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Computational morphogenesis and construction of an acoustic shell for outdoor chamber music

Gabriele MIRRA[a], Eduardo PIGNATELLI[*], Sergio PONE[b]

[*]inlogicdesign, Naples, Italy
Via Annecchino 190, Naples, Italy
eduardopignatelli@inlogicdesign.com

[a]inlogicdesign, Naples, Italy
[b]Associate Professor, Department of Architecture, University of Naples Federico II, Naples, Italy

Abstract

This paper presents a deterministic method to design acoustic chambers for outdoor performances, and emphasises the benefits of a computational morphogenetic approach to the problem. It represents the newest outcome of a research program, conducted by *ReS-Team* and sponsored by *VPM*, on the development of the acoustic chamber *ReS*. The research work is based on the interaction between two different topics – *Computational Morphogenesis* and *Acoustics* - which proceed on independent but parallel paths. As a computational tool for any Python®-based environment, it aims to fill the gap between the architectural and acoustic design. By means of geometrical acoustics theory, descriptive geometry and genetic algorithms, the acoustic performance of a given topology is optimised according to defined acoustical parameters. The awareness of possible variations in the acoustic configuration is also increased. Applications are meant to predict the acoustic behaviour within any semi-reverberant field of an acoustic environment.

Keywords: Computational design, computational morphogenesis, acoustics, genetic algorithms, optimisation, acoustic optimisation, timber structures, acoustics, shell, acoustic chamber, open-air.

1. Introduction to open-air acoustic music: theory and practice

Recent studies in *Architectural Acoustics* are moving towards a connection between *Cognitive Sciences* and *Room Acoustics*, to enrich the definition of *good acoustics*. In early 1996, L.L. Beranek[3] wrote: “For that individual – the concertgoer – a number of elements come together to create that pleasure: the composition, the conductor, the orchestra, and the hall”. That particular definition highlights how subjective and complex a good listening experience can be, and especially stresses the contribution of other factors that cannot be controlled by acoustic design. For these reasons, the assumptions made in this paper are based on literature of successes in acoustic applications, which approach the design mainly through a heuristic process.

1.1. The problems of playing chamber music outdoor

Every professional musician knows that performing acoustic music in open-air conditions is the best scenario to run into extraordinary failures. In this particular case, the open-air propagation of sound can be described by a free field acoustic model, in which the contribution to the total perceived sound levels comes only from the direct sound. This condition defines a non-uniform acoustic field, whose quality is considerably different in every neighbourhood and prevents both an excellent aural experience by concertgoers and a reliable musical performance by the musicians. As far as audience or players are concerned, the quality of the acoustic system depends on both subjective perceptions and objective parameters. The method presented in this paper will refer to the design parameters of a concert hall as the target quality for outdoor chamber music concerts. The propagation of sound in indoor state is generally modelled as a reverberant field condition, where the most of the emitted energy is preserved and the contribution of the reflected sound prevails on the direct sound. Therefore, a field in which the acoustic quality is not dependent by the listener position is defined. When dealing with acoustic performances in an open-air space, four main issues can be raised. According to musicians:

a. The difficulty of hearing each other while playing, given the lack of reflecting surfaces. With no feedback, the player is not aware of what kind of sound reaches the listener's ear, musicians included.
b. Sounds are short-lived, due to the absence of reverberation, which makes a space sound *dry* to musicians used to play in a reverberating room.

According to audience:

a. Distance from the sound source causes a strong decay and insufficient loudness in most areas. The perception of the *piano* and the *pianissimo* dynamics is compromised and therefore the whole listening experience. To control these effects, the *sound pressure level* has been employed.
b. The uneven human ear perception of tones at different frequencies requires a carefully balanced selection of the reflected sound spectrum. In open-air, where no reflection occurs and no selection is possible, the outcome is an unbalanced listening experience.

As for the morphogenetic process, *sound pressure level* is the only value considered, due to its high priority in open-air conditions, compared to other acoustic parameters, though in a late stage of design a complete acoustic analysis is performed.

1.2. Acoustic concept: Objectives and Background

The problem of playing in open-air conditions is usually countered by addition of an active acoustic system – described by Poletti[12] – for the simplicity of its design, and for the availability of a ready-made acoustic setup to rent. Despite its wide commercial distribution, it has many shortcomings, due to the digital processing of the audio signal such as: alteration of the frequency spectrum; difficulty to identify the real sound source; change in the nature of the sound, especially its timbre and colour. To overcome these shortcomings, this research focuses on passive acoustic systems as a new perspective for the acoustic design of outdoor spaces. As a full reverberant field propagation state cannot be achieved outdoor, the remedial strategy is to design a system of reflective and diffusive devices, in the form of an acoustic reverberant chamber. Actually, most examples of acoustic design for outdoor spaces combine passive and active systems. Only two examples of a pure passive system are worth considering in this paper, due to the central importance of a morphogenetic method in the acoustic design.

1. The design method that led to Soundforms®, described by Bassuet et al.[2], which opened the way to a more accurate design for acoustic chambers.
2. The acoustic shell that provided the design basis of the artefact presented in this paper, ReS, explained by Di Rosario et al[4] and Pignatelli et al[11].

The design of such acoustic chamber is hereafter explained, from the morphogenesis to the construction of three among the four acoustic devices of ReS: the main shell, the cilia system, the array canopy. The morphogenetic process is analysed as the characterization of three main parts: the topological space, the benchmarked analyser and the evaluation criteria; it will proceed to a detailed report of the multiple optimisation processes, which is meant as a contribution to the awareness of an iterative evolutionary strategy, and then to an analysis of experimental results; it will go through the study of the relationship between the acoustic shell and the bespoke designed spatial structure and the presentation of the construction; it will conclude with verification of on-field acoustic measurements.

2. The morphogenetic approach to design

Computational morphogenesis has already been applied to explore the design possibilities of an acoustic shell with the highest acoustic performance. Historically it has been used to handle structural optimisation problems[13], while its application in *Architectural Acoustics* has only recently been discussed by Mendez[8], Sassone et al.[16] and Bassuet et al.[2]. This process entails a heuristic approach to problem solving, taking advantage from computational techniques such as genetic algorithms. It involves the construction, analysis and evaluation of a certain topological space. Through a GA, it follows a recursive path, performing a continuous improvement of the form, that leads to the most efficient space configuration. Furthermore, the whole process builds a landscape of solutions which enhances the awareness of the problem, as pointed out by Ohmori[9]. The development of the algorithm followed three main steps: ***a.*** Description of a topological space; ***b.*** Acoustic analysis through a bespoke Image-Source algorithm; ***c.*** Data extraction and fitness definition.

2.1. Topological space

Topological space is meant as a non-metric space built by the relationships among geometric entities subjected to a prescribed set of generative and transformative actions, Aish[1]. Designing such a space means designing all the possible solutions in a confined environment and the environment bounds themselves. To guide the construction process, the shapes of the previous *ReS* versions are analysed and interpreted as an expression of a topological space to be described. Through the shape analysis, the following topological invariants are founded: ***a.*** The shape is generated by the loft of a series of profile curves lying on parallel planes whose position is defined by translational vectors; ***b.*** Assuming a main profile, the others are obtained scaling it by different factors; ***c.*** The main profile can be described as a polyline interpolated through a set of points lying on a 2^{nd} degree master curve. These invariants provide the iterative steps for the construction of a topological space whose parameters are:

a. The master curve proportions, which define the proscenium width and height.
b. The shape subdivision in the longitudinal section, controlled by the number of translational vectors.
c. The shape subdivision in the transverse section, controlled by the number of the master curve parameters.
d. The shape morphology, controlled by the evaluation parameters on the master curve.
e. The depth of the shell in longitudinal section.
f. The longitudinal shape, controlled by the different scaling factor for different sections.
g. The distance between the bottom of the shell and the sources.

The variation domain of each parameter is defined according to technological and functional considerations. For instance, the lower values of parameters affecting the shell dimensions are fixed to ensure a minimum functional space for a sextet orchestral performance. The combination of this few parameters provides a huge number of solutions (Fig. 1) whose complexity is far away from the relatively simple shapes of the acoustic shells analysed. This fact is very helpful in the early GA runs to understand how complex variations affect the shell performance.

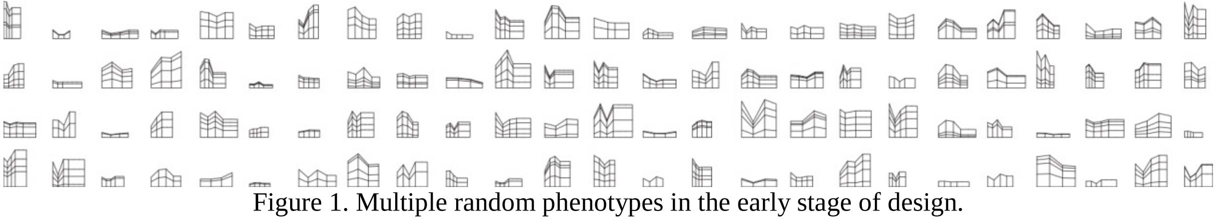

Figure 1. Multiple random phenotypes in the early stage of design.

2.2. The development of *Aeolus*: an evaluation tool based on the Image Source reflection model

In order to test the fitness of a given configuration of the topological space, an evaluation tool has been developed. The theoretical basis comes from geometrical acoustics, which allows modelling the interaction between a sound wave and the surrounding environment. This discipline employs some principles of geometrical optics, such as the Snell law, to study in terms of rays propagation, sound waves phenomena like reflection. Several methods exist to trace the paths of a sound ray bouncing many times over reflective objects, some of them are known under the name of *Ray-Tracing* techniques, where the input system is given by one or more: sound sources, reflective surfaces and target geometries or receivers. The simplest version of *Ray-Tracing*, explained by *Haines*[5], performs a ray casting to explore the ray paths resulting from sound bouncing over reflective surfaces. The accuracy of this method relies strongly on the number of initial rays and the extension of the target surfaces[6]. Conversely, *Aeolus* is based on a more accurate version of ray-tracing known as *Image Source*, explored by *Martin* and *Guignard*[7]. This method involves a reversed construction process, going from the target to the source points passing through the reflective objects. Once a reflection order *N* is fixed, a data tree is populated with the image sources obtained through a recursive mirroring of the input source on the reflective surfaces. Next, for each tree path, which represents a unique bouncing pattern, the algorithm tries to draw the ray for each target location. The benefits of *Image Source* method relies all in its high accuracy, while the computational effort is very high. Whereas the amount of possible bouncing patterns to test, grows exponentially with *N*, for a simple scene (1 source, 5 reflective surfaces and 9 targets), the computational time becomes intractable just after the 4th reflection order. Moreover, at the same N value, the percentage of reflection patterns producing useful rays is close to zero (Fig. 2). The time-consumption issue, which causes the preference of *Ray-Tracing* for the most common software implementation, is not considered a problem for the current work, because in the particular condition of semi-reverberant field only early reflections are strong enough to critically affect sound levels in the audience area.

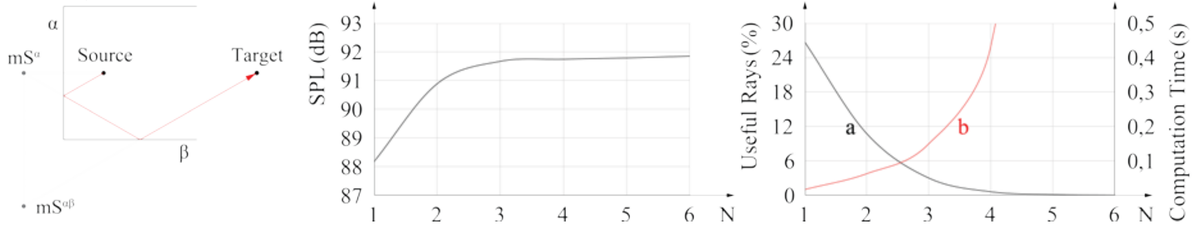

Figure 2. *Image Source* method; Reflection orders contribution to SPL; Computational costs over accuracy.

2.3. Evaluation criteria and problem formulation

The *Image Source* method has been applied to study the shape capability to reflect sound until the 2nd reflection order. Furthermore, to include direct sound a section of the tool tests for collision events between rays and any surface in the scene. The Output consists of lists of polylines, representing the paths of different emitted sound rays, for each target location. By means of simple acoustic equations, it is possible to transform the geometrical information into an acoustic parameter. Assuming an omnidirectional source, so that the emitted energy results directionally independent, and fully reflective surfaces, the total *Sound Pressure Level* for each target is calculated as:

$$SPL_{TOT} = \sum_{i=0}^{N} 10^{\frac{L_w - 20\log_{10}(l_i) - 11}{10}} \tag{1}$$

Where: SPL_{TOT} is the *Sound Pressure Level* on a specific target; N is the number of incoming rays; L_w is the sound power measured at 1 meter from the source location; l_i is the length of the i^{th} ray. For each generated shape, a global fitness is defined by summing SPL_{TOT} values for the whole array of targets. To consider also a distribution index, a penalty function is included. The resulting formulation is:

$$min_x\ f_1(x) = -\left[\left(\sum_{i=1}^{N} x_i\right) - kX^*\right] \quad \text{subject to:} \left\{\begin{array}{l} d \in [3.0,5.5] \\ n \in [3,9] \\ r \in [0.3,2.0] \\ y \in [1.0,2.3] \\ \vec{s} = (s_0, s_1, s_2, \ldots, s_{\max(n)} \in [0.50,1.00]) \\ \vec{l} = (l_0, l_1, l_2 \in [0.50,5.00]) \end{array}\right\} \tag{2}$$

Where: N is the number of targets; x_i is the $\mathrm{SPL_{TOT}}$ referred to i^{th} target; k is the weight of the penalty function; X^* is the number of $\mathrm{SPL_{TOT}}$ values under the threshold x^*; d is the longitudinal dimension; n

is the longitudinal subdivision parameter; r is the curve proportion parameter; y is the distance of the shell from the sources; $\vec{s}$ is the scale factor vector; $\vec{l}$ is the transverse evaluation parameters vector.

2.4. A benchmark test

Aeolus has been applied on a test-case, to compare the results with a benchmark. It consists of a simulation performed with *CATT-Acoustic™*, a widely known acoustic prediction software, which includes spectrum analysis, diffraction and scattering in addition to reflection. The aim is to validate the tool and to prove that early reflections, i.e. 1st and 2nd order, represent the main contribution to SPL_{TOT}. The test geometry consists of a sphere quarter subdivided into 36 planar surfaces. Simulations have been performed both assuming an omnidirectional sound source emitting 111 dB at 1kHz, placed below the shape and a target surface of 14 by 20 meters, sampled into 280 receiver points. A detailed analysis is also performed on *CATT-Acoustics*, calculating higher reflection orders for a linear array of 10 target points. These results are compared with the ones obtained running *Aeolus* on the same targets.

tan(b)	*tan*(a)	*tan*(b)-*tan*(a)	*b-a*	
+0.60	+1.10	-0.50	+0.80	*5.5m*
-0.95	-1.25	+0.30	-0.20	*7.5m*
-0.70	-0.70	+0.00	+0.40	*9.5m*
-1.45	-1.50	+0.05	+0.40	*11.5m*
-0.70	-0.50	-0.20	+0.50	*13.5m*
-1.10	-1.40	+0.30	+0.10	*15.5m*
-0.45	-0.45	+0.00	+0.70	*17.5m*
-0.05	-0.40	+0.35	+0.70	*19.5m*
-0.35	-0.35	-0.20	+1.40	*21.5m*
			+1.00	*23.5m*

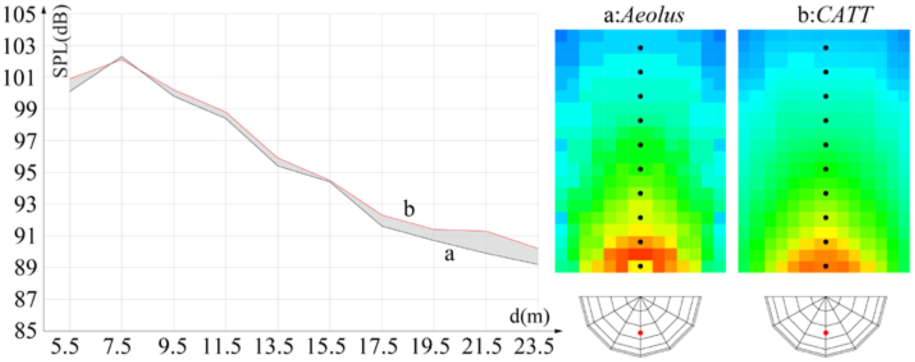

Figure 3. Results of the benchmark comparison between *Aeolus* and *CATT-Acoustics*.

Fig. 3 shows that no relevant differences can be observed in terms of *SPL* distribution. In addition, the graph of sound decay and the table show that *Aeolus* lightly underestimates sound levels, with a mean error of +0.58dB. The variance δ between the difference quotients *tan(a)* and *tan(b)* is always below half the unit.

3. Optimisation as an acoustic design strategy

The application of the optimisation process to ReS 4.0 is henceforth presented. This part of the paper aims to briefly depict the advantages of the morphogenetic approach, which is oriented not only toward an optimised solution, but especially toward a progressive and iterative knowledge. It will go through three main topics:

1. The morphogenesis of the *Main Shell*, to ensure a high standard of acoustic performance; it will be presented in three essential steps, from an almost theoretical environment to progressively more realistic settings; special attention is paid to domain boundaries, to sources position and number and to optimised phenotypes.
2. The quick decay of the sound emitted by the foreground sources, a critical issue that led to design *Cilia* system, to improve the acoustics in the far end of the audience.
3. The *Array* system, its contribution to fine-tune the acoustic chamber, and to customize different orchestra set-ups.

3.1 The Main Shell basic design and its optimisation

3.1.1 *Early applications*

The early applications of the method are meant to provide the basic knowledge about the formulated problem: the sound source is unique and omnidirectional; it is placed in the centre of the shell, whose position parameter does not allow the source to get closer than 1.5m; the target system is defined by 45 receivers properly spread on a 20m x 12m area; all variables are involved, to maximise the exploration of the evolutionary algorithm. Results after 100 generations show end-product problems of the optimisation process: the above conditions make the panels behind the sound source inefficient within the prescribed domain, as they do not perform any useful reflection. An adequate convergence of the topology is achieved around the 50th generation. Further applications have been performed with many changes in the topological space domain. In particular, the correction of the shell position parameter domain allowed phenotypes with a much higher fitness value to be found, and shows that the performance of the shell is strongly affected by the position of the source.

3.1.2 Further applications and final design

Once achieved the basic knowledge about the relationships between the domain definition and its according performance, an application to real context has been studied. The source input is represented by a sextet configuration as a mean distribution among multiple orchestra set-ups; the receivers system consists of 34 target points. The new shell design variables and their domains are designed according to the previous evolutionary stories, and on technological and architectural constraints. Especially: the number of reflective surfaces is set to constant; the translation domain is set to allow a minimum distance of 0.5m between the shell bottom and the rear sources.

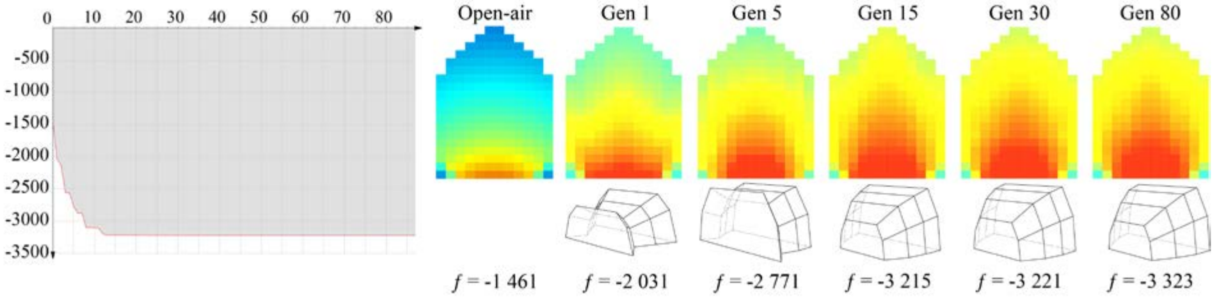

Figure 4. Plot fitness along generations; phenotypes of the final design optimisation process.

Fig. 4 shows a fast and efficient convergence of the optimisation algorithm after 15 generations, due to a controlled exploration process. The genotype of the final solution presents many genes whose value is close to the boundaries of their own domain. This depends on the cut-off process of the domains limits produced by two types of constraints: on one hand, each domain has been carefully limited after early applications, to exclude a-priori inefficient configurations; on the other hand, the real problem presents technological limits. It is clear that, as far as the genes are limited to this particular condition, their contribution to the domain cut-off process depends on technological issues.

3.2 The critical decay and the Cilia system optimisation

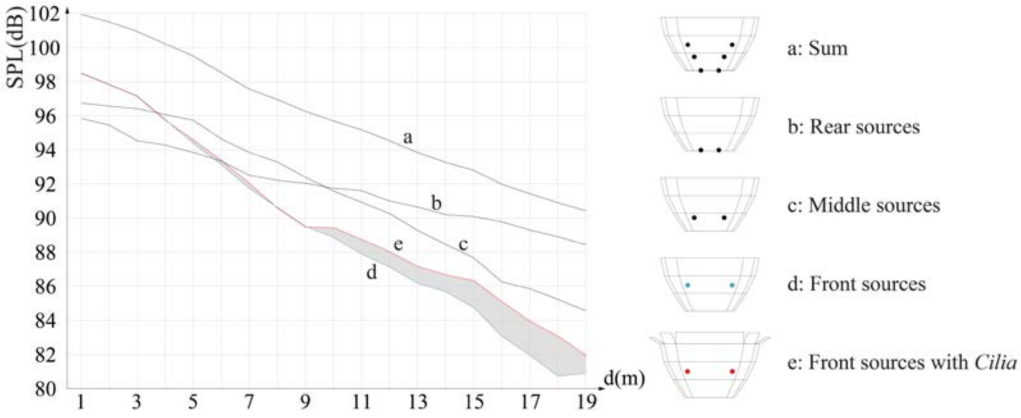

Figure 5. Critical sound decay of the foreground sources and benefits of the *Cilia* System

Further in-depth analyses of the optimised acoustic response show a strong variation in the performance between rear, middle and front paired sources as shown in Fig. 5. The foreground sources critical decay of sound, as distance increases, foreshadows to a new role of the *Cilia* system, whose shape relies on a morphogenetic process: the management of the solution robustness. In this phase, the acoustic quality of the shell strictly depends on the players position, so that the transition from an easy global *SPL* optimisation to a source-weighted optimisation is accomplished.

$$min_x \ f_2 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i + x_i^0 - \bar{x})^2} \qquad \textit{subject to:} \begin{cases} \vec{l} = (l_0, l_1, l_2, l_3, l_4 \in [0.1{,}0.9] \\ \vec{r} = (r_0, r_1, r_2, r_3, r_4 \in [0{,}60] \end{cases} \tag{3}$$

Where: N is the total number of targets; x_i is the *SPL* value on the i^{th} target; x_i^0 is the SPL value on the i^{th} target just for the main shell; $\bar{x}$ is the arithmetical mean of $\sum x_i + x_i^0$.

Fig. 5 shows that the fitness function described above takes into account only the targets whose parameter value is below a defined threshold, just for the weaker emitters, to guarantee an equalisation among sources and even distribution of the sound pressure, both in space and time, on the audience. It is clear how the affected areas present an average increase of 1dB.

3.3 Acoustic customization and fine correction

Once achieved a robust fundamental phenotype, more accurate studies are performed to customise the chamber for specific configurations of musicians. This further improvement requires two independent but parallel advancements: the implementation of specific instrument directivities in the acoustic prediction software – whose effects are described by Pätyen and Lokki[10] – and the study of new optimisation objectives for the *array* device in a frequency-based acoustic environment.

3.3.1 Symphony orchestra instrument directivities

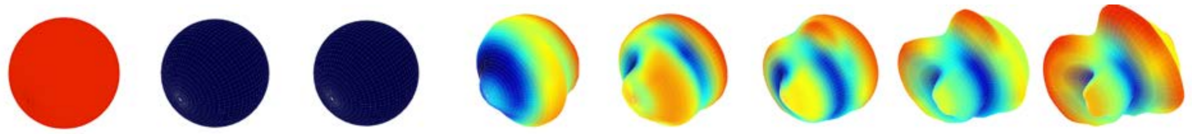

Figure 6. Sound power maps of a Violin at 125Hz, 250Hz, 500 Hz, 1kHz, 2kHz, 4kHz, 8kHz, 16kHz.

The implementation of instrument directivities has key role in the acoustic customisation. As shown in Fig. 6, the emissive power map noticeably varies within the whole spectrum, affecting the entire acoustic response of the shell. Taking into account different source types leads to a deterministic approach to optimisation. It permits to minimise the sensitivity to variations reducing the number of aleatory variables towards a less noisy uncertainty model, specifying the acoustic response of the shell to different scheduled orchestra configurations. The data matrix is translated into native *Grasshopper*™ information to be graphically represented, and a bespoke numerical database is created as excellently described by Puczok[14]. Briefly, when an acoustic ray is traced, its spatial global angles are extracted and compared with the polar coordinates system of the directivity information, to find the closest sound power that matches those specific angles. This value represents the sound level measured at 1 meter from the source location in that particular spatial direction.

3.3.2 The array canopy role and its optimisation in a frequency-based environment

The array realises an additional reflective layer that works as a specialized sound filter – based on the work by Rindel[15] – for defined musician set-ups. Composed by five rows of five HDF square panels – 50 cm per side, spaced-out of 10 cm each, 2.2 m above the players – the system works in the mid-high frequency spectrum. It is designed to correct the uneven distribution in space and time of the sound energy and to support the musicians mutual listening capability. All the orchestra configurations scheduled by the *VPM 2015 Festival* have been studied, and a shape for each players' set-up has been proposed: duo, trio, quartet, quartet with piano, sextet, octet and 24 members orchestra. Because of the brevity of this paper optimisation process analyses will be omitted, but we are going to describe the topological space and the fitness function. To create an homogenous filter regardless of local inclinations, each panel starts on a circumference whose centre is on the edge of its previous one. Recursively the whole canopy is created. The performance is described by the SPL on the audience with a bonus function to equalise the entire response:

$$min_x\ f_3(x) = -\left[\left(\sum_{i=1}^{n} x_i\right) + kX^*\right] \quad \textit{subject to:} \begin{cases} \vec{R} = (R_0, R_1, R_2, R_3, R_4 \in [-30,+30]) \\ \vec{r} = (r_0, r_1, r_2, r_3 \in [-30,+30]) \end{cases} \tag{4}$$

Where: x_i is the *SPL* of the i^{th} target; X^* is the number of targets whose *SPL* is above x^*; k is the bonus weight parameter; R_0, R_1, R_2, R_3, R_4 are main rotation angles; r_0, r_1, r_2, r_3 are secondary rotation angles. Even if this design stage aims to a high specialisation of the acoustic performance through a steep convergence of the optimisation strategy, it does not plan to diverge from a robust solution. Specific perturbations in the design model – position and orientation of musicians – are excluded through the previously described emitter’s directivity models, which orient the optimisation on the way to a deterministic approach.

4. Relationship between structure and shell

Turning the digital shape of the acoustic shell into a feasible object presents two main problems: firstly, the high area density of the panels, i.e. 20 kg/m^2, essential to respect the acoustic mass-law; on the other hand, since the shell derives neither from a structural optimization nor from a traditional form-finding process, its geometry is not structurally efficient. The solution adopted for the past ReS versions was to design an independent structural system to which the shell elements were hung. This system was developed through an analogue design process, where the technological and acoustic issues were faced together at the same design stage. The structural concept was strictly related to the definition of a regular acoustic shell made by small elements, easy to manage and to be lift up. At the last step of the research, which leads to *ReS 3.0*, the morphogenetic approach has been introduced as a form-improvement tool, controlling just local orientations of the given panels – depicted by *Pignatelli et al.*[11]. For the current work, since the panels dimensions are not provided, the structural design and the specific problems of an unexpected shape can be faced only once the optimal solution is reached.

4.1. A cable-stayed shell

The adopted solution has been inspired by cable-stayed bridges. It is supported by some considerations around the optimised shape: **1.** The mass of the central panels is the main load; **2.** The lower panels can be supported by the ground; **3.** This typology allows to use the structure also as the only construction site machine, avoiding the use of cranes. Each transversal section of the shell is designed with the same schema, where the central panel is hanging from four navy ropes passing on pulleys secured to the struts and then anchored to the ground. The struts are arranged on two hollow cross-section beams linked by a front arch. Each member is made up of smaller elements mechanically joined and stiffened at each connection by filling the cross-section. Further filling elements also strengthen the most stressed parts of the structure, allowing a local enhancement of the structural performance without critically raising the cost. The resulting structure is a timber spatial frame with three support nodes and an overall weight of just 0.4t. The scheme allows the loads to be transferred to the struts as normal forces, moved to the beams as point loads acting on its plane of highest flexural rigidity, and finally transferred to the ground. This solution allows saving the acoustical shape without compromising the performances of the structure in terms of economy and structural efficiency.

Figure 7. Built prototype at *VPM Festival* of ReS 4.0. Photo courtesy of *Daniele Lancia* and *Gabriele Mirra*.

5. **Shell performance: acoustic measurements on site**

On-site acoustic measurements have been made on the built shell and a concise summary is hereafter presented, emphasising the difference with the predicted optimised results. It has been observed that they coherently diverge by a mean error of -0.54dB and a standard deviation of 2.82. Specialised full detailed acoustic analyses and results interpretation are described by *Di Rosario et al.*[4].

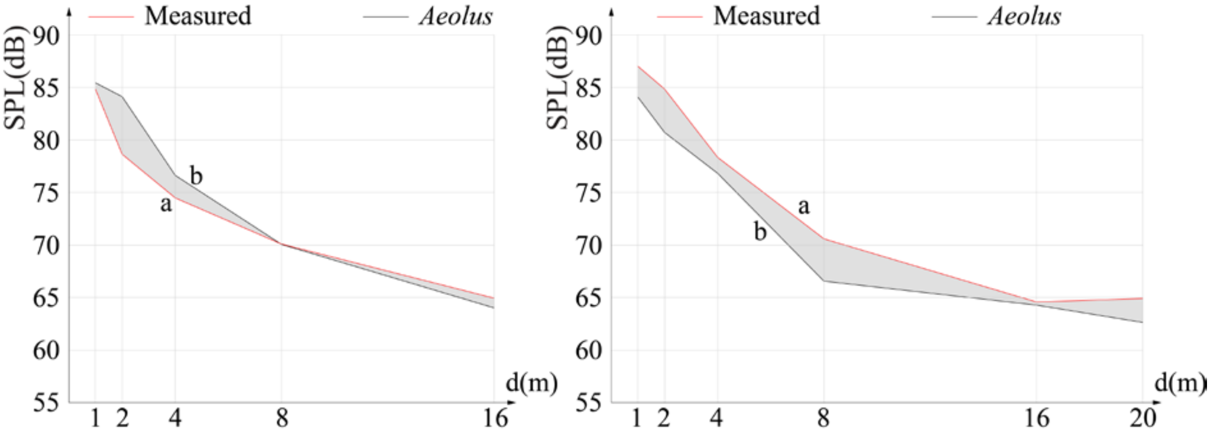

Figure 8. Comparison between measured and predicted SPL. From left: Right Audience, Central Audience.

6. **Conclusions and future work**

In this paper a computational morphogenetic method to design acoustic shells for outdoor music concerts is presented. The work moves from the results reached in 2015 by the *ReS* research program, and represents its last update. The method combines *Aeolus* – a flexible set of tools for acoustic predictions based on a bespoke coded and benchmarked *Image Source* algorithm – with the evolutionary algorithm *SPEA-2* for the optimisation. It can be used to evaluate several configuration of a defined topology, increase the awareness of the studied problem, and find the fittest solution. A real case application is discussed to validate the method. A conclusive prototype of the optimised shell has been built during the 4rd edition of the workshop *VPM* (Villa Pennisi in Musica), where on-field acoustic measurements took place. The overall accuracy of the method has been confirmed by experimental data, which slightly diverge from predicted results also due to the massive presence of vegetation along the measurement paths. The critical sound decay of the foreground sources shows that the contribution of each source to the global *SPL* is not equal. Despite the introduction of a new role of the Cilia system, this issue is not resolved. Besides, high perturbations in position and orientation of the players have been observed during the Festival concerts, showing deficiencies in the emitters modelling. Further studies will focus on a more efficient fitness function formulation, capable to describe the equalisation of the contributions to the global *SPL* of each sound source, regardless of the emitters positions. In addition, source perturbations will be implemented through the formulation of a more complex uncertainty model by means of perturbation functions towards a probabilistic approach.

7. **Acknowledgements**

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