Proceedings of the International Association for Shell and Spatial Structures (IASS)
Symposium 2015, Amsterdam
Future Visions
17 - 20 August 2015, Amsterdam, The Netherlands

Acoustic optimization of funicular shells

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Abstract

Funicular shell structures are usually associated to synclastic shapes, which are concave towards the inside. The use of these shapes as sound reflective ceilings in auditoria is generally avoided as they can cause undesirable sound concentrations. These are the source of acoustical defects, such as echoes and colouration, and tend to have a negative subjective impression by the audience. Existing concert spaces built with synclastic shapes thus typically had to be altered by invasive sound reflective surfaces and treatments that significantly influence their spatial quality.

Previous research on the use of Multi-Objective Genetic Algorithms (MOGAs) for the shape optimization of concert spaces shows the acoustic potential of freeform, continuous surfaces with both convex and concave areas, and the difficulty of achieving high standards with synclastic shapes (Mendez Echenagucia et al. [13], Mendez Echenagucia [14]). Thrust Network Analysis (TNA) is capable of generating compression-only shapes that go beyond synclastic surfaces, thus presenting an opportunity for the use of funicular structures for concert auditoria (Block [6]).

This paper presents the use of Multi-Objective Genetic Algorithms (MOGAs) for the acoustical optimization of compression-only shell structures. The MOGA combines ray-tracing simulation for the study of the acoustical quality of the spaces with TNA for the generation of freeform funicular shapes. The method is exemplified in the case study of a multi-purpose room in Barranquilla, Colombia.

The MOGA employed in this paper uses the independent force densities in the TNA framework as design parameters to control the shape of the ceiling. In other words, the geometry is not controlled with a parametric model that moves control points to modify the shape, but by modifying the force distribution and boundary conditions of a TNA model. In doing so, the MOGA generates shapes that are all compression only.

Keywords: early-stage design, room acoustics, form finding, funicular shells, multi-objective optimization, genetic algorithms.

1. Introduction

1.1. Funicular shells for concert auditoria

The acoustical quality of spaces intended for the enjoyment of music is greatly dependent on their size and shape. The distribution and arrival time of reflected sound energy is strongly determined by the shape and position of sound reflecting surfaces in relation to sound sources and the audience. Concave surfaces concentrate sound over small room areas while convex surfaces diffuse sound over larger areas. Funicular shell structures are usually characterized by synclastic shapes which are concave towards the inside, creating the risk of sound concentrations in small audience areas, echoes and sound colouration. Examples of buildings in which this problem occurred, are the Royal Albert Hall in London and the Tonhalle in Dusseldorf. These rooms originally had spherical dome ceilings, which caused concentrations that could not be fixed without major alterations that obscured the domes from the sound source (Vercammen [21]). In both cases, unsuccessful attempts were made to correct the problem by adding sound-absorbing and diffusing surfaces to the domes, but the problem was only solved by hanging sound reflectors under the domes, which significantly affect the space (figure 1).

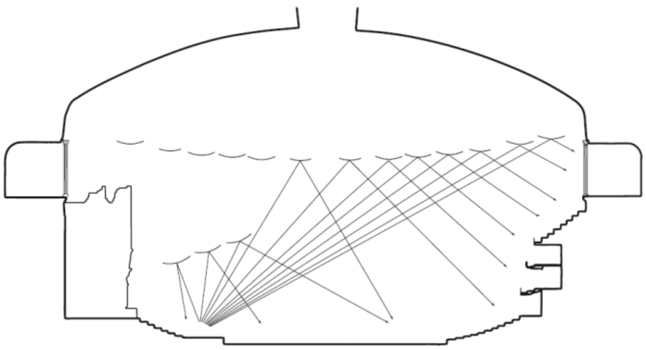

Figure 1: Longitudinal section through the Royal Albert Hall showing suspended reflectors (Barron[3])

For this reason, most concert spaces have false ceilings, which are not self-supporting. In order for them to be sound reflecting in all sound frequencies, and to avoid vibrations, these surfaces tend to be quite heavy and costly. They are usually hanging from a substructure that needs to take these high loads. The present paper proposes the use of Thrust Network Analysis (TNA) in combination with multi-objective optimization for the purposes of generating funicular shapes that can combine an efficient (and stiff) shell structure with sound-reflecting surfaces that distribute sound energy appropriately.

1.2. "Fábrica de Cultura" Barranquilla

The method presented in this paper is being used for the design of a multi-purpose auditorium in the project "Fábrica de Cultura". This building is an arts school to be built in the heart of Barranquilla, Colombia, it is designed in a collaboration between the Urban Think Tank chair of architecture and Urban design, the chair of Architecture and Building Systems and the Block Research Group, all at

ETH Zurich. The Block Research Group is contributing to this joint research project with the development of the vaulted structure for the auditorium. The structure consists of a ribbed, thin-tile vault spanning a space of 20 by 40 meters. The room is planned for 500 spectators, and is to be used by students and performers predominantly for amplified music and theatre, with the additional possibility to be used for unamplified performances of small ensembles.

2. Methodology

2.1. Room acoustic parameters

In the late 1890's, W.C. Sabine developed the concept of the Reverberation Time, which became the basis for the study of room acoustics to come. Since Sabine, the subjective impressions experienced by listeners (like reverberation, intimacy, clarity or sound strength) have been related to objective measures or room acoustic parameters. Each parameter has been developed to represent one aspect of the overall sound quality in a given point in the room, for a specific sound frequency. Reverberation times, as well as most other acoustical parameters, are calculated from the measured impulse response in that given point in the room. The impulse response is defined by the ISO 3382-1 standard as "the temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point in the room" (ISO [11]). Room acoustic parameters are the subject of the ISO 3382-1 standard. A historical description of the parameters is presented in Lacatis et al. [12]. A comprehensive study of each parameter, their Just Noticeable Differences (JNDs) and proposed optimal values or ranges is given in Abdou and Guy [1].

The quality of the acoustics in each point of the room is achieved by obtaining optimal values for a set of room acoustic parameters, describing a range of subjective impressions, such as reverberation, clarity, strength, and listener envelopment. Acousticians usually select specific parameters and their optimal values, according to the purpose of the room. For example, rooms intended for symphonic orchestras require high reverberation times and rooms intended for speech require high clarity and definition.

2.1.1 Distribution of Acoustical Quality

ISO 3382-1 parameters are measured in different positions inside the concert spaces, each measurement is representing the acoustical quality of that position. The distribution acoustical quality inside concert spaces is not uniform (Akama et al. [2]). Source to receiver distances, as well as local conditions such as vicinity of sidewalls, balcony overhangs and balcony fronts make for substantial differences between listening positions. To get an idea of the overall quality of the entire space, measurements have to be made in many different positions in the room, and with those measurements a calculation of the distribution of acoustical quality can be made. Such a calculation of the distribution of sound quality is presented with the following equation:

$$QD_i = \frac{1}{N} \cdot \sum_{j=1}^{N} \Delta JND_{i,j} \cdot W(P_i) \tag{1}$$

Where $QD_{,i}$ is the distribution of the ith acoustic parameter, N is the number of listening positions, $W(P_i)$ is a weighting function (in this case a Gaussian curve), and $\Delta JND_{i,j}$ is the difference between the optimal value of parameter P_i and the measured value of that parameter at listening position j. The difference is normalized using the Just Noticeable Difference for that parameter JND_i as shown in the following equation*:*

$$\Delta JND_{i,j} = \frac{P_{i,j} - P_{i,opt}}{JND_i} \qquad (2)$$

2.1.2. Acoustic simulation

The impulse response in existing concert spaces is measured by recordings of an impulse emitted on stage by an omnidirectional sound source. It is now common practice to simulate the impulse response and, the deriving room acoustic parameters, using computational models. The most widely used models are the ray tracing and the image source models.

The acoustic simulations in this paper were done with the use of Pachyderm Acoustical Simulation, a Plugin for Rhinoceros (Van der Harten[18]). Pachyderm Acoustical Simulation is a collection of acoustical simulation algorithms for use in Rhinoceros, ranging in purpose from prediction to auralization. Among its features are a growing number of simulation algorithms that can be performed using mesh or NURBS models. Pachyderm combines the image source method with the ray-tracing technique.

2.2. Thrust Network Analysis

Thrust Network Analysis (TNA) is a form-finding method capable of generating funicular discrete networks under vertical loading conditions. It gives the designer a high degree of control over the shape by allowing different force flow assumptions in the network (Block [6]).

If **Γ** and **Γ*** are two planar graphs with the same number of elements, and if **Γ*** is the convex, parallel dual of **Γ**, then **Γ** and **Γ*** are the form and force diagram of a three-dimensional thrust (= compression-only) network **G** (figure 2)**.** This network is in equilibrium under vertical loads applied to its nodes, and has **Γ** as its horizontal projection and Gamma* as its horizontal equilibrium (Van Mele et al. [19]).

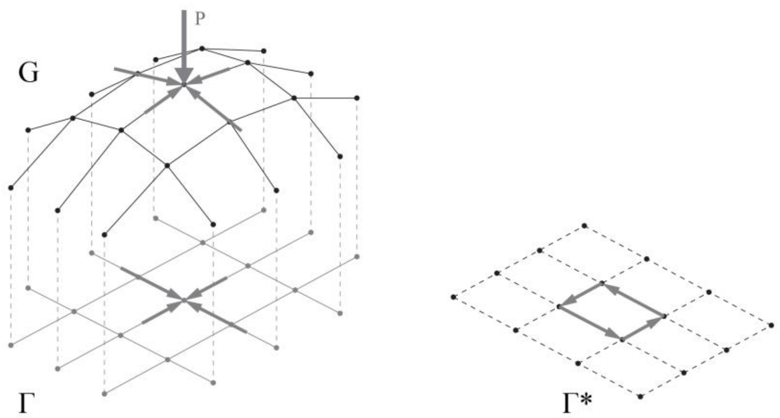

Figure 2: TNA dual graph

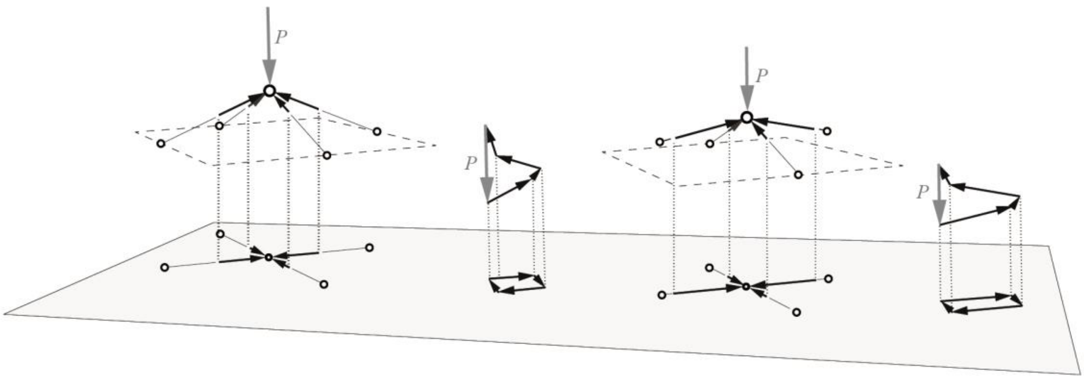

Figure 3: Indeterminacy of a four-bar node (Block [7])

The static indeterminacy of nodes in thrust network with a valency higher than three allows for the existence of more than one force diagram **Γ*** that satisfies the convexity and parallelity requirements for the network **G** to be in equilibrium in compression only. A longer force branch in **Γ*** results in a shallower thrust network (figure 3). This feature is exploited in TNA to generate different funicular shapes with the same form diagram, allowing the designer to explore multiple solutions.

2.3. Multi-Objective Genetic Algorithms

Multi-objective search or optimization differs from single objective in that in order to compare two solutions and determine which one is best (solutions A and B for example) multiple objective functions are considered, and not just one. If objective functions are contrasting, it may not be the case that solution A outperforms B in all functions. Instead, it may be the case that A outperforms B in one function, while B outperforms A in another. This relationship is studied with the concept of dominance. The concept of dominance can be summed up with the following statements:

- In order for solution A to dominate solution B, solution A has to outperform or equal B in all functions, as well as outperform B in at least one function.
- If solution A outperforms or equals solution B in all objective functions except one in which solution B outperforms A, then A and B do not dominate each other.

A non-dominated solution is one that is not dominated by any other in the solution pool. A non-dominated solution typically dominates many of the others in the pool, and it is never dominated by others. A non-dominated solution may not dominate all other solutions, but none that dominate it (Deb [9]). The Pareto Front, also called trade-off set or non-dominated set, is the set of all non- dominated solutions in a given group. They represent the set of solutions that cannot be said to be better from each other if all objective functions in the problem are considered.

Genetic Algorithms (GAs) are a family of search algorithms based on natural selection the evolution of the species (Goldberg[10]). First proposed by John Holland in the mid 1970's in the University of Michigan, they have been successfully employed in many varied fields of study, including the architecture and construction field. Modifications on the original GA also allow their use for multi-objective problems; these are called Multi-Objective Genetic Algorithms (MOGAs). This paper employs a specific MOGA, called NSGA-II (Deb [9]).

2.4. TNA as a parametric model for MOGAs

GAs have mostly been used in architecture and structural design to modify the geometry of a building component while optimizing a performance value such as structural efficiency or cost. Changes in geometry are made using a parametric model able to modify the coordinates of control points, and in turn, modify the geometry of building. The coordinates of those control points then become the variables for the GA, they are coded and used as chromosomes in the genetic operators (figure 4). The values that these coordinates are allowed to take, are always coded into the GA, thus constraining the parametric model to the range of possibilities desired (the search space). The GA will then proceed to search for the optimal solutions contained in this search space according to the fitness functions selected. However, the constraints given to the GA do not need to be geometrical in nature, they can also be performance related if such constraints are known.

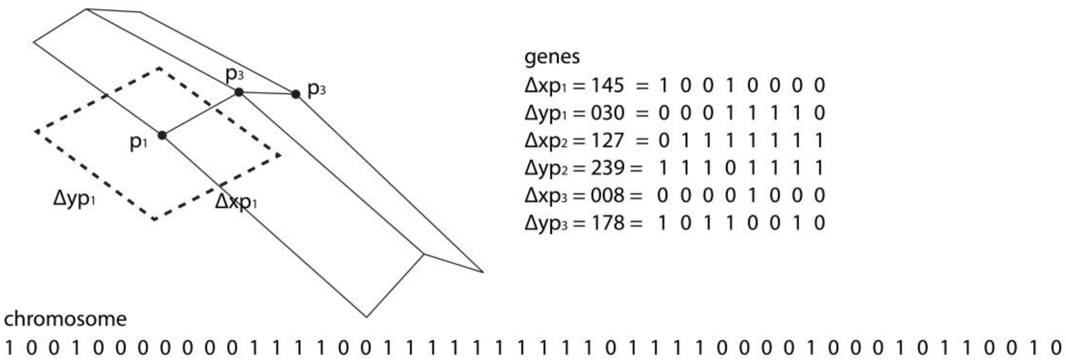

Figure 4: Parametric model coding for GA

The use of TNA as the parametric model in a GA search process for shell structures, presents the opportunity to constrain all solutions generated to be compression-only shells. In the same way that geometrical parametric models constrain solutions to be inside a user defined search space, a TNA model constrains solutions to be funicular shapes, making up the search space entirely of compression-only shells. This not only means that the search space is strictly made up of the kind of structural shapes that we are interested in, but also that we can do without a structural fitness function in our genetic search process. Both of these advantages greatly improve the efficiency of the GA and simplify the analysis of the results.

2.4.1. Forces as GA variables

The direct relationship between branches in the force diagram **Γ*** and the shape of the thrust network **G** presents the opportunity of using the lengths of the independent force branches as the variables in the genetic search process (Block and Lachauer [8]). Note that because the form diagram **Γ** is kept fixed during the search, controlling these force branches is thus the same as controlling the force densities q = f/l.

2.4.2. Encoding Isomorphism

The coding of the GA variables and their corresponding solution is very important for the GA to function properly. Each chromosome should correspond to a unique solution that has a different fitness value than all other solutions in the design space. Likewise, each solution in the design space should be represented by only one chromosome. When different chromosomes represent the same solution, they are said to be **isomorphic**. This problem is referred to as representational redundancy or encoding isomorphism (Ronald[17]). Encoding Isomorphism can represent a severe problem in the GA process. If the gene pool, at any generation, is made up of mostly isomorphic solutions, then the GA will not be able to select from a diverse set of solutions, meaning that the fitness values of the population will remain stagnant. Stagnation is addressed in GAs with operators that include random changes in the chromosomes, such as the mutation operator. However, when isomorphism is present in the coding, no changes in the chromosome can guarantee an improvement, since solutions with different chromosomes can have the same fitness value.

Encoding isomorphism is easy to avoid when more traditional parametric models are used, when each part of the chromosome represents a coordinate for a control point. The solution is defined in an unambiguous way by the combination of control point coordinates, and the variable is coded accordingly. However, when the genetic variables do not directly represent the solution and its phenotype, then it is easy to have encoding isomorphism problems. An example of encoding isomorphism can be found in (Mendez Echenagucia [14]).

In the specific case presented in this paper, encoding isomorphism could have been present if the changes in the branches of the force diagram would not respect equilibrium, and further adjustments would be required to achieve it. In other words, if the form diagram **Γ** is considered to be fixed, and the GA generates a force diagram **Γ*** that is not the convex and parallel dual of **Γ**, then the force diagram would have to be further modified to get it in equilibrium. After this modification, the resulting thrust network would not only be the result of the genetic variables, but also of the modification to find equilibrium. In such a scenario, it would be common for different chromosomes to result in the same force diagram and thrust network, and hence the same acoustic fitness value (encoding isomorphism).

To avoid this problem, the TNA model is set up such that every chromosome generated by the GA will result in horizontal equilibrium. Both the form and form diagram are rectangular, and nodes are all positioned according to a grid. In addition, all of the nodes in the boundaries are considered to be supported nodes. If the GA modifies the force diagram while still keeping the force edges inside the axis of a grid, then all proposed solutions will be in equilibrium, as the form and force edges will always be parallel (Van Mele and Block [20]). In such a setup, we can set up the GA to modify the length of entire rows or columns of force branches. The genetic variables will then be the width of each row and column of force edges, avoiding encoding isomorphism.

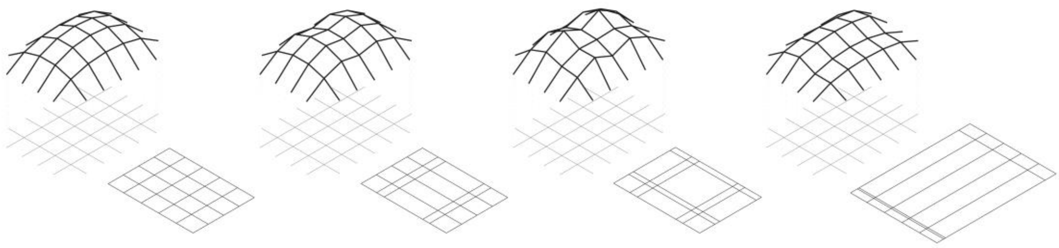

Figure 5: TNA as parametric model – four possible outcomes

2.4.3. RhinoVAULT API

RhinoVAULT (Rippmann et al. [15, 16] is an interactive tool for the creation of funicular shapes inside Rhinoceros® that was developed by the Block Research Group. RhinoVAULT is based on TNA and contains an API that allows the user to incorporate Rhino Vault functions into Rhino Python scripts. This functionality was exploited in the development of the TNA parametric model. The MOGA was set up in such a way as to generate funicular shapes directly from values out of the genetic search process.

3. Multipurpose room for "Fábrica de Cultura" Barranquilla

3.1. Room description and requirements

The multipurpose room for the "Fabrica de Cultura" project has a 18.5x25m rectangular in plan with the stage at one of its ends. The room's ceiling and main reflecting surface is a funicular shell covering the entire room area and supported at its edges. A large portion of the audience seating area is inclined towards the stage at a 17° angle.

The program for the school requires this room to be used for lectures, theatre, dance, Colombian music as well as the occasional classical performance from a small ensemble. From a room acoustics point of view, these requirements can be simplified into three room configurations: speech, amplified and unamplified music.

3.2. MOGA inputs and fitness functions

3.2.1. GA inputs

The MOGA was set up to run for 60 generations with a population size of 50 individuals. The MOGA was coded using binary strings. The crossover operator was the simple crossover with a random crossover point. A mutation operator was also employed, mutations were done on the binary strings depending on a mutation probability of 0.15. This means that 15% of all genes in the chromosome of each individual was subject to mutation.

3.2.2. Fitness Functions

Based on the characteristics of the room and its requirements, three room acoustic parameters have been selected to be studied by the MOGA: Early decay time (EDT), definition (D50) and sound strength (G). Three fitness functions are used in this study, one for each parameter, all using equation (1) for the Quality distribution QD. This results in three fitness values (QD_{EDT}, QD_{D50} and QD_G). QD values are normalized by the JND of each room acoustic parameter. For this reason they go from 0 to 1, 1 being the optimal value. The MOGA presented in this paper maximizes the QD values for each one of the selected parameters. Table 1 shows the optimal value and JND for each one of the room acoustic parameters used.

Table 1: Room acoustics parameters

Parameter	**Frequency**	**Subjective Impression**	**Optimal Value $P_{i,opt}$**	***JND***
EDT	500-1000Hz	Reverberation	2.0 (s)	10%
D_{50}	500-1000Hz	Definition	> 0.5	5%
G	500-1000Hz	Sound Strength	Barron's Curve (Barron [4])	1 (dB)

3.2.3. GA Variables

This paper presents the use of force branches in a TNA model as GA variables. In the case study of the multipurpose room in Barranquilla, the force branches are changed in entire rows as explained in section 2.4.2. In the GA this is accomplished by two sets of variables, one selects which row or column is modified, and the second selects the length of the branches in that row or column.

In addition, the multipurpose room has two arches at its ends, one behind the stage and one at its entrance. These arches are also variables in the GA search process. The height and inclination of the arch behind the stage, as well as the height of the arch at the entrance are also GA variables. Figure 6 shows the variables setup for the arches used in this case study as well as the rows and columns of the force branches.

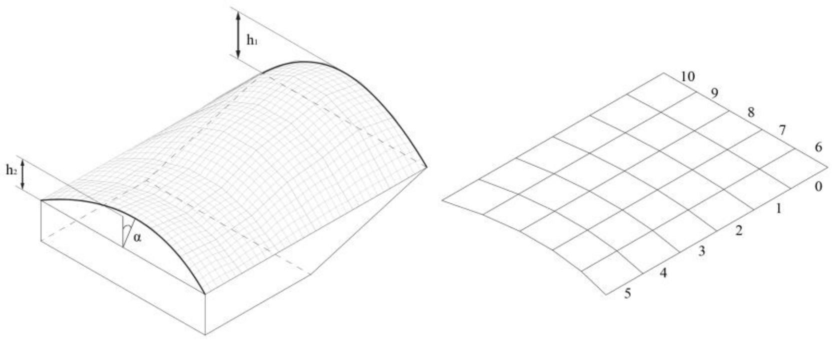

Figure 6: GA variables

Table 2 sums up the complete set of GA variables used in this paper.

Table 2: GA variables

Number	**Variable**
1	Arch 1 height
2	Arch 1 angle
3	Arch 2 height
4	Force branch set 1
5	Force branch set 2
6	Force branch set 3
7	Force branch set 4
8	Force branch 1 length
9	Force branch 2 length
10	Force branch 3 length
11	Force branch 4 length

3.3. Results

The MOGA presented in this paper contains three fitness functions, and therefore the result is a 3D Pareto front. Figure 7 shows 2D sections of the 3D Pareto front. Figure 7a shows the Pareto front formed by the QD_{EDT} and QD_{D50} fitness functions. This front shows the most contrast between the two functions, and this is to be expected as QD_{EDT} represents the impression of reverberation and QD_{D50} shows sound definition and speech intelligibility. The higher the reverberation the lower the definition of sound. This contrast is however manageable, the MOGA was able to find funicular shell shapes with QD values for both functions that are quite close to 1. Figure 7b and 7c show the fronts created by QD_{EDT} and QD_G, and QD_{D50} and QD_G respectively. These figures show very little contrast between the functions, and the MOGA was also able to find quite high QD values for all functions.

Out of these shapes, one of selected for further development, based on its QD values, spatial quality and other architectural considerations. Figure 8 shows the selected shape. It shows a funicular shape with convex and concave elements. The convex longitudinal section on top of the stage seems to be of particular importance for the uniform distribution of optimal acoustic parameter values.

4. Discussion

The present paper presents the use of Multi Objective Genetic Algorithms for the acoustic optimization of funicular shapes by means of Thrust network analysis as a parametric model. The MOGA maximized the acoustic quality distribution for parameters EDT, D_{50} and G with great results.

A good distribution of room acoustic parameter values, as found by the MOGA in the present paper, is achieved by avoiding sound concentrations that are typical when concave shapes are present.

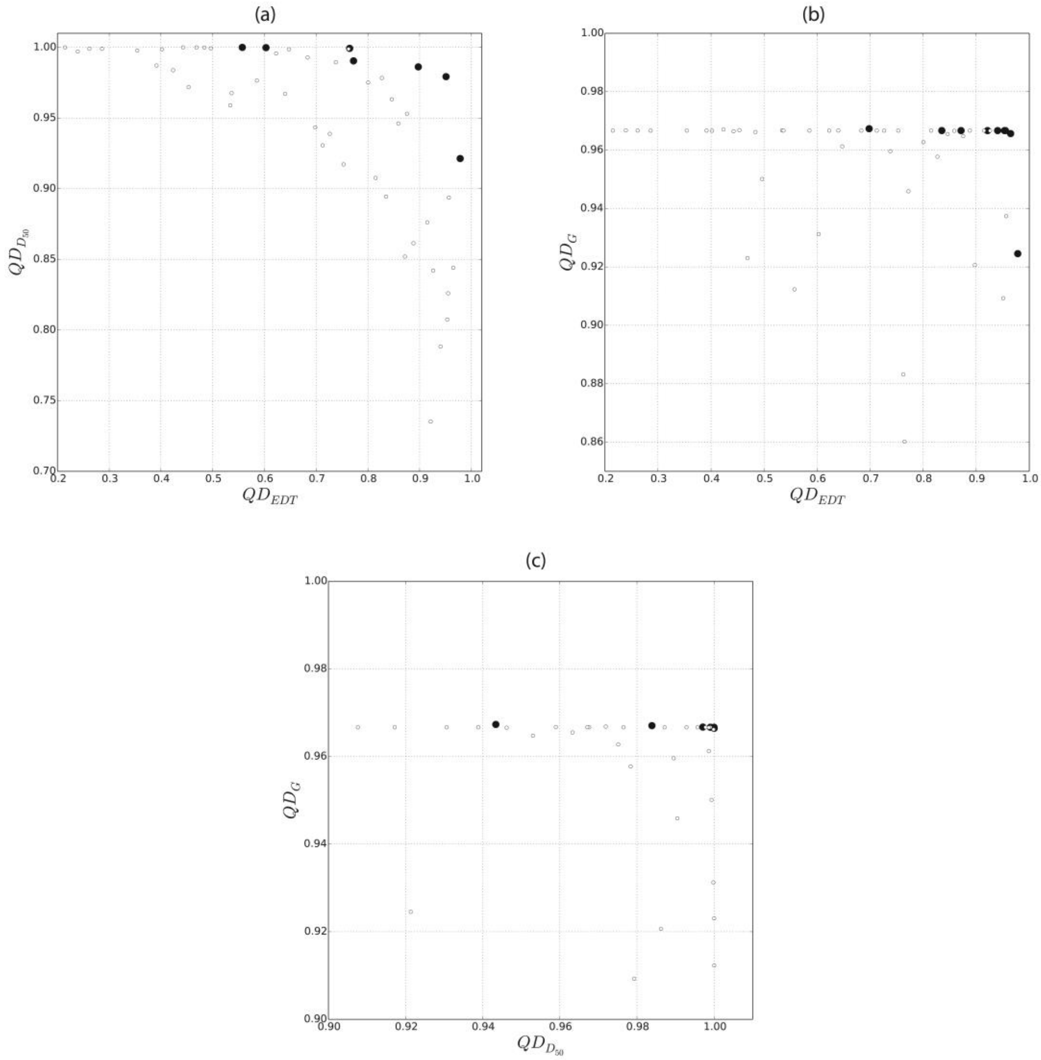

Figure 7: Pareto Fronts for the Barranquilla Multipurpose room

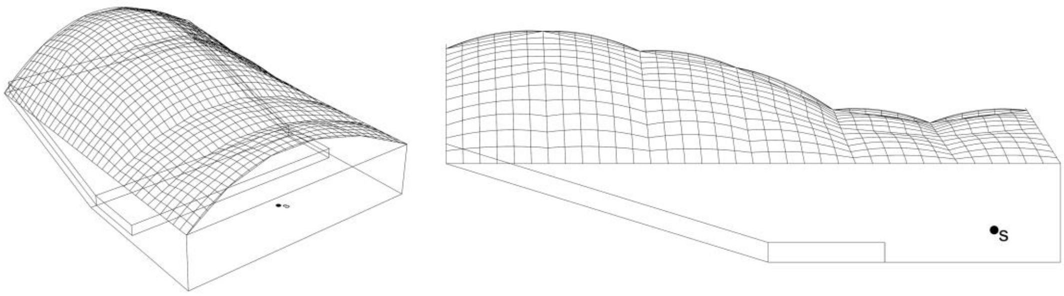

Figure 8: Selected solution

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