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The Effect of the Shape of Curved Ceilings on Sound Quality, Sunlight, and Heat Absorption in Lecture Halls

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Research Article

Abstract

Architects' most essential design concern from the past to the present is the geometry of the ceiling form. By analyzing the geometry of various curved ceiling forms, one can find a suitable form in terms of heat absorption, sunlight, and sound quality. The geometry of the form is directly affected by the amount of volume, surface area (ratio of span ratio to height), and the equation of fit of its curve. This study examines the types of curved ceilings based on form geometry in terms of sound quality and sunlight. The main question is what effect does the geometry of the curved ceiling types have on sound quality, amount of sunlight, and heat absorption? The present study investigates Reverberation time, speech transfer index, speech clarity, amount of sunlight, and shading of the speech space in different arcs based on the equations of curve fitting and body shape. Each selected sample is drawn algorithmically in Grasshopper and using Odeon for acoustic simulation and Grasshopper to simulate the absorption of radiant energy of sunlight and the amount of shading and using the Energy Plus, Ladybug plugin. Descriptive analysis of forms with scatter matrix diagram and correlation coefficient analysis between architectural, acoustic, and sunlight variables were performed by Pearson method with SPSS22. The analysis shows that by increasing the amount of area, volume and slope of the curve, it reduces the quality of reverberation time and the speech transmission index, and increases the amount of shade performance, sunlight and shade absorption.

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1. Introduction

The difference between architecture and other arts in simultaneous production is aesthetics regarding its structure, stability, and application (Song et al., 2016). Determining the shape of a building is the most critical task in the architectural design process (Pena et al., 2021). The initial shape of the building affects performance and construction cost, daylight usage, energy consumption, shadow performance, acoustics, functional accessibility, and solar utilization, and other features (Agirbas, 2019). Shape search becomes a crucial step in the conceptual design phase because its results are inputs for later stages of the design process, the construction phase, and throughout the life cycle of the building (Pena et al., 2021). One of the main parts of the building is the structure of the ceiling geometry and architectural form (Hamed Sardar et al., 2023), which has significant effects on energy consumption and thermal comfort of the sound quality of the building (Vasegh et al., 2020). The geometry of the building ceiling has significant criteria for determining the thermal performance of the building in terms of form (Fooladi et al., 2016). One of the strategies used in architecture is to control the sun's radiation and the resulting heat through shade (Zare and Ghanbari, 2022). Shape and form affect the reception of sunlight on the surfaces of domed buildings, and each affects the sound quality of the interior space so that the surface more exposed to sunlight increases heat absorption (Shiri et al., 2020). Recently, acoustics have been considered in non-professional music venues such as libraries, offices, multipurpose spaces, lecture halls, etc. (Cairoli, 2018; Kaarlela-Tuomaala et al., 2009; Xiao and Aletta, 2016). To create acoustic quality through architectural form, the geometry of the ceiling form is one of the most critical factors. When a speech signal is broadcast in space, the speech transmission index, bending time, and speech resolution of this frequency in the transmission path are affected by the architectural form and change and affect the sound quality of the environment (Munteanu et al., 2018; Gramez and Boubenider, 2017; Robinson et al., 2014; Tervo and Tossavainen, 2012). Due to the stability of curved or domed ceiling s in Iranian architecture, one of the best examples for simultaneous study in acoustic quality is the amount of sunlight absorption and shading. Applying these patterns in contemporary architecture in terms of acoustic and thermal efficiency requires understanding the relationship between the components of the architectural body and the acoustic and thermal components simultaneously with each other. This can be applied by recognizing the effect of the geometry of the forms in different dimensions of the current architecture. The present study investigates the components of sunlight absorption, shading, and acoustic components of the dome space in dome form in different arches based on curve fitting equations. Architectural parameters (surface, volume, height, and rise (ratio of height to orifice)) and the curvature of different arches significantly affect the components of time and velocity, speech transfer index, speech clarity, heat absorption, and solar radiation put. This research tries to analyze and answer this central question:

Influence of architectural parameters and equation of curvature of different types of arches on the components of sound quality, heat absorption, and radiation

What is the Sun? To answer the above questions, the research process is defined as follows

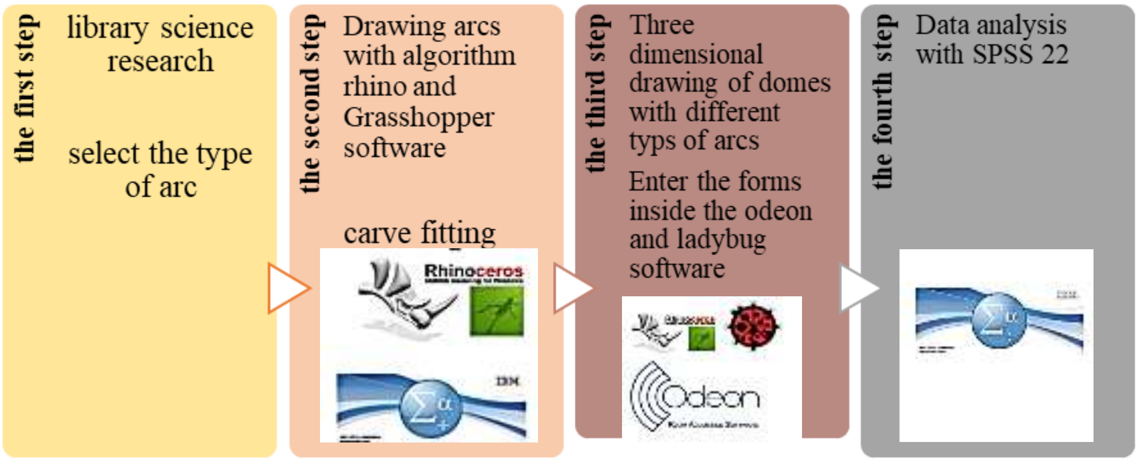


Fig 1 Research Process

1.1. Research Background

Less research has been done on the geometry and proportions of domed and arched ceiling s, taking into account all aspects of architecture or environmental comfort. A group of researchers focused on geometric properties (Farshad, 1977; Huerta, 2007); mathematics (Capilla Tamborero et al., 2021; Izadpanah, 2018), and proportions (Capilla Tamborero et al., 2021; Feizolahbeigi et al., 2021). Other researchers have examined the proportions, type, and shape of arcs due to sunlight (Fooladi et al., 2016; Fathy, 2010; Biwole et al., 2008). Some other studies have presented geometry and proportions, emphasizing acoustic analysis (Ismail and Eldaly, 2018; Inoue et al., 2009). Previous researchers who have worked on the geometry of dome arches have paid less attention to the acoustic aspects, the effect of sunlight, and the absorption of sunlight in different types of arches at the same time.

1.2. Ceiling Form Geometry

Since the birth of architecture, geometry has been, is and will be (Omranifar et al, 2023). Geometry has long been the basis for architects to create architectural works, especially in Iran (Beigi et al., 2019). The field of geometry knowledge is two concepts related to each other, number and shape, which are entirely dependent on mathematical knowledge, and sometimes one is considered (Noghrekar, 2013). Architecture, geometry, and proportions are two inseparable components because making motion within a regular geometric system is essential (Beigi et al., 2019). Past Iranian architecture is a relative geometric system in which the dimensions are obtained with specified coefficients from each other and by dividing and drawing geometric shapes. The set of specific ratios between the components as well as the component and the whole is called the system of proportions (Mojtaba et al., 2011). There is a close relationship between geometry and its arrangement in all stages of architectural work development (Beigi et al., 2019). In shaping the building, pre-thinking is the most influential factor in covering the building (Memarian and Safaeipour, 2018). Ceiling covering in Iranian architecture has a high priority and importance over other organs. Compared to the world's architecture in different eras, this architecture is dazzling in terms of the variety and richness of coatings, as if it has no other concerns (Safaeipour and

Pourmand, 2012). Various arches have been used to make Iranian arch and dome coverings from the past to the present. A mixture of several arcs is part of a specific geometric shape, such as a part of a circle, hyperbole, or any known geometric curve (Pirnia, 1994). Researchers have categorized arches from different perspectives, such as sharpness, rise, and morphology (Nima Vali Bey, 2012).

Application of ceiling geometry compatible with sunlight

Sunlight is one of the most significant natural factors in the constant change of climatic conditions of a point on the earth's surface. Sunlight, which causes light and illumination, eventually turns into heat and affects the region's climate. The shape and form of the building should be to the favorable or unfavorable thermal effects of the environment (Shiri et al., 2020). Accordingly, some forms and forms are superior to others in different regions. Heat loss of the building has a significant impact on the shape of the building (Shiri et al., 2020). Dome ceilings in hot and dry climates and ceilings reduce room temperature in summer and reflect more radiation than flat ceilings (Runsheng et al., 2003). Dry between winter and summer, they absorb more radiation in summer and less in winter than vertical surfaces (Shiri et al., 2020).

Application of ceiling geometry in harmony with acoustics

Indoor quality, IEQ (Indoor Environmental Quality) is considered an indicator of comfort level that is not limited to thermal conditions but includes thermal comfort, sound comfort, indoor air quality, and visual comfort (Mihai and Iordache, 2016). Many researchers have studied the quality of sound in the room. Also, the objective parameters of sound to express the quality of sound in the room, analysis of factors affecting the quality of sound, and possible solutions for sound quality in the room (Zhao et al., 2015). Large halls, in many ways, represent the pinnacle of acoustic design (Everest and Pohlmann, 2015). In general, the acoustic design of large halls is twofold: first, the space that is typically for lectures and the spaces that are usually for music. The former emphasizes speech comprehension, while the latter emphasizes sound for music. Even the largest hall is not so different from the smaller room in some acoustic aspects. In general, the essential and basic criteria of acoustics are equal. Large halls should have the least ambient noise with internal and external sources. The amount of time should be by the values in Figure 2.

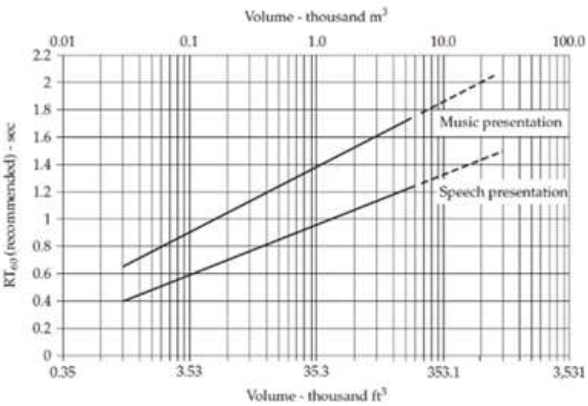


Fig 2 Vaccination time diagram in large-scale halls (Everest and Pohlmann, 2015)

It should be noted that all acoustic needs must be compatible with the needs of aesthetic and functional architecture (Everest and Pohlmann, 2015). Calculation of many components is required for modern acoustic design, one of the leading acoustic parameters for designer's time and time again (Elkhateeb et al., 2016). Vaccination means that the sound remains in a closed environment until the sound output stops. Over time, a series of reflections or echoes reduces its strength by limiting absorption and air loss. Vakhansh has been described by Mulan (1983) as a continuous presence of sound and audible after cutting off the sound source. Technically, the time required to reduce 60 decibels of sound is called the "wear time." A fraction from seconds to five seconds and more in small rooms. It varies up to vast areas, such as prayer halls in mosques. Different rooms and activities require different opening times for acceptable sound quality. The best time to speak is less than 1 second for speech and more than 1 second for music. Short speaking times are essential for clear speech. Otherwise, the constant presence of resonant noise obscures the underlying sound and causes speech to become blurred. Larger rooms seem to require longer opening times, as with lower sound frequencies. According to Berg and Stork (1995), the best reading time for a speech should be less than 1 second in 500 Hz and less. The opening time of a room should be proportional to the function and volume of the room (Othman and Mohamed, 2012).

Comprehension is the highest design priority for any hall intended for spoken words. That is true in many places of worship, halls, and theaters. Audio systems are often used to overcome acoustic limitations and for greater clarity in vast spaces (Everest and Pohlmann, 2015). Speech comprehension is the percentage of a word or words that listeners properly hear. That is a vital element of human communication. Without a significant understanding of speech, communication becomes difficult. Good comprehension is affected by RT time, background noise, and the listener's distance from the speaker. The three elements, timing (RT) and background sound, are influenced by the room's architecture. Therefore, more attention should be paid to them in the design phase (Othman and Mohamed, 2012). Nexon (2002) emphasized that in the draft version of the ISO 9921 standard in "Assessing Speech Communication," speech comprehension is defined as "measuring the effectiveness of speech comprehension." Measurement is usually expressed as a percentage of a properly understood message. Speech comprehension does not mean the quality of speech. Speech comprehension is related to the number of things that are correctly detected. In contrast, speech quality is related to the quality of speech signal reproduction according to the amount of audible distortion. Thus, a message that lacks quality may still be understandable (Othman and Mohamed, 2012). The speech Transmission Index (STI) is an objective criterion for determining speech transmission (Hossam Eldien, 2013). Loss of speech signal transmission is caused by reflection, interference, and background noise (GOŁAŚ and SUDER-DĘBSKA, 2009). Helps to contribute to speech quality" (Kuttruff and Mommertz, 2013). According to Barnett (1999), the STI reference value varies from 0 = bad to 1 = excellent. At this scale, an STI of at least 0.5 is desirable for most applications (Barnett and Acoustics, 1999) (Figure 3).

Fig 3 Speech Transmission Index Scale (Source: Barnett and Acoustics, 1999)

Figure 4 Graph of the amount of physical quantities of sound quality based on the ISO3382 standard used in the design and evaluation of lecture halls.

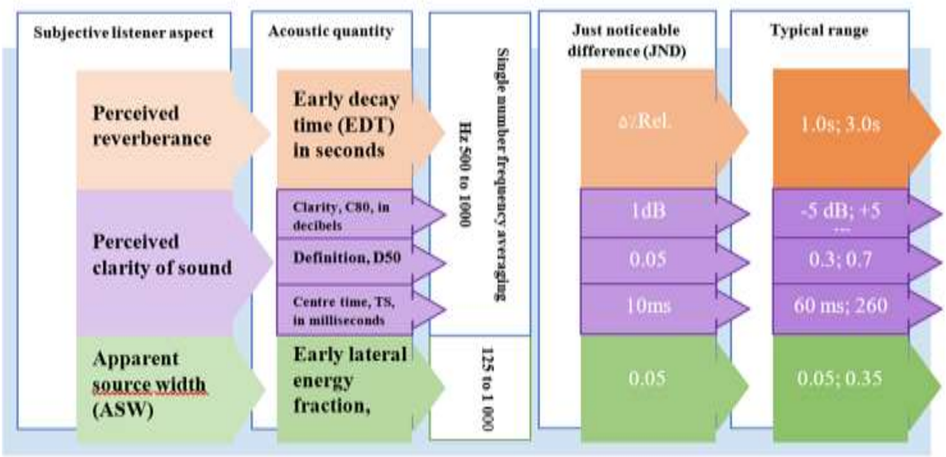


Fig 4 Diagram of several assumed physical quantities that determine the sound quality (Source: iso 3382, Skålevik, 2008)

2. Research Method

The present study investigates the analysis of the amount of sunlight received and heat absorption in the range of shadows and acoustic components in the form of a curved ceiling to explain the optimal shape of the lecture space. For the first time, this study investigates the sound quality component, the amount of sunlight received, and heat absorption in the shadow range based on the body and the curve fitting equation. The method of data collection is library and simulation. Library data collection tools (articles, books), software simulation (Odeon, Grasshopper, Energyplus), and data analysis tools are SPSS software. Using a combined method (simulation, descriptive analysis), this research comprises applied articles. The research method is that GrassHopper software was drawn algorithmically after selecting the types of arcs by the experts of each sample in the traditional method of masters not to change the line mode. Karl Friedrich, with SPSS software, performed the least-squares method. Then the 3D forms were simulated in Odeon software, and on the other hand, the 3D forms were simulated in Grasshopper software with the Ladybug plugin. In the following, the scalar matrix diagram performed a descriptive analysis of each acoustic indicator, the amount of sunlight received, and heat absorption in the shadow range. Finally, the amount of sunlight and heat absorption in the shadow range was analyzed by the Spearman method in SPSS software to analyze the architectural and acoustic components. Table 1 below presents the variables and metrics examined.

Table 1 Variables and metrics studied in this study.

		Architectural form	Acoustic	Energy
Components	**Conceptual construction**	The geometry Form ceiling	Acoustic comfort	Thermal behavior buildings
	Variable	Computational geometry, Form	Acoustic quality	Solar energy absorption
	Measures	**Computing:** slop of curve, **physical:** Volume, Area, Ratio Height to span	(reverberation time)RT, (the clarity) C80, (speech transmission index) STI	Solar radiation received and shade

In this research, the arc type of the samples was selected purposefully with the opinion of experts according to the purpose of the research. Table 2 describes the selected samples based on the physical characteristics of each sample. Also, from the point of view of experts, selected examples of arches of selected domes have historical value and are used in buildings today.

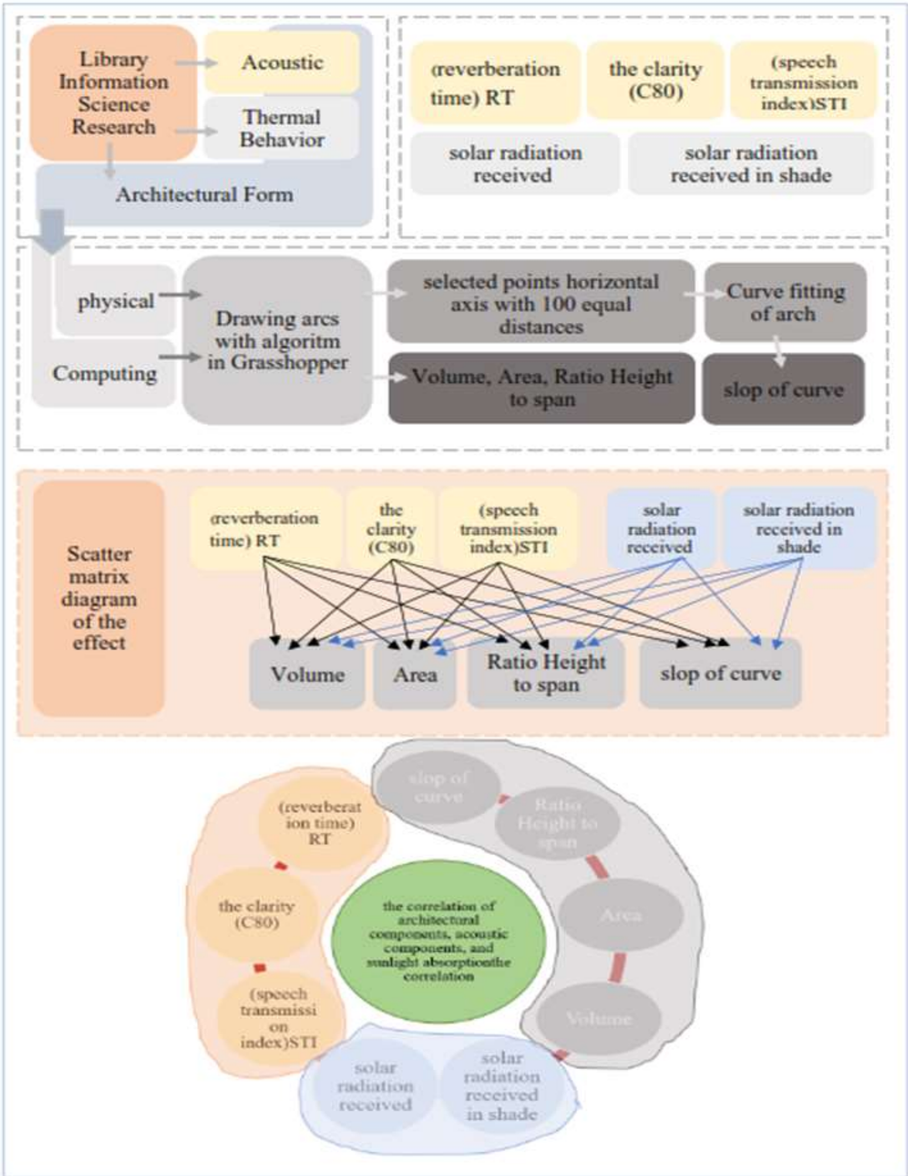


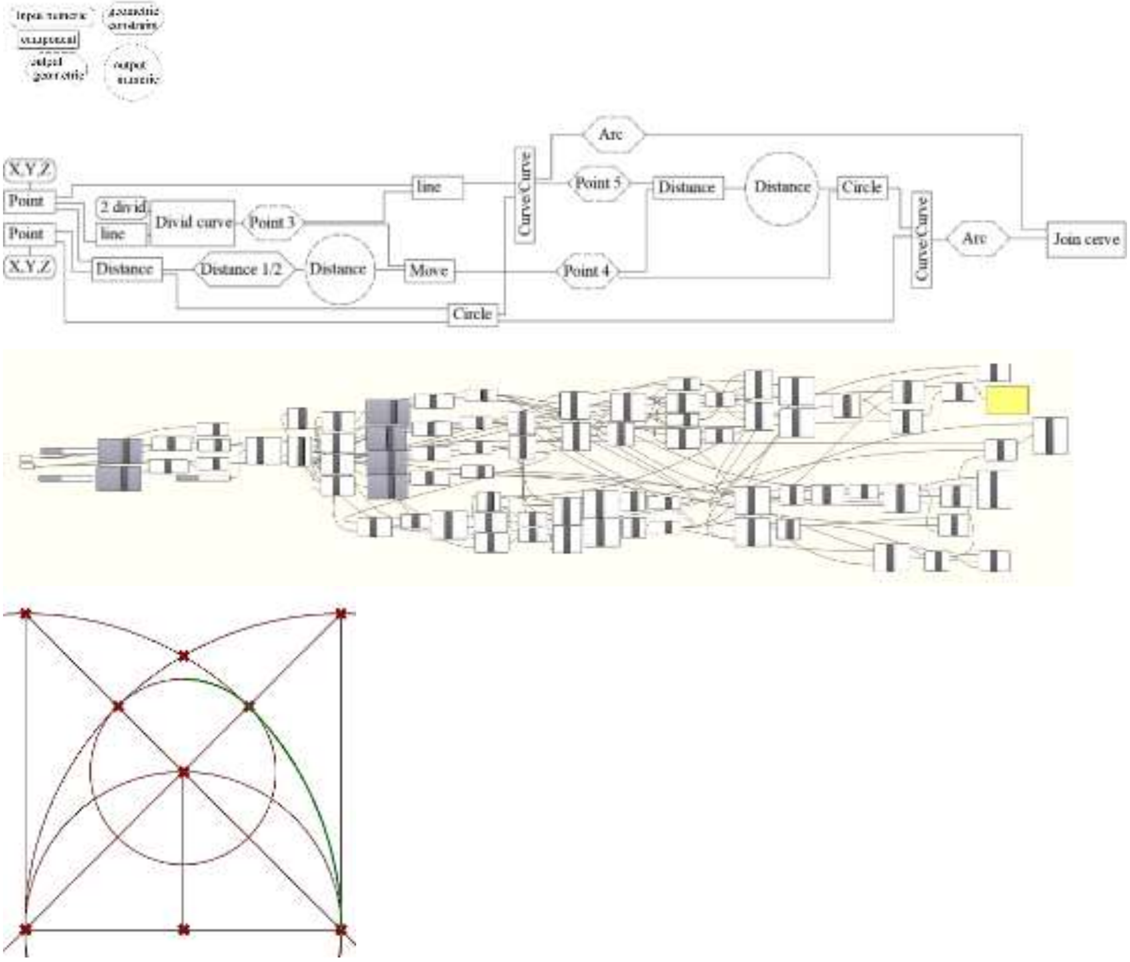
Fig 5 Research method

Table 2 Description of room model with different types

Physical characteristics	Volume m3	Area m2	Span m	Height m
1	1328.23	478.57	15	11.89
2	550.31	267.02	15	5.74
3	698.09	304.84	15	7.28

4	629.67	287.94	15	5.62
5	696.54	304.11	15	6.53
6	473.76	249.39	15	4.81
7	910.54	360.39	15	8.98
8	889.08	354.02	15	8.22
9	965.58	377.31	15	9.98
10	905.8	358.62	15	8.73
11	958.64	374.61	15	9.77
12	887.83	353.37	15	8.03

In most research done for drawing arches, drawing curves on arches and visually comparing them with a known arc with bending has been used (Izadpanah, 2018). Many bends can be used to approximate an arc. The closest bend to the arch has been carefully selected according to the difference between several bends and the drawing arc (Izadpanah, 2018). However, from Horatha's point of view, every person sees the curve he likes in the arc (Huerta, 2007). To prevent this error, the curve fitting and expression of the type of arches were performed by the matrix method, and to check the fitting error by the Least squares method, Carl Friedrich Gauss was performed. First, to fit the curve in GrassHopper software, each of the selected arcs with the same aperture was drawn by the master method in this software. Figure 6 is an example of the drawn algorithm of one of the arcs in Grasshopper software.



For each of the twelve arcs, it is drawn specifically based on that method in the software, which is drawn above the algorithm of arc number 1.

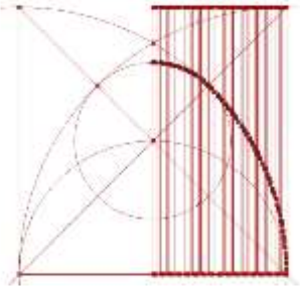


Fig 6 Example of an algorithm plotted in the Grasshopper software (Source: Authors)

It is necessary to select the appropriate points on the curve connections for analysis. These points should be selected homogeneously based on what experts say in all arcs (Izadpanah, 2018). The base points of the arc were selected as starting points, and their horizontal axis (openings) with 100 equal distances. Based on the values obtained in SPSS software. The least-squares method is used to check the amount of error. Table 3 describes the selected samples based on the mathematical properties and the image of the arc arcs of each sample.

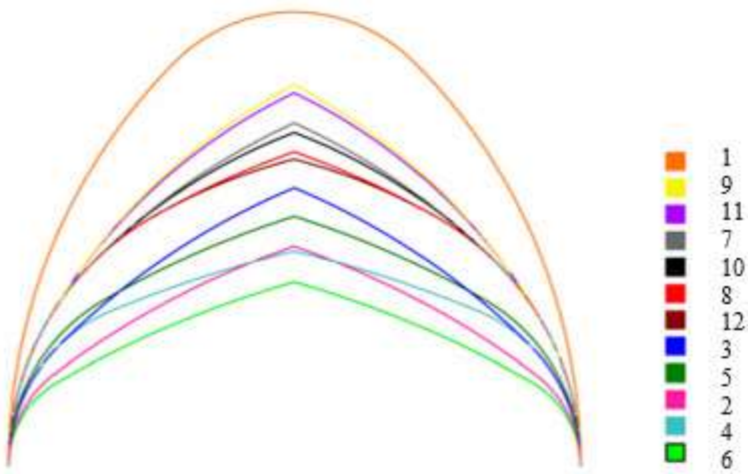
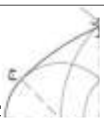


Fig 7 Drawing arc arches selected by experts

Table 3 Description of curve fitting arches

Arc 	**Curve Fitting**				
	X3	X2	X1	b	r
12	0.027	-0.4322	2.6451	1.3201	0.987223
11	0.0191	-0.333	2.5679	1.3156	0.98929
10	0.0235	-0.3784	2.5249	1.3664	0.990892
9	0.0187	-0.3246	2.5601	1.316	0.972347

8	0.0282	-0.4392	2.6547	1.3178	0.981526
7	0.0235	-0.3714	2.5055	1.3749	0.986656
6	0.01	-0.1557	1.1465	0.8516	0.988843
5	0.0222	-0.3335	1.9946	1.1412	0.982735
4	0.0229	-0.3384	1.8803	1.0652	0.993252
3	0.0134	-0.2221	1.7583	1.0709	0.988294
2	0.0103	-0.1682	1.3386	0.9073	0.993111
1	0.0246	-0.4945	3.684	1.8955	0.981494

Architecturally and acoustically, it is essential to anticipate the sound characteristics of a prefabricated lecture hall. During the twentieth century, simulations were performed with the physical model of the hall. From the early 1960s, computer simulations of the development room led to the prediction and analysis of architectural designs. There are two geometric methods, one for the direct sound to the receiver and the other for the sound propagated to the corresponding surrounding surfaces before reaching the receiver. There are two geometric methods in Odeon.

In this research, to simulate Odeon software, it is considered that this software is a basis for researchers and a valuable tool for consulting companies in the objective and subjective field of acoustic room (Naylor, 1993). The Odeon program uses a combined primary wave tracking method to determine possible reflectance sequences (Naylor, 1993). Sound waves are sent from a source inside the room, followed by a reflection in the room, and the output data is stored for later use in determining the reflections received at one point (Naylor, 1993). The presentation of the 3D model in the Odeon allows the acoustics to be produced, described, and heard. This study created all room models using Grasshopper 3D software and then imported them into Odeon Room Acoustic 9.0 software. According to the sample dimensions of similar spaces in Iranian architecture expressed in the research background (Hossam Eldien, 2013; Rezazadeh Ardabili et al., 2018) and a cube with dimensions of 15 meters under the curved ceiling is the same for all models. That is to prevent the effect of volume change on acoustic parameters and to ensure analysis based on the characteristics of the dome (Kassim et al., 2014). Verification included a water tightness test in determining that the room model was examined to ensure the simulation accuracy and that all forms were completely closed, as shown in Figure 8 as an example of two models. The first parameter to be set is the amount of background noise in lecture halls. In lecture halls, the recommended noise standard for the HVAC system is NC 35 (Crocker, 2007). This simulation aims to identify the effectiveness of the form, the type of arc, and the fit of the curve, which is why the functional materials assigned to each similar model have been used in other models. The sound source informs it is the point type that emits natural sounds in the environment. The sound source in each figure is 1 meter from the edge of the wall and is 1.8 meters high from the floor. Table 4 shows the values entered in the Odeon software setting and the absorption coefficient (α) for the surface of the rooms and their floor, and at the bottom of the speaker volume table used by each model in Table 4. In the dome model, the materials, the opening of the dome, and the space under the dome were considered equally so that only the main variable, the shape of the dome, could be examined. Figure 8 Examining some examples of closed forms in Odeon software source.

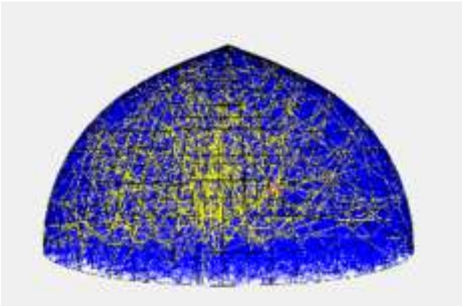


Fig 8 Examining some examples of closed forms in Odeon software (Source: Authors)

Table 4 First part of the statistical data entered in the software and the second part is the absorption coefficients (α) for the room level, and the third part is the speaker power (Source: Authors)

Statistical Data							
Environmental Conditions RH%	Environmental Conditions Temp. C^0		Number of rays use		Axis Point source		Point receiver
50.00	20		900000		1.8, 7.5, 1.7		27
The absorption Coefficients (α) for rooms' surfaces							
Material	Octave band centre frequency (Hz)						
	125H	250H	500H	1000H	2000H	4000H	NRCC
Floor							
Carpet, heavy, on concrete	0.02	0.06	0.14	0.37	0.60	0.65	0.29
Ceilings							
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07	0.005
Sound power of omni-directional speaker used in both experiments (Omni. SO8).							
Frequency (Hz)				250	500	1000	2000
Sound power (dB)				69.6	74.8	71.8	63.8

In all models, the location of the receiver and speaker is fixed. For example, the Form 6 model is located in Figure 9.

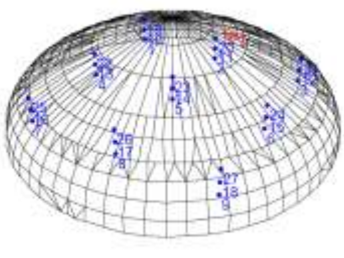


Fig 9 Location of transmitter and receiver Model 6 For examples of forms (Source: Authors)

To check the amount of sunlight received on the outside of the building, a method is needed that can simulate sunlight on the surface of the models with great accuracy. To simulate sunlight on surfaces, they need to show the components of location, time, weather conditions, and the effect of shadows on external surfaces in the analysis. Therefore, for analysis, it is necessary to use a suitable tool to receive and evaluate sunlight on the exterior of the building. Radiance, Daysim, and ArcGIS Ecotect software are for evaluating sunlight on building surfaces (Brito et al., 2012; Freitas et al., 2015; Andersson et al., 1985). To analyze solar radiation, radiance software can be used that analyzes small scales with high accuracy using the Perez Diffuse Radiation Model (Perez et al., 1990; Perez et al., 1987). The basis of this software is based on algorithms that write with a visual algorithm in the GrassHopper environment. Radiance software is proposed for analyzing sunlight in a three-dimensional model with high-precision complex curve geometry. The simulated samples in Rhino 7 software are set at zero degrees. In this study, using the EPW file of Yazd city, which is one of the hottest cities in Iran, was included in the software. Receiving sunlight on the hottest day of the year at 16:00 and the whole year is considered. Figure 10 shows Form 6 of the simulation with the ladybug plugin.

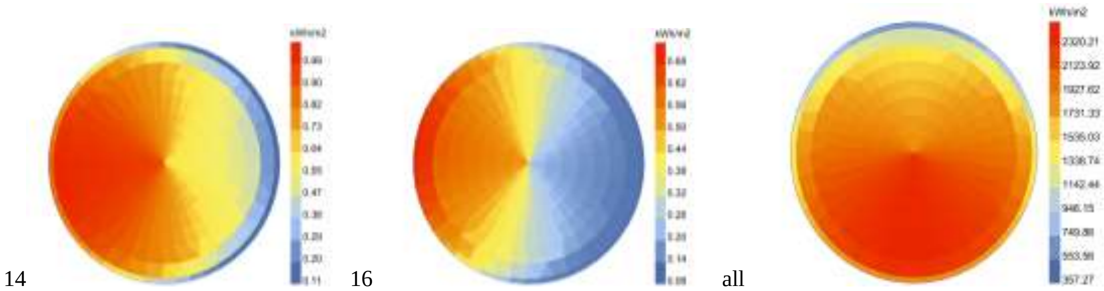


Fig 10 Simulated image in Grasshopper software Ladybug plugin

3. Findings

In this section, each of the research objectives is a descriptive analysis of the components of sound quality and the amount of solar radiation and heat absorption in the shadow range based on the architectural body parameter and the coefficient of variables of the arc fitting equation. In the following, the components of sound quality and the amount of sunlight received, and heat absorption in the shadow range is expressed, respectively.

3.1. Analysis and Adaptation of Acoustic Data of Dome Form

The simulated forms in GrassHopper software were entered into Odeon 9 software. The amount of time-lapse components, sound clarity, and speech transmission index of each dome form were obtained. Table 5 is the data obtained from the simulation.

Table 5 Ratio time, speech resolution, and speech transfer index obtained from model simulations (Source: Authors)

Number of forms	Reverberation Time	Clarity (C50)	Index Transmission Sound
12	3.64	-3.40	0.53
11	3.74	-3.48	0.52
10	3.62	-2.11	0.55
9	3.75	-3.45	0.52

8	3.62	-3.35	0.53
7	3.61	-2.10	0.55
6	2.29	-0.76	0.62
5	3.09	-2.56	0.56
4	2.93	-1.93	0.57
3	3.10	-2.17	0.57
2	2.29	-0.55	0.61
1	3.63	-3.36	0.53

The most critical component of acoustic quality is its time in the speech space. Other components of the speech transmission index are used as an objective and physical criterion to determine the quality of speech. The speech transfer index is the interval between zero and one, the best case 1, and the worst-case 0. Another component of speech clarity is that the ratio of initial sound energy to late sound energy should be between the numbers 5- and +5. According to Table 5, Form No. 6 with a height of 4.81, area of 249.39, a volume of 473.71 and a slope of 0.06 with a time of 2.29, transmission index of 0.62 and speech resolution of -0.76, form No. 2 with a height of 5.74, area 267.02, volume 562.37 and a slope of 0.06 With a vowel time of 2.29 and a speech transfer index of 0.61 and a speech resolution of -0.55, followed by form No. 4 with a height of 5.62, an area of 287.94, a volume of 629.67 and a slope of 0.13 with a vowel time of 2.93 and a speech transfer index of 0.61 and a speech resolution of 1. 93-, respectively, have the lowest amount of speech time, speech clarity and the highest amount of speech transmission index. As shown in table 5, form No. 1 with a height of 11.89, area of 478.57, a volume of 1306.08 and a slope of 0.14 with a time of 3.62, a transfer index of 0.52 and a speech resolution of -36.36, Form No. 11 with a height of 9.77, area 374.61, volume 938.19 and Slope 0.11 with a rotation time of 3.74 and a speech transfer index of 0.52 and a speech resolution of -3.48, followed by Form No. 9 with a height of 9.98, area 377.31, volume 944.89 and a slope of 0.14 with a rotation time of 3.75 and a speech transfer index of 0.52 and resolution. Speech 3.45 and at the end of Form No. 12 with a height of 8.06, area 353.37, volume 880.80 and a slope of 0.16 with a rolling time of 3.75 and a speech transfer index of 0.53 and a speech resolution of 3.40, respectively, the highest rolling time, speech clarity and minimum They have a speech transmission index. The simulation data are analyzed using the Scatter matrix diagram in Figure 11.

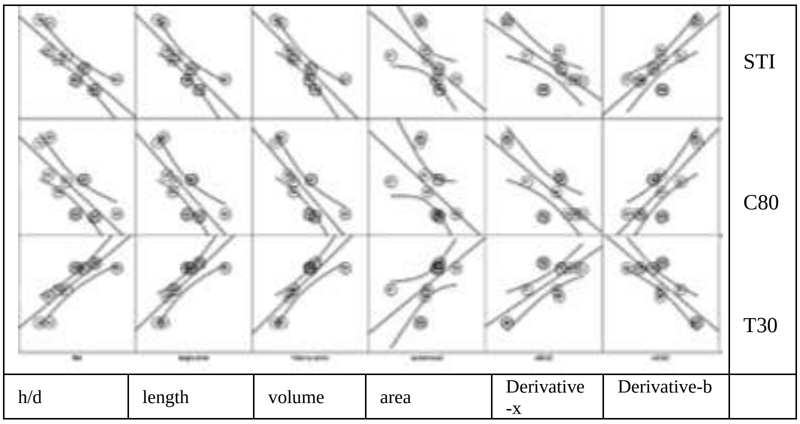


Fig 11 Scatter matrix diagram effect of volume, area, height-to-dome ratio, arc length, and arc curve slope on acoustic components (Source: Authors)

According to Figure 10 of the Scatter Matrix diagram, the effect of architectural components on sound quality with increasing volume, area, height to dome ratio, arc length, and slope of the arc curve increases the amount of time. It decreases the speech transmission index and speech clarity. This diagram shows that the sound quality decreases with increasing the amount of volume, area, height to dome ratio, arc length, and slope of the arc curve. Form 2 in Figure 11, has less bending time, higher speech clarity, and a higher transfer index than form 4, both of which have approximately equal area, volume, and height-to-mouth ratio, but Form 2 has a lower curve slope than form 4. That indicates that the type of curve shape and reducing the slope of the arc curve increase the amount of sound quality components of the dome.

3.2. Analysis and adaptation of data on the amount of solar radiation and heat absorption in the shadow range of the dome form

The amount of shading on the form and receiving sunlight was obtained using Rhino software (GrassHopper). An algorithm with Ladybug plug-in, Honeybee with Plus Energy Radiance rendering engine, was written to study sunlight on the surface of various domes. The type of arch, volume, area, and height of the opening of the domes, which is a component of the body of the dome form, affect the amount of sunlight received. In modeling the shape of the domes, the materials, the opening of the dome, and the space under the dome were considered equally to examine only the main variable, the shape of the dome. Table 6 is the data obtained from the simulation with Ladybug software.

Table 6 Area of shadow and sunlight, and at the bottom of the table, the amount of shadow and sunlight is expressed

Number of form	Area Shade						Area Radiation Sunlight					
	Area Shade 14 m^2		Area Shade 16 m^2		Area Shade all year m^2		Area Radiation Sunlight 14 m^2		Area Radiation Sunlight 16 m^2		Area Radiation Sunlight all year m^2	
	The ratio of area 14 to all	Area 14	The ratio of area 16 to all	Area 16	The ratio of area all year to all	Area all	The ratio of area 14 to all	Area 14	The ratio of area 16 to all	Area 16	The ratio of area all year to all	Area all
1	0.48	231.56	0.53	255.67	0.23	110.04	0.59	247.02	0.47	222.9	0.77	368.53
2	0.24	64.55	0.48	127.25	0.08	20.36	0.88	202.47	0.52	139.76	0.92	246.66
3	0.34	105.01	0.5	151.64	0.11	33.6	0.74	199.83	0.5	153.2	0.89	271.24
4	0.29	83.4	0.47	135.19	0.13	37.04	0.83	204.54	0.53	152.74	0.87	250.9
5	0.3	92.24	0.49	148.08	0.13	39.51	0.75	211.87	0.51	156.03	0.87	264.6
6	0.2	48.91	0.45	112.12	0.07	17.84	0.88	200.48	0.55	137.27	0.93	231.56
7	0.4	145.81	0.52	186.13	0.16	58.27	0.6	214.58	0.48	174.27	0.84	302.13
8	0.38	135.11	0.51	180.56	0.16	56.82	0.66	218.91	0.49	173.46	0.84	297.2
9	0.43	163.02	0.52	196.84	0.17	64.4	0.64	214.29	0.48	180.47	0.83	312.92
10	0.4	143.53	0.51	184.37	0.16	58.27	0.61	215.09	0.49	174.25	0.84	300.36
11	0.42	157.58	0.52	194.75	0.17	65.49	0.6	217.03	0.48	179.86	0.83	309.12
12	0.38	135.11	0.51	180.03	0.16	56.82	0.67	218.25	0.49	173.33	0.84	296.54

Solar radiation received

Number of form	Shade			Solar radiation received		
	Shade 14 Kwh/m2	Shade 16 Kwh/m2	Shade all year Kwh/m2	solar radiation received 14 Kwh/m2	solar radiation received 16 Kwh/m2	solar radiation received year Kwh/m2

	The ratio of received 14 to all	received 14	The ratio of received 16 to all	received 16	The ratio of received all year to all	received all	The ratio of received 14 to all	received 14	The received of area 16 to all	received 16	The ratio of received all year to all	received all
1	0.16	55.49	0.21	43.99	0.08	83289.41	0.84	281.10	0.79	169.03	0.92	950605.25
2	0.07	17.59	0.22	29.57	0.01	10627.87	0.93	235.04	0.78	101.93	0.99	714021.42
3	0.10	24.95	0.21	29.11	0.03	22780.04	0.90	225.78	0.79	110.52	0.97	691274.41
4	0.06	16.33	0.22	30.50	0.04	27633.98	0.94	240.39	0.78	106.30	0.96	696725.88
5	0.08	19.28	0.22	29.87	0.04	28552.90	0.92	228.90	0.78	106.53	0.96	680059.28
6	0.04	9.51	0.21	24.24	0.02	9961.25	0.96	220.22	0.79	92.60	0.98	624010.12
7	0.14	36.15	0.23	33.80	0.05	38037.20	0.86	217.15	0.77	115.99	0.95	730000.62
8	0.11	30.41	0.23	35.50	0.05	38461.56	0.89	235.27	0.77	115.75	0.95	753578.13
9	0.13	37.08	0.21	35.12	0.05	43769.90	0.87	243.10	0.79	132.95	0.95	773524.08
10	0.15	38.23	0.23	35.03	0.05	38037.20	0.85	220.05	0.77	116.02	0.95	751785.61
11	0.12	31.91	0.21	32.08	0.06	43898.91	0.88	226.24	0.79	122.84	0.94	709091.21
12	0.11	30.41	0.24	35.62	0.05	38461.55	0.89	236.43	0.76	115.91	0.95	755811.80

The amount of energy received by sunlight on the surface of the form of domes is affected by the shape of the curve, the slope of the curve, the ratio of height to the opening, area, and volume. Table 6 examines the amount of area and absorption of radiant energy in the form of domes at 14, 16, and all hours of the year and the ratio of shadow and sunlight to total shadow and sunlight. According to Table 6, the highest absorption of sunlight on the hottest day of the year in Yazd at 14:00, Form 1 with 281.09 KWh / m2, respectively, Form 9 with KWh / m2242.09 KWh / m2, followed by Form 1 with 16, respectively. The rate is 169.01 KWh / m2, Form 9 with a rate of 132.83 KWh / m2, which is the lowest amount of solar energy received at 14 hours, respectively, Form 8 with a rate of 217.15 KWh / m2, Form 10 with a rate of 220.4 KWh / m2, and at 16 hours, respectively. Form 6 is 92.5 KWh / m2, Form 11 is 101.93 KWh / m2. Table 6: The ratio of the area of absorption of sunlight to the total area of shadow and sunlight at 14 hours is the hottest hour, and the day of Form 1 with 0.59 is the lowest, and the highest is Form 6 with 0.88. The highest ratio of absorption rate was received by Form 6 with 0.96 and the lowest by Form 1 with 0.84. Figure 11 data analysis chart shows the amount of sunlight received and heat absorption in the shadow range from the Ladybug simulation using the Scatter matrix method.

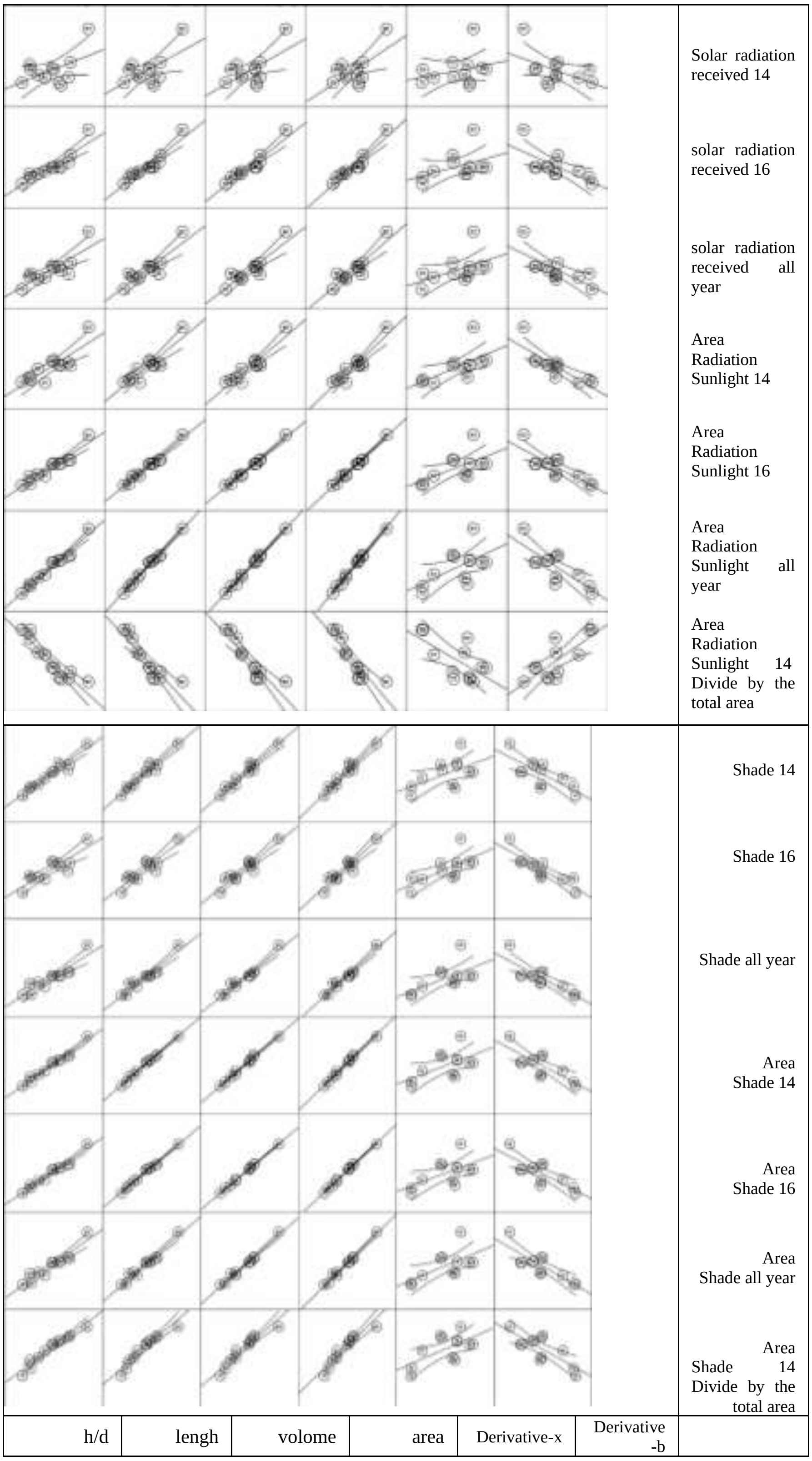


Fig 12 Scatter matrix diagram of the effect of volume, area, height-to-dome ratio, arc length, and arc curve slope on components receiving sunlight and heat absorption in the shadow range (Source: Authors)

The scatter matrix diagram in Figure 12 shows the effect of height to orifice ratio, volume, dome surface, length, and slope of the arc curve on the components of receiving sunlight and heat absorption in the shadow range. By increasing the ratio of height to opening, volume, the dome's surface, length, and slope of the arc curve, the area and amount of solar energy received directly increases—the area and amount of energy received by direct sunlight in the shade increases. In Figure 11, the area receiving solar radiation energy at 14 o'clock decreases as the ratio of height to aperture, volume, dome surface, length, and slope of the arc curve decreases. Form 4 in Figure 12 has the ratio of solar energy to the total dome less area and the amount of solar energy and area and the amount of solar energy received in the shadow more than form 2, both of which have approximately the same area, volume, and height to the crater. However, form 2 has a lower curve slope than form 4. It indicates that the type of curve shape and decreasing the slope of the arc curve increases the amount of area components and the amount of solar energy and the area and amount of solar energy received in the shade and reduces the ratio of solar energy to the entire dome.

3.3. Correlation between Acoustic Components, Amount of Sunlight, and Heat Absorption with Architectural Components

Pearson correlation coefficient was used to test the relationship between acoustic variables, the amount of sunlight received, and heat absorption in the range of shade and architecture. Figure 13 Correlation diagram of sound quality for the components of time of onset, speech resolution with frequency 500 and speech transmission index and the amount of solar radiation and heat absorption in the shadow range at 16 hours and the whole year and the ratio of solar energy to total energy reception the dome with architectural components is shown by Spearman correlation test (Fig 13).

	c80500	d50500	edt500	t30500	ts500	sti	solar radiation 14	solar radiation 16	solar radiation all year	Shade 14	Shade 16	Shade all year	Area Shade 14	Area Shade 16	Area Shade all year	Area Sunlight 14	Area Sunlight 16	Area Sunlight all year	Area Sunlight 14 Divide by all	Area Sunlight 16 Divide by all	Area Sunlight all year Divide by all	Area Shade 14 Divide by all	Area Shade 16 Divide by all	Area Shade all year Divide by all
height	-0.76	-0.68	0.85	0.85	0.84	-0.83	0.52	0.91	0.82	0.97	0.87	0.91	0.99	0.98	0.95	0.84	0.95	0.98	-0.92	-0.96	-0.93	0.97	0.96	0.93
htd	-0.76	-0.68	0.85	0.85	0.84	-0.83	0.52	0.91	0.82	0.97	0.87	0.91	0.99	0.98	0.95	0.84	0.95	0.98	-0.92	-0.96	-0.93	0.97	0.96	0.93
lengh	-0.76	-0.68	0.82	0.82	0.82	-0.81	0.60	0.95	0.88	0.97	0.91	0.96	1.00	1.00	0.98	0.90	0.98	1.00	-0.89	-0.93	-0.96	0.96	0.93	0.96
Volome	-0.61	-0.54	0.66	0.66	0.67	-0.65	0.62	0.94	0.89	0.97	0.94	0.97	1.00	1.00	0.99	0.93	0.99	1.00	-0.90	-0.93	-0.97	0.96	0.93	0.97
Area dome	-0.53	-0.46	0.59	0.60	0.59	-0.58	0.64	0.95	0.90	0.97	0.94	0.98	1.00	1.00	0.99	0.93	1.00	1.00	-0.88	-0.92	-0.97	0.95	0.92	0.97
Derivative-x	-0.73	-0.68	0.76	0.77	0.75	-0.74	0.28	0.44	0.50	0.55	0.70	0.63	0.59	0.60	0.63	0.63	0.62	0.58	-0.66	-0.59	-0.75	0.64	0.59	0.75
Derivative-b	0.80	0.73	-0.81	-0.82	-0.82	0.80	-0.50	-0.69	-0.73	-0.76	-0.87	-0.84	-0.80	-0.81	-0.84	-0.83	-0.83	-0.80	0.77	0.74	0.90	-0.79	-0.74	-0.90

Fig 13 Correlation between acoustic components, amount of sunlight, and heat absorption with architectural components

The thermal diagram of the correlation of architectural components, acoustic components, and sunlight absorption is located in which the components of height to the opening, height, volume, dome area, curve slope, and arc length with a value above 0.53 are directly related to the amount of time and that they are inversely related to the components of speech clarity and speech transmission index or correlation rate greater than 0.5. In other words, increasing the amount of architectural components increases the amount of reading time. It decreases the amount of speech transfer index, which decreases the sound quality of the speech environment. Components of height to the aperture, height, volume, dome area, curve slope, and arc length with a rate above 0.53 are directly related to the amount of sunlight absorption, the amount of sunlight absorption in the shade, and the area of each of them and an inverse relationship with a rate above 0.5 with the ratio of the area of sunlight to the total area and the area of the shadow to the total area. Increasing the components of volume, area, height-to-dome ratio, arc length, and arc curve slope increases the amount of energy absorption. However, dome performance increases with increasing span ratio, dome curve slope, and more shading.

4. Conclusion

The ceiling is one of the factors affecting the thermal and acoustic quality of the building. Dome ceilings have superior structural stability due to their application. Due to its high structural performance, it is necessary to improve its efficiency in other aspects, including thermal and acoustic performance. Vacation time (T30), speech resolution (C80), and speech transfer index (STI) are the main factors of sound quality from the perspective of architects in large-scale lecture halls. Sunlight and heat absorption in the shade range is the leading causes of heat loss through the shell. This study used the amount of sunlight, heat absorption, and acoustic components simultaneously in widely used arcs.

Increasing the volume, area, height-to-dome ratio, arc length, and slope of the dome arc curve increases the amount of time to bend, decreases the speech transmission index, and reduces speech clarity. It indicates that sound quality decreases with increasing the volume components, area, height to dome ratio, arch length, and slope of the dome arch curve. Increasing the ratio of height to span, volume, dome surface, length and slope of the arc curve, area and amount of solar energy received and the area and amount of solar energy received in the shade increase directly, but the shading performance on the form increases. These results are from the research done in acoustics such as Kazem, Yalmaz and Aref, Din and Anvar. In terms of heat absorption with Sarposhan and Yaghoubi, Gofz et al., And Shiri et al., Dome forms have almost equal volume, area, height to dome ratio, and arc length. Domes with lower arc curves have higher quality in acoustic components such as bending time, speech transfer index, and speech clarity. Dome forms have approximately equal volume, area, height-to-dome ratio, and arc length but have a higher curve slope in shading on the form.

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