THE EFFECT OF ACOUSTIC PARAMETERS ON FINDING THE FORM OF A CONCERT HALL USING ODEON

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Abstract. As concert halls are important acoustical environment for human being nowadays, achieving a good form (shape) of a concert hall plays an important role at the initial steps of design process. Therefore, the size and the form of the hall are vital factors which aid achieving the best results in acoustical design. The authors utilized the acoustic computer simulation program Odeon which calculated the parameters of reverberation time, clarity, lateral fraction. The study discusses with a seating capacity of 380. The article presents the result of acoustic simulations and comparison of the acoustic parameters of the proposed forms of halls by the authors. The purpose of this modest investigation was to achieve a good form of hall, which resulted in the form of horse-shoe shaped hall satisfying the recommended values of reverberation time, clarity and lateral fraction, with the reverberation time values of 1.15 seconds at 250 Hz and 0.92 seconds at 500 Hz satisfying the target (0.9 ~ 2.3 s), clarity value of 2 dB and 1.8 dB satisfying the ideal clarity value ([-1 to 3] dB) and lateral fraction values of 24 %, 20 %, 12 % and 10 % at mid-frequencies (250 Hz to 1000 Hz) satisfying the target value (10-35 %).

Key words: reverberation time, clarity, lateral fraction, acoustic computer simulation program.

1. Introduction

The Oxford Dictionary defines acoustics as “relating to sound or the sense of hearing”. In the sphere of physics science relates to room, the term acoustics is used to explain the properties or qualities of a room or building that determine how sound is transmitted in it (Iswati, 2016). The widespread stimulant for room acoustic modeling is to enable the construction of acoustically better environments, especially in concert halls. In recent decades, the importance of acoustic quality in concert halls is known to audience. In concert halls, an inevitable matter to be considered is the acoustic quality, which can make architecture suitable for the performance and appreciation of music. In another point of view, the most important characteristic of any concert hall must be the sound that it delivers to the listener. Obviously, a well-designed concert hall can provide an undoubtedly unforgettable experience for the audience.

Concert halls can be designed and built in practically any form and size. In General, (plan) forms of concert halls are, Shoebox/rectangular, Fan-shape, Terraced hall, Arena, Horse-shoe, and Vineyard. The Philharmonie in Munich, the Finlandia hall in Helsinki and Lieberhalle; in Stuttgart, are good examples for fan shaped hall. Renowned concert halls as well as Musikvereinssaal in Vienna, Konzerthaus in Berlin and the Symphony Hall in Boston, are Shoebox shape. An example of a hall with a horseshoe-shaped plan is the Salomea Kruszelnicka Academic Opera and Ballet Theatre in Lviv, also called the Lviv Opera House (Kamisiński, 2010).

In a concert hall, the acoustic quality of the room is usually judged from audience preference (Suyatno *et al.*, 2019). Moreover, acoustic modeling and simulation can be used to affirm that the acoustic design targets are obtained. Nowadays, acoustic simulations are utilized in numerous architectural design processes which result in great success.

In the first place, the most commonly used room acoustic simulation model is Geometrical acoustics (GA) that was used in this study. Until today, all deterministic simulation methods based on GA utilize the physical model of image sources (ISs), where each IS represents a specific sequence of specular reflections on the room's faces (Vorländer *et al.*, 2015).

Many studies have conducted an acoustic simulation analysis, calculating acoustic parameters through computer simulation programs in the early planning phase in order to achieve good acoustic results throughout recent decades that are shown in Table 1.

The form of a concert hall is determined by a variety of factors, including, but not limited to, acoustics. One of the greatest challenges and responsibilities of an acoustician is to educate the design team of the implications of room shape and size which fundamentally determine the range of possible acoustical outcomes, so that design decisions are well informed and consistent with the perceptual goals. Listeners want to be engaged actively by the music, but the acoustical implications of this goal are complex and highly subjective (Hochgraf, 2019).

Campbell *et al. (*2015*),* it is apparent that in order to have acoustic harmony, it is important to carefully consider all three of the room acoustic qualities and descriptors to achieve: a short reverberation time, low sound levels and high speech clarity. So to achieve room acoustic comfort in group rooms it is quite clear that we need to measure and consider all three of these parameters in order to understand the true picture of how a room will respond to sound and whether it will be fit for purpose in reality.

The goals of this paper is to find a good form of concert hall in order to help the designers and acousticians to speed the designing process. Therefore, six simple forms of halls were proposed by the authors, as well as Shoe-box, Trapezoid, Fan-shape, Horse-shoe, Oval and egg shape. Additionally, the best form was obtained by comparing three parameters namely, Reverberation time (RT), Clarity (C80) and Lateral fraction (LF).

Table 1. Studies about acoustic parameters and their results (source: authors).

Author	Year	Title	Result
Rindel *et al.*	2013	Simulations, Measurements and Auralisation in Architectural Acoustics	It is concluded that conducting room acoustic measurements correctly may be more difficult than it appears at first glance, and both measurements and simulations require high level acoustical qualifications by the operator.
Jedidi and Boulila	2016	Acoustic study of an auditorium by the determination of reverberation time and speech transmission index	The results showed that the measured and calculated values were consistent with those proposed by the standards for speech auditoria, and are in line with the speech intelligibility requirements.
Jeong *et al.*	2018	Acoustic Design of a Classical Concert Hall and Evaluation of its Acoustic Performance – A Case Study	The analysis results of the acoustic simulation modeling and site measuring based on the acoustic design were all satisfied the target acoustic performance.
Zainudin *et al.*	2018	Prediction of Classroom Reverberation time using Neural Network	The NN displayed a good and efficient performance.
Jurkiewicz *et al.*	2015	Stavanger Concert Hall, Acoustic Design and Measurement Results	The analysis of the measurement results confirms the acoustic success of this new concert hall in Stavanger and its very good place in the list of the most successful recent concert halls.
Campbell, Nilsson and Svensson	2015	The same reverberation time in two identical rooms does not necessarily mean the same levels of speech clarity and sound levels when we look at impact of different ceiling and wall absorbers	In the long term it would be good to have enough evidence from many rooms about how the acoustic parameters are actually perceived and appreciated, for and during speech communication activities and how we can find better ways to predict /model and measure more simply and accurately to secure good acoustic comfort in practice.
Suyatno *et al.*	2019	Evaluation of stage acoustic parameters of Grha Sepuluh Nopemeber room	The stage of Grha Sepuluh Nopember cannot be said to be good as music (space) room or concert hall, but it is more suitable to be used as speech room. Therefore, it should have some improvement in order to make it functioned as performance room or concert hall.
Yadav *et al.*	2018	Reverberation time improvement of lecture auditorium: A case study	It is found that acoustic performance of the lecture auditorium has significantly improved using curtains on the windows and furniture.
Jeon *et al.*	2012	Acoustical remodeling of a large fan-type auditorium to enhance sound strength and spatial responsiveness for symphonic music	The results show that sound strength (G) was improved by 5 dB and binaural quality index (BQI) by 0.24, whereas the occupied RT at mid-frequencies became variable from 1.47 to 2.24 s.
Akama *et al.*	2010	Distribution of selected monaural acoustical parameters in concert halls	Three large-scale measurement campaigns were conducted in which impulse responses were measured at 1427, 180, and 511 locations. Relatively large differences in the obtained parameters compared with well-known difference thresholds suggest that determining the distributions of parameter values is important. Contour maps are therefore used to display the distributions along with mean values.

2. Methodology

2.1. Acoustic simulation

In order to obtain acoustic parameters through simulations required first making a three-dimensional drawing of the room. The simplified acoustic model of the hall-shapes used for the simulations was created by utilizing the Rhinoceros modelling software. Suitable calculation parameters were then inserted (such as the length of impulse responses), the characteristics of the finishing surfaces (absorptions and scattering coefficients) and the specification of the sound source and receiver. Transmission coefficient assigned to all surfaces are zero. It can be noted that the value of 1 tells nothing of the distribution of this diffusely reflected sound. In contrast a scattering coefficient with a value of 0 corresponds to an ideally specular reflection (Savioja and Svensson, 2015).

Simulations were run with angular absorption (soft materials only) and reflection order. Hall shapes contain shoebox, Trapezoid, Fan shape, Horse shoe and Egg, and oval. Note that, sphere and square are excluded due to lack of plan style similarity. In these halls doors, furniture and stairs are excluded, and they are simply simulated due to decreasing calculation speed.

Concert halls are divided into the stage area and audience area. These halls have a capacity of 480 spectators. The audience were modeled in boxes with height of 0.8 m. If the number of indoor seats is 500 or below, over six sound receivers should be installed (Jeong *et al.*, 2018). Therefore, 9 receivers are located with the height of 0.4 m above the audience boxes.

In spaces like concert hall it`s more important to guide sound where it is most needed, rather than to eliminate energy from the space, as absorbers do (D'Orazio *et al.*, 2017).

The dimensions of the stage are approximately 12 * 25 m. The distance between the furthest row seat and the stage is 35 m. The ceiling from stage is 8 m. The vertical viewing angle of the audience is 27°. Noted that Acoustical condition varies significantly between different seats (Hochgraf, 2019).

The acoustic simulation of mentioned halls is completed using the software Odeon V.14.03 combined. In accordance with ISO 3382-1:2009, source position should be located 1.5 m above the floor. For the measurement of the ISO3382 room acoustic parameters the source must be as Omni-directional as possible (Rindel *et al.*, 2013). It is quite clear that an Omni-directional source has to be used in order to excite the measured space uniformly in all directions (Jambrosic *et al.*, 2008). Accordingly, an Omni-directional as a point sound source was positioned at a height of 1.5 m above the stage.

Materials used in ceiling, on the roof and walls are respectively: 50 mm thick wood-wool, 3-4 mm asbestos or ply wood sheets, 3 mm wood veneer with 50 mm studs.

The sound absorption coefficient of the interior finishing material is a very important element for determining the acoustic parameters of the room (Seo *et al.*, 2019). Scattering coefficient and Absorption coefficient of materials simulated in Odeon are shown in Table 2.

Table 2. Characteristics of the finishing surfaces for all halls (source: authors).

Material for:	Scattering coefficient	Absorption coefficient
Audience, medium upholstered seats	0.6	0.83
Walls	0.02	0.09
Floor	0.02	0.05
Stage	0.02	0.05
Ceiling	0.02	0.99

Apart from the Impulse response length and Number of early rays, which were inserted manually for Oval, Egg and Horse shoe halls, the default calculation parameters in Odeon were inserted for halls (in Table 3 which illustrates the inserted calculation parameters). Calculation for all 6 halls mentioned above, were conducted twice or more for deriving the ideal results.

Frequency band for acoustic simulation by Odeon analysis tool in the range from 63 Hz to 8000 Hz are presented in this study. The acoustic simulation process is shown in Fig. 1.

3. Establishment of target values

3.1. RT

Pradeepa and Ramachandraiah (2020) stated that RT is the time required for sound to decay 60 dB. American physicist Wallace Sabine introduced the first design tool that is able to accurately predict the acoustic performance of new buildings; Sabine's formula for the calculation of reverberation time gave architects the ability to predict acoustic performance prior to construction. Sabine's study of sound and the dissemination of his research sparked the development of the field of architectural acoustics (Peters and Peters, 2018).

The Sabin formula is as follows:
Equation 1: $T = 0.161V/A$
where: T is Reverberation Time in second and V is room volume (m^3)
Equation 2: $A = \Sigma\ \alpha$
where: α = is the total absorption of each boundary surface of the room (m^2), i.e. Σ (surface area x coefficient of absorption) (Iswati, 2018).

Table 3. Inserted calculation parameters for all halls (source: authors).

Halls	Impulse response length (ms) (default in Odeon)	Maximum reflection order	Transition order	Number of early rays	Number of early scatter rays	Key diffraction frequency (Hz)
Shoebox	1000	10000	2	2000	100	707
Trapezoid	1000	10000	2	2000	100	707
Fan shape	1000	10000	2	2000	100	707
Oval	3200	10000	2	23912	100	707
Egg	3200	10000	2	23912	100	707
Horse shoe	2000	10000	2	6620	100	707

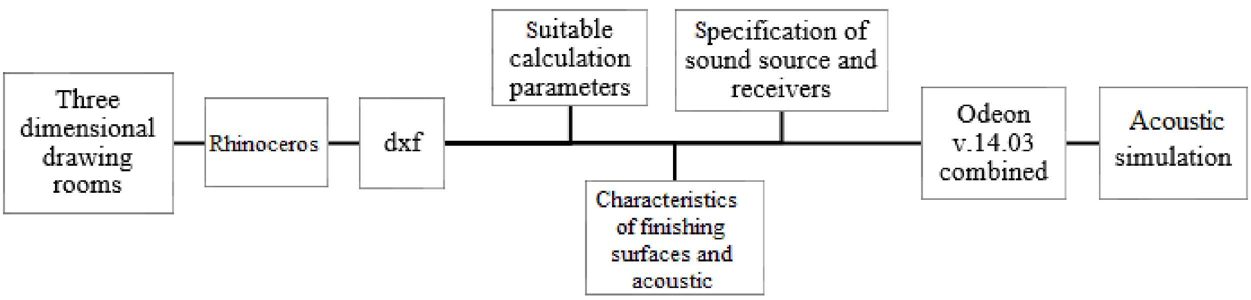

Fig. 1. Different components involved in acoustic simulation (source: Authors).

Talking about perceived reverberation, Early decay time (EDT should be high for instruments and low for speech. Terms high and low mean higher or lower than the corresponding T30 value. About clarity, instead, C80 should be high for speech intelligibility but for instruments, it depends also on the nature of the sound. Hence, a piano needs a low clarity, a violin needs a high clarity where high and low respectively mean above and below 0 dB (D'Orazio *et al.*, 2017).

According to Barron and Egan M.D., the recommended RT for music venues is between 1.4 and 1.7 seconds (Jeong *et al.*, 2018). According to theatre design standard, the recommended value of the reverberation time for designing the multi-functional hall, is 0.9 ~ 1.2 s (1000Hz) (Xu and Liu, 2014). According to Odeon manual, recommended RT for symphonic music hall is 1.7 ~ 2.3 seconds (Christensen *et al.*, 2016). Thus, the target RT of six halls was set to 0.9 ~ 2.3 seconds.

3.2. C80

The greater the increase in the C80 value is, the shorter the sound connection becomes. The greater the increase in the C80 value is, the shorter the sound connection becomes. While the clarity improves, the sound is not naturally connected. On the other hand, the greater the reduction in the C80 value, the longer the sound connection becomes. As the latter sound energy is delivered before the former sound energy is reduced, the two sounds overlap (Jeong *et al.*, 2018).

C80 is Logarithmic ratio between early (0-80 ms) and late (after 80 ms) energy (Hochgraf, 2019). According to Barron, the recommended C80 of a music venue is between -2 and +2 (Jeong *et al.*, 2018). According to Odeon manual, recommended C80 for symphonic music hall is -1 to +3 dB (Christensen *et al.*, 2016). Therefore, the target C80 of 6 halls was set to [-1, +3] dB.

3.3. LF

LF refers to the ratio of the sound energy reflected laterally to the sound energy reflected from all directions. In other words, LF shows the sense of spatiality surrounded by sounds (Jeong *et al.*, 2018).

The arrivals of the lateral reflections depend on the width of the hall, i.e., the narrower the hall the sooner they arrive. When the listener moves sideways from the center of the hall to a position near a side wall, the direct sound and the first reflection from that wall arrives at nearly the same time and the reflection from the opposite side wall comes at a later time. This creates a larger space between the direct sound and the latest reflection.

Lateral fraction typically measured as a mean of the 125 Hz, 250 Hz, 500 Hz and 1,000 Hz values. The early lateral fraction measured in rooms generally ranges from 0.05 to 0.50, meaning between 5 % and 50 % of the sound arrives from the side.

Average value was found to be 0.18, and target LF values range from a minimum of 0.10 to a maximum of 0.35. Generally, higher values are better, but in rare cases one can have too high a value and sound sources may be difficult to localize (Ermann, 2015).

The recommended LF for music venues is between 10 and 35% (Jeong *et al.*, 2018). According to Christensen *et al.* (2016), recommended LF80 for symphonic music hall is > 0.2. Thus, the target LF of all halls was set to 10- 35 %.

4. Acoustic simulation results

4.1. RT

According to help in Odeon version 14.03, the software calculates the room's RT using the Sabine formula to give an estimate of the reverberation time. The software calls this evaluation a quick estimate. Modified values are calculated using a mean absorption coefficient, which is derived with respect to the probability of the individual surfaces being hit by particles, not the area of the individual surface. The modified values should be considered more reliable, as it does to some extent take into account the shape of the room. The values using the modified mean absorption coefficient are labelled Modified Sabine. Therefore, these values were used in this work as the values calculated with the formula of Sabine. T Sabine and modified T Sabine values of named hall shapes are shown in Table 4, and Table 5.

According to the ideal values mentioned above, Horse shoe, Oval and egg shaped halls have suitable ranges for modified T Sabine.

The average RT values of Horse shoe hall, Oval shaped and Egg shaped hall at 500 Hz and 1000 Hz was estimated at: 1.02 and 0.99, 1.20 and 1.17, 1.45 and 1.40 seconds respectively, satisfying the target (0.9 ~ 2.3 s). Horse shoe and Oval shaped halls are ideal for music venues.

4.2. C80

The acoustic simulation results of the proposed hall-shapes for concert hall in term of C80 distributions for 8 octave bands from 63 Hz to 8000 Hz are given in Table 6.

According to Table 6, none of the proposed hall shapes for concert hall satisfy the target C80 ([-1, +3] dB) except the Horse shoe hall at 63 and 125 Hz, with the values 2 and 1.8 dB.

4.3. LF

The acoustic simulation results of the proposed hall-shapes for concert hall in term of LF distributions for 8 octave bands from 63 Hz to 8000 Hz are shown in Table 7.

Table 4. Reverberation time cf. T Sabine formula, of halls with 9 receivers by Odeon combine (source: authors).

T (sec.) for:	Frequency (Hz)							
Hall shapes	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Shoebox	0.94	0.93	0.73	0.66	0.67	0.65	0.61	0.48
Trapezoid	0.95	0.95	0.74	0.67	0.68	0.65	0.62	0.48
Fan-shape	0.94	0.94	0.73	0.66	0.66	0.64	0.61	0.47
Egg	1.46	1.46	1.42	1.45	1.40	1.34	1.16	0.76
Oval	1.28	1.28	1.21	1.20	1.17	1.12	1.00	0.68
Horse shoe	1.63	1.62	1.19	1.02	0.99	0.95	0.88	0.62

Table 5. Reverberation time cf. modified T Sabine formula, of halls with 9 receivers by Odeon combined (source: authors).

T (sec.) for:	Frequency (Hz)							
Hall shapes	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Shoebox	1.05	1.05	0.72	0.61	0.62	0.60	0.57	0.45
Trapezoid	1.04	1.04	0.72	0.60	0.61	0.59	0.56	0.44
Fan-shape	1.02	1.02	0.71	0.61	0.61	0.59	0.56	0.45
Horse shoe	1.83	1.82	1.15	0.92	0.89	0.85	0.79	0.58
Oval	1.81	1.80	1.06	0.81	0.74	0.72	0.68	0.52
Egg	2.18	2.17	1.26	0.96	0.87	0.85	0.79	0.58

Considering the ideal LF for music venues (10 ~ 35 %), Shoebox, Trapezoid, Fan-shape and Horse-shoe halls are good for music venues.

According to recommended values of RT, LF and C80, the best choice for concert hall design among all recommended hall shapes is Horse shoe hall.

Table 6. The Clarity of the named hall shapes for concert hall (source: authors).

C80 (dB) for: Hall shapes	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
Shoebox	5.0	5.1	7.1	7.1	5.3	5.9	6.5	9.8
Trapezoid	5.5	5.4	8.1	8.7	7.2	7.8	8.5	12.0
Fan-shape	5.0	4.9	7.5	8.3	7.0	7.6	8.2	11.6
Oval	5.2	4.9	10.1	16.9	17.8	17.0	17.3	19.7
Egg	4.0	3.7	9.2	17.4	19.3	18.4	19.0	21.7
Horse shoe	2.0	1.8	5.7	10.0	10.9	11.3	11.3	14.1

Table 7. The Lateral fraction of the named hall shapes for concert hall (source: authors).

LF for: Hall shapes	Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
Shoe-box	0.239	0.236	0.223	0.232	0.255	0.247	0.245	0.226
Trapezoid	0.228	0.228	0.219	0.222	0.242	0.235	0.234	0.217
Fan- shape	0.220	0.220	0.212	0.123	0.230	0.223	0.223	0.206
Oval	0.283	0.283	0.215	0.097	0.029	0.034	0.048	0.040
Egg	0.281	0.282	0.209	0.080	0.019	0.023	0.027	0.022
Horse shoe	0.248	0.248	0.203	0.127	0.109	0.106	0.111	0.098

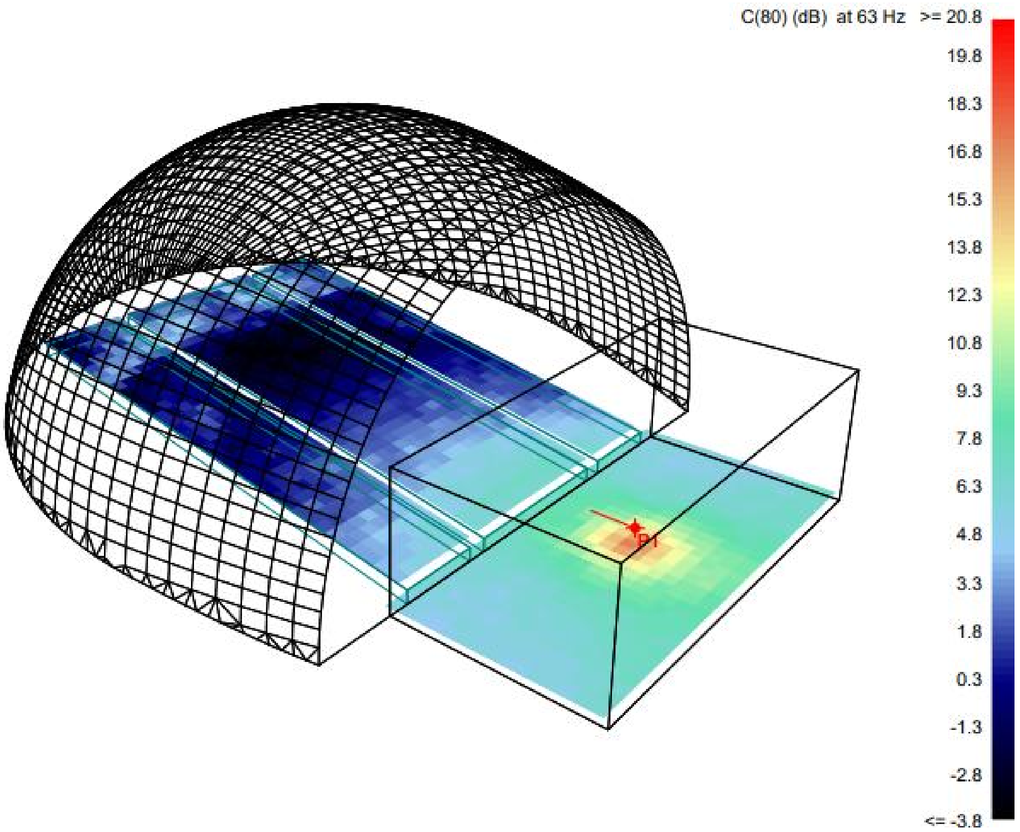

Fig. 2. Mapping distribution of C80 at 63 Hz in Horse shoe shape hall (source: ODEON V.14.03 combined).

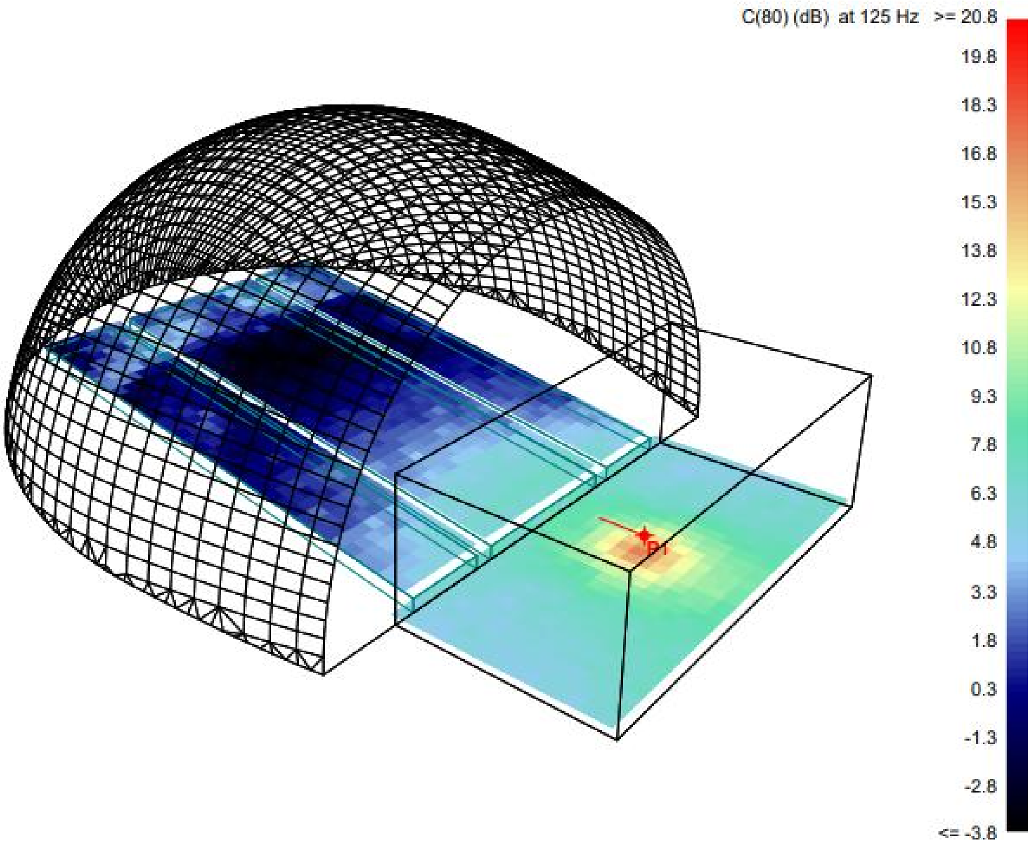

Fig. 3. Mapping distribution of C80 at 125 Hz in Horse shoe shape hall (source: ODEON V.14.03 combined).

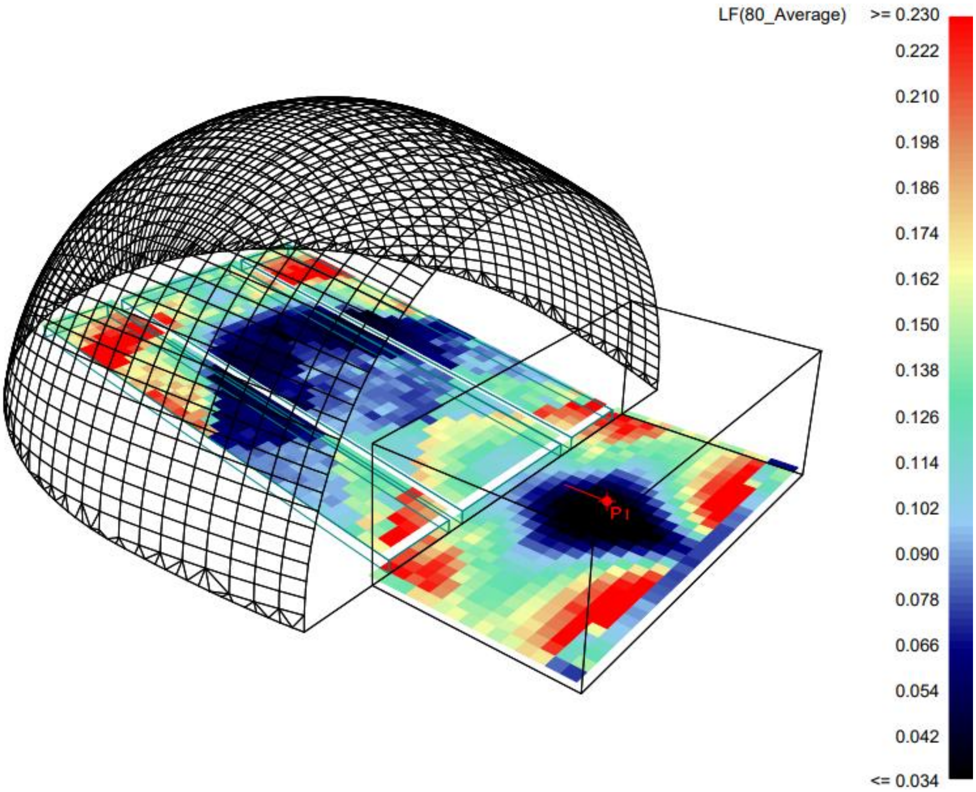

Fig. 4. Mapping distribution of LF (80_Average) in Horse shoe shape hall (source: ODEON V.14.03 combined).

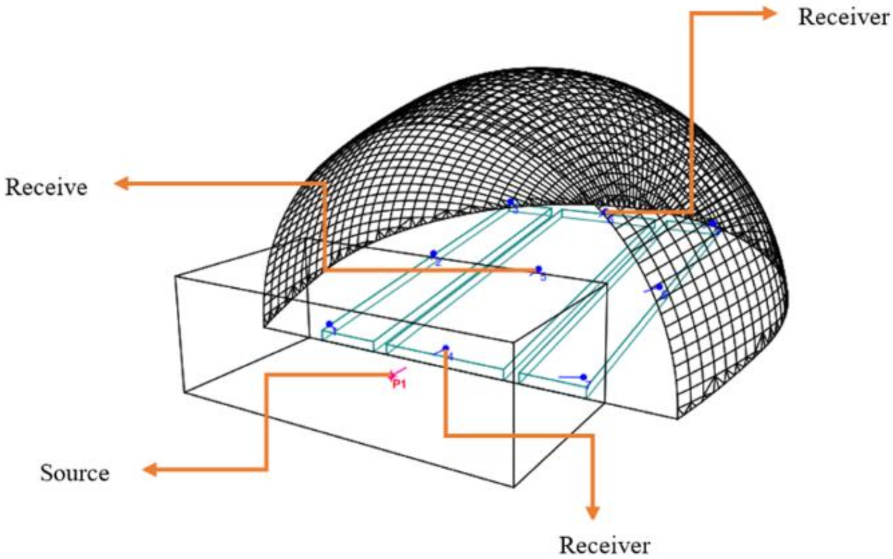

Fig. 5. Source and receivers (source: ODEON V.14.03 combined).

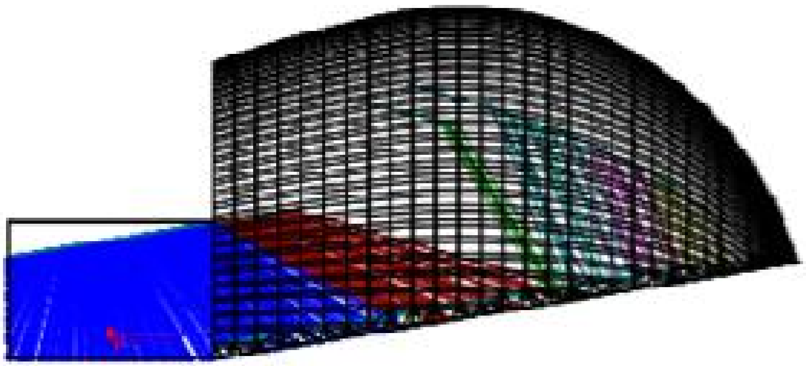

Fig. 6. Reflection rays from proposed canopy and reflectors on ceiling (source: ODEON V.14.03 combined).

Maps of calculated acoustic parameters as well as C80 and LF are shown for selected receiver surfaces including stage and the audience. The grid responses that illustrate the calculated parameters for a grid of receivers for the Horse shoe shape hall are as shown in Fig. 2, Fig. 3 and Fig. 4; only the frequencies 63 Hz and 125 Hz in Fig. 2 and 3 are presented for illustration purposes.

4.4. Investigation of proposed hall

The simulated grid maps for horse-shoe hall reveal that the lateral fraction in this hall is not provided for approximately 2 third of the side rows near the stage. Therefore, some reflectors need to be apply for the rows near the stage. In order to show reflecting in this hall 3 receivers (4, 5 and 6) were selected, Fig. 5.

The ceiling shapes should be able to better reflect the sound to the front row seating position in order to increase the overall sense of reverberation (Xu and Liu, 2014). Therefore, the ceiling shape which can reflect the sound to the front row seating position was proposed by authors that is shown in Fig. 6.

The ceiling height has to be height enough so that lateral reflection from the side walls reach the listeners before the ceiling reflection. High ceilings and large upper volumes in the halls enable also the late reverberation to develop and bloom. In addition, high ceilings increase the time between the direct sound and late reverberation which enables early lateral reflections from the side walls and under the balconies to reach the audience well before the enveloping reverberation surrounds the listeners (Lokkie and Patynen, 2019).

For room presence, listeners prefer to be fully enveloped by room sound. All of the room around the listener should be "acoustically active" and this includes the parts of the room above us and behind us (Kahle *et al.*, 2015). When the structure of a stage is close to the sound source, it has an important effect on the early reflections. Barron proposed minimizing the stage for strong early reflections (Seo *et al.*, 2019). The proposed hall shape has a flat canopy.

Therefore, the reflections on the ceiling shape proposed to reflect sound to further receivers in back rows, as well as receiver 5 and receiver 6 in Fig. 7 and Fig. 8.

Reflecting path from sound source to all receivers as well as receivers 4, 5 and 6 in this proposed hall shows that it is possible to reflect sound to audience in the furthest points by applying reflectors above the audience area on ceiling.

5. Conclusions

As the concert halls are venues which enables people to experience enjoyable times, the design of the hall shape is the most important factor. The paper presents the result of acoustic simulations and comparison of the acoustic parameters of Shoe-box, Trapezoid, Fan-shape, Horse shoe, Oval and Egg forms by the authors.

The analysis results are as follows:
By comparing the acoustic parameters at 63 Hz, it was found that the highest reverberation time was 1.63 seconds at 63 Hz for Horse-shoe hall. Whereas, the lowest reverberation time at 63 Hz was 0.94 seconds for Shoebox shape hall. The highest reverberation time cf. modified T Sabine formula was 2.18 seconds for Egg shaped hall at 63 Hz. Whereas, the lowest reverberation time cf. modified T Sabine formula was 1.02 seconds for Fan shaped hall at 63 Hz. The highest clarity was 5.5 dB for trapezoidal hall. Whereas, the lowest clarity was 2 dB for Horse-shoe hall. The highest LF was 0.281 for Egg shaped hall at 63 Hz. Whereas, the lowest LF was 0.22 for Egg shape and Horse-shoe halls (Fig. 9, Fig. 10, Fig. 11 and Fig. 12). In conclusion, Egg shaped hall has the highest reverberation time and the highest value of LF. Furthermore, trapezoidal hall has the highest C80. By contrast, Shoebox and Fan shaped halls have the lowest RT, Horse-shoe has the lowest C80, Oval and Fan shaped hall have the lowest LF at 63 Hz.

In accordance with acoustic simulation results, considering the Reverberation time values of six hall shapes at mid-frequencies, Shoebox, Trapezoid and Fan-shape was fewer than 0.9 seconds which means these three shapes are not suitable for music venues or even multi-functional hall. Whereas, the RT values of Horse shoe hall reached 1.15 s at 250 Hz, 0.92 s at 500 Hz, Oval shaped reached 1.06 s at 250 Hz and Egg-shaped hall reached 1.26 s at 250 Hz and 0.96 s at 500 Hz. Therefore, Horse shoe, Oval, Egg shapes are suitable for concert hall as they satisfied the target RT value (0.9 ~ 2.3 s).

According to simulation results, considering the C80 values of six hall-shapes, none of the mentioned hall-shapes reached the ideal value of C80 but the Horse shoe shape with the value of 2.0 dB at 63 Hz and 1.8 dB at 125 Hz satisfying the recommended C80 value ([-1, +3] dB).

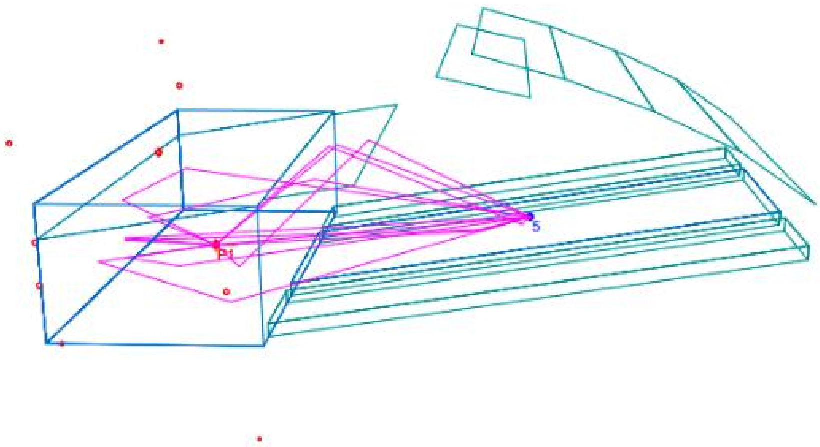

Fig. 7. Reflecting path from source to receiver 5 after applying canopy (source: ODEON V.14.03 combined).

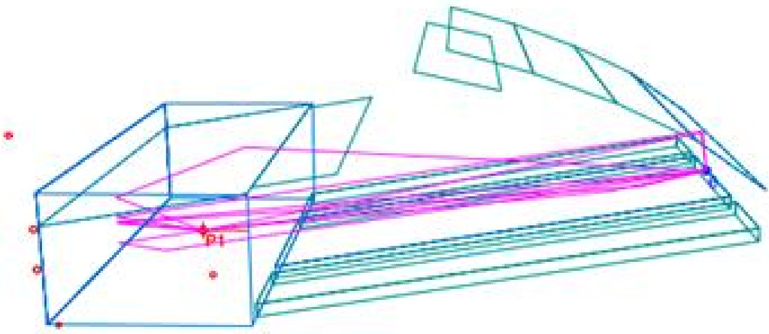

Fig. 8. Reflecting path from source to receiver 6 after applying canopy (source: ODEON V.14.03 combined).

Based on the LF values derived from acoustic simulation, Shoe-box, Trapezoid, Fan-shape obtained the satisfying target (10 ~ 35 %) for 8 frequency band. However, egg and oval shape-halls obtained the target value at 63- 1000 Hz, and Horse shoe reached the ideal LF value at 63- 4000 Hz.

As a result, based on comparison of acoustic simulation results of six proposed concert hall forms; considering the target values of RT, LF and C80 for six proposed hall-shapes, the conclusion is that the Horse shoe form tends to be a good choice for designing a concert hall.

Using the simulation results comparison of before and after the selected form named as Horse shoe, the authors proposed improving acoustic conditions of the hall as well as applying reflectors on ceiling and canopy on the stage.

Comparing the simple Horse shoe hall-shape and the one after, some recommendation would be fruitful to achieve better results as well as, use of more absorptive material on the back wall, vertical posts or statues on the side walls.

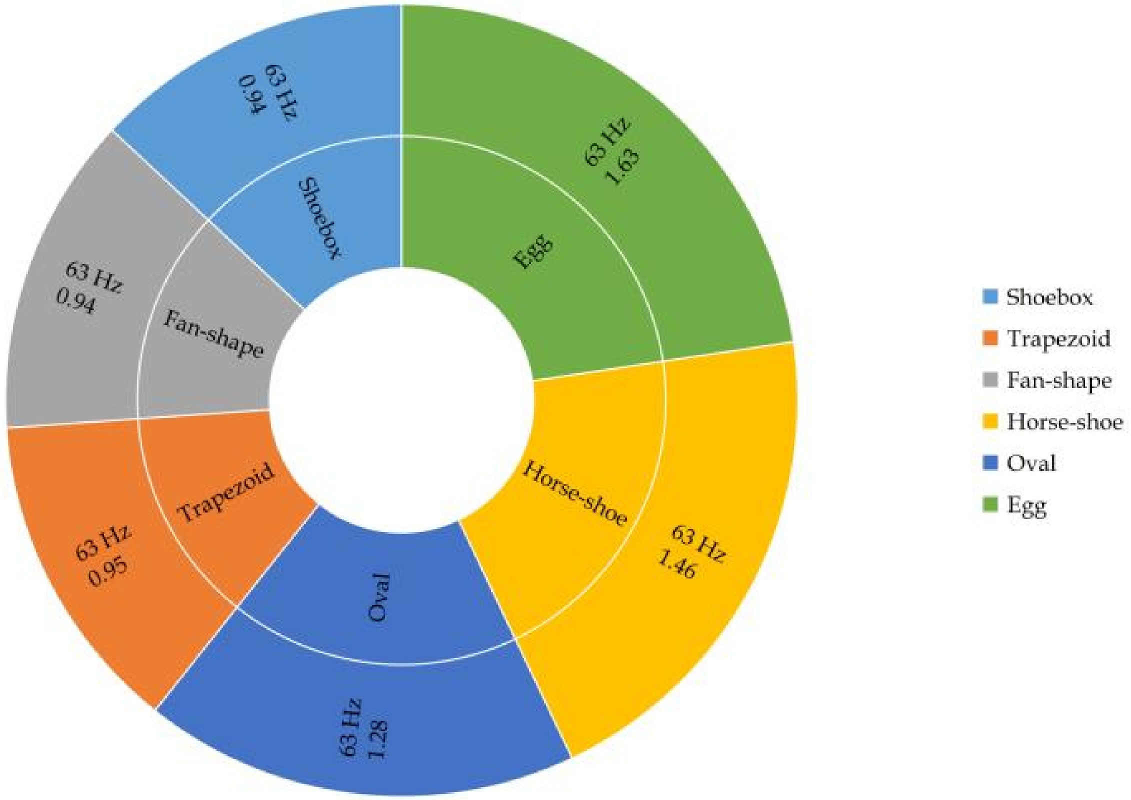

Fig. 9. The chart of Reverberation time cf. T Sabine formula, of halls (source: authors).

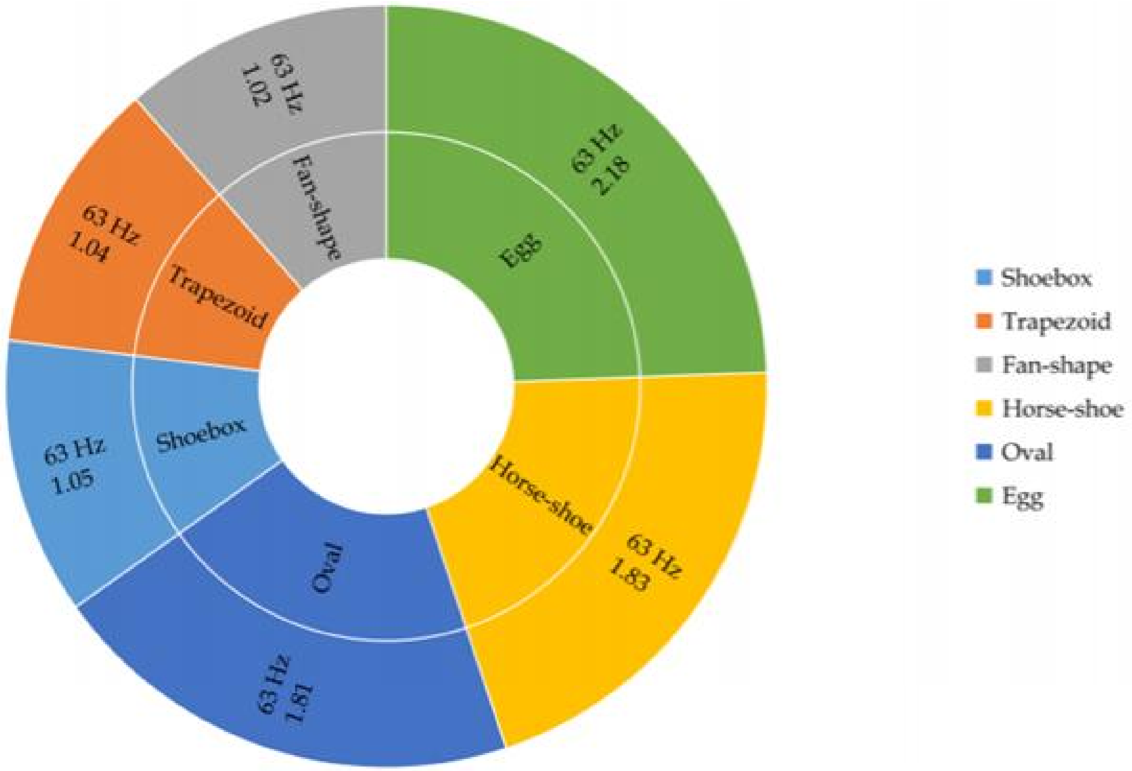

Fig. 10. The chart of Reverberation time cf. modified T Sabine formula, of halls (source: authors).

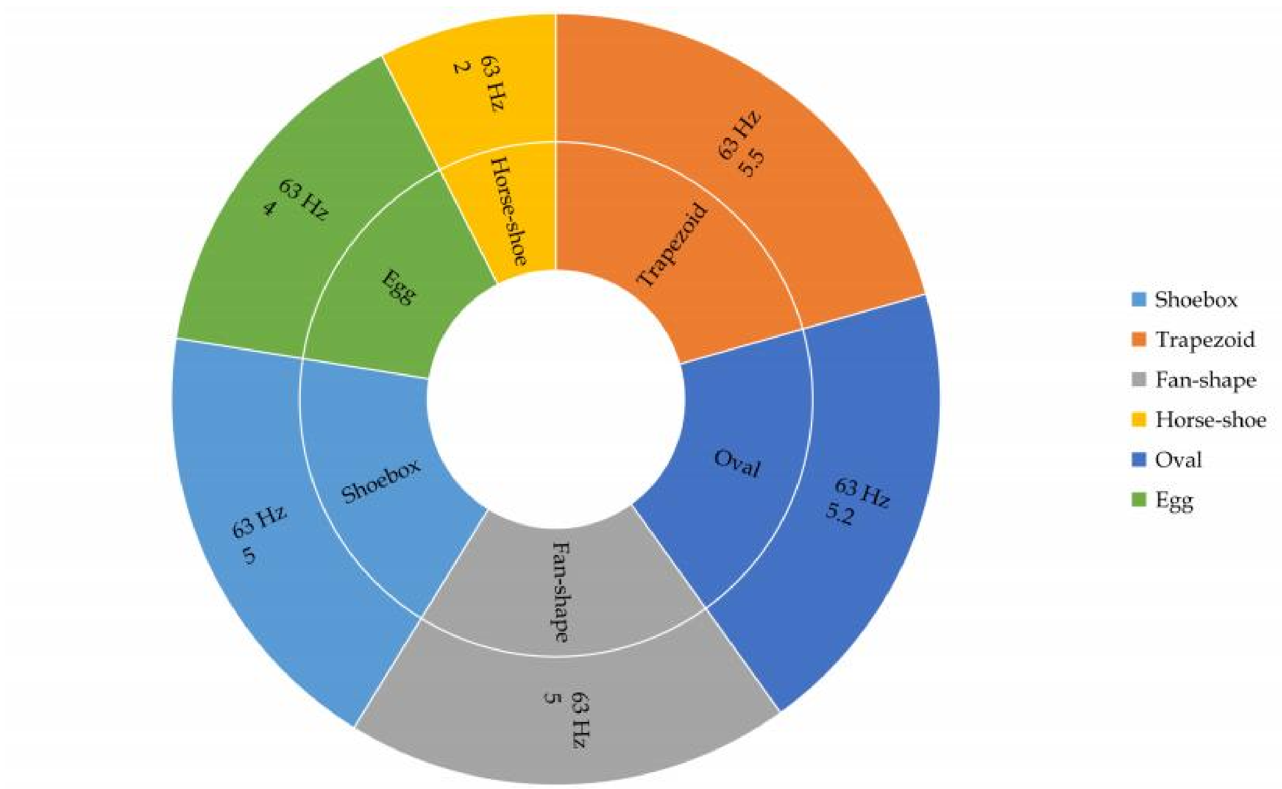

Fig. 11. The chart of the Clarity of the named hall shapes for concert hall (source: authors).

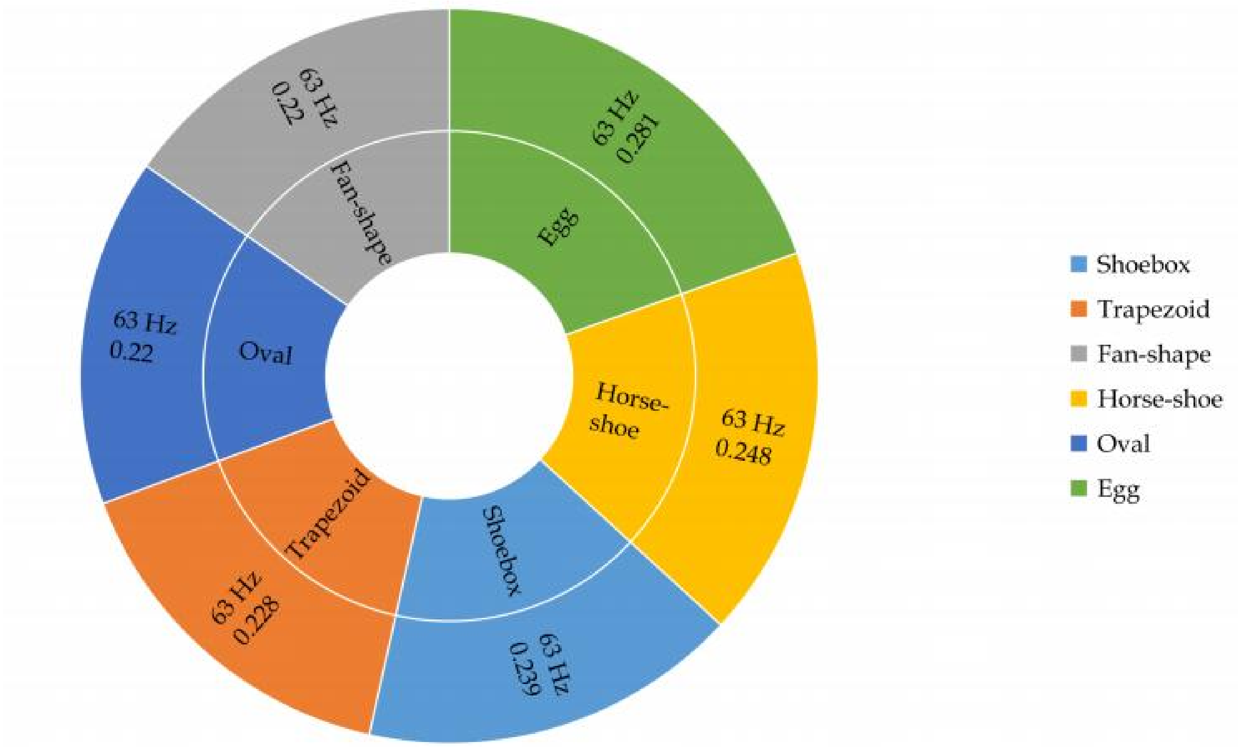

Fig. 12. The chart of Lateral fraction of the named hall shapes for concert hall (source: authors).

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