Evolution of an Instrumental Architecture

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The paper illustrates the architectural capacities of combining computational methods, such as genetic algorithms, acoustic simulation and parametric modeling, with material properties and a simple spatial programme in the developing of a performative and aesthetical sound based architecture. The paper presents a new architectural working method, a developed digital model and a resulting 1:1 pavilion. The work emphasizes and finds deep architectural potentials by combining material, spatial and human aspects into the formation of an aesthetical and performance oriented architecture.

Keywords: *Evolutionary Computation, Acoustic Analysis, Acoustic Pavilion, Environmental Architecture*

INTRODUCTION

Architectural spatial sensation is partly defined by its sonic environment. That is, it's acoustic properties and the activities that are performed in this space. While poor acoustic properties have its substantial effect on spatial quality, it is rare, besides large concert halls, that spaces undergo evaluation of their sound based properties. In addition, when evaluation is performed it is commonly as a post-design process rather than an active integrated factor for architectural creation. The architectural theorist Steen-Eiler Rasmussen elaborates.

"Can architecture be heard? Most people would probably say that architecture does not produce sound, it cannot be heard. But neither does it radiate light and yet it can be seen. We see the light it reflects and thereby gain an impression of form and material. In the same way we hear the sounds it reflects and they, too, give us an impression of form and material..." (Rasmussen 1964)

Thus, when forming and materialising a space, acoustics are formed too. For the creation of architectural form and material application, the presented work is based on an evolutionary computation strategy, paired with an integrated acoustic simulation to allow a direct feedback between the evolution of form/material and evaluation of acoustic performance. Previously, Sato et al. has shown a model in which acoustic simulation of reverberation time is directly paired with an computational search algorithm, by modifying the overall spatial geometry in large triangular planes determining the geometry of a concert hall towards a specified acoustic target. (Sato et al. 2004). Similar studies of modifying large spatial geometries by a computational search algorithm has been shown in the transformation of an existing concert hall by Spaeth and Menges (Spaeth & Menges 2011) and in another concert hall study by Pugnale (Pugnale 2009). The studies bear much resemblance to the work by Sato, but induce more visual design control as determined by the design parameters that can be included for design progression.

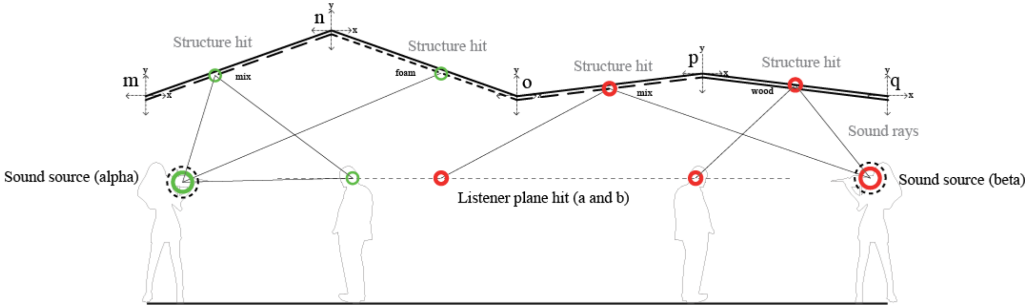

Figure 1
Schematic diagramme of simplified geometric model for multi-objective reciprocal fitness requirement

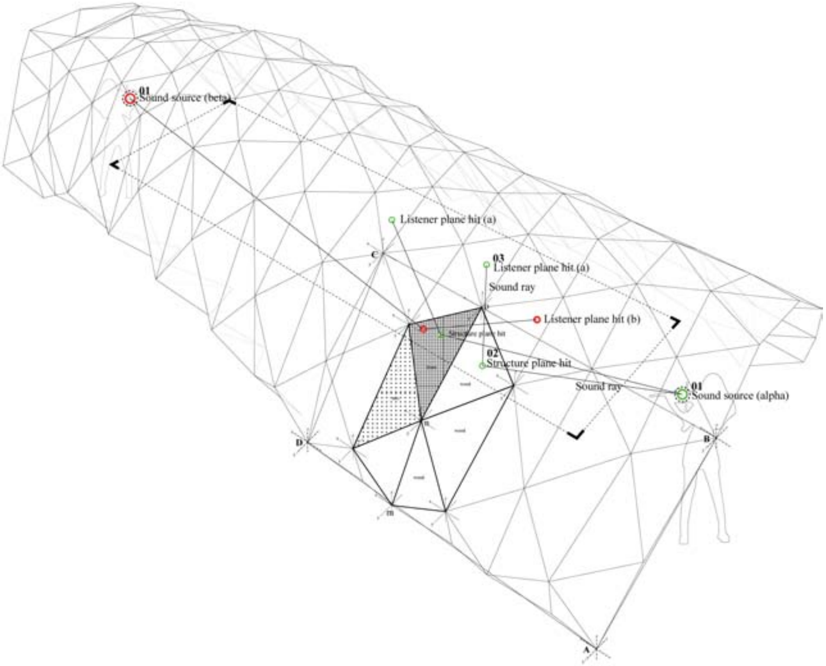

Figure 2
A. The primary geometry defining the overall space form. B. The secondary geometry defining the folding structure allowing differentiated angling of the panels as a variable to alter sound rays and to create structural integrity. C. Surfaces that digitally can change through three absorption coefficient states. The state of the surface subsequently informs the milling pattern density of the sandwich element.

Another study of a concert hall, applying an agent-based algorithm was explored by Lim, with particular focus on the large roof reflectance to improve the distribution of sound across a deep space (Lim 2011) in which a digital modelled ceiling change curvature as a way to physical modify the expression and properties of the sound reflecting ceiling. In a different scale, Peters et al has explored the architectural model as related to acoustic properties, with a specific focus on the effect of patterning surfaces inducing specified sound scattering (Peters & Olesen 2010). Contrary to Sato et al studying the overall geometry of the space, Peters is focusing on a wall segments acoustic properties by predetermined design patterns. In a later study Peters et al construct a 1:1 wall segment, exploring similar effects of scattering but with the intention of directing the sound towards a singular point, and shield of another zone with the same wall. The procedure between analysis and modelling is iterative but not automated as a looping design system (Peters et al. 2011). Thus, recent architectural acoustic studies related to the early design phases appear to be approached on two different scales, the large concert hall scale, predominantly focused on geometry, computational parametric models and potentially linked between analysis and visual model with modification by search algorithms, or small scale physical studies of components of singular wall segments towards surface articulations by segregated analysis and modelling activities.

The hypothesis of this work is that a heterogeneous acoustic environment can be developed in the early design phase through computation, so as to become instrumental for the musician by the musicians spatial positioning.

METHODS

The studies are based upon the gathering of different digital techniques; parametric modelling, spatial simulation and evolutionary computation. Combining these techniques form the instrumental setup that enable the design research investigations.

Parametric Model

The space structure used is based on an origami folded structure that is changeable at two levels within the structure. The first (primary), figure 2(A), is the overall folding form of the structure that is controlled in a series of control points forming a 'simple tunnel' geometry. The control points have freedom of movement in x,y,z axis, but without the ability to overlap and collapse the geometry. The second (secondary), figure 2(B), level is linked to the primary structure, with a higher control point resolution. These control points have freedom of movement in x,y,z axis, but without the ability to overlap or spatially 'dissolve' the folded logic of 'hill' and 'valley' points that ensure a folded geometry's structural integrity of the origami organisation. The secondary level consist through this organisation subsequently of a series of triangular reflective faces, figure 2(C), which can be set to one of three states, each representing a different material property and thus different sonic absorption coefficients. The materials used are plywood with an absorption coefficient of 0.1 at 500 Hz and foam with an absorption coefficient of 0.9 at 500 Hz. The materials are combined in sandwich element with foam in the middle and plywood on both sides encapsulating the foam. The cross section of the material make-up has a structural thickness of 43mm. By combining the materials, high structural stability across the plates are created, with the important ability of changing absorption coefficients by perforating the sound reflective inner surface of the space.

Acoustic Equations

Different architectural acoustic equations exist, with the simplest, however acknowledged, being the Sabine equation, calculating the reverberation time RT60, that is the time it takes sound to diminish from 60 dB. From this the Norris-Eyring equation is developed and to this work more important the Millington-Sette equation is developed that offers a higher resolution of the evaluated space as material definition is established to a more detailed degree than the above two equations to which the former was applied in previous studies by the authors (Foged et al 2012). Important to this work is the ability of the Millington-Sette equation to separate different material parts and their geometry, working with heterogeneous material and geometrical assemblies. Millington-Sette equation for architectural acoustics (RT = reverberation time, V = volume, Si = surface of material, Ai = absorption coefficient of surface material):

$$RT60 = \frac{0.161 \cdot V}{\sum \left(-Si \ln\left(1 - Ai\right)\right)} \tag{1}$$

Acoustic Simulation

From the Millington-Sette equations a specific acoustic simulation method is developed. This is done, based upon the introduction of a 'listener plane' that is spread out horizontally within the parametric space in the height of the audience ears. The Millington-Sette equation does not integrate specific acoustic properties at a specific point within a given space, to which we have integrated a ray-tracing functionality that allows evaluation of the sound perceived at the listener plane. Furthermore, this allows tracing the sound pressure at the listener plane by the equations (G = sound pressure, r1 = distance from sound source, r2 = another distance from sound source, L1 = sound pressure at r1, L2 = sound pressure at r2, AbsCo = material absorption coefficient) [1]:

$$L2 = L1 - 20 \cdot \log\left(\frac{r2}{r1}\right) \tag{2}$$

$$dB = 10 \cdot \log\left(1 - \text{AbsCo}\right) \tag{3}$$

Reverberation time and sound pressure level combined serve as the acoustic simulation of the intended design space.

Evolutionary Computation

An evolutionary algorithm is utilised in order to drive the acoustic performance forward. This algorithms progressively searches to improve the design (phenotype) based upon its genotypic mechanisms of selection, crossover and mutation functions. Much literature on the subject of evolutionary computation and genetic algorithms can be found from the authors John Holland, inventor of the genetic algorithm (1992a, 1992b) and David Goldberg (1988) who has studied and developed the techniques in various applications, John Frazer (1995) who explored early architectural potentials. Martin Hemberg (2001) et al has later developed a surface based approach as an abstract method for organising space and Christian Derix (2010, 2012) exploits the opposite concrete and utility capacities for organisation of buildings and urban environments. A readily available solver, Galapagos, is chosen, developed by David Rutten [2] in the framework of Rhinoceros and Grasshopper by McNell Software. This is chosen based upon the focus to develop a method for 'Evolution of an Instrumental Architecture', rather than the tweaking of the crossover mechanisms within a genetic algorithm. Of importance, however, is the development and description of the fitness function, based upon above simulation method and architectural acoustic intentions.

Fitness function

The fitness function describes what to search for. Without it, the algorithm would wander endlessly without finding anything, whether being close or far from a good result. The nature of the fitness function is that it must be described with a single number value and thus a multi-objective search that intents to create more than one specific acoustic property within the same space is in need of a function that allows this. Furthermore, to stress the capacity of the method, it is chosen to create two 'opposite' architectural acoustic properties within the same space. By having a position 'Beta' in one end of the 'tunnel' that searches for a short reverberation time, approximately 0.9 seconds (good for speech) and a position 'Alpha' in the other end of the tunnel that searches for a long reverberation time, approximately 1.4 seconds, (good for classical music) the positions search would logically neutralise each other in the fitness function. The acoustics are evaluated from above described simulation method in both positions and inserted into the equation;

$$f = \beta + \left(\left(\frac{1}{\alpha} \right) \cdot m \right) \quad (4)$$

So that when the reverberation time 'Alpha' increases in the fitness function, it actually decreases in its acoustic description.

The variables that can be altered in the genetic algorithm are the x,y,z coordinates of the primary and secondary geometric setup described above and the additional application of the material on the inside of the structure. As part of the fitness function describes the material absorption coefficient this too can be a variable, which influences the performance of the space. Two materials are chosen, wood and foam, which have very different absorption properties, wood 0.1 and foam 0.9, at 500 Hz. Additionally, a 'mix' between the two materials can be made through having a surface that is partly wood and partly foam. This causes the search space to move from 3 dimensions, to 6 dimensions, by the 3 different material properties added to the x,y,z dimensions.

The generative model is run in two different modes, a) search with all variables activated and b) search with successive variables activated, by first generating form and then generating material organisation. The search modes were processed on standard computational laptop hardware.

RESULTS

Below chart illustrates the computed evolution of sound properties from the two positions, 'Alpha' and 'Beta' within the pavilion space on the listener plane. The y-axis of the graph has reverberation time values from 0-1.4, and the x-axis of the graph has iteration time values from 0-1000. Below illustrated evolution chart is based on searching maximum RT60 in 'Alpha' and minimum RT60 in 'Beta' to test the acoustic boundary performance of the space. The computed results stabilise at 'Alpha' =1.4 and 'Beta' = 0.2 after 700 iterations. Thus, from an initial starting point of almost equal RT60 in both positions, the method clearly modifies the organisation of reflective geometry and material distribution causing a multi-objective sound space to be evolved.

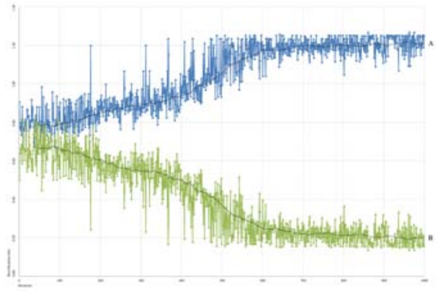

Figure 3
Computed evolutionary progression of the solution, with reverberation time (0-1.4) in y-axis and iterations in x-axis (0-1000).

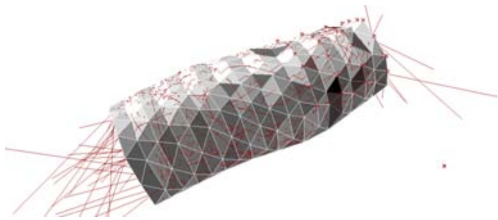

Figure 4
Screenshot of digital model with gray-scale representation of the material organisation of the triangles, with black being high reflective, dark grey semi-reflective and light grey being absorbing sound rays in red

The developed method and following experiments find that the combination of evolutionary computation and acoustic simulation can be used as a strategy to evolve a sound oriented instrumental architecture based on spatial and material organisation. Furthermore, if design time is an issue, the work finds that the method can be divided into two successive steps by first organising the space structure and second organising the material application, thus reducing the 6 dimensional search space into two runs of 3 dimensions. Additionally, this clarifies the effect of the procedure in relation to each aspect (space and material). However, it also may reduce the potential of finding a solution in the 6 dimensional solution space. Beyond numerical research based upon

Figure 5
Acoustic Pavilion 2012 as seen along the harbour front in Aalborg

the developed computational models were the pavilion constructed in 1:1 in order to allow for qualitative analysis by the performing musicians. Based on post-play qualitative questioning, the musicians found that the structure enhanced the reverberation time and thus extended the instrumental capacities of the non-amplified instruments. Positioned in the low reverberation end of the space, a musician noted that the sound was clear, but without enough reverberation time. This can be interpreted as negative, even though in this particular case it is actually positive, in the sense that the musicians were, without knowing, placed in the low reverberation end of the space.From an aesthetic design perspective, the 2-level (primary, secondary) parametric model opens for design intent influence, such as modification of element proportions, size, and change of general form. Such factors can be both computably and manually modified and thus the method moves beyond a singular aim of engineering optimisation towards a more holistic model of architecture and engineering as collaborative effort. Another aspect of architectural aesthetics is related to the repetitive organisation of triangles that forms the structure. This structural pattern is continuous, but with variation created by both designer and by the computational method allowing a dual authorship of the final articulation. The material-spatial-occupier (structure-sound environment-human) complex is thus achieved through a visual articulated continuity with variations, offering tactile, audible and visual aesthetics perceivable by positioning and repositioning through the space.

DISCUSSION

As setup of the research project a small architectural space was preferred due to the possibilities of creating a 1:1 demonstrator with subsequent performance by musicians and audience. A first issue arises in the capacity of creating long reverberation times in very small spaces as the sound will need to bounce several times to extend the audible period to a desired level for classical music. Due to fabrication issues (fabrication accessibility and on-site modifications to a zero-tolerance geometry) wood was chosen as the outer sandwich element structure and therefore reflective surface. Other materials with

Figure 6
The pavilion as seen from inside with musicians performing during the three-day culture festival. Different levels of perforation of the wood surfaces are detectable next to the musicians located in the low reverberation end of the space.

smaller absorption coefficients would be an initial potential for improving the material capacity within the study. This would allow greater abilities to differentiate between low and high reverberation times for different positions. The acoustic analysis takes into account an audience filled space. This aspect could be developed to allow for an empty, partial occupied or filled space, which would directly affect the absorption of the rays bouncing of the floor area. However, the space was filled during the performances and therefore little difference between the studies and the realised space was minimal. Nevertheless, one musician noted, somewhat humorously, that the reverberation time would be further prolonged and improved if no audience were present allowing the sound to bounce of the concrete floor area.

ACKNOWLEDGEMENTS

The authors would like to give a special thanks to Chris Strunck and Andreas Larsen and thanks to Rumle Petersen, Mathis Vittrup, Simon Rhode Malm, Audun Wold Andresen for a tremendous effort in helping with manufacturing and assembling the Acoustic Pavilion 2012. Also, we would like to thank the Institute for Architecture and Media Technology, Aalborg University and Realdania for financial support that made realisation of the project possible. The project was developed as a collaboration between AREA, BRATH and Aalborg University

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