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Music from Balconies: Simulated Acoustic Performance of Sitelumbeo Batak Toba Traditional Houses

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Abstract

This paper examines the *sitelumbeo*-type house among the Batak Toba people in North Sumatra, Indonesia, as a venue for traditional *gondang* music performances during celebrations and rituals marking key life events. Using digital models and acoustic simulations of three *sitelumbeo* houses from hamlets in Samosir Regency, Lake Toba, the study evaluates Sound Pressure Level (SPL), Reverberation Time (RT), Clarity (C_{50}), and Definition (D_{50}) for outdoor music and indoor speech scenarios. The results indicate associations between the combined house geometry and simulated sound distributions. The roofed configurations exhibited SPL increases of about 1.32–1.65 dB, calculated as the difference in averages, compared to the roofless model (A0). Indoors, RT tends to be short (ranging from 0.13 to 0.66 s across different frequency bands), with C_{50} of 4.73 to 25.91 dB and D_{50} values above 74.80%, supporting speech clarity under modeled conditions. These simulations suggest that the design and layout of *sitelumbeo* houses support two different acoustic settings: rhythmic music outdoors and speech indoors, within the limits of a three-house simulation-based study. The findings highlight the importance of acoustically responsive design in traditional architecture and invite further inquiry into performance-oriented spatial criteria in contemporary housing.

Keywords: acoustic assessment; music performance; traditional houses; Batak Toba

1. Introduction: *Gondang* Music and the Batak Toba Ceremonies

In Batak Toba households, rhythmic performances are integral to traditional social and religious rites held during ceremonial feasts that mark significant life events. These events include birth celebrations, weddings, moving into a new home, establishing a new hamlet (*huta*), harvesting, funerals (*saur matua*), and exhumation ceremonies (*mangongkal holi*), all of which demonstrate compliance with their customary social laws or *adat* [1,2]. Each ceremony is led by rhythmic performances and enhanced by the *tor-tor* dance, a sacred and symbolic movement; without it, the ceremony would be deemed incomplete [1].

These rites bring together the Batak Toba community across time and locations. They are grounded in their indigenous social law, which serves as an enduring set of norms and rules. This link remains strong even after the adoption of Christianity, as the community continues to honor the ancestral faith that originally inspired these traditional feasts [3,4]. Traditional music and customs persist [5], with elements of this musical tradition incorporated into and adapted for modern liturgical music [6]. The *gondang* rhythmic music is therefore vital for the Batak Toba to uphold their adat, especially during celebratory feasts or *ulaon adat*, including marriage ceremonies. The Batak Toba continue their traditions even as outmigrants in other Indonesian cities, such as Medan [7,8] and the capital, Jakarta,

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adapting their ceremonial protocols to fit their urbanized lifestyle [9]. Large wedding venues are popular among the Bataks in the Greater Jakarta area [10], as they substitute for their original houses and hamlets to accommodate numerous guests (up to 1000 pax), provide non-halal catering, and offer layouts that fit their rituals, including a venue for *gondang* musical performances; all of these are in high demand.

The performance of *gondang*, like that of other musical forms (e.g., the philharmonic), depends on the venue, which serves as a link between the instruments and the audience during ceremonies [11]. Without specific architectural features or designated places of worship [12,13], Batak Toba houses and hamlets serve as venues for rituals and as a medium for *gondang* performances. However, previous studies mainly focus on the cultural aspect [3,5,6,14] or the instruments [15,16], rather than on the venue itself, as in other forms of Indonesian traditional music. Most of them, such as *gamelan* or *angklung*, are played in open-air venues [17], such as the Balinese *banjar* [18], with fewer venues available to host them [19], or in semi-open venues like *pendopo* [20]. The acoustic performance of Batak Toba houses as ritual venues, however, remains underexplored; this study addresses that gap by analyzing how *sitelumbeo* house geometry and materials shape *gondang* and speech delivery.

Accordingly, this study asks: How do variations in *sitelumbeo* house geometry and material configuration shape the distribution of outdoor *gondang* sound and indoor speech acoustics during Batak Toba ceremonial use? To answer this question, this study evaluates simulated acoustic performance in two ceremonial settings: outdoor *gondang* performance and indoor speech. Using digital 3D models of three selected houses in *Rhino 3D* with the *Pachyderm* plug-in [21–23], the study compares simulated Sound Pressure Level (SPL) distributions outdoors and, indoors, SPL, Reverberation Time (RT), Clarity (C_{50}), and Definition (D_{50}). These comparisons assess associations between modeled house configurations and acoustic outcomes, but do not isolate the independent effects of sound radiation, roof form, wall inclination, enclosed volume, or material properties.

2. Materials and Methods

2.1. Ceremonial Space Setting Rules

The spatial organization of the *sitelumbeo*-type house, designed to host ceremonial functions, is divided into three main zones: (1) the interior hall (*jabu*) with the hearth (*tataring*) at the center; (2) the mezzanine level, subdivided into two parts—(a) the inner space (*bonggar-bonggar*) and (b) the outer, balcony-like area (*loting*); and (3) the outdoor front yard (*alaman*) adjacent to the home's façade (see Figure 1). This zoning places the mezzanine floors at the two ends of the house, where the audience gathers, creating a two-way stage for acoustic performances.

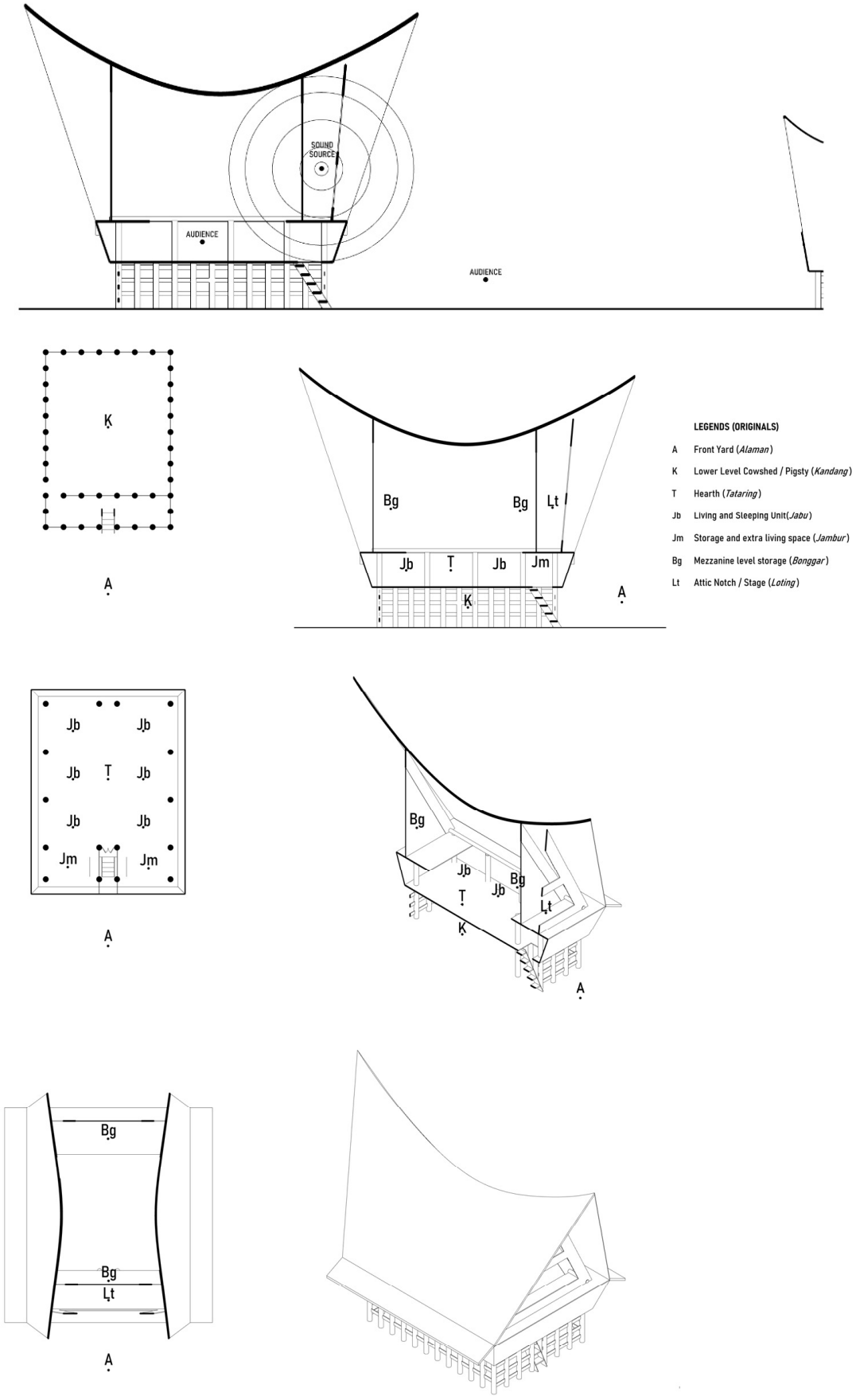


Figure 1. The *sitelumbeo* house's zoning, shown in plans and section diagrams.

2.1.1. Outdoor Ceremonies

In their fortified hamlets (Figure 2), Batak Toba traditional houses are arranged in rows along an axis, facing each other across a central public yard (*alaman*). The hamlet's boundaries are protected by high stone walls or ramparts, often with trees or bamboo bushes (Figure 3a), or by earthen mud due to its greater availability (Figure 3b). The *alaman* serves as the communal gathering space in front of the homes, with a *sitelumbeo*-type house serving as a stage. According to Batak Toba kinship rules, only one house can host a ritual event at a time, and other villagers actively participate, playing a supporting role [2]. This spatial layout sets the context for the acoustic simulation in this study.



Figure 2. An aerial photograph of a Batak Toba hamlet, showing its fortified layout with rows of houses facing each other and creating a communal gathering space.



(a) **(b)**

Figure 3. Batak Toba hamlet with trees or bamboo bushes (**a**) or earthen mud (**b**) as fortification and at the same time delineating the venues for outdoor ceremonies, including *gondang* performances.

2.1.2. Indoor Ceremonies

Although multi-family occupancy in communal houses such as the *sitelumbeo* or *ruma bona* has declined and most Batak Toba now live in single-family homes, they still gather in their traditional dwellings for rituals and family events. During these times, the house's interior zoning (or *jabu*) provides designated seating for guests participating in rituals or ceremonies, as shown in Figure 4. De Boer [24], Niessen [25], and Napitulu [26] describe how seating is organized into zones during ceremonial events, following specific rules: the *jabu bona* (JBn) zone is reserved for the head of the household, the ego of the family name or *marga* "E," and his wife, along with young children. The *jabu tampar piring* (JTP) zones are designated for the host's *marga* peer (*dongan sabutuha*), usually his younger brother or *anggi ni partubu*. In Samosir, it is also common for non-*marga* visitors (*anak manjae*) to sit in this zone. The master of the ceremony or speaker (*raja panire*), usually a fellow dweller of the hamlet with the same family name or *marga* (*dongan sahuta*), also sits in the same JTP zone. Both *jabu bona* (JBn) and *jabu tampar piring* (JTP) are located on the house's right side when viewed from the entrance.

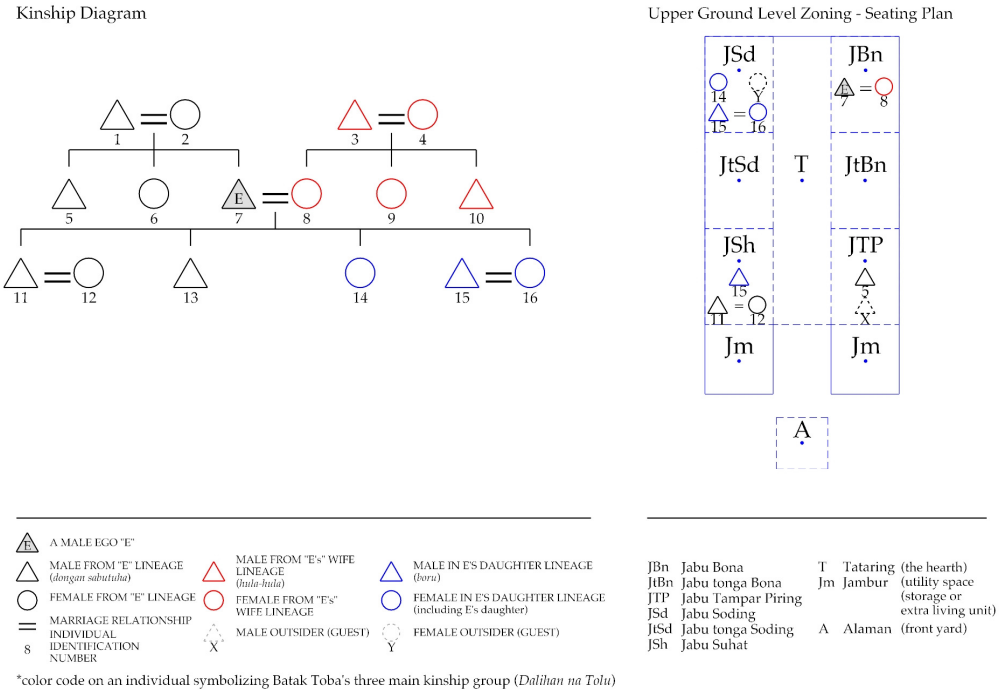


Figure 4. The kinship-based seating arrangement diagram for ceremonies in a Batak Toba interior.

On the left-hand side of the house, the *jabu soding* (JSd) seats the host's daughters (*boru*), if married, and their husbands (*hela*), forming a group of wife-takers (*marga boru*). It also seats other guests' wives (*inganan hundul ripe angka na ro*). During a marriage ceremony, the in-laws, *hula-hula*, the family of the master's wife, or the master's mother's family, as the wife-giver group, are seated at the *jabu suhat* (JSh); the bride and groom sit in the central area between *jabu bona* and *jabu tampar piring*, or in a *jabu tonga bona* (JtBn) zone; this is where the master of ceremonies takes his place. In a funeral, the deceased's coffin is placed in the middle between *jabu soding* and *suhat*, forming a space called a *jabu tonga soding* (JtSd). Additional guests, villagers, or visitors from other villages can also be seated in the *jabu tonga soding* (JtSd). The front mezzanine, *bonggar-bonggar*, and the adjacent balcony are designated for the *gondang musicians*, who perform during the ceremony. Many modern Batak Toba homeowners are aware of the seating hierarchy when planning their interior layout, particularly for social gatherings and rituals, as observed. During ceremonies held in contemporary banquet halls, the same seating conventions remain in effect.

Purba [1] further outlines the rules and procedures for conducting ceremonial feasts, as does Simon [27], with adaptations that include the role of *gondang*. Their descriptions of ceremonial feasts suggest a sequential use of space, with situational plans and section drawings of the home and surrounding areas used for the ceremonies, and with spaces marked according to the seating arrangement.

2.2. Sound Source: Gondang and Speech

During ceremonies, the *gondang* ensemble features several rhythmic instruments: five differently sized, roughly tuned drums (*taganing* or *taganining*), a large bass drum (*gordang*), a set of four gongs (*ogung*), an iron percussion plaque (*hesek-hesek*), and a large double-reed melodic instrument called the *serunai bolon*. These are vital components of the sacred ritual or official musical category of the Batak Toba, distinct from more secular forms of entertainment music [14,15]. Figure 5 illustrates the arrangement of musicians and their instruments in line during a performance. The instruments are also classified into four categories based on the Batak and their European Hornbostel/Sachs equivalents [28]: percussion or *alat pukul* (including idiophones, membranophones, and tube zithers), bowed string instruments or *alat gesek*, plucked string instruments or *alat petik*, and wind instruments or *alat tiup* (aerophones).



Figure 5. A group of *gondang* musicians playing their respective instruments at the front attic of a *sitelumbeo* house during a funeral ceremony (*saur matua*) at Harian Boho sub-district, Samosir Regency, North Sumatra, July 2012 (photograph by the author).

Table 1 outlines the standard instruments used in a *gondang* performance, including their European classification and typical frequency range. Reported variations in instrument combinations are few, and the instruments' unique tonal characteristics show a distinct separation of the high-frequency range, as shown in Table 1. The group is led by the *taganing* player, who serves as the conductor of the performance and is also known as the *pargonsi* ('the music maker'). Another sound source is the master of ceremonies' speech, with a human voice ranging from around 100 Hz to 5000 Hz; the male voice peaks near 400 Hz [29]. Their patrilineal kinship system and *adat* laws prescribe that a man, kin to the male host of the same family (*marga*), typically leads these ceremonies, and his voice is given priority. He usually stands on the upper ground inside the house at the JtBn zone or at ground level at the *alaman*.

Table 1. The *gondang* music instrument frequency range.

Instruments		Equivalent Instruments	Frequency Range (Hz)	
Serunai Bolon	Large conical double reed (woodwind)	shawm (bassoon)	60	620
Taganing or *Taganining*	Five approximately tuned drums	drums (toms-timpani)	60	210
Gordang	Large bass drums	bass drums	60	100
Ogung	Four gongs	gongs	300	3500
Hesek-hesek	Percussion plaque made from iron	xylophone	700	3500

2.3. Methods: Modeling, Simulation and Scenarios

Acoustic simulations are conducted digitally to assess the spatial quality of these festivals' main venues, particularly those of the *sitelumbeo* or *jabu bolon* traditional house types. The *sitelumbeo* type is regarded as the most advanced of the four known types [30]—*siamporik*, *angkola*, and the converted granary (*sopo*) types—and is used for ceremonies. The primary differences between *sitelumbeo* and other house types concern the size of the front attic balcony, which can accommodate four to six musicians (*pargonsi*), and the shape and size of the overarching saddle roof, as indicated by the number of roof frames (*sitelumbeo* has three, while others have only two).

2.3.1. Generative Modeling

The simulation uses digitally modeled houses created in *Rhino 3D* (version 7) [23], with house shapes generated by a *Grasshopper* (version 1.0) algorithm, a visual scripting plugin for *Rhino 3D*. The geometric data are collected from house samples in three hamlets near Lake Toba, North Sumatra, Indonesia—the homeland of the Batak Toba.

The algorithm digitally constructs the house's geometry, including (1) timber posts, (2) walls with openings as spatial boundaries, (3) triangular roof frames (*sitindangi*), (4) upper ground, (5) mezzanine floors, (6) front and (7) back facias, and (8) the roof with overhangs (Figure 6). The geometric generative instructions enable iterative changes to roof and wall shapes, with other building parts adjusting accordingly by modifying wall inclination parameters, allowing the creation of various home geometries for simulation, all generated from a single modeling instruction.

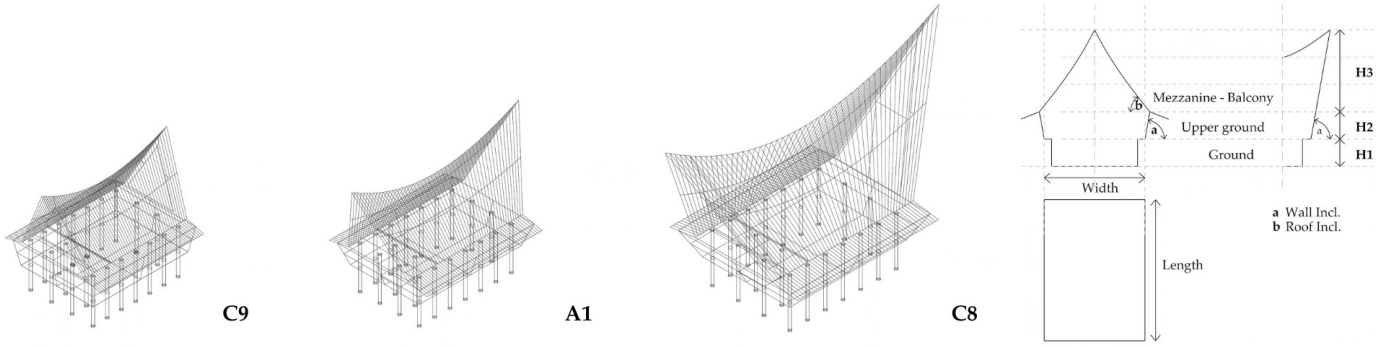


Figure 6. Algorithm-generated *sitelumbeo* house models, with selected house components for simulation, from three hamlets in the Toba-Samosir Region.

2.3.2. Simulation Phases

The simulations occur in three phases: (1) measuring acoustic variables, including (a) sound distribution via Sound Pressure Levels (SPL) and (b) acoustic qualities such as

Reverberation Time (RT), Clarity (C_{50}), and Definition (D_{50}); (2) visualizing sound wave distributions in outdoor and indoor settings during *gondang* performances and ceremonies led by the master of ceremonies; and (3) comparing different house shape configurations, focusing on wall and roof angles. The third phase examines how varying wall and roof inclinations affect the house's geometry and volume.

2.3.3. Assessments Parameters

Sound Distributions: Sound Pressure Level (*SPL*)

Sound waves propagate outward in all directions through a medium, typically losing energy as they expand. In open air, such as in the Toba Batak front yards, the inverse-square law states that sound energy from a point source decreases by about 6 dB, while waves from a line source decrease by 3 dB for each doubling of distance. In a free field, sound intensity is inversely proportional to the square of the distance. Other elements within the medium can further diminish sound energy, depending on their material properties. Sound Pressure Level (SPL) is a logarithmic scale for sound pressure [31]. Loudness is therefore measured by intensity, which reflects the energy passing through a unit area. In practice, we measure sound pressure rather than intensity, though both indicate the number of sound waves.

To measure SPL in real-world situations, sound level meters are placed at various distances from fixed points near the source, and the resulting changes in sound level are charted as a function of distance. A pink-noise signal is used at the source and recorded by microphones positioned at different points for analysis. In this study, SPL is digitally simulated. SPL measures the strength of a sound wave; by taking readings at various locations around the source, we can map sound propagation based on the shape, position, and material of the element under examination. In this context, the unique shapes, volumes, and materials of Toba Batak houses are studied to assess their influence on sound distribution and SPL mapping.

Sound Quality: Reverberation Time (RT)

Reverberation is the persistence of sound waves in the air after the sound source stops emitting sound. It is a defining factor in room (indoor) acoustics and a significant characteristic in enclosed spaces where high-quality speech and music are present [31]. Reverberation Time (RT) is the time required for sound energy to decay by 60 dB from its initial value at termination. The RT is influenced by the room's total sound absorption and volume. Higher absorption leads to faster decay of sound energy. Conversely, greater room volume means fewer sound waves strike the room surfaces, contributing to slower decay and, hence, a higher RT. The definition follows the formula:

$$RT = \frac{0.16\ \mathrm{V}}{\sum \mathrm{A}} \quad (1)$$

where V is the room volume (in m^3) and $\sum$A the total absorption in the room (in metric Sabin) [29].

RT may vary with position within a room, making spatial location an influential factor in variations in reverberation time. Thus, mapping RT values can modulate a room's sound-field behavior.

Excessive reverberation can impair speech intelligibility and alter how music is perceived. It is difficult to separate musical judgment from a space's acoustics, and different types of music and instruments have distinct acoustic requirements. A longer RT can reduce musical definition and clarity and lower speech intelligibility.

Sound Quality: Clarity (C_{50})

Direct sound is the sound wave that reaches the listener within 50 to 80 milliseconds. Clarity is then defined as the dB difference between the sound energy a listener receives as direct sound and the reverberant energy (the entire energy arriving after 50–80 milliseconds). Clarity, in general, is categorized into two: (1) C_{50}, the clarity for speech, and (2) C_{80}, the clarity for musical measurements [32]. The mathematical definition of clarity is formulated as follows:

$$C_{50} = 10log\left(\frac{E_{50}}{E_{\infty} - E_{50}}\right) dB \quad (2)$$

Clarity (C_{50}) measurements are related to RT: longer RT yields a proportionally smaller C_{50} value. A C_{50} value greater than +3 dB meets the criteria for speech intelligibility ranging from good to excellent [33], ensuring that speech is audible and words are easily distinguishable.

Sound Quality: Definition (D_{50})

Definition (D_{50}) measures a listener's ability to understand or identify a sound as the percentage of received sound energy in the first 50 milliseconds relative to the total acquired energy:

$$D_{50} = \left(\frac{E_{50}}{E_{\infty}}\right)\% \quad (3)$$

D_{50} is a parameter used to evaluate speech clarity in a room. D_{50} > 50% indicates good speech clarity.

2.3.4. Geometry Setup

The digital models are created for three *sitelumbeo* houses of different volumes based on the measurements in Table 2, representing the medium, minimum, and maximum: house samples A1, C9, and C8, respectively. Varying roof and wall inclinations affect the houses' volumes; thus, houses with greater width or length are not necessarily the largest in volume. Geometric volumes are the combined enclosures of the upper ground floor and roof floor levels: A1 = 49.61 m^3, C8 = 127.85 m^3, and C9 = 39.48 m^3. Another model, a 'no roof' model (house sample A0), is included as a reference; its geometry is based on the average medium house (A1) with the roof removed, and it has a volume of 29.8 m^3. The wall and roof geometries are generated by a shape algorithm that adjusts wall inclinations based on measurements at three points: minimum = 80° (house sample C9), median = 71° (house sample A1), maximum = 62° (house sample C8). The boundary for the house geometry is a single-layer closed polysurface, with geometric depth not modeled but accounted for in the material settings.

Table 2. *Sitelumbeo* sample house measurements.

Sitelumbeo		W (m)	L (m)	Ratio (L/W)	Wall Incline (deg.)	Roof Incline (deg.)	H1 (m)	H2 (m)	H3 (m)
A1	*Huta Raja*	4.20	6.20	1.48	71	57	1.43	1.14	3.63
A2		5.32	10.00	1.88	74	59	1.61	1.19	4.59
A3		6.23	10.60	1.70	71	55	1.52	1.39	4.85
B4	*Huta Namora*	4.36	8.00	1.83	79	58	1.60	1.49	2.70
B5		5.86	7.35	1.25	82	58	2.16	1.97	3.40
B6		4.28	5.54	1.29	60	60	1.52	1.74	5.24

Table 2. *Cont.*

Sitelumbeo		W (m)	L (m)	Ratio (L/W)	Wall Incline (deg.)	Roof Incline (deg.)	H1 (m)	H2 (m)	H3 (m)
C7	*Huta Ginjang*	5.42	7.18	1.32	67	61	1.54	1.31	5.67
C8		5.32	7.09	1.33	62	60	1.52	1.40	5.45
C9		4.40	5.80	1.32	80	54	1.31	1.33	3.30
C10		5.63	7.68	1.36	71	61	1.59	1.40	5.43
	MAX	6.23	10.6	1.88	82	62	2.16	2.21	5.67
	MIN	3.65	5.44	1.25	60	54	1.31	1.14	2.70
	MEDIAN	5.32	7.27	1.35	71	58	1.53	1.40	4.72
	AVERAGE	4.79	7.12	1.49	71.5	58.5	1.56	1.52	4.29

2.3.5. Sound Source and Receivers

Simulations are conducted in two digital scenarios (see Figures 7 and 8): (1) an outdoor ceremonial scene with musicians at the front of the attic and spectators in the yard (*alaman*), and (2) an indoor ceremony with the master of ceremonies in the *JtBn* zone and the audience seated according to ritual seating rules.

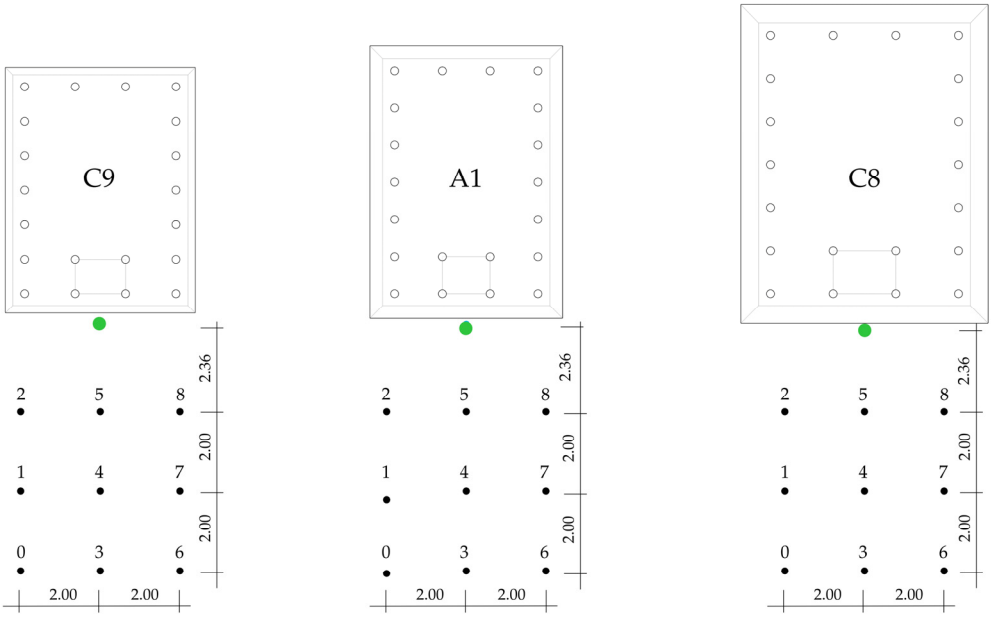


Figure 7. *Sitelumbeo* house's outdoor acoustic simulation scenario.

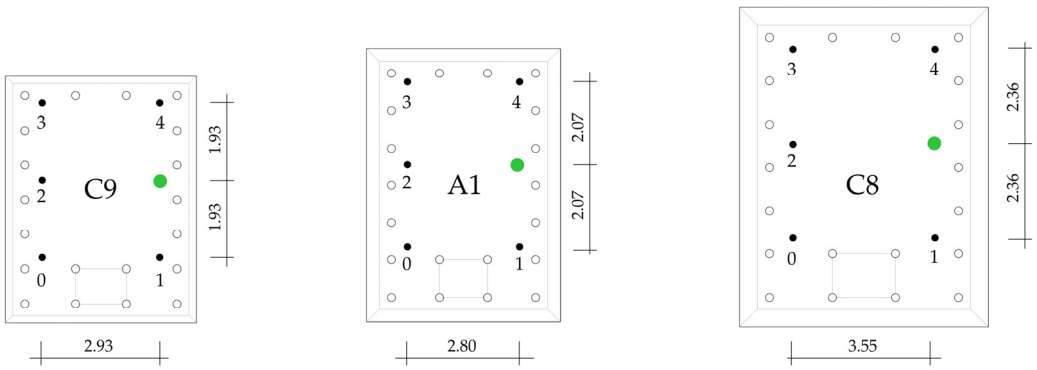


Figure 8. *Sitelumbeo* house's indoor acoustic simulation scenario.

The receiver and source points are placed in the model as follows. For outdoor simulation, a set of measurement points, representing the receivers, covering the house's front yard (*alaman*) where a ceremony takes place is arranged in a 2-m-spaced 3-by-3 grid labeled 0–8, with the point labeled 5 (the 1st row, 2nd column point) as the anchor, located 2.36 m from the midpoint of the front-row timber posts in the -*y* direction. The measurement points are elevated by 1.5 m in the *z*-direction above the ground. The *gondang* music sound source is represented as a point with coordinates: x is the midpoint of the house, y is an offset of 0.5 m in the x direction measured from the first row of timber posts, and z is a coordinate hovering 1.2 m above the mezzanine floor, with the actual height varying as $z = H_1 + H_2 + 1.2$ m. For indoor simulation, a set of 2 by 3 measurement points, labeled 0–4, is generated from the centers of six evenly divided zones of the floor area, elevated to a height of $z = H_1 + 1.2$ m to simulate seated listener positions. The source point is at $z = H_1 + 1.5$ m, simulating the standing position of a male speaker.

Javanese *gamelan* provides a useful reference for estimating *gondang* source levels because both are large instrumental ensembles whose sound intensity varies according to the number, type, and spatial arrangement of instruments [34]. *Gamelan* ensembles may include up to 75 instruments, and their arrangement can substantially affect musicians' exposure. During a performance of "*Gambyong Pare Anom*," on-stage sound levels ranged from 75 to 97 dB, reaching 105 dB in certain arrangements [34]. Comparable variations can reasonably be expected in *gondang* performances. However, because no published source-level measurements specific to *gondang* are currently available, this study adopts 90 dB across all frequencies with omnidirectional radiation as a standardized proxy within the documented range for comparable ensembles. This value is not intended to represent the actual acoustic energy received at the measurement points or the perceived quality for each frequency. Rather, it provides a consistent reference for examining relative changes in sound pressure levels and spatial sound distribution under different building geometries, particularly roof configurations. By holding the source level constant, the simulation isolates the influence of architectural geometry on sound propagation without evaluating the effects of frequency-dependent source levels, directivity, or actual received energy.

Measurements span 125 Hz to 4000 Hz, in accordance with *Pachyderm's* preset octave bands (bands 1–6) to simulate outdoor events. In an indoor event simulation, a single sound source representing human speech is positioned 1.5 m above the upper ground floor and emits at 65 dB.

2.3.6. Material Properties

The digital model uses timber as the material property for all simulated components. Timber panels with gap construction are used for walls, floors, and roof ceilings. Solid wood is used for structural elements (columns and beams), and their absorption coefficients are presented in Table 3. In the indoor simulation scenario, ceilings are modeled as timber slats or thatched roofs made of coconut palm fiber, representing early roofing materials that were replaced with zinc [24].

Table 3. *Sitelumbeo* houses absorption coefficients for simulation.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Timber	0.31	0.33	0.14	0.10	0.10	0.12
Coconut Palm Fiber	0.10	0.20	0.34	0.67	0.79	0.80

Absorption coefficients for timber are taken from the Pachyderm dataset, which draws on several references [35,36]. Absorption coefficients for coconut palm fiber (or palm fiber, in short) are adopted from two studies comparing sound absorption coefficients

for natural fibers [37,38]. In the reference [38], measured absorption coefficients reported in Table 2 are available only for the 125–2000 Hz range, whereas Table 3 presents sound absorption predictions based on the Delany–Bazley model for the full 125–4000 Hz range. The absorption coefficient at 4000 Hz was therefore estimated by extrapolating from the calculated and measured values.

Ground conditions constitute an important boundary condition in outdoor acoustic simulations because their absorptive and reflective properties can influence sound-wave propagation. In the studied hamlets, however, ground surfaces vary substantially: *Huta Raja* has a thin concrete covering, *Huta Namora* consists mainly of earth with stone-covered circulation areas, and *Huta Ginjang* is almost entirely bare earth. Including these different surfaces would therefore introduce an additional site-specific variable, making it difficult to distinguish the acoustic effects of ground reflections from those produced by the houses' geometry. Because this study specifically examines how Batak house form influences sound propagation from the balcony to the receiver, the ground was modeled as fully absorptive (100%). This idealized boundary condition prevents the ground from acting as a reflective surface, thereby isolating the contribution of building geometry, particularly the differences between roofed and unroofed models. Consequently, the simulated Sound Pressure Level (SPL) at each receiver point is determined by direct sound from the *gondang* and reflections from the house geometry. The resulting SPL values should therefore not be interpreted as exact representations of field conditions, but as comparative indicators of how building and roof geometry shape sound-pressure changes and spatial sound distribution when the variable influence of ground surfaces is excluded.

2.3.7. Simulation Setting

The simulation settings were designed to keep environmental and material parameters constant, so that differences in acoustic behavior could be attributed primarily to the houses' geometric configurations. Outdoor acoustic simulations were conducted in *Pachyderm* (version 2.5) using two complementary solution methods. For the impulse-response simulation, the receiver was defined as stationary, and the image-source reflection order was limited to one to examine direct and first-order reflected sound. The ceremonial setting using *gondang* was simulated via ray tracing with 100,000 rays, selected to minimize ray convergence within a 1000 ms cutoff time.

Environmental conditions were standardized across the models using an average air temperature of 20 °C, a relative humidity of 80%, and a static air pressure of 1000 hPa, corresponding to the region's average climatic conditions [39]. Outdoor atmospheric attenuation was calculated in accordance with ISO 9613-1 [40] as implemented in the *Pachyderm* plug-in. The same environmental parameters were retained for the indoor simulations, while indoor attenuation was modeled using the Evans–Bazley method. Maintaining consistent environmental conditions reduced the influence of environmental factors on comparisons among the geometric configurations.

Material absorption coefficients were assigned through *Rhino 3D* layers: (1) walls and floors forming the house enclosure, (2) structural posts and triangular roof frames, (3) roof geometry, (4) triangular screens, and (5) ground surfaces. Layers 1–3 were modeled as timber, and the roof material's absorption coefficient could be replaced with that of palm fiber in the second set of simulations. The ground was assigned an absorption coefficient of 1.00 to suppress ground reflections. This assumption does not represent the full acoustic behavior of actual terrain; rather, it isolates the influence of the house geometry by preventing reflected sound from the ground from obscuring geometrically induced differences among the models.

Scattering was set to 0.01 for all materials except the screens, which were assigned a scattering of 0 because their modeled surfaces were assumed flat. The characteristic dimension was standardized at 25 mm. Material transparency was disabled because all modeled components were treated as opaque. Potential transmission associated with porosity or panel gaps was therefore incorporated into the assigned absorption coefficients rather than modeled through a separate transparency parameter. Under these controlled assumptions, the absorption coefficient served as the principal parameter representing material behavior.

To assess numerical repeatability, models were simulated three times using identical parameters. Model A1, representing a roofed house with palm-fiber absorption coefficients assigned to the roof geometry, was selected here as a sample for the trial analysis (Table 4). The RT, C_{50}, and D_{50} values from all three runs exhibit numerical precision to two decimal places (0.01) and were evaluated individually rather than averaged. Comparing the complete datasets across the three trials allowed us to determine whether the acoustic patterns remained consistent across repeated simulations or depended on a single run. The differences among the trials therefore indicate the degree of numerical repeatability achieved.

Table 4. Three-Trial Test of Indoor Measurement Data for the A1 Model with a Palm Fiber Roof.

	Frequencies		**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
Reverberation Time (s)	A1 (Palm Fiber)	1st attempt	0.28	0.23	0.24	0.16	0.14	0.13
		2nd attempt	0.28	0.23	0.24	0.16	0.13	0.12
		3rd attempt	0.28	0.23	0.24	0.16	0.14	0.13
Clarity—C_{50} (dB)	A1 (Palm Fiber)	1st attempt	12.13	14.78	13.81	21.17	25.25	26.71
		2nd attempt	12.02	14.76	13.70	21.19	25.40	26.85
		3rd attempt	12.18	14.83	13.73	20.80	24.58	25.91
Definition—D_{50} (%)	A1 (Palm Fiber)	1st attempt	94.20	96.76	96.00	99.23	99.69	99.78
		2nd attempt	94.06	96.75	95.90	99.24	99.71	99.79
		3rd attempt	94.26	96.80	95.92	99.17	99.65	99.74

These simulations were intended as controlled comparisons of geometric configurations rather than validated predictions of field conditions. Because no field measurements were conducted, the results indicate how sound waves behave under the specified modeling assumptions but do not fully represent the acoustic performance of the houses in their actual physical and environmental contexts. Future research should examine the broader ritual setting, including hamlet boundaries, surrounding structures, terrain, and variable environmental conditions.

2.3.8. Simulation Scenarios

Two scenarios are set: outdoor and indoor acoustic simulations. Each affects the sound field differently: in indoor spaces, sound waves reflect off room surfaces, whereas in outdoor environments, they travel freely through the air. The indoor environment of the Batak Toba is primarily used for speech, like a voice auditorium; therefore, a higher level of speech intelligibility is required for its intended purpose [33]. In contrast, the outdoor setting for *gondang* performances is tailored to musical demands, featuring a specific type of music that is optimal for listening [41].

3. Results

The measurements are from two model settings: (a) outdoors, where Sound Pressure Levels (SPL) are measured to assess *gondang* performance, and (b) indoors, where (1) Sound Pressure Levels (SPL) (Figures 9 and 10, Table 5 for outdoors; 11 and 12 for indoors),

(2) Reverberation Time (RT), (3) Clarity in C_{50}, and (4) in D_{50} (Table 6) are measured to assess speech performance. All are analyzed to characterize sound delivery in each setting.

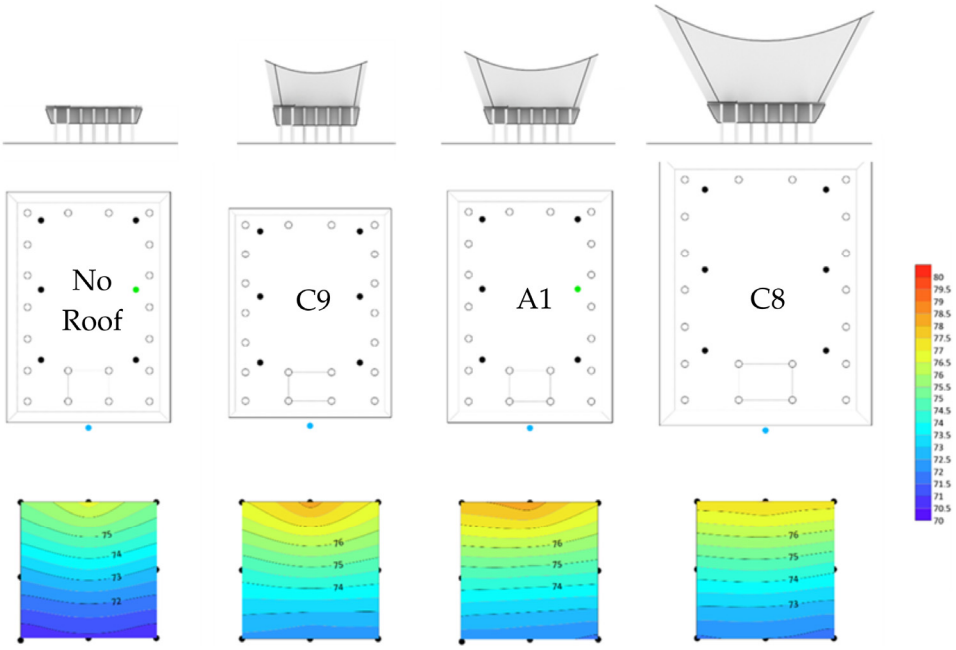


Figure 9. Simulation Results: Outdoor Sound Pressure Level (SPL) Distribution Map.

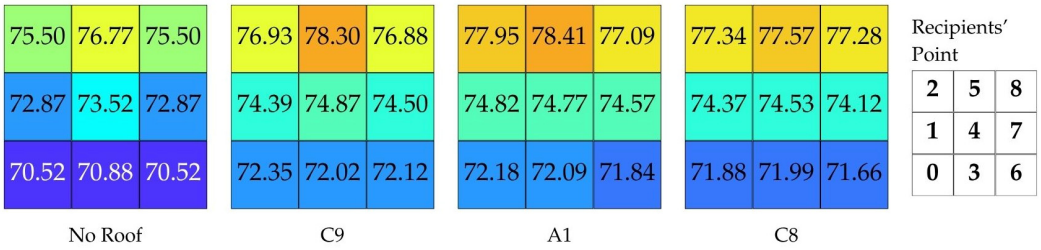


Figure 10. Simulation Results: Outdoor Sound Pressure Level (SPL) Values.

Table 5. Summary of Average SPL Values (dB) and Differences Across Measurement Points.

Value	Location			No Roof	C9	A1	C8
Average	First row		Point 2, 5, 8	75.92	77.37	77.81	77.39
	Second row		Point 1, 4, 7	73.09	74.59	74.72	74.34
	Third row		Point 0, 3, 6	70.64	72.16	72.03	71.84
	Overall		All Points	73.21	74.71	74.86	74.53
Difference	First to third row	Second column	Point 5 and 3	5.89	6.29	6.32	5.58
		First column	Point 2 and 0	4.98	4.58	5.77	5.45
		Third column	Point 8 and 6	4.98	4.76	5.25	5.63
	Second to third column	First row	Point 5 and 8	1.27	1.42	1.32	0.28
		Second row	Point 4 and 7	0.65	0.37	0.20	0.41
		Third row	Point 3 and 6	0.36	0.10	0.25	0.33
	First to third column	First row	Point 2 and 8	0.00	0.05	0.86	0.05
		Second row	Point 1 and 7	0.00	0.11	0.24	0.24
		Third row	Point 0 and 6	0.00	0.23	0.34	0.23

Table 6. Simulation Results: Indoor Acoustic Quality (RT, C_{50}, and D_{50}).

	Frequency		125 Hz	250 HZ	500 HZ	1000 Hz	2000 Hz	4000 Hz
RT (s)	No Roof		0.08	0.08	0.10	0.10	0.10	0.09
	C9	Timber	0.26	0.23	0.43	0.49	0.44	0.38
		Palm Fiber	0.30	0.25	0.28	0.20	0.17	0.16
	A1	Timber	0.20	0.19	0.34	0.40	0.38	0.34
		Palm Fiber	0.28	0.23	0.24	0.16	0.14	0.13
	C8	Timber	0.31	0.29	0.58	0.66	0.61	0.52
		Palm Fiber	0.54	0.38	0.34	0.19	0.16	0.15
C50 (dB)	No Roof		34.54	35.63	29.96	29.18	29.96	31.25
	C9	Timber	13.58	14.78	7.38	6.24	7.08	8.62
		Palm Fiber	11.25	13.78	12.07	17.45	20.63	21.89
	A1	Timber	16.72	17.73	9.65	8.19	8.57	9.69
		Palm Fiber	12.18	14.83	13.73	20.80	24.58	25.91
	C8	Timber	11.93	12.94	5.89	4.73	5.42	6.72
		Palm Fiber	6.85	9.84	10.52	18.81	22.88	24.23
D50 (%)	No Roof		99.96	99.97	99.89	99.87	99.89	99.92
	C9	Timber	95.73	96.72	84.37	80.61	83.41	87.77
		Palm Fiber	92.89	95.89	94.05	98.20	99.13	99.35
	A1	Timber	97.90	98.33	90.18	86.79	87.76	90.27
		Palm Fiber	94.26	96.80	95.92	99.17	99.65	99.74
	C8	Timber	93.95	95.14	79.48	74.80	77.64	82.39
		Palm Fiber	82.85	90.57	91.81	98.68	99.48	99.61

3.1. Outdoor Scenarios

In the outdoor setting, RT, C_{50}, and D_{50} were not treated as primary indicators because sound propagates from the source toward the front yard, whereas in enclosed conditions these parameters are generally more informative. Nevertheless, propagation is influenced by the combined arrangement of the roof overhangs, floors, triangular roof frames, and other building components. Outdoor performance was therefore evaluated primarily using the sound pressure level (SPL) distributions shown in Figures 9 and 10.

The configurations that included roofs produced higher SPL values in the front-row audience area than the roofless configuration. The average difference between the roofed and roofless configurations ranged from 1.45 to 1.89 dB for the first-row area. The first-row SPL was approximately 75.92 dB in the roofless configuration and 77.37–77.81 dB in the roofed configurations. Across all measurement points, the average SPL of the roofed configurations was 1.32–1.65 dB higher than that of the roofless configuration.

Among the three Toba Batak house configurations, A1 exhibited the highest average front-row SPL at 77.81 dB, compared with 77.37 dB for C9 and 77.39 dB for C8.

The combined house geometry was also associated with variations in SPL among the measurement points. In the roofless configuration, A0, the SPL differences between the first and third rows were 5.89 dB in the center column and 4.98 dB in both side columns. In C9, the corresponding differences were 6.29 dB at the center, 4.58 dB on the left, and 4.76 dB on the right. A1 exhibited differences of 6.32 dB at the center, 5.77 dB on the left, and 5.25 dB on the right. In C8, the corresponding differences were 5.58 dB at the center, 5.45 dB on

the left, and 5.63 dB on the right. C8 therefore exhibited the most similar front-to-rear *SPL* differences across the three columns within the tested configurations.

A similar pattern occurred in the center-to-side (second-to-third column) comparisons. In C8, the differences in the first, second, and third rows were 0.28, 0.41, and 0.33 dB, respectively. C9 and A1 exhibited larger first-row differences of 1.42 and 1.32 dB, whereas their second- and third-row differences ranged from 0.10 to 0.37 dB. Compared with A0, the roofed configurations generally exhibited smaller center-to-side differences in the second and third rows. Figure 10 further shows that the higher SPL values at point 5 in C9 and A1 contributed to the larger first-row center-to-side differences in these configurations.

As summarized in Table 5, C9, A1, and C8 exhibited similar average SPL values of approximately 77.53 dB in the first row, 74.55 dB in the second, and 72.01 dB in the third. Their sound-contour lines were also flatter than those of the roofless configuration.

Overall, the results indicate that the combined geometry of the houses is associated with both the *SPL* received by the audience and its spatial distribution across the measurement points. The presence of a roof distinguishes the roofed configurations from A0 and may contribute to the observed differences; however, its independent effect cannot be determined without controlled comparisons that hold other geometric components constant.

3.2. Indoor Scenarios

3.2.1. Sound Distributions (SPL)

As in the outdoor analysis, the indoor configurations differ in several interrelated geometric characteristics, and the results are interpreted as associations between SPL distribution and the house's combined geometry.

The roofed configurations exhibited smaller ranges between their highest and lowest SPL values than the roofless configuration (A0). In A0, this range reached 3.83 dB. Among the timber models, the ranges were 2.68 dB for C9, 2.03 dB for A1, and 1.97 dB for C8. Among the models with coconut palm fiber roofing, the corresponding ranges were 3.38, 2.88, and 3.08 dB. These results describe the numerical differences in SPL between the roofed configurations and A0. However, because the configurations incorporate interacting architectural features, the differences cannot be attributed solely to the roof or any other component.

Figures 11 and 12 show the longitudinal and lateral variations in SPL within the *sitelumbeo* house geometric configurations. The timber models generally exhibited smaller SPL ranges and higher average SPL values than the palm-fiber models. This pattern is consistent with the higher absorption coefficients assigned to palm fiber, particularly at mid- and high frequencies. In both material configurations, the differences between the highest and lowest SPL values remained below 5 dB. This numerical range is reported descriptively and is not interpreted as evidence of perceptual equivalence among the measurement positions.

Compared with A0, the roofed configurations also exhibited higher SPL values and smaller center-to-side differences at several measurement points. These patterns may be associated with the greater enclosure provided by the combined roof, wall, floor, and frame geometry, which limits the amount of sound escaping into the open air [31]. Similarly, the larger house configurations generally exhibited lower SPL values, but the independent effect of room volume cannot be established because volume varies together with other geometric characteristics.

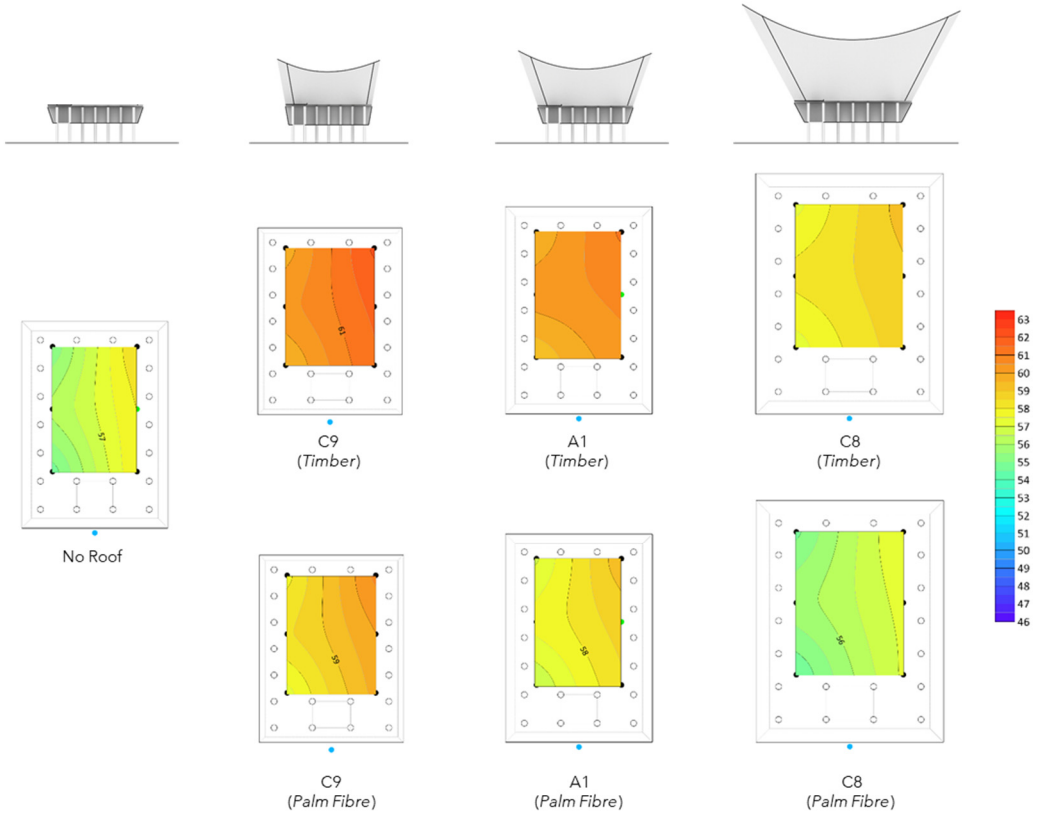


Figure 11. Simulation Results: Indoor Sound Pressure Level (SPL) Distribution.

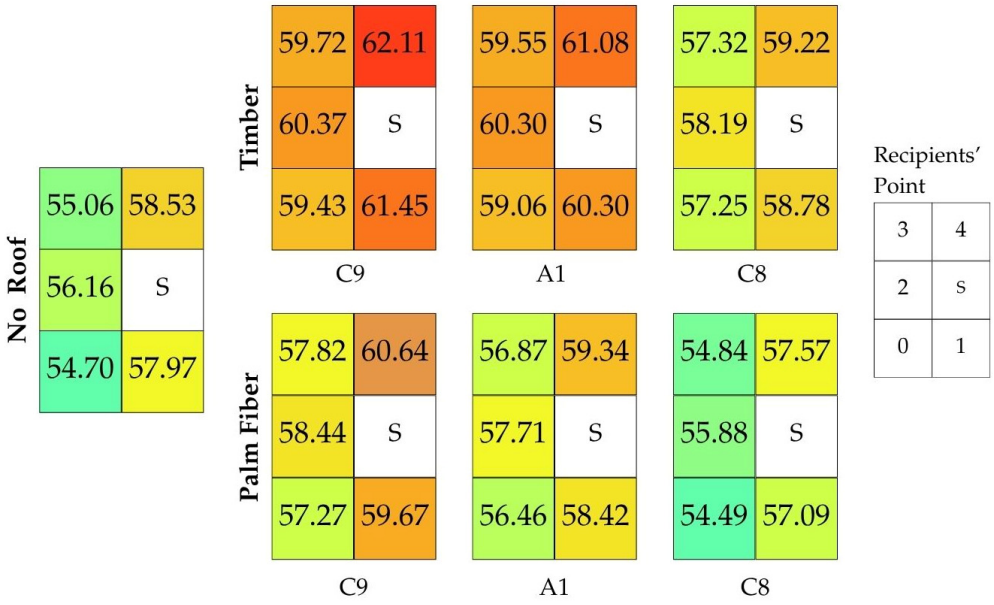


Figure 12. Simulation Results: Indoor Sound Pressure Level (SPL) Value on Measurement Points.

3.2.2. Sound Quality (RT, C_{50}, and D_{50})

Table 6 summarizes the RT, C_{50}, and D_{50} values from the indoor simulations. RT ranges from 0.13 to 0.66 s across the simulated house geometric configurations and frequency bands, with C8—the largest house—showing the highest values. For each frequency, Table 6 reports the arithmetic mean of each parameter across the six receiver positions by averaging the RT, C_{50}, and D_{50} values at the five measurement points.

In C8, RT is 0.58 s at 500 Hz with a timber roof and 0.34 s with a palm-fiber thatched roof. Timber reduces RT more at low frequencies, whereas palm fiber lengthens RT at low frequencies but shortens it at high frequencies. Even though C8 is nearly three times the

volume of C9, the RT value is not markedly different and remains short, indicating that the house geometry configuration, including increased volume, roof angle, and materials, helps sustain speech-friendly acoustics.

The RT, C_{50}, and D_{50} values were also compared with reference criteria for speech-related acoustic conditions. Recommended RT values for conference rooms range from 0.85 to 1.30 s [41], while approximately 0.50 s may be appropriate for small rooms [29]. These benchmarks provide contextual references rather than direct design targets or evidence of speech suitability for the *sitelumbeo* houses. D_{50} values of at least 50% and C_{50} values above 3 dB have also been used as reference criteria for speech clarity [33].

These short *RT* values may also be suitable for rhythmic music such as Batak *gondang*, although further, more specific investigation into the *gondang* characteristic suitability is still required. The *serunai bolon* requires a clear high-frequency response, while gongs and percussion benefit from controlled reverberation that preserves rhythmic clarity [29]. Both timber and palm fiber roof materials meet these acoustic requirements, though palm fiber delivers stronger performance, particularly in high-frequency absorption. These results should be interpreted cautiously because the simulation does not isolate the independent effects of material, roof form, wall inclination, or room volume. Instead, each modeled house should be understood as an integrated acoustic system of interacting geometric and material elements.

Across the simulated configurations, D_{50} exceeds 50%, and C_{50} exceeds 3 dB, while the RT at 500 Hz ranges from 0.24 to 0.58 s. At the same frequency, D_{50} ranges from 79.48% to 95.92%, and C_{50} ranges from 5.89 to 13.73 dB. These values fall within the cited speech-related criteria [41] under the specified simulation conditions.

Together, SPL, RT, C_{50}, and D_{50} reflect the combined effects of geometric and material interactions in the *sitelumbeo* house, exhibiting a modest sound-damping effect that improves speech clarity.

4. Discussion

The results suggest that the *sitelumbeo* house can be understood not only as a dwelling and a cultural form but also as a spatial setting with distinct acoustic characteristics. In Indonesian traditional music, acoustic outcomes arise from relationships among instruments, materials, and performance spaces. Examples include the resonance of *angklung* bamboo tubes [42]; the acoustic properties of *gamelan* tin-bronze [43]; and the relationship between *gamelan* performance and the open form and pyramidal roof of the Javanese *pendopo* [20,44]. Within this broader context, the *sitelumbeo* house provides a distinct spatial setting for Batak Toba ritual activities.

The simulations indicate that the combined house geometry is associated with the modeled distribution of *gondang* sound toward the alaman. By contrast, the indoor simulations report RT, C_{50}, and D_{50} values relative to speech-related reference criteria. This suggests that the sitelumbeo house should be understood as a spatial and acoustic system shaped by ceremonial needs. Its integrated configuration of interacting geometrical spaces (balcony, roof, wall inclination, and enclosed interior) and material elements does not merely accommodate activities; it helps structure how sound is produced, distributed, and heard during rituals.

This potential relationship between domestic architectural configuration and acoustic conditions may be relevant as the settings for Batak Toba ritual practices change. In North Sumatra, some communities separate daily dwellings from traditional houses built in accordance with *adat* [45]. Ceremonies may also extend onto empty land or public roads when the *alaman* is unavailable (Figure 13). In cities such as Jakarta, purpose-built halls are increasingly used for large ceremonies when contemporary residential settings lack

sufficient space. However, the present simulations do not compare the acoustic performance of these alternative settings with that of traditional houses.



Figure 13. Ceremonies with *gondang* music played in the front yard, extending to a public road, on Samosir Island, North Sumatra, January 2021 (photograph by the author).

The findings therefore support the view that traditional houses are not only domestic shelters or symbolic cultural forms but also configurations that may shape the spatial conditions for culturally specific activities. The sitelumbeo house illustrates the architectural organization of "systems of settings within which systems of activities take place" [46], some of which involve sound production and reception. Further controlled simulations and field measurements are needed before specific acoustic criteria can be assigned to individual architectural components or applied to culturally responsive contemporary housing.

5. Conclusions

This study examined the simulated acoustic performance of three *sitelumbeo* Batak Toba houses under two scenarios: outdoor *gondang* performance and indoor speech. Under the specified modeling assumptions, the results indicate associations between the combined house geometry and simulated sound distribution. The presence of a roof distinguishes the roofed configurations from the roofless model, but its independent contributions cannot be disentangled from the effects of walls, floors, frames, dimensions, inclinations, and other geometric characteristics. Outdoors, the first-row SPL was approximately 75.92 dB in the roofless model and 77.37–77.81 dB in the roofed models. Across all receiver positions, the average SPL of the roofed models was 1.32–1.65 dB higher than that of the roofless model. These numerical differences should not be interpreted as statistically or perceptually significant.

For the indoor speech scenario, the simulated RT, C_{50}, and D_{50} values were compared with cited speech-related reference criteria. At 500 Hz, RT ranged from 0.24 to 0.58 s, C_{50} ranged from 5.89 to 13.73 dB, and D_{50} ranged from 79.48% to 95.92%. These values meet the cited numerical criteria under the specified assumptions and boundary conditions, indicating acoustic conditions supportive of speech clarity. Although the simulations do not provide direct perceptual verification or conclusively establish suitability for indoor ritual activities, they offer quantitative evidence of speech-supportive acoustic performance. Because *gondang* music has different acoustic requirements, these findings are specific to speech and should not be applied directly to *gondang* performance.

Taken together, the findings support the central claim that the geometry and materials of the *sitelumbeo* house are acoustically consequential within the modeled conditions. The results do not demonstrate that the roof or any other individual component independently determines acoustic performance. Instead, they show that changes in the overall configuration are associated with measurable differences in the SPL distribution and indoor acoustic parameters.

The absence of field validation does not diminish the comparative value of the simulations, as all configurations were assessed using the same computational framework and standardized environmental, source, material, and boundary conditions. This consistency allows differences among the models to be examined under specified conditions. Nevertheless, without measurements from existing houses, the simulations cannot establish how accurately the values represent actual ritual or domestic environments. Existing houses may contain construction irregularities, panel gaps, material deterioration, variable ground and weather conditions, ambient noise, occupancy effects, and source variations that are not fully represented in the models. The present results should therefore be understood as internally comparable simulation evidence rather than externally validated predictions of in situ acoustic performance.

Future research should proceed through two complementary stages. First, field measurements should be conducted at corresponding source and receiver positions in existing sitelumbeo houses to test and calibrate the simulation results. This process should document source characteristics, material absorption, construction openings, environmental conditions, occupancy, and background noise. Second, controlled parametric simulations should vary roof form, wall inclination, floor elevation, room volume, and materials independently to estimate their respective contributions. Expanding the sample of houses and testing different environmental, occupancy, and hamlet configurations would then provide a stronger basis for evaluating whether the patterns identified here apply more broadly to Batak Toba houses and their role in ritual practice.

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Abbreviations

The following abbreviations are used in this manuscript:

A	*Alaman* (Front Yard)
Bg	*Bonggar* (Mezzanine Level Storage)
Jb	*Jabu* (Living and Sleeping Unit)
JBn	*Jabu Bona*
Jm	*Jambur* (Utility Space—Storage or Extra Living Unit)
JTP	*Jabu Tampar Piring*
JSd	*Jabu Soding*

JSh	*Jabu Suhat*
JtBn	*Jabu Tonga Bona*
JtSd	*Jabu Tonga Soding*
K	*Kandang* (Lower-level Cowshed/ Pigsty)
Lt	*Loting* (Attic Niche)
T	*Tataring* (The Hearth)

Glossary

Adat	Social and customary law of a traditional community
Alaman	The home's front yard forms part of a public street or a hamlet's public square
Gondang	Traditional rhythmic musical performance of the Batak
Hesek-hesek	Percussion plaque made from iron
Jabu	A dwelling unit. A zone in a ruma serves as the residence of an elementary family living with their kin in a cohabitation arrangement. The allocation and nomenclature of jabu are governed by the Batak Toba kinship relations. One ruma may have up to six jabu.
Marga	Batak Toba patrilineal kinship system. A family name.
Ogung	A collection of four-tuned gongs
Pargonsi	A leading musician in gondang performances
Raja Hata	A male acting as the master of ceremonies in the Batak Toba ceremonies
Ruma	A traditional Batak Toba home
Serunai bolon	A Batak Toba wind instrument, a kind of aerophone
Sopo	Rice barns or granary. A building typology used to store rice, valuables, heirlooms, and other harvests also serves as a sleeping quarter for Batak Toba adolescent males.
Taganing	Five approximately tuned drums
Ulaon	A traditional adat event or festivities

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