’s reverberation formula, longer reverberation times can be achieved by increasing room volume and minimizing sound absorption by using reflective materials on large surface areas. Both strategies were applied in the first design, which features the highest ceiling (Figure 1) among all four designs, and predominantly reflective surfaces to preserve sound energy and extend reverberation time. Details of the material selection and ceiling height used in the final configuration of Design I are provided in Table 2.

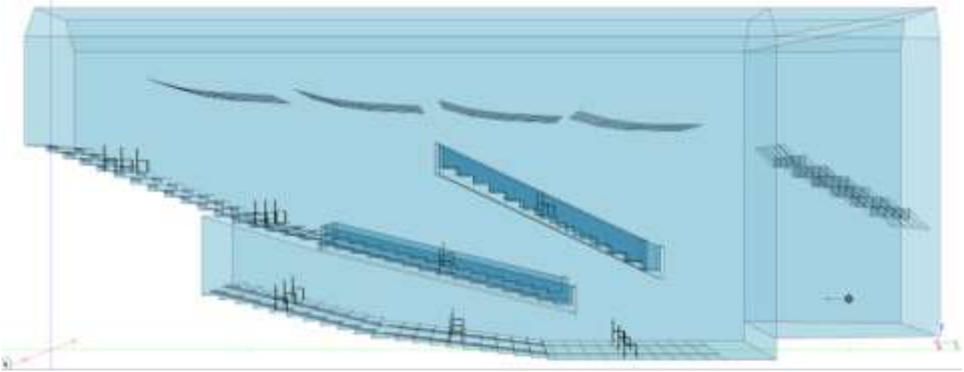

Figure 1. Side view of concert hall geometrical configuration: Design I

After finalizing the first design, the subsequent configurations were derived by modifying either the ceiling height or surface materials (Table 3). The second design (Design II), intended for Classical music with a shorter reverberation time, utilizes the same surface materials but features a lower ceiling. This approach allows change in reverberation time to result solely from reduced room volume while keeping materials consistent. The third and fourth designs (Design III and IV)—intended for Opera and angklung music, respectively—features the same dimensions as the second design (Figure 2), including the lowered ceiling height, but differ in some surface materials. The third design, which requires a shorter reverberation time than the second, modifies only the ceiling by using a moderately more absorptive material and taking advantage of its large surface area. The fourth design, with the shortest reverberation time, retains the ceiling material from the third design and adds absorptive material on the rear wall to further reduce reverberations.

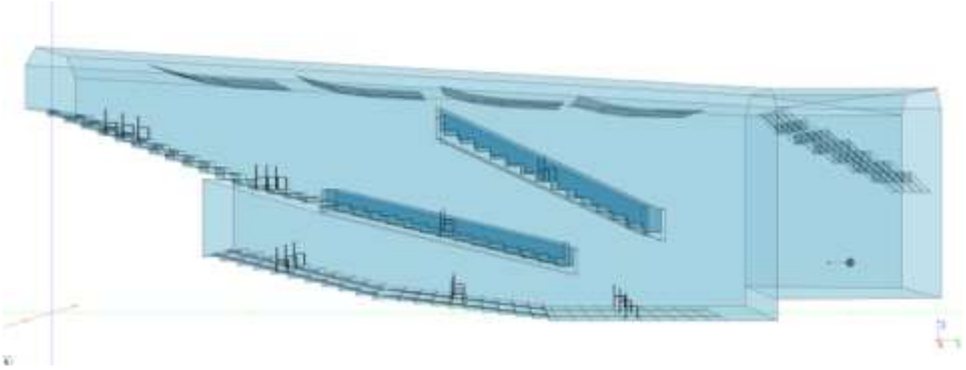

Figure 2. Side view of hall geometrical configurations: Design II, III, and IV

Table 2. List of geometrical configuration and surface materials absorption coefficients for Design I, obtained from EASE 5 material database

Part	Description	Absorption coefficient (α)						
		125	250	500	1k	2k	4k	8k
Floors	Wood, audience floor, 2 layers, 33 mm on sleepers over concrete	0.09	0.06	0.05	0.05	0.05	0.04	0.03
Walls and balcony sides	Concrete block, plastered	0.06	0.05	0.05	0.04	0.04	0.04	0.04
Ceiling	Plaster, ceiling, 30 mm w/ lighting and ventilation	0.14	0.12	0.08	0.06	0.06	0.04	0.02
Stage walls and floor	Wood, stage floor, 2 layers, 27 mm over airspace	0.10	0.07	0.06	0.06	0.06	0.06	0.06
Reflectors	2x13 mm plasterboard on steel frame, 5 cm mineral wool in cavity, surface painted	0.15	0.10	0.06	0.04	0.04	0.05	0.06
Audience seats	Audience seats, fully occupied, lightly upholstered	0.51	0.64	0.75	0.80	0.82	0.83	0.84
Ceiling height	16.5 m							

Table 3. List of design changes in geometrical configuration and surface materials absorption coefficients for Design II, III, and IV

Part	Description	Absorption coefficient (α)						
		125	250	500	1k	2k	4k	8k
Ceiling (Design III)	Plywood 12 mm thick perforated 5 mm diameter holes 6200 m2 11% open area with 60mm deep air space behind	0.20	0.30	0.48	0.38	0.27	0.28	0.30
Ceiling (Design IV)	Ceiling tiles, acoustic	0.38	0.41	0.52	0.72	0.85	0.95	1.00
Rear wall (Design IV)	Fabric covered panel, 6 pcf rockwool core	0.46	0.93	1.00	1.00	1.00	1.00	1.00
Ceiling height (Designs II, III, IV)	11 – 13 m							

Acoustic Simulation

Using EASE 5 Third Edition software, the simulation began with the first design configuration. Acoustic simulations were performed using room mapping feature in the EASE Eyes module. Mappings were calculated using the ray-tracing-based AURA method, which provides a complete set of acoustic parameters according to ISO 3382. A loudspeaker was placed at the center of the stage as an omnidirectional sound source, and audience planes were defined as planar receivers covering the entire audience area at an ear height of 1.2 m above each surface to represent seated listeners. Audience area mapping was conducted to evaluate both average values and distribution of acoustic parameters. Audience areas included both the lower and upper (terrace and balcony) levels to ensure full coverage of all listeners. During the initial design iterations, shorter calculations were performed using a lower number of particles (lower resolution) and shorter cut-off time length. Once satisfactory results were achieved and the hall configuration was finalized, longer calculations with a higher number of particles (higher resolution) and longer cut-off time length were carried out to obtain more refined results. Although this process was more computationally demanding, additional processor cores (calculation threads) were utilized to reduce simulation duration.

The results of the simulations are in the form of acoustic parameters, namely RT_{30}, C_{80}, T_s, LF, SPL, and G, with reverberation time being the primary focus of evaluation. The average reverberation time was first compared against the target value, followed by other acoustic parameters which also must fall within their respective ideal range, to determine if the design is sufficient. Once satisfactory, the simulation proceeded to the next design configuration. This process was repeated for all configurations until each design met all the specified design criteria to fulfil the acoustic requirements for each respective music genre.

During the design iteration process, simplified simulation settings were used to reduce computation time and costs. This involved using fewer particles (lower resolution) and shorter lengths to obtain preliminary estimates of the acoustic parameters. Once ideal results were achieved and design configurations were finalized, more accurate simulations were conducted using higher particle counts (higher resolution) and extended lengths to obtain more precise and more refined results. Calculation configuration setting for the acoustic simulation is shown in Figure 3.

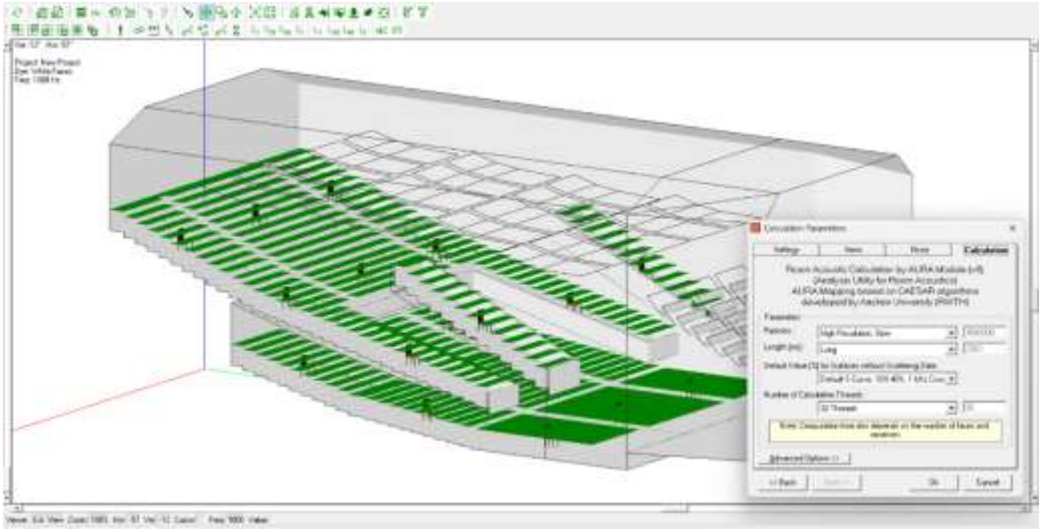

Figure 3. Calculation configuration setting in the AURA mapping window of EASE 5

RESULTS AND DISCUSSION

According to the acoustic simulation results (Table 4), all hall design configurations achieved RT30, BR, LF, C80, Ts, and G values within the recommended ranges for their respective designated music genres. The average reverberation times for each hall configuration appear to be evenly spaced which suggests distinct acoustic profiles. Acoustic simulation results exhibit an even distribution in reverberation time at 1 kHz with values close to the average and minimal deviation. This applies for all the design configurations as shown in the spatial distribution maps displayed in Figure 4. These outcomes indicate that the acoustic designs successfully meet the acoustic requirements of each genre, which shows the hall's ability to accommodate diverse performance needs.

Table 4. Recommended acoustic parameter values and simulation results at 1 kHz for each hall configuration

Configuration/ Designated genre	Design I (Romantic)	Design II (Classical)	Design III (Opera)	Design IV (Angklung)
Parameter	Ideal	Result	Ideal	Result
RT30 [s]	1.9 – 2.1	2.0	1.6 – 1.8	1.7
BR	1.1 – 1.5	1.1	1.1 – 1.3	1.2

Configuration/ Designated genre	Design I (Romantic)	Design II (Classical)	Design III (Opera)	Design IV (Angklung)
LF [%]	10 – 35	22	10 – 35	22
C80 [dB]	-2.0 – 2.0	0.5	-2.0 – 2.0	1.4
Ts [ms]	70 – 150	118	70 – 150	100
G [dB]	3 – 10	5.5	3 – 10	5.4
Total SPL [dB]	-	82	-	82

RT is inversely proportional to C_{80}, as observed in all design configurations. Design I, with the longest RT, exhibits the lowest C_{80}, while Design IV, with the shortest RT, has the highest C_{80}, in which all C80 values are within the recommended range [10]. This trend also applies to the Ts, where Design I has the longest Ts, indicating that the sound energy is more concentrated in the late reverberant sound, causing a sense of spaciousness. In contrast, Design IV has the shortest Ts, which makes the energy more centered towards the early direct sound, which enhances a sense of envelopment and intimacy [5]. The higher early and late sound energy in configurations with longer RT causes a higher G, where Design I has the highest G, due to larger volume and more reflective surfaces, and Design IV has the lowest G, due to a smaller volume and more absorptive surfaces. These acoustic attributes show a clear contrast between designs I and IV, with a balanced progression in designs II and III. This indicates a relatively linear change in acoustic properties across the four configurations.

Most of the selected materials exhibit a rather uniform absorption indicated by a relatively flat trend in the absorption coefficient across the entire frequency spectrum. This characteristic results in BR for all design configurations falling at the lower end of the recommended range [11] for each music genre, around 1.1—1.2, indicating a balanced sound energy between low and mid frequencies. The identical transversal geometry of all hall configurations yields uniform LF values, which falls in the center of the recommended range [1]. This indicates a balanced spatial impression and sound envelopment across all hall configurations [5], [6]. The SPL values across all hall configurations are relatively uniform, which suggests that the perceived intensity remains consistent despite the differences in reverberation, particularly in configurations with additional sound absorption.

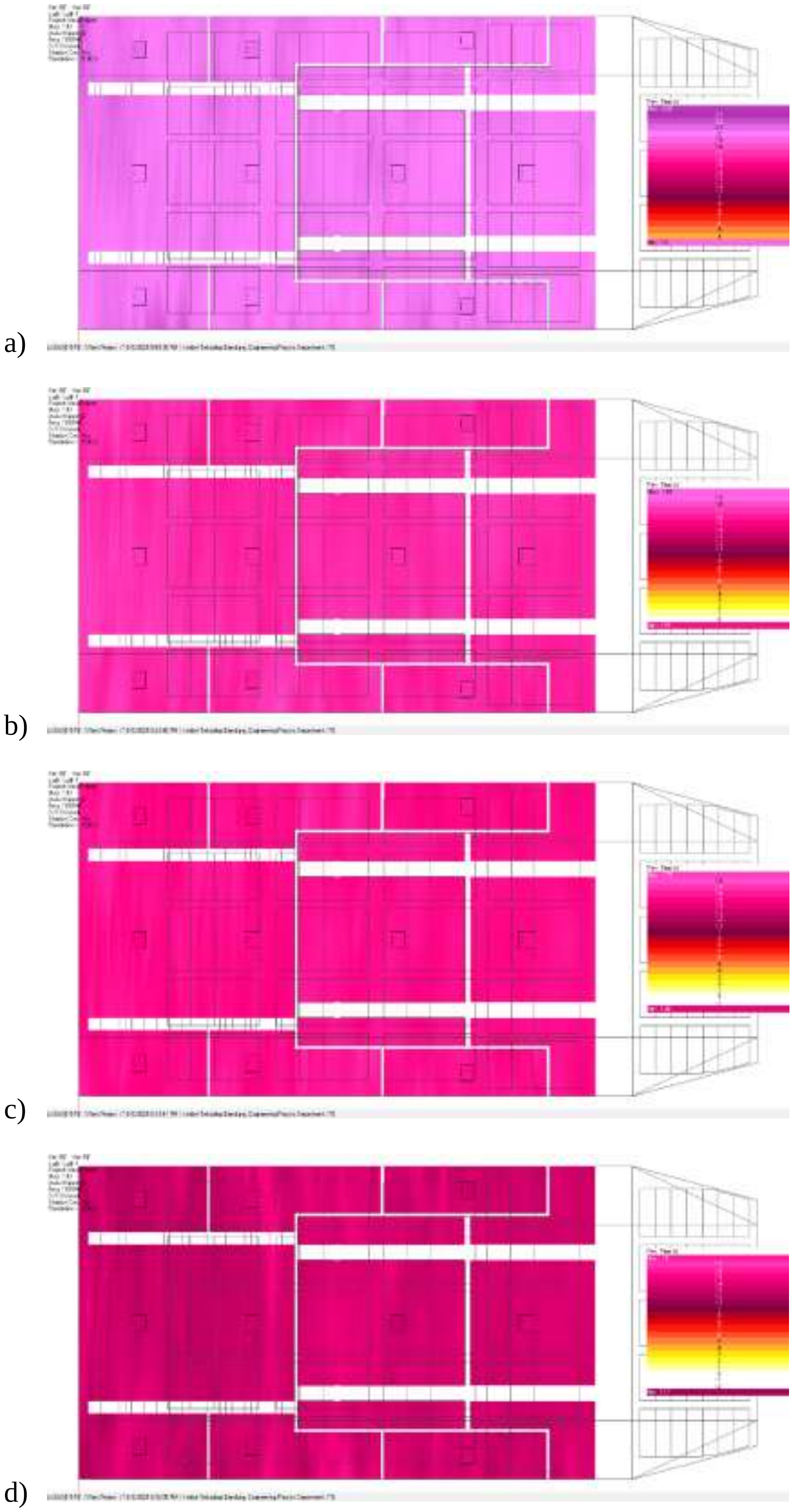

Figure 4. Reverberation time (RT_{30}) distribution map at 1 kHz on audience areas: a) Design I, b) Design II, c) Design III, d) Design IV

CONCLUSION

This study demonstrates that, with the proper configuration, variations in geometry and surface materials can produce acoustically distinct spaces with different reverberations while ensuring all key acoustic parameters are within the optimal range. This highlights the potential of variable acoustics in concert hall design as a versatile solution to accommodate the distinct acoustic requirements of various musical genres, ranging from Western classical music to Indonesian traditional music. Its application extends beyond these examples, including other music genres, different types of traditional music, instrument variations, and vocal-based performances such as choirs and plays. Such versatility supports the development of acoustically adaptable concert halls that can accommodate diverse functional demands promote cultural inclusivity.

For future works, it's worth considering to include not only absorption coefficients but also scattering coefficients. In doing so, the simulation can better replicate sound reflection and diffusion behavior based on real surface characteristics rather than assuming all reflections as perfectly specular from smooth surfaces. Material diffusivity could also be tailored by incorporating assymetry in surface treatements to promote spatial impression quality, which is associated with the interaural cross-correlation coefficient (IACC). With these additional steps, the design evaluation would not only focus on achieving target values for individual parameters but also extend to evaluating aspects such as spatial sound distribution and reflection patterns. Furthermore, acoustic simulation could be extended to include auralization using sound samples from recordings of orchestral or traditional music instruments. This would provide further insight into how the designed concert hall would sound like, followed by listening tests to evaluate subjective perceptions of both performers and listeners.

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