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An Integrated Computational Approach for the Design of Tailored Acoustic Surfaces

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Abstract
The paper outlines a multi-scalar method for the design of acoustics surfaces combining absorption, reflection, and diffusion properties, tailored for improving the acoustic comfort of existing spaces. A case-study application referring to a semi-enclosed meeting room within an open-plan co-working space is described. The approach is based on a computational process for the design of acoustic surfaces from wood-cork composite, where the performance differentiation is achieved through modulating parametrically their local and global geometry. Aided by an unsupervised learning algorithm, the properties defining the acoustic performance of the wood-cork composites are correlated into a feature map. The material characterisation of the acoustic surfaces, i.e. assigning the composites with the required acoustic properties is achieved thanks to this map.

Keywords: room acoustics, computational performance-based design, eco-sustainable material system.

1 Introduction

Acoustics influences strongly our well-being in indoor environments which makes it a factor of crucial importance for the built environment and our lives. Despite that, the design for sound is not addressed in the current practice nor is properly integrated into the development of the architectural design. This leads to poor acoustic comfort in general and makes the implementation of acoustic solutions very difficult, especially for existing buildings. This lack of design integration is addressed in this paper, which outlines a method for the design of acoustic surfaces with complex geometry combining absorption, reflection, and diffusion properties, tailored to improve the acoustic comfort of existing spaces. A case study, a semi-enclosed meeting room (MR3) within an open-plan co-working space with pronounced acoustic issues, TAG Calabiana in Milan, Italy, is used for illustrating the proposed workflow (Figure 1).

Figure 1 - TAG Milano Calabiana - view of the “flexi” area (left) and Meeting Room 3 (right).

2 Methodology

The methodology for the development of complex acoustic surfaces with properties tuned for specific existing sound field conditions follows three main steps.

1) Analysis of the pre-existing state and definition of boundary conditions

The existing sound field is studied through an audio-visual survey performed following a workflow previously developed by the author [1]. The data gathering provides two objective maps representing the existing space: a) SPL levels expressed as L_{EQ} values and b) time-averaged motion heatmap. The maps allow the designer/architect to quarry several important characteristics and directly embed them in the performance design of the acoustic surfaces:

- *Differentiation of the acoustic treatments* - Overlapping the L_{EQ} and motion heatmaps, combined with the evaluation of the basic acoustic parameters, such as reverberation time, speech intelligibility etc., creates a panoramic overview of the existing sound field. Knowing that the different acoustic treatments (absorption, reflection, diffusion) tackle specific sound field conditions, their amount and distribution within the space are defined;
- *Material characterisation* - The ⅓ octave-frequency-band L_{EQ} maps allow for the problematic bands with insufficient or excessive SPL values to be easily individuated and the frequency-dependent material composite characteristics of the absorptive, diffusive and hybrid surfaces to be decided;
- *Geometric characterisation* - Individuating the spatial location of "hot" activity zones through the motion heatmaps allows for identifying the locations of sound sources and receivers and using them as direct input for informing the global geometry of the surfaces. As such the spatial location and orientation of the reflective, absorptive and diffusive surfaces within the space can be assigned.

2) Material characterisation

The material system for the acoustic surfaces uses two ecologically friendly materials, wood and cork joined in a composite such as to ensure either absorptive, reflective, diffusive or hybrid properties. The composites are coupled with the patented technological system, developed by the industrial partner of the research, Wood-Skin®, that allows three-dimensional surfaces to be produced from flat sheets. Milling both sides of the sheets, the polymer mesh inside is revealed and a hinge is created permitting the rigid sheet to fold. The absorptive coefficients of a large set (more than 150 samples) of different composites were characterized in an impedance tube in previously developed research [2]. Each test sample was characterised with 23 values defining their performance: a) the thicknesses of the top and bottom materials; b) the depth of the air cavity behind the composite; c) the perforation ratio and d) the resulting absorption coefficients in ⅓ octave frequency bands. To assign the most suitable wood-cork composite to the acoustic surfaces, in order to render their properties frequency-specific, the contribution of each variable to the performance needed to be understood. In order to extract the correlation data, the results were mapped and clustered using an unsupervised learning algorithm, Self-Organising Map (SOM).

3) Multi-scalar approach for geometric characterization

During the preliminary studies preceding this paper, it was understood that geometry holds a significant role in defining some of the acoustic performance characteristics. As a result, a multi-scalar approach is introduced where the three-dimensionality defined in terms of global shape and local surface characterisation is explored as a guiding element in the acoustic performance design.

By modifying the geometry on the global scale we can control:

1) Amount and distribution of acoustic surfaces;
2) Orientation of the surfaces for controlling first-order reflections or providing sound absorption closer to the source (derived from the survey of the existing conditions);
3) Absorption and hybrid properties by controlling the air cavity depth behind the surfaces.

Modifying the geometry in the local scale controls:

1) Absorption properties by defining the perforation patterns;
2) Diffusive and hybrid properties by introducing surface corrugations and determining the dimensions of the depths and widths, responsible for the diffusive properties.

3 Analysis of pre-existing state and definition of boundary conditions

3.1 Acoustic measurements and room acoustics simulations

In-situ measurements of the reverberation time in the co-working space and acoustic simulations in Odeon were performed in order to provide additional information about the sound field. According to the International Standards [3] and various researches on open-office acoustic comfort, the resulting values are way beyond the recommended for most activities Tr ≤ 1,0 s at 125 Hz. The in-situ measurements report an average T_{20} at 125 Hz = 1,75 s. These values are confirmed also by the simulations, showing an average T_{20} at 125 Hz = 1,63 s.

Some other parameters are also analysed. The Early Decay Time (EDT) at 500 Hz is 2,00 s which confirms the users' perceptions of poor speech clarity in MR3. The average Speech Transmission Index (STI) value is 0.5 which means that the users inside MR3 are able to clearly understand the speech, meaning that the sound privacy is relatively poor and might lead to distractions. Another important factor is the Speech Interference Level (SIL) of 87,7 dB. The distance between the source and the receiver is approximately 10 m so this value is extremely high. The SPL for all receivers is also the highest around 1000 Hz.

3.2 Audio-visual data gathering - SPL and user activities mapping

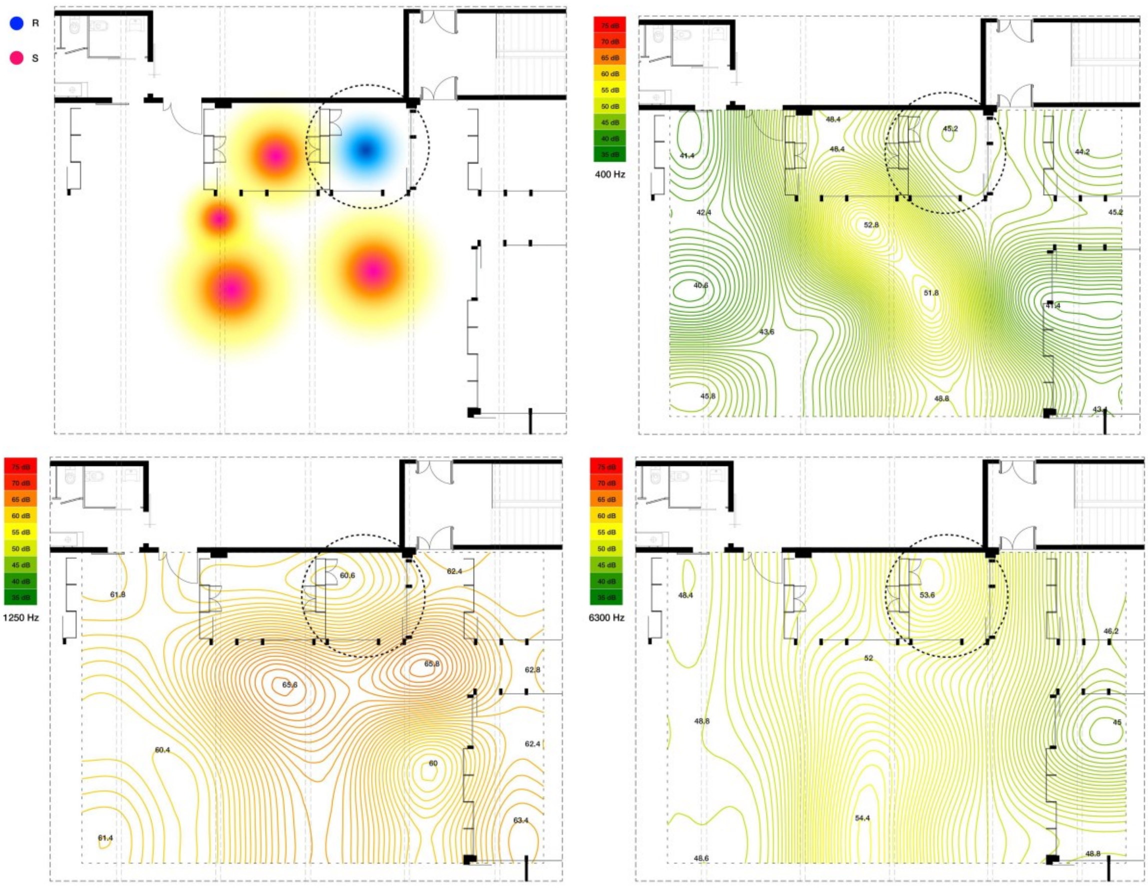

Figure 2 - Sources and receivers positions resulting from the survey (top left); Contour map for L_{EQ} at 400 Hz (top right), 1250 Hz (bottom left) and 6300 Hz (bottom right).

The results from the audio-visual data gathering focus on the sound pressure levels distribution and the activities patterns of use of the space by the users. In all frequency bands, the peaks with the highest SPL values are located between the sources, fluctuating in between them. The video observations evidence that the "corridor" is a place with a high concentration of movements but not present for a prolonged amount of time. It can be assumed that disturbing noises are less likely to be generated from there. The other two main "hot" spots where the most movements/noise comes from are 1) the adjacent room and 2) the "flexi" area. During the measurements, in the flexi area, there were two separate sources of noise. Due to the close proximity, the adjacent room can be considered the primary source of disturbance (Figure 2 - top left).

3.3 Performance requirements and design boundary conditions

According to the analysis of the existing conditions, the surfaces needed for mitigating the sound coming from outside MR3 should provide:

- Attenuation in the 500 - 4000 Hz range to treat the noises coming from the "flexi" area, the adjacent office room as well as absorbing the first-order reflections from the boundary wall (Figure 2 - top right; bottom left);
- Reflective surfaces to block and redirect as much as possible of the remaining sound preventing it from entering the room.

The surfaces targeting the sound field inside MR3 instead should provide:

- Sound attenuation in the low range 250 - 1600 Hz reducing the peaks with high SPL in the room (Figure 2 - bottom left);
- Diffusion for uniform sound distribution in the high speech frequency range 2000 - 4000 Hz and partial attenuation of the remaining sound (Figure 2 - bottom right).

4 Global geometric characterisation

4.1 Early design morphogenesis

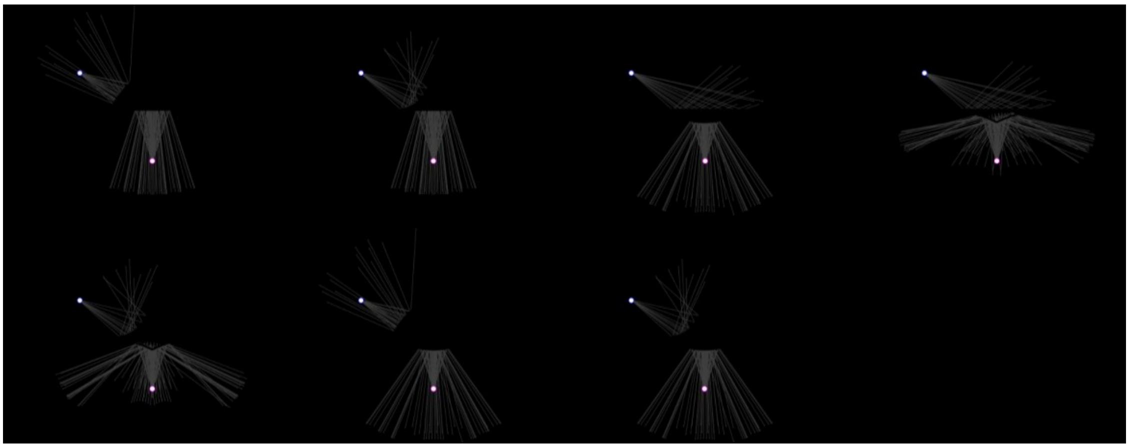

Figure 3 - Ray tracing simulation of several shape configurations

An independent suspended structure not covering the entire footprint of the meeting room was evaluated as the most feasible solution in terms of fabrication, installation and lighting. Following these constraints, the initial bounding box dimensions are set to 300 cm x 300 cm x 100 cm. The explored morphology tries to maximize the surface area without increasing the footprint area. The global geometric studies initiated with a diagrammatic approach, where several geometries formally synthesizing the design requirements were evaluated performatively (Figure 3).

The design envisioned four separate hyperbolic paraboloid surfaces each sharing two edges, thus maintaining the structure suspended. The space enclosed between the surfaces serves as an air cavity varying in thickness. Concave, double convex and flat surfaces are designed and coupled in different configurations, and their acoustic performance is evaluated using ray tracing. Two sources for the rays are used, one targeting the top surface for sound blocking, and one, inside the room, targeting the bottom surface for sound diffusion.
The ray-tracing demonstrates that both the convex and concave surfaces redirect the sound away from the room. However, the concave surface distributes the sound energy towards the high ceiling where it is returned with less intensity (2,5,7). The flat surface is not as effective because the incident sound arrives at it later compared to the other geometries, and is reflected specularly without significantly reducing the intensity (3,4). Considering a sound source placed directly under the acoustic surfaces, the best diffusion is achieved by the convex surface which distributes the rays rather uniformly at a wider angle (3,6,7). The convex surface tends to focus the rays towards the focal point of the surface (4,5). From the analysed geometric typologies, option 7 proves optimal in satisfying all the design requirements.

4.2 Multi-objective optimization process

A multi-objective optimization algorithm (Octopus plug-in Grasshopper) is used to performatively evaluate and find the optimal design morphology combining sound reflection from the top surfaces with uniform distribution inside the room, keeping the design footprint as small as possible. For these to be achieved three main objectives are set:

1) Maximizing the rays hitting the top two surfaces, i.e. blocking and absorbing as much as possible the incoming sound from the "flexi" area and the adjacent room. The number of rays hitting the top two surfaces is found by finding the interactions between the first, second and third-order reflections with the surfaces. The number is compared to a reference surface providing maximum sound blocking, and the difference is proportionally expressed.

2) Maximising the reflection area off the two bottom surfaces, i.e. providing optimal diffusion. Evaluating the diffusion is done first by finding the intersection points of the first-order reflections with a hemisphere built at the barycentre of the surfaces. Then a surface is constructed encompassing all the intersection points and its area measured.

3) Minimizing the side lengths of the surfaces thus minimizing the overall area maintaining the fabrication constraints. The lengths of the surfaces of the initial input model are measured and arithmetically averaged to provide for a single number input in the optimization algorithm.

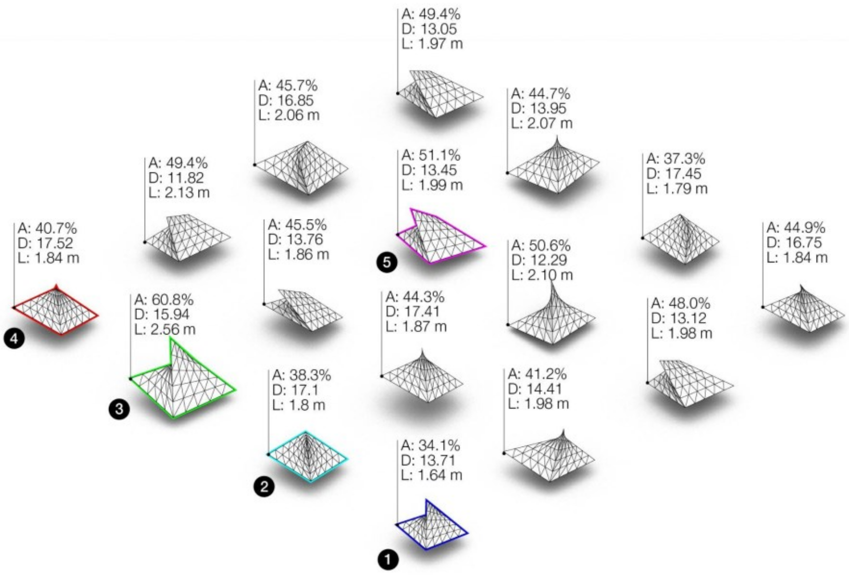

Figure 4 - Optimization results: 1) Shortest side lengths; 2) Highest diffusion value; 3) Highest absorption area; 4) Optimal negotiation between the values; 5) Selected candidate.

The Pachyderm plug-in for Grasshopper is used for the acoustic evaluation of the design iterations. Pachyderm is an open-source collection of geometrical simulation techniques employing ray-tracing and image source methods.
The optimization is run for five generations with 100 samples. Sixteen candidates are selected from the Pareto front first by picking the three dominating solutions for each objective and then choosing the best solutions negotiating the three objectives. The results show that all candidates have an edge extending over towards the source which ensures sound blocking and maximum absorption. As for the bottom surfaces, the best results are achieved when they are parallel to the floor (Figure 4). The candidate offering the best compromise between the first and the third objectives is selected. Further adjustments are done in order to accommodate characteristics like the thickness of the backing material, eliminating sharp angles incompatible with the fabrication constraints and other dimensional changes. The design chosen for the bottom surfaces is not the most optimal, however, this is mitigated by introducing phase-grating diffusion alongside the geometric sound dispersion, which provides additional absorption.

5 Material characterization and embedding material system properties in the digital design

The material characterization of each surface is derived by the empirical tests of the absorption coefficient of various wood-cork composites, combined with the performance requirements defined during the survey of the existing conditions. In order to facilitate the material selection, the empirical findings are clustered in a feature map using a Self-Organizing Mapping (SOM) algorithm.

5.1 Mapping of empirical findings

The composites are characterised in an impedance tube, where the sound is emitted at normal to the sample incidence. In reality, the sound hits the surface in multiple random directions. The first step of the mapping process is transforming all the alpha values from normal to random incidence. The Paris' formula is used to get approximate random incidence values for all the samples [4,5]. The Paris' formula defined in the literature is:

$$\alpha_s = \frac{E_a}{E_i} = 2\int_0^{\frac{\pi}{2}} \alpha(\theta) cos\theta sin\theta d\theta = \int_0^{\frac{\pi}{2}} \alpha(\theta) sin(2\theta) d\theta \quad (1)$$

where α_s is the random incidence absorption coefficient and $\alpha(\theta)$ is the absorption coefficient in the free field at an incident angle θ.

The 23 parameters characterizing the composites are organized in Excel and streamed in Grasshopper where the values are normalized. They represent the 23 dimensions that the SOM algorithm has to cluster and map on the basis of their topological relationship. The representation of the 23 dimensions in a three-dimensional environment is very challenging. For facilitating the visual understanding, each composite and its characteristics are represented as two stacked parallelepipeds. The top one represents the facing material, while the bottom one is the backing material. The X dimension of the parallelepipeds is the arithmetically averaged alpha in the low-mid frequency range, while the Y dimension is the average alpha in the mid-high frequency range. The Z dimensions represent the thicknesses of the facing and backing materials in proportion. The colour and transparency represent the thickness of the air gap (Figure 5 - left).
The data is mapped onto a two-dimensional 11 x 11 data grid. The SOM consists of this grid where all nodes have the same dimensionality as the training data. During the training, the grid nodes try to approximate the input data as close as possible, self-organizing until convergence is reached. Once the training is completed, the multi-dimensional data is organized in a grid of rows and columns. The training data is then replaced by the input absorption coefficient alpha diagrams, placed in the indices of rows and columns corresponding to their position on the SOM grid (Figure 5 - right).

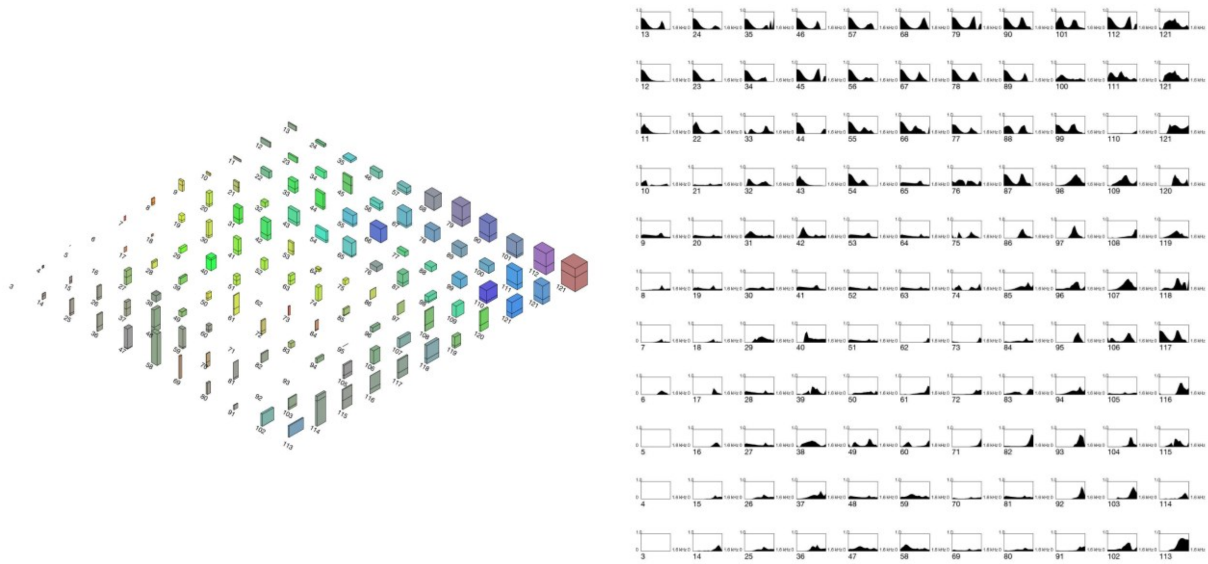

Figure 5 - Feature map of the absorption coefficient and material properties data (left); The absorption coefficient graphs clustered according to the feature map (right).

5.2 Assigning material composites

The most important feature of the SOM algorithm is in its capability to classify new incomplete data. In the SOM grid, a new sample can be clustered by finding the closest node, done by comparing the Euclidean distance of the new sample to every single node in the map and finding the closest one. This unit is known as the Best Matching Unit (BMU) since its vector is most similar to the input vector [6]. The distance between the input vector and the weights of the node is calculated by the Euclidean distance formula (2):

$$Dist = \sqrt{\sum_{i=0}^{i=n}(V_i - W_i)^2} \quad (2)$$

where V is the current input vector, and W is the node weight's vector. When measuring the distances the missing dimensions (the missing values characterizing the required composite) are ignored.

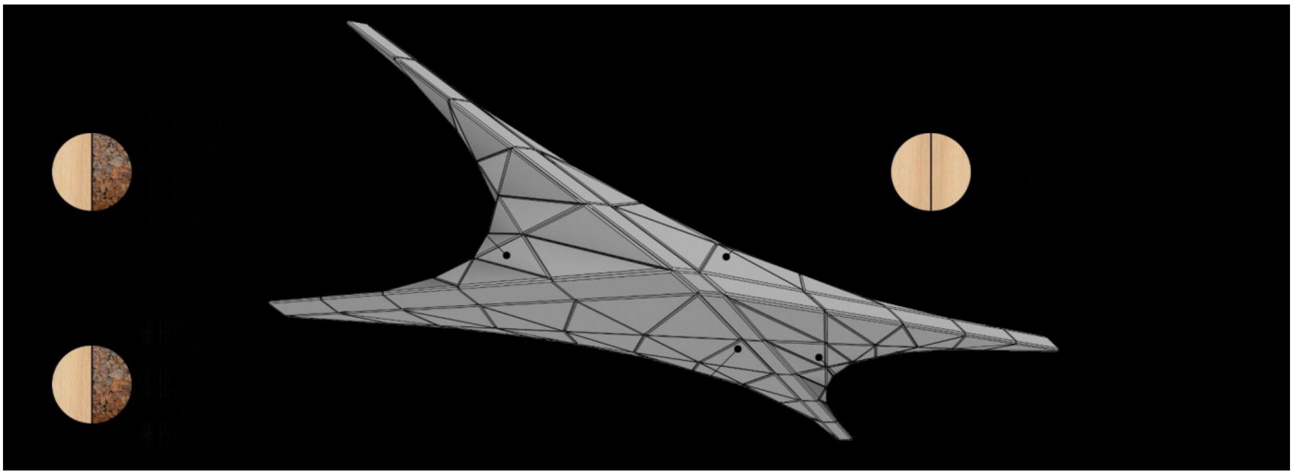

Figure 6 - Characteristics of the acoustic surfaces

Following this workflow and given the required ranges for absorption known from the analysis of the existing space, the composites for each surface are defined. The values characterizing the new data are the approximated absorption coefficient values for each ⅓ octave frequency band and the thickness of the air cavity behind the surface known because of the geometry. The suggested by the SOM algorithm composites were compared to the actual impedance tube test results for the composite on the BMU and an agreement between the suggested and actual behaviour was found. As such each of the acoustic surfaces is performatively characterised (Figure 6).

6 Local geometric characterisation

In order to understand the distribution of absorptive, diffusive and hybrid treatments on the bottom surfaces, a colour-coded map is created based on the intersection points of the first-order reflections with the hemisphere, defined priorly (Figure 7 - left). The hemisphere is discretized in equal size elements and thus populated with equidistant points. From this set of points, only those located in the areas without rays intersections are selected. They represent the zone where the sound diffused from the surface should be redirected to in order to achieve uniform sound distribution. This operation is done for two sound source locations and both surfaces.

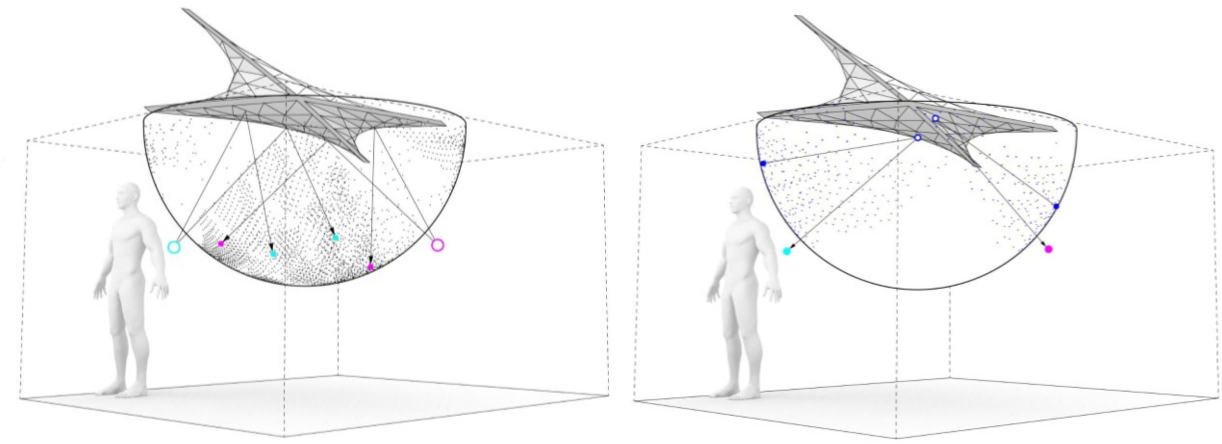

Figure 6 - Analysis of the uniformity of the reflections from the bottom surfaces (left); Finding the locations on the surfaces of the target rays (right)

The mapping of the points back to the surfaces follows the simple geometric principle of reflection from flat surfaces - the incident angle equals the reflection angle. Each point on the hemisphere is connected to the source with a line. From the lines' midpoints, a plane perpendicular to the line is generated. In this way, the curve where the plane intersects the surface is found (Figure 8 - right). The point closest to the midpoint is where the ray would hit the surface. Each point on the surface is then connected both to the source and the points on the hemisphere. In order to check that the interaction points are correct, a plane centred at each projected point on the surface is built perpendicular to the initially generated planes. Then a ray-tracing algorithm is used to visualize the reflected rays and their intersection points with the hemisphere. From the projected points a coloured map is generated showing in black the areas which should reflect the rays such as to hit the target points (Figure 8 - left).
Besides denoting the location of reflecting surfaces, the map is also used for defining the locations of absorptive and hybrid areas. The white spots on the map coincide with the areas focusing a part of the reflected rays, thus creating a density of points onto the hemisphere. In order to mitigate this effect potentially producing strong reflections in certain areas of the meeting room, absorption is provided. The grey areas instead show the transitional zones with hybrid treatment. In this way, a smooth gradient of performance is created ensuring uniformity of the reflected sound in the room.

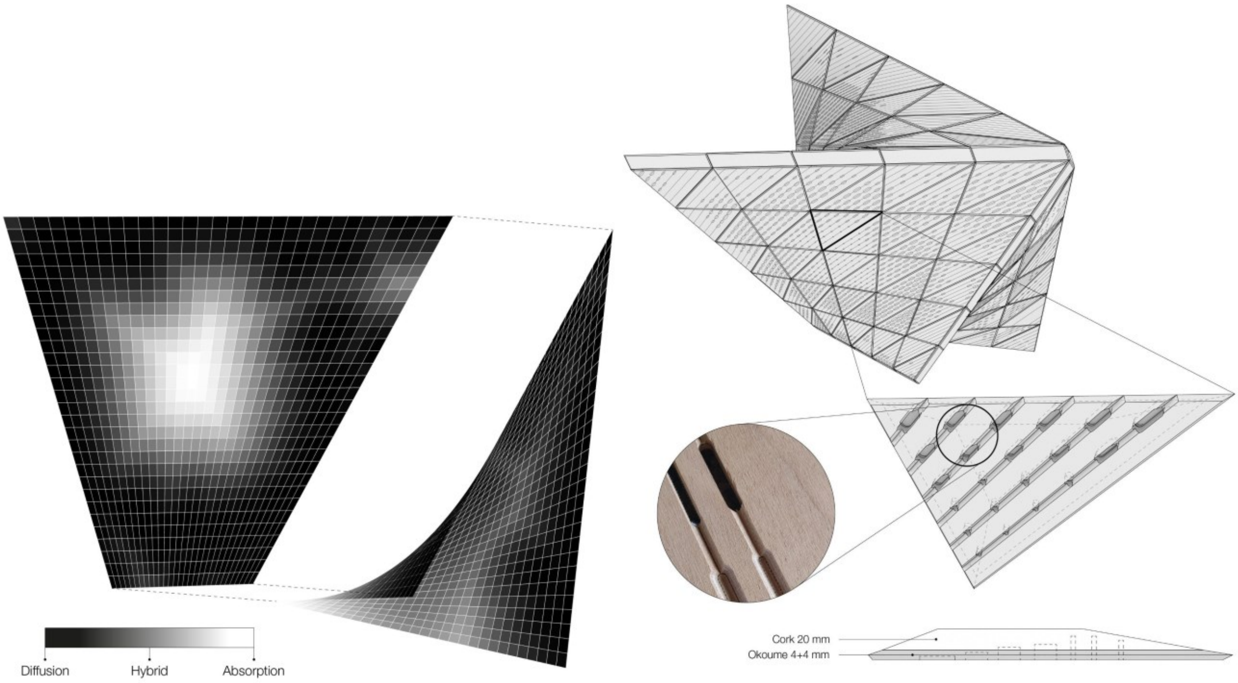

Figure 8 - Performance map (view from the bottom) for the bottom surfaces (left); pattern study and distribution (right).

Figure 9 - Acoustic surfaces

Two of the most typical perforation patterns, holes and lines, are explored for the local surface treatment. The goal was to look into the opportunities given by these rather simple geometric elements in differentiating as much as possible a surface according to given performance boundary conditions. The lines and points are thus distributed according to the colour map, defining the various performance zones. The holes start from the centre white areas where absorption is needed. A Helmholtz type absorber is created allowing perforation of the cork in the back and focusing on the low frequencies. Instead, in the black areas where diffusion is expected, lines are distributed providing geometric diffusion resulting from the surface irregularities. In these areas, cork is not exposed. Finally, the grey areas are dedicated to phase-grating diffusion where the holes are gradually transformed into elongated lines. In these areas cork, having different impedance than wood is exposed in order to provide for phase-grating diffusion and respectively also absorption (Figure 7 - right).

7 Conclusions

The paper describes an approach for the design of acoustic surfaces with differentiated performances answering to specific sound field conditions of existing spaces. The developments resulted in a digital design workflow where existing interior sound field parameters and user activities were integrated with the material system properties allowing the design, simulation and evaluation of acoustic surfaces that respond to the programmatic, performance and user necessities. The workflow is applied in a real-life case study, a co-working space, TAG Milano Calabiana where acoustic issues of excessive noise, speech disturbance and others are reported. The proposed multi-scalar approach serves as a design instrument that allows the differentiation of performances within the same material system by means of geometric characterisation. The application of neural networks for the classification of complex empirical data not only allows for complex multi-dimensional information to be sorted and properly analysed by the designer but also allows for new incomplete data to be clustered in the generated feature map by topological similarity. This can potentially be used for mapping much more complex feature datasets of materials and composites providing an opportunity for the extended use of new ecological materials for architectural acoustic applications. The next developments include the finalization of the acoustic surfaces, i.e. production files preparation and fabrication.

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