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APPLYING GENETIC ALGORITHMS TO THE OPTIMUM DESIGN OF A CONCERT HALL

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Genetic algorithms (GAs), a form of evolutionary computing, have been applied to the design of concert halls. The application of a GA to a system for optimizing a concert hall in terms of four orthogonal factors of a sound field is discussed. The first model was an optimization of the proportions of a hall of the typical shoebox type. The second model is the optimization of the plan of the hall. The results show that the optimized form of the first model is similar to Grosser Musikvereinsaal. The second model took on different characteristics according to the preference for which it was optimized. A leaf-shaped plan is a typical result of the maximization of the scale values of preference for the audience area.

1. INTRODUCTION

The theory of subjective preference allows a sound field to be evaluated in terms of the following four orthogonal acoustical factors [1]: the listening level (LL), the initial time-delay gap between the direct sound and the first reflection (Δt_1), the subsequent reverberation time (T_{sub}), and magnitude of the interaural cross-correlation function (IACC). Several experiments have been carried out to examine the independent effects of the four orthogonal factors on subjective preference [1]. Linear scale values of preference have been obtained by using the law of comparative judgment. Furthermore, the units derived from experiments with different sound sources and different subjects were almost constant, so the scale values may be added to obtain

$$S \approx S_1 + S_2 + S_3 + S_4, \tag{1}$$

where S_i ($i = 1, 2, 3, 4$) are the scale values for the respective orthogonal factors. Equation (1) indicates four-dimensional continuity. Procedures for designing the sound fields of a concert hall are illustrated in Figure 1. The above temporal and spatial factors are carefully designed, in order to satisfy both left and right human cerebral hemispheres for each listener, for the conductor, and for each musician on the stage. The final goal is to maximize the scale value of subjective preference, and this is reflected in the final scheme of the concert hall.

The genetic algorithms (GAs) [2], a form of evolutionary computing, have recently been applied to a variety of complex engineering problems. The algorithm is started with a set of solutions (represented by "chromosomes") that is called a population. Solutions from one population are taken and used to form a new population. Solutions are selected to form new solutions (referred to as offspring) according to their fitness—the more suitable a solution is, the greater its chance of reproducing. New populations are generated by

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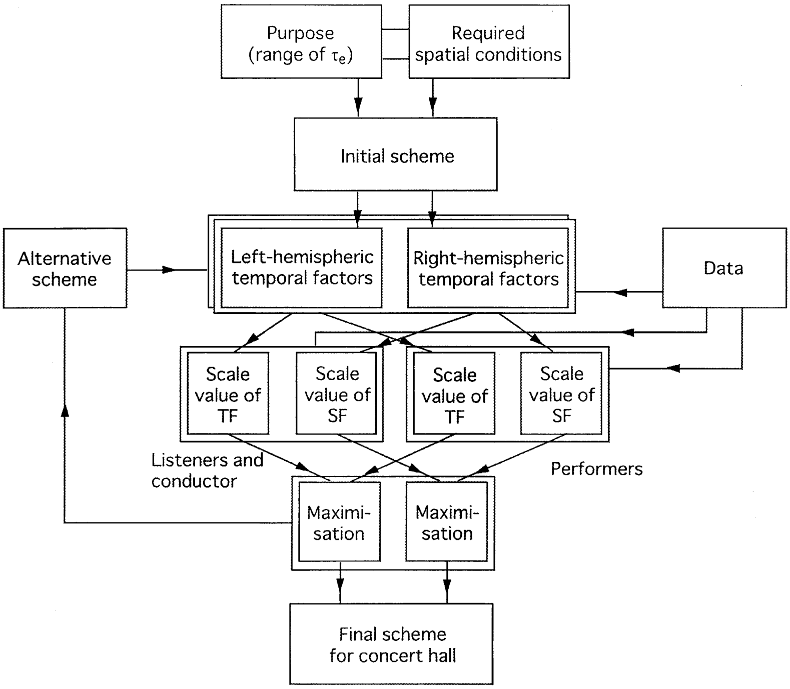

Figure 1. Procedures for designing sound fields in a concert hall. The final goal is to maximize the scale values of preference. In this study, a GA system was applied to create alternative schemes that produce better scale values.

crossover and mutation from selected chromosomes. This is repeated until some condition (for example, the number of populations generated or an improvement over a previous best solution) is satisfied.

In this study, a GA system was applied to the design of concert halls. The GA system was used to generate the alternative scheme on the left-hand side of Figure 1. Those architectural schemes which produce higher scale values of subjective preference are selected in the process of evolution. Initially, this technique was applied to optimize the proportions of a shoebox hall. The plan of the shoebox hall was then optimised.

2. PROCEDURE

2.1. OUTLINE

The initial scheme for the hall was a shoebox shape. The orthogonal factors were calculated for halls of various shapes by using the image method. The scale values of subjective preference were employed as fitness functions. Those hall shapes that produced higher scale values were selected as parent chromosomes. To create a new generation, the room shapes were modified and the corresponding movement of the vertices of the walls was encoded in chromosomes, i.e., binary strings. After GA operations that included crossover and mutation, new offspring were created. The fitness of the offspring was then evaluated in terms of the scale values of subjective preference. This process was repeated until the end condition (2000 generations) had been satisfied.

2.2. ACOUSTICAL SIMULATION

The orthogonal factors for a source on the stage were calculated at each of a set of seats. The single omnidirectional source was assumed to be at the centre of the stage, 1.5 m above the stage floor. The receiving points that correspond to the ear positions were 1.1 m above the floor of the hall. The image method was used to determine the amplitudes, delay times, and directions of arrival of reflections at these receiving points. In an earlier study, the Kirishima International Concert Hall was taken as an example in showing that, across the main floor of the hall, there was good agreement between the values of the four orthogonal factors as measured in the real hall and as calculated by simulation [3]. Therefore, the method to evaluate the sound field was the same method as was used in that study. Reflections were calculated up to the second order to reduce the calculation time. Note that second order reflection is enough to provide convergence of the physical factors for a listening position near the stage. In addition, there is no change in the relative relationship among the factors obtained from calculations performed up to the first, second, third, and fourth order of reflection. The averaged values of the interaural cross-correlation functions (IACC) for five music of motifs (Motifs A–E [4]) were also calculated.

2.3. FITNESS FUNCTION

The behaviour of the scale value in relation to each orthogonal factor gives the following expression for S_i.

$$S_i \approx -\alpha_i |x_i|^{3/2}. \tag{2}$$

Here, the parameters x_i and coefficients α_i are listed in Table 1. In this calculation, the scale values of subjective preference due to the LL and IACC, i.e., S_1 and S_4, were used as the measure of fitness because these spatial factors are directly affected by the geometrical shape of a hall. The most preferred listening level, $[LL]_p = 20\log[P]_p$ in Table 1 may be assumed for a particular seat position in the room under investigation. S_2 and S_3 were excluded because S_2 due to the Δt_1 is related to the size of the room, and S_3 due to the T_{sub} can be controlled by adjusting the absorption of the walls and the volume of the hall.

TABLE 1

Objective parameters and coefficients

i	x_i	α_i	
		$x_i \geqslant 0$	$x_i < 0$
1	$20\log P - 20\log[P]_p$ (dB)	$\approx 0{\cdot}07$	$\approx 0{\cdot}04$
2	$\log\dfrac{\Delta t_1}{[\Delta t_1]_p}$	$\approx 1{\cdot}42$	$\approx 1{\cdot}11$
3	$\log\dfrac{T_{\rm sub}}{[T_{\rm sub}]_p}$	$\approx 0{\cdot}45 + 0{\cdot}74\,A^{\dagger}$	$\approx 2{\cdot}36 - 0{\cdot}42\,A^{\dagger}$
4	Interaural cross-correlation (IACC)	$\approx 1{\cdot}45$	—

$^{\dagger}A$ is the total pressure amplitude of reflections relative to that of the direct sound.

2.4. GA SYSTEM

In this study, modifications of the shape of the room were encoded in a chromosome which consists of a single binary string. An example of the encoding of the chromosome is given in Figure 2. The first bit indicates the direction of motion for the vertex. The other $n-1$ bits indicate the range over which the vertex is moved. Here, simple room shapes were used to reduce the calculation time and the single binary string has 140 bits at most. However, it is possible to process the binary string of 300 or 400 bits [5] if more time is spent on the calculation.

A crossover step can then be made. In crossover, genes were selected from parent chromosomes and used to create a new offspring. Some crossover point within a chromosome was chosen at random and everything before this point was copied from the first parent while everything after this point was copied from the second parent. After the process of crossover, mutation was applied. This is to prevent all solutions in a population from falling into a locally optimal solution to the problem. Mutation is the application of a random change to the new offspring. A few randomly chosen bits of the chromosome were switched from 1 to 0 or from 0 to 1.

3. MODEL 1

Firstly, the proportions of the shoebox hall were optimized. The initial geometry is shown in Figure 3. In its initial form, the hall was 20-m wide, the stage was 12-m deep, the room was 30-m long, and the ceiling was 15 m above the floor. As shown in Figure 4, the sound source was placed at the centre of the stage and 4.0 m from the front of the stage and 72 listening positions were prepared. The range motion for each sidewall and the ceiling was ± 5 m from the respective initial positions, and the distance through which each was moved was coded on the chromosome of the GA. Scale values at the listening positions other than those within 1 m of the sidewalls were included in the averages ($\overline{S_1}$ and $\overline{S_4}$). These values were employed as the measure of fitness. In this calculation, the most preferred listening level, $[LL]_p$ in Table 1, was set for the frontal seat near the stage.

The results of optimization of the hall for $\overline{S_1}$ and $\overline{S_4}$ are shown in Figure 5. The width and length were almost the same in the two results, but the respective heights indicated opposite characteristics. The height of the ceiling that maximizes $\overline{S_1}$ was as low as possible within the allowed range of motion (Figure 5a). The height that maximises $\overline{S_4}$, on the other hand, was at the upper limit of the allowed range of motion (Figure 5b).

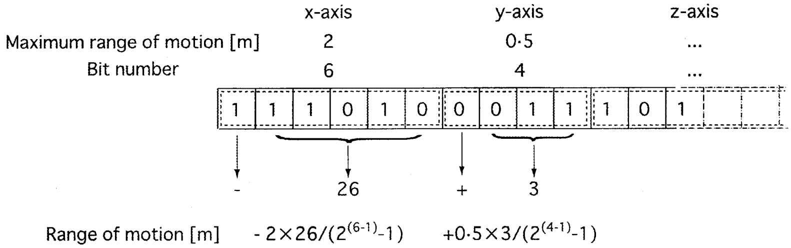

Figure 2. An example of the binary strings used in encoding of the chromosome to represent modifications to the room's shape.

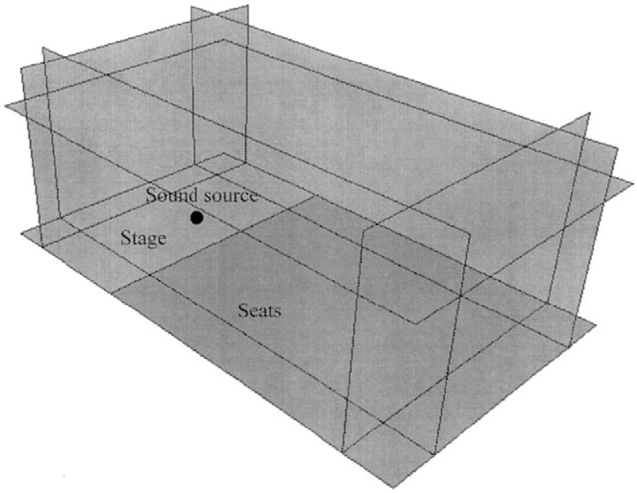

Figure 3. The initial dimension of the room used as a basis for Model 1. The range of motion of each sidewall and the ceiling is ± 5 m from the respective positions in the initial form.

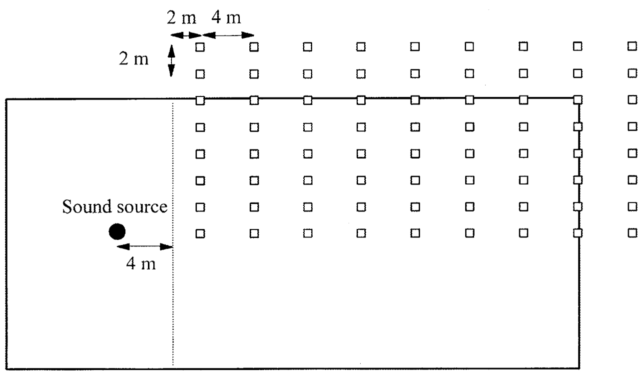

Figure 4. Source position and listening positions for the calculations to optimize Model 1. Listening positions were distributed throughout the seating area on a 2×4 m grid. Scale values at the listening positions other than those within 1 m from the sidewalls were included in the averages ($\overline{S_1}$ and $\overline{S_4}$).

4. MODEL 2

Next, the floor plan was optimized, with the results for Model 1 as the starting point. The hall in its initial form was 14-m wide, the stage was 9-m deep, the room was 27-m long, and the ceiling was 15 m above the stage floor. This initial form is shown in Figure 6. The sound source was again 4.0 m from the front of the stage, but was 0.5 m to one side of the centre line and 1.5 m above the stage floor. The front and rear walls were vertically bisected to obtain two faces, and each stretch wall along the side of the seating area was divided into four faces. Excluding the effects of the ceiling shape and the tilted angle of the sidewalls on the sound field, the ceilings were kept level with the ground and the walls were kept vertical (i.e., tilting was not allowed) to examine only the plan of the hall in terms of maximizing $\overline{S_1}$ and $\overline{S_4}$. Each wall was moved

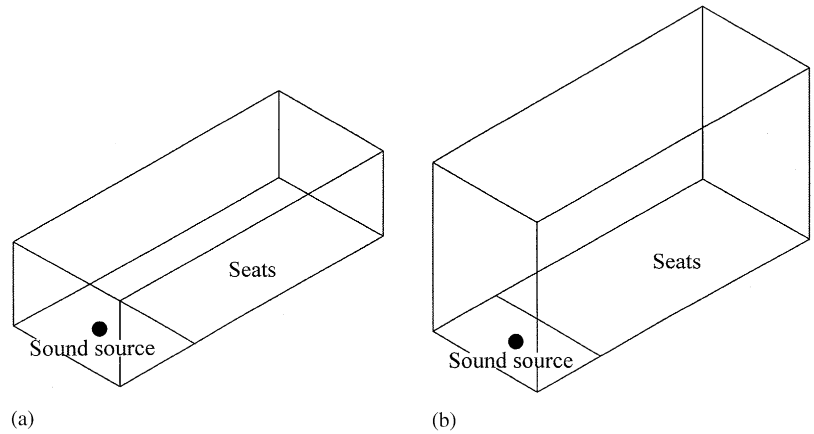

Figure 5. Results for Model 1: (a) geometry optimized for $\overline{S_1}$; (b) geometry optimized for $\overline{S_4}$.

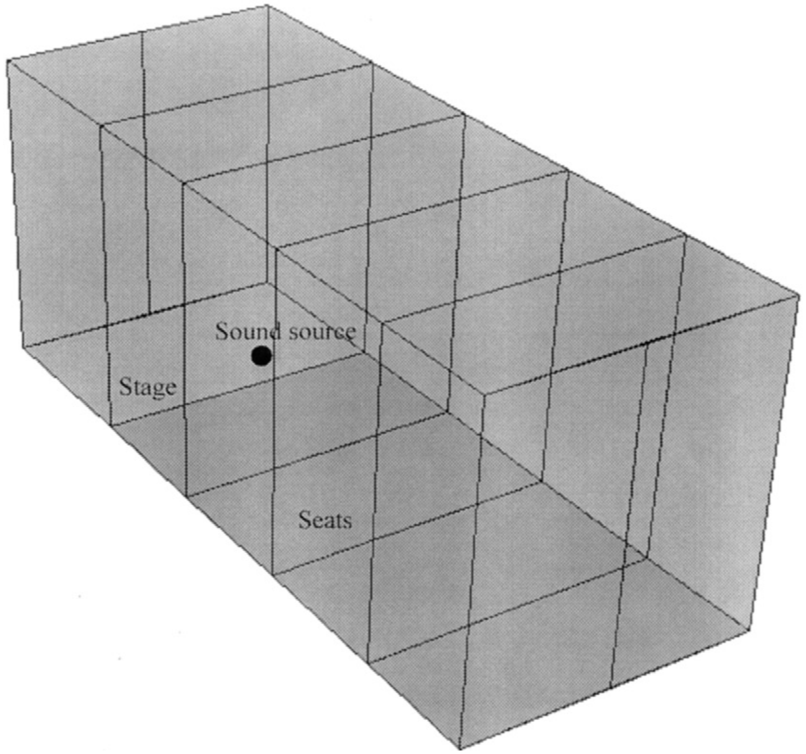

Figure 6. Initial dimension of the room for Model 2. The rear wall of the stage and the rear wall of the audience area were divided into two. Sidewalls were divided into four.

independent of the other walls. In the acoustical simulation using the image method, the openings between walls were assumed not to reflect the sound. Forty-nine listening positions were distributed throughout the seating area on a 2×4 m grid. In the GA operation, the sidewalls were moved so that any of these 49 listening positions were not excluded. The moving range of each vertex was ± 2 m in the direction of the line normal to the surface (Figure 7). The co-ordinates of the two bottom vertices of each surface were encoded on the chromosomes for the GA. In this calculation, the most preferred listening level was set for a point on the long axis (central line) of the hall, 10 m from the source position.

The result of optimizing the hall for $\overline{S_1}$ is shown in Figure 8 and contour lines of equal $\overline{S_1}$ values are shown in Figure 9. To maximise $\overline{S_1}$, the rear wall of the stage and the rear wall of the audience area took on concave shapes. The result of optimizing for $\overline{S_4}$ is shown in Figure 10 and contour lines of equal $\overline{S_4}$ values are shown in Figure 11. To maximize $\overline{S_4}$, on the other hand, the rear walls of the stage and the audience area took on convex shapes.

5. DISCUSSION

The optimization for Model 1, produced optimized proportions for the shoebox form. Table 2 shows the comparison of the proportions we obtained and those of the Grosser Musikvereinsaal, which is an example of an excellent concert hall. The length/width ratios are almost the same. The height/width ratio of Grosser Musikvereinsaal is intermediate between our results for the two factors. For the ceiling of the hall, the height that maximized $\overline{S_1}$ was the lowest within the allowed range of motion (Figure 5a), so that more energy should be provided from the ceiling to the listening position because the optimum position in terms of the listening level was assumed to be at the frontal seat near the stage. To maximize $\overline{S_4}$, on the other hand, the ceiling took on the maximum height in the possible range of motion (Figure 5b). Reflection from the ceiling was not required in this case because the IACC is decreased by the reflections from the lateral walls.

The optimization for Model 2 was used to examine the plan of the hall. The front and rear walls took on opposite characteristics to maximize $\overline{S_1}$ and $\overline{S_4}$. To maximize $\overline{S_1}$, the rear walls of the stage and the audience area took on concave shapes so that the sound was reflected to the seats directly. To maximize $\overline{S_4}$, on the other hand, the rear wall of the stage and the rear wall of the audience area took on convex shapes, since this avoids reflections from the median plane. With regard to the sidewalls, both $\overline{S_1}$ and $\overline{S_4}$ are maximized by a plan that is leaf shaped.

As for the conflicting requirements for S_1 and S_4, the maximisation of S_4 may take priority over that of S_1. For all subjects tested, the preference increases with decreasing

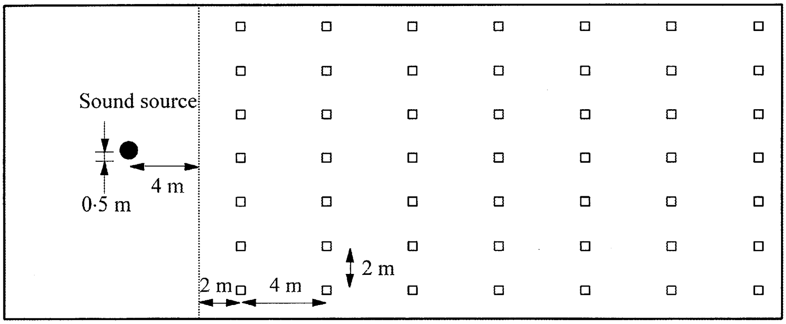

Figure 7. Source position and listening position used for calculation in Model 2. Forty-nine listening positions were distributed throughout the seating area on a 2×4 m grid. Motion of the sidewalls was not allowed to exclude any of these 49 listening positions.

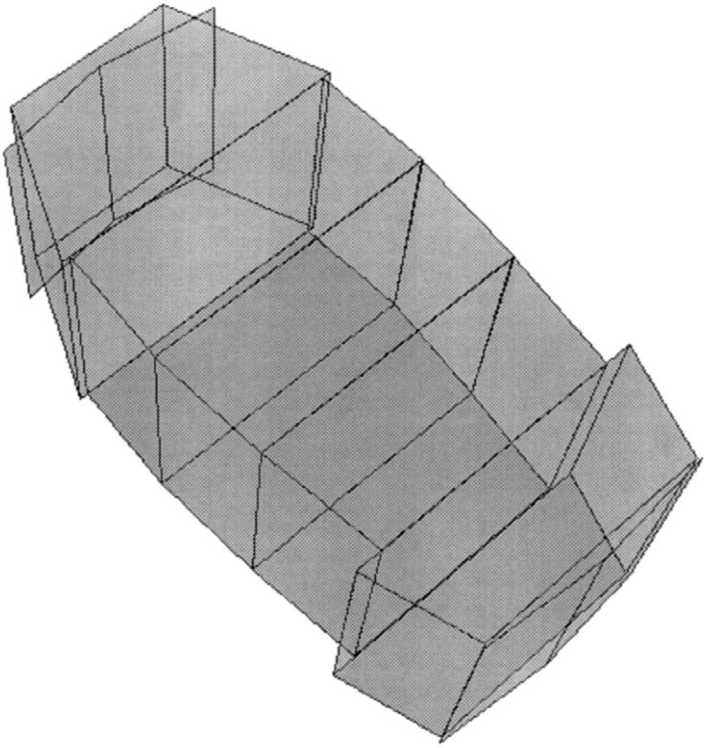

Figure 8. Geometry of the hall as optimized for $\overline{S_1}$.

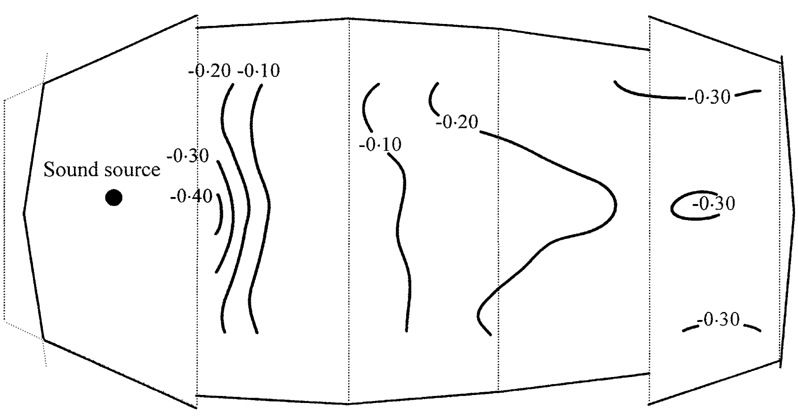

Figure 9. Contour lines of equal $\overline{S_1}$ values calculated for the geometry shown in Figure 8.

IACC [6, 7] while there is a large individual difference in the preferred LL [8]. Listeners can choose the seat with respect to the preferred LL.

6. CONCLUDING REMARKS

Examples of the application of a GA system to the acoustical design of a concert hall have been presented. The genetic algorithms (GAs) are made applicable to acoustical

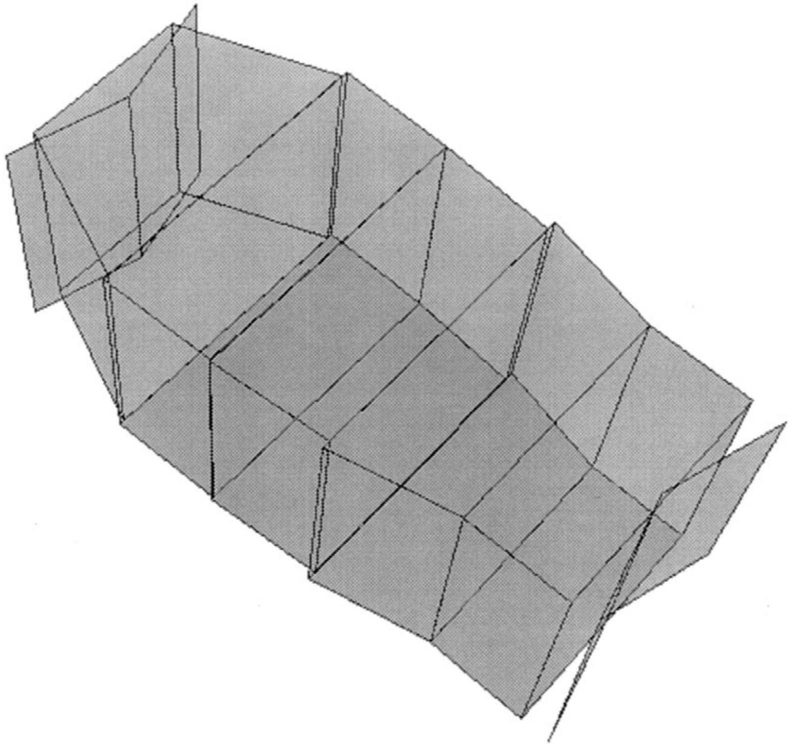

Figure 10. Geometry of the hall as optimized for $\overline{S_4}$.

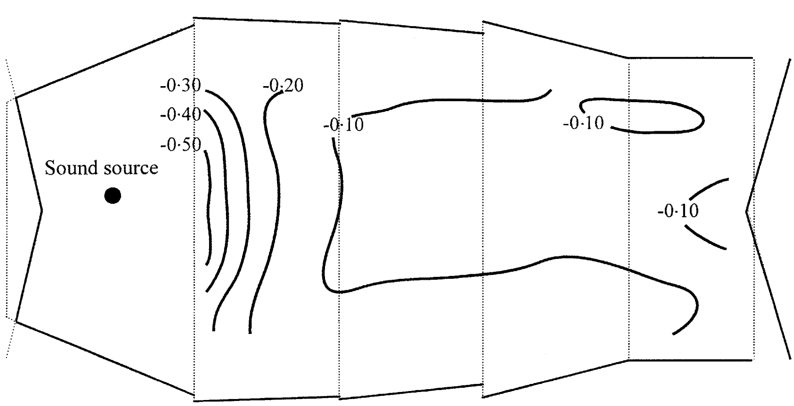

Figure 11. Contour lines of equal $\overline{S_4}$ values calculated for the geometry shown in Figure 10.

TABLE 2

Comparison of proportions for the optimized forms and the Grosser Musikvereinsaal

	Length/width	Height/width
Optimized for $\overline{S_1}$	2·50	0·71
Optimized for $\overline{S_4}$	2·57	1·43
Grosser Musikvereinsaal	2·55	0·93

design by using the theory of subjective preference. The results of optimization showed the importance of having sidewalls so that lateral reflections are provided. A leaf-shaped plan is a typical result of the maximization of the scale values of preference for the *LL* and the IACC for the audience area. A GA system may be applicable to identify various forms (including complex forms) having higher scale values than the conventional shoebox shape [5].

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