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Publication date
2016

Document Version
Final published version

Published in
Proceedings of the Symposium on Simulation for Architecture and Urban Design (simAUD 2016)

Citation (APA)
Vlaun, N., van Waart, A., Tenpierik, M., & Turrin, M. (2016). A Sound Working Environment: Optimizing the Acoustic Properties of Open Plan Workspaces Using Parametric Models. In R. Attar, A. Chronis, S. Hanna, & M. Turrin (Eds.), *Proceedings of the Symposium on Simulation for Architecture and Urban Design (simAUD 2016)* (pp. 239-246). simAUD.

A Sound Working Environment: Optimizing the Acoustic Properties of Open Plan Workspaces Using Parametric Models

Nick Vlaun, Arend van Waart, Martin Tenpierik and Michela Turrin

Delft University of Technology
Delft, the Netherlands
{n.j.v.vlaun, a.vanwaart, m.j.tenpierik, m.turrin}@tudelft.nl

ABSTRACT
Optimizing the acoustic environment of open plan offices is a complex task due to the large number of design parameters that must be considered. In current practice, acoustic analysis – even in a simplified form – is not naturally integrated into the design process of office spaces. Applying digital acoustic simulation in architectural design currently requires a time consuming back-and-forth transition between geometric modelling programs and specialist analysis software. In this study, an acoustic ray tracer was developed within Grasshopper and coupled to Galapagos in order to optimize the acoustics of an open office space. This tool has been tested and validated through a case study performed on an existing office space in the Netherlands. This study demonstrates the possibility to computationally optimize open plan workspaces by way of acoustic analysis performed on a parametric model. In its current form the presented model is still limited in its features and calculation speed. Hence, further development of the tool is needed in order to facilitate a truly seamless iteration and hands-on evaluation of different design configurations (with respect to room acoustic performance).

Author Keywords
Parametric design; acoustic simulation; room acoustics; multi-objective optimization; performance-based design

ACM Classification Keywords
I.6.5 [Simulation and Modeling]: Model Development; J.5 [Arts and Humanities]: Architecture; J.6 [Computer-Aided Engineering]: Computer-Aided Design (CAD)

INTRODUCTION
Over the last two decades, modern non-territorial offices with large open work environments have seen a surge across Europe. Past research shows that user complaints tend to increase with the application of open planning in the workplace. Compared to small enclosed offices, workers generally experience a loss of privacy and tend to be distracted more easily in large open workspaces that they share with colleagues [2, 13]. Noise is identified as a root cause of these problems and often poses the most severe indoor environment problem in open offices [16]. Optimizing the acoustic environment of an open plan office is a complex task due to the number of design parameters that must be considered [5]. The very concept of open office planning itself already invites some level of acoustical compromise, since the conflicting requirements of good speech communication and good speech privacy are asked to co-exist in a single physical environment [2, 24]. In other words, the office space should facilitate good speech intelligibility so colleagues can effortlessly engage in conversation. At the same time, privacy may be desired because we want a conversation to remain confidential and not be understood by others. In other cases speech noise is seen as a main source of disturbance [6, 10, 25]. Direct person-to-person speech propagation in a room can be lowered by placing screens, the effectiveness of which increases with their size: essentially acoustic performance will improve the closer you get to a cell-type office. Altogether this poses a predicament which is deemed too complex for most architects and is thus left to specialists who get consulted in later stages of the design process.

The relation between acoustic performance criteria and building properties is described and assessed using terms such as reverberation time, which are typically expressed in the form of mathematical equations. A point of contention can be made that most architects do not innately utilize such formulas. A translation into geometric representation would be better suited for application in design practice. In other words, design team members could gain understanding for the implications of certain decisions if information on acoustic requirements is directly expressed in room shape and material properties [4, 24]. Currently there is a lack of appropriate toolsets which allow us to easily evaluate the acoustic quality of design proposals in an interactive fashion. Though specialized acoustic analysis software packages do exist, these currently do not offer seamless interoperation with popular 3-D modelling programs. Their application in office design is also far from commonplace.

This work is motivated by the idea that knowledge on room acoustics, relevant to the design process, can be made more accessible to design professionals if it is visualized directly in a (parametric) architectural 3-D model. It is of our contention that acoustic design guidelines are too generalized to account for the intricacies of any specific

SimAUD 2016 May 16-18 London, UK

project. This calls for the development of an acoustic analysis definition which is easy to use and can be rapidly implemented in an iterative design workflow. By matching design alterations with corresponding acoustic predictions, the building physical implications of our proposals will be made evident, which would enable us to come to better informed decisions. In this project, we incorporated acoustic analysis in a parametric model and studied the merits of applying it to an automated optimization process. The main point here is that the results of acoustic simulation serve directly as feedback for the geometric and material reconfiguration of an architectural model.

TERMS AND PARAMETERS

Frequency and SPL

Sound consists of longitudinal pressure oscillations in air, which get meaning upon interpretation by human hearing. The sound wave is described by its wavelength and amplitude, which correlate to perceived pitch and loudness respectively. The frequency of sound determines the height of its tone (i.e. high frequencies correspond to high tones). In reality sounds are nearly always composites built up of many tones occurring at once. Human speech, for instance, contains frequencies in the range from 200 Hz to 5 kHz [3].

Sound pressure describes small positive and negative pressure variations in relation to atmospheric pressure we normally experience. Sound pressure level (SPL) is a logarithmic expression introduced to cover the wide range of pressure variations that can be detected by human hearing. It is a quantification related to the perceived loudness of sound, which is expressed in the decibel (dB) unit. The following equation applies:

$$L_p = 10 \log \left(\frac{p_{eff}^2}{p_0^2} \right) \tag{1}$$

p_0 is a reference pressure (20 μPa). SPL is not additive: a doubling of sound pressure equates to an increase of 6 dB. A normal level of human speech at 1 m distance is rated at 60 dB [3]. For the most important frequencies the smallest change in SPL detectable by human hearing, or 'just-noticeable difference' (JND), lies in the order of 1 dB [12].

Sound strength (G) is used to indicate the contribution of a room to the measured sound level from a sound source. In simple terms, this parameter effectively compares the sound level in a real room to the sound level an anechoic chamber with the same sound source [14].

Spatial decay rate of speech

The spatial decay rate (DL_2; $D_{2,S}$) indicates the decrease of sound with distance from the sound source. To be more precise, spatial decay is measured per distance doubling. A high decay roughly translates into low sound propagation over large distances, and vice versa. The inverse square law applies for sound propagation in a free field condition (outside without obstacles to reflect or block sound). The sound pressure of a spherical wave front, emitted by an omnidirectional point source, decreases by 50% each time the distance from the source is doubled: thus the spatial decay rate is 6 dB per distance doubling in this case. Target values for the spatial decay rate in an office depend mainly on the work activities, where tasks requiring high amounts of concentration will obviously lead to more stringent requirements. ISO/NEN 3382-3:2012 gives a general target value of $D_{2,S} \geq 7$ dB for open plan offices with good acoustic conditions [15].

Absorption and scattering coefficients

These are numeric expressions for material and surface properties. When a sound wave encounters a structure part of its energy is absorbed, part is reflected and the rest is transmitted through the structure [9]. The absorption coefficient (α) denotes the portion of sound which is not reflected. Hard materials reflect more sound than porous materials, and thus have a lower absorption. The scattering coefficient (s) is that portion of the reflected sound energy (1 – α) which does not travel in specular direction. This portion, which increases according to the roughness of a surface, instead reflects diffusely in all directions, as illustrated in *figure 1*.

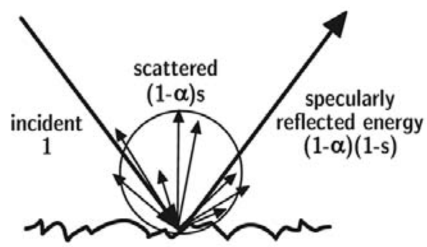


Figure 1. Energy reflected from a corrugated surface into a scattered and specular reflected portion [28]

DIGITAL SIMULATION OF ACOUSTICS

Sound wave theory, though correct from a physical point of view, is not deemed to be beneficial when it comes to dealing with practical issues in architectural acoustics. Computer simulations are instead typically based on the principles of geometrical acoustics: herein the concept of a wave is replaced by the concept of a sound ray [17, 28]. Analogous to light rays in optics, a sound ray is seen as a straight line along which a small portion of sound energy travels. Where sound in reality travels through a room from one person to another, rays in a simulation propagate from a defined source point to a receiver, interacting with the geometry of the room model along the way. The task in geometrical acoustics is to find the paths of sound connecting the source and the receiver [21]. Wave phenomena like diffraction and interference are typically neglected. Wavelength or frequency of sound is also not inherent to ray-based simulation models [22]. Ultimately geometric acoustics provides an approximation of the acoustical environment in a room. Its application is however justified if the dimensions of the room and its walls are large compared to the wavelength of sound [17].

Basics of ray tracing

For the simulation of sound in large rooms two geometrical methods are generally distinguished: ray tracing and image source model. These approaches have contradictory (dis)advantages. This has led to the development of hybrid models that seek to combine the best features of both methods [21, 22], which are typically found in commercial acoustic analysis software such as CATT-Acoustic [11] and ODEON [20]. A pure ray tracing algorithm is utilized in this study, due to its relative ease to implement compared to more complex hybrid methods.

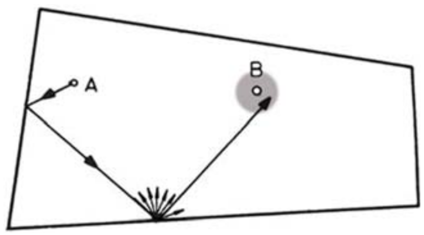


Figure 2. The principle of ray tracing [17]: the method is used to find sound paths between a certain point A (the source) and one or several points B (receivers)

In ray tracing a large number of rays are emitted from a source point in various directions (in our simulations we use an omnidirectional source emitting over 10.000 rays). Each ray carries a portion of the initial sound energy. Rays encountering the room boundary (walls) are subject to energy loss by absorption and will reflect and scatter as described further on. With each hit, rays lose energy according to the absorption coefficient of the wall. Tracing continues until a ray has no significant amount of energy left or a certain distance is reached. Counting volumes are used as receivers to record energy and elapsed time for every intersecting ray. Our model incorporates spherical receivers of variable size. As the use of receivers of constant size leads to systematic errors [18], the volume of a receiver is made a function of room size, source-receiver distance and amount of rays emitted by the source [29]:

$$V_{receiver} = \log\left(V_{room}\right) \cdot d_{SR} \cdot \sqrt{\frac{4}{N}} \qquad (2)$$

Modelling reflections

The direction in which sound energy is reflected off a structure depends on wavelength of the sound in question on one hand; and the shape, roughness and materialization of the surface on the other hand. As previously illustrated in *figure 1*, two types of reflection are distinguished:

- Specular reflections – Essentially the behavior of sound bouncing off a smooth and hard surface is similar as light being reflected by a mirror. The angle of incidence is equal to the angle of reflection in this case;
- Scattering – In practical cases room surfaces mostly have an irregular texture. When a sound wave encounters a convex or rough surface a distinct portion of the reflected energy is scattered evenly, instead of being limited to a singular specular direction.

The distribution of scattered sound energy follows Lambert's cosine law. This roughly comes down to the reflection of energy in all directions, the intensity of which is highest at a reflection angle perpendicular to the surface [17, 28]. From a computational perspective, generating new rays at each reflection point to model scattering is not feasible, as it would lead to an explosion of calculation time. For application in a computer model, one scattering angle is instead (randomly) chosen for each reflection at a time according to Lambert distribution. In our case we consider both specular and scattering reflections at the same time, applying a method for reflection modelling referred to as 'vector mixing' [8]. As shown in *figure 3* a single resultant reflection direction is determined by directly combining specular and diffuse reflections through weighted vector addition. The scattering coefficient determines the weighting between the two, with a coefficient of 0 equating to pure specular reflection and 1 equaling purely random scattering.

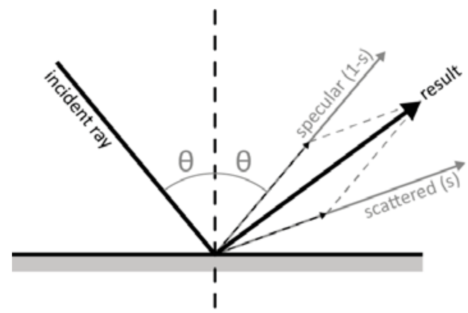


Figure 3. Construction of reflected ray by weighted addition of a specular reflection and a scattering vector [8]

The notion that scattering directions are chosen at random is important. An acoustic simulation can be performed twice with the same exact setup, but yield slightly different results between both runs. Though these differences are often not noteworthy in terms of human hearing, they are not small enough to completely ignore when we start to consider comparison of multiple design configurations. This inherently means simulation will be performed multiple times. This randomness issue has, at the time of writing, not been truly addressed.

Implementation in the parametric model

The process of software acoustical simulation consists of three subsequent elements [1]: source conception, the modelling method of the room (comprising the definitions for the geometric model and the tracing procedure) and modelling of the receiver. Our implementation of acoustic simulation in a parametric model follows the basic scheme of *figure 4*. The geometry and materials of the investigated

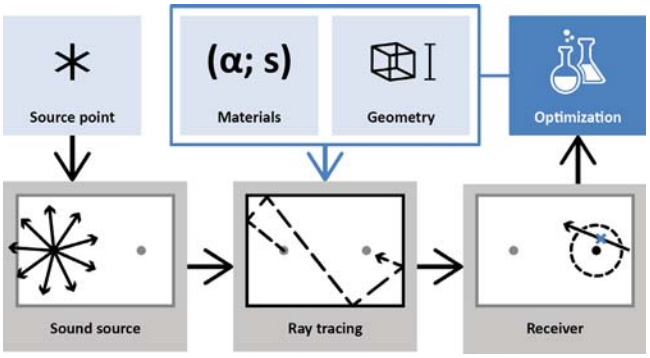


Figure 4. Principle of the acoustic ray tracing routine applied in an optimization process

room serve as input for the simulation. This is in our case done using a 3-D NURBS model created in Rhinoceros 5, in which objects with different materials are categorized in separate layers within the program. The ray tracing process yields a data set, including sound paths and a record of energy attenuation, related to the input. This data is interpreted at the receiver, where it is filtered to leave only relevant information, which is then converted to a single number parameter (sound pressure level in this particular case). The processed outputs of one or more receivers, along with other quantified characteristics of the modelled configuration, are used as a scoring mechanism to drive an automated process of optimization. Dependent on the outcome of acoustic analysis, geometry and material properties are changed, then re-analyzed.

Grasshopper model

Grasshopper is a graphical programming interface editor that integrates with the modelling tools of Rhino [23]. Logic is defined through the use of visual components containing predefined sets of code, which serve as building blocks for a model. By stringing components together a network of dependent operations is created. As such, the interrelation between parts of the created network represents itself visually as a block scheme on the canvas of Grasshopper. *Figure 5* shows the component network of our developed acoustic analysis tool. This definition contains two custom C# scriptable components which handle the ray tracing process and part of the receiver modelling:

- Tracing process – Takes starting rays and room geometry as input. The room geometry is inserted as a colored mesh, in which the color channels are used to temporarily store absorption and scattering coefficients. The traced rays and remaining energy at each reflection point are returned as output;
- Ray history interpreter – From the previously generated total tracing history, this component checks which segments of every ray cross a receiver (all non-relevant data is discarded). The amounts of energy left for crossing rays and their distance to the center point of a receiver are output. This information is later converted to quantifiable acoustic parameters (such as SPL and DL_2).

Multi-objective optimization with Octopus

Negotiating the architectural implications associated with limiting sound propagation in open workspaces, by definition comprises a trade-off between diverse aesthetic and acoustic performance measures. Multi-objective optimization, defined as the synthetic search for optimal values for two or more of such conflicting objectives [7], comes into play. The compromise between different performance aspects is described here through Pareto optimization, which is a state in which one thing can only improve at the expense of another [7]. Our definition incorporates the Octopus plugin for Grasshopper [27]. Octopus is an optimization engine developed by developed by Robert Vierlinger in cooperation with C. Zimmel and Bollinger+Grohmann Engineers. It utilizes SPEA-2 and HypE evolutionary algorithms to negotiate the space of possible design configurations, in order to find the front of Pareto optimal solutions. Evolutionary algorithms are stochastic search methods that mimic the metaphor of natural biological evolution and / or the social behavior of species [26]. The approach of evolutionary solving is characterized by the assessment of a pool or population of

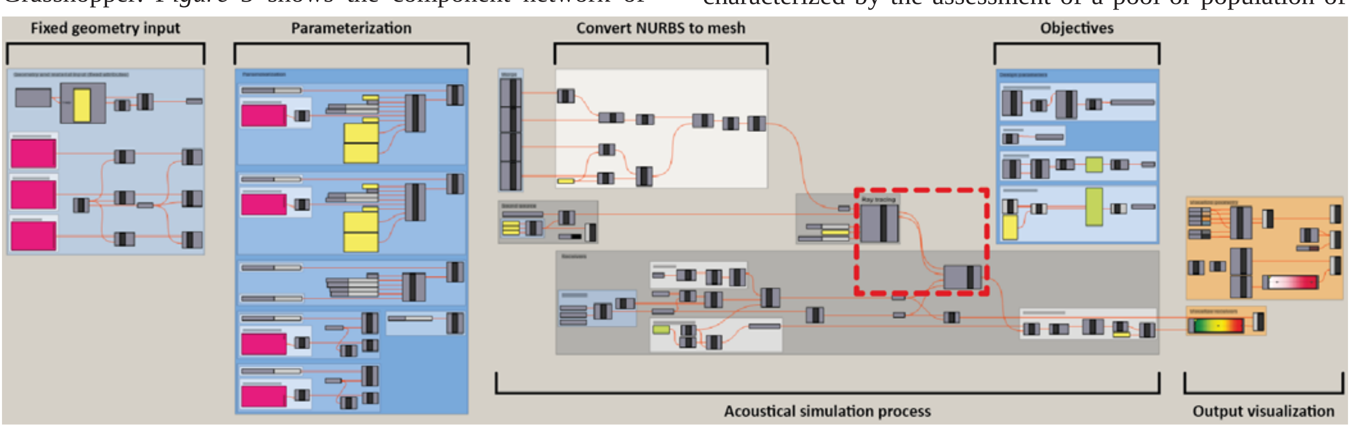
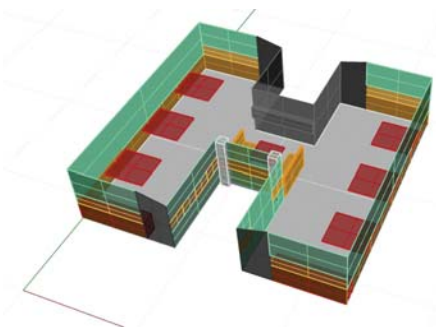


Figure 5. Component network of the Grasshopper definition: the custom scripted components are denoted by the dashed line

design solutions, rather than a single solution. Out of this pool, individual solutions are selected according to their adjustment to performance goals. New solutions may be generated through mutations and crossovers of previous elites, which are those configurations displaying the most favorable traits with respect to the fitness criteria [19]. In Octopus solutions are plotted in real-time on a 3-D graph, in which each axis represents a predetermined design criterion. In all, our overall process is aimed at finding a set of configurations in which a vast improvement of room acoustic characteristics is balanced with a limited degradation in the open appearance of the indoor space.

Model Validation

In order to benchmark the accuracy of the developed definition, its results are compared to those of a full detailed simulation run performed in CATT-Acoustic 8. An existing office space in the Netherlands which, for purposes of anonymity, will be referred to as 'office A' (*figure 6*) serves as our case study. The investigated workspace exemplifies a typical Dutch office by its layout and activities.

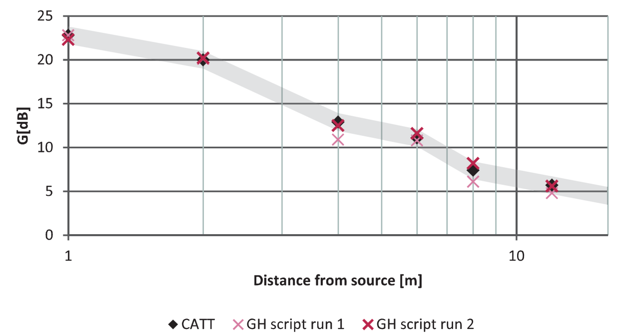


α [-]	s [-]
0,14	0,60
0,03	0,30
0,50	0,10
0,18	0,30
0,03	0,30
0,13	0,10
0,90	0,10

Figure 6. Rhino model of office A

Both simulations are based on the same Rhino model and the same measurement setup: a set of receivers placed in a straight line at fixed distances from a single sound source. The CATT-Acoustic program is set to utilize a detailed image source method with radiating surface sources for early specular and diffuse reflections, combined with ray tracing for late reflections. The simulations are assessed for the 500 Hz octave band only, with the material coefficients assigned to each surface as previously listed. Ray truncation time is kept consistent at 1 s, while the number of rays used within CATT is determined automatically by the program (amounting to over 18.000 rays in this particular instance). The results of the comparisons are shown in *figure 7*.

At two receiver positions deviations were observed between the measurements of CATT and Grasshopper which exceed just-noticeable differences. Upon inspection these receivers turned out to be partially intersecting with geometry. This a well-known detection problem of volume receivers [18]. The issue was corrected in a second run by moving the measuring line 0,3 m upwards. The differences for both SPL and DL_2 fall within the margin of error of the calculation in the corrected runs.



	1m	2m	4m	6m	8m	12m	DL_2
CATT	22,8	20,0	12,9	11,1	7,4	5,7	**6,0**
Run 1	22,8	20,1	10,9	10,8	6,1	4,8	**6,5**
Run 2	22,3	20,2	12,5	11,6	8,2	5,6	**5,8**

Figure 7. Comparison of the results returned by the Grasshopper definition vs. CATT-Acoustic

EXPERIMENTAL SETUP

The final optimization was performed using the model of office A. Within the modelled room a single source and several receivers are placed at a height of 1,2 m in fixed positions as indicated in *figure 8*.

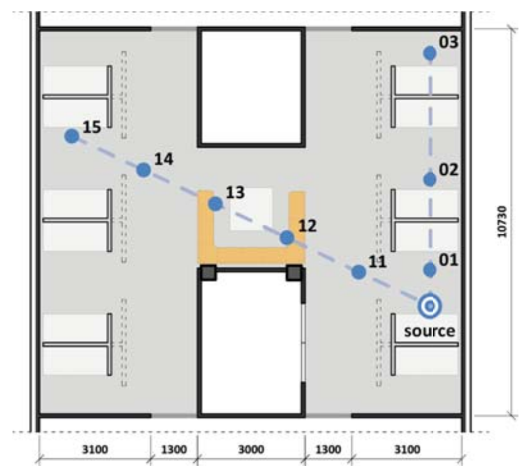


Figure 8. Floor plan of the 'office A' case study with measurement positions for acoustic simulation

Each time the design configuration is changed the SPL is measured at these receiver positions. The specific goal of the optimization runs is to maximize acoustic performance at places in the room where people might work (which equates in this case to a minimization of SPL). At the same time, the conflicting criteria of keeping the amount of added absorption and the size of placed screens to a minimum need to be satisfied. The following parameters are defined:

- Amount of absorption (minimized) – Calculated for each instance by multiplying the area of the surface with its absorption coefficient. All of the results are then summed for a room total;

- Surface area of screens (minimized) – The amount and size of screens that are placed within the room are viewed as antithetical to the open nature of the space;
- DL_2 (maximized) – Sound decay is measured across two lines of receivers. The first line is made up of receivers 01-03. The second line runs through receivers 11-15. DL_2 is obtained through linear regression of the measured SPL values at each consecutive receiver. This thus yields two values, one for each line, which are eventually averaged to a single value.

Variables

The starting point for the final model is the given space of office A in its current layout and material properties. The position of all the walls, the floor and ceiling, plus all furniture is fixed. The variables are as follows:

- Ceiling – The ceiling has been subdivided in 18 panels. These can have their absorption coefficient independently changed between 3 values (0,50; 0,70 or 0,90);
- Outer walls – The non-glazed portion of the façade is divided in 4 parts on each side according to the position of the desks. These parts can assume one of 3 values (0,10; 0,30 or 0,50) for its absorption coefficient. Glazed area remains unchanged;
- Internal walls – All of the glazed internal walls are parameterized. Every wall is divided over its height in three partitions. The middle portion is a closed panel with changeable absorption (0,10; 0,30 or 0,50), changeable dimensions and variable vertical position;
- Screens – Finally screens are placed in between and alongside the desks. Their height can vary in increments of 30 cm in the range of 0,9 m to 1,8 m. Their absorption coefficient is fixed to 0,30.

OPTIMIZATION RESULTS

The Octopus optimization presented here was performed on a custom built desktop computer, fitted with an i7-5920K CPU clocked at 3,8 GHz (calculations are single-threaded) and 8GB of RAM. Octopus' settings were mostly kept to their defaults, applying HypE reduction and mutation. The population size was set to 250 per generation. The total execution time of the process amounted to 11 days. During this time 141 generations were completed, which brings the total amount of evaluated design configurations to 35.250, averaging a calculation time of 26,2 s per solution.

The solutions yielded from the optimization process are graphed in *figure 9*. Each dot represents a unique solution. The position it has in the chart determines the performance of the solution in question with respect to the given parameters. In a sense, the position of the dot in the graph mathematically describes which objectives are prioritized in that particular model configuration. Theoretically speaking, solutions plotted closest to the origin of the chart should exhibit the best overall performance. One thing that is evident from the given results, is that the solutions with the highest sound decay ratings (those lowest on the vertical axes of all graphs) always employ a combination of high absorption and most screen area, as expected. In comparison to the current office, practically all of the configurations on the Pareto front score better when it comes to sound decay. This is attributed to the fact that office A in its current state has no screens whatsoever placed in between the desks. None of the optimized design instances approach this extreme due to the solution space being constrained in that regard.

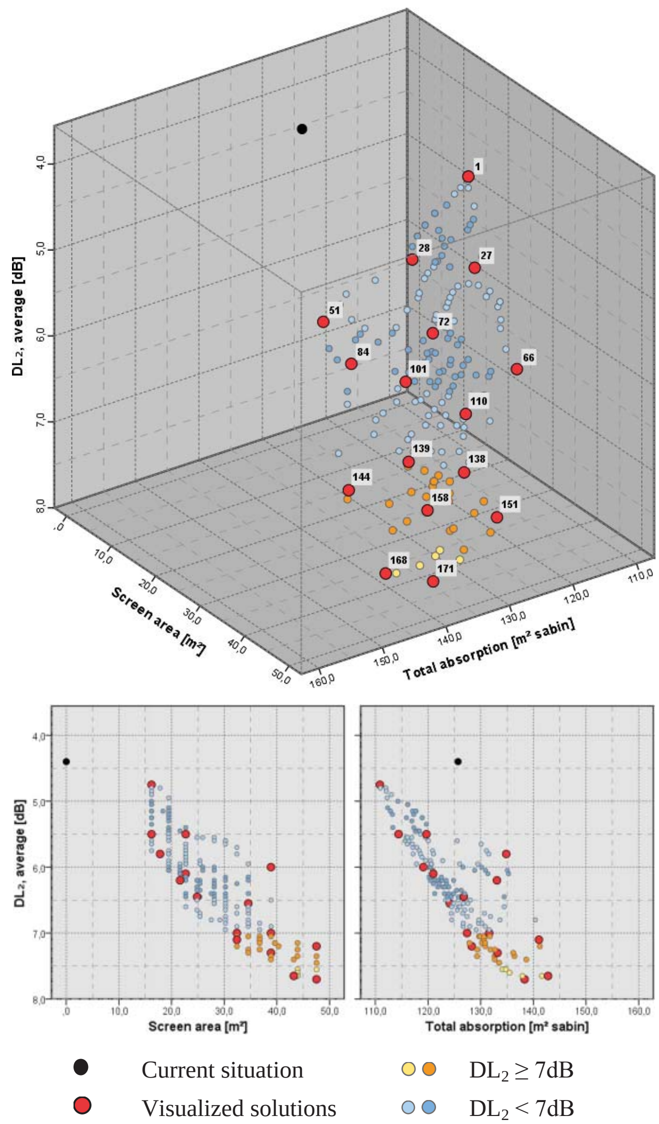


Figure 9. Pareto optimal solutions of the final generation of the optimization graphed

Upon further inspection it is also striking that the model instances with the highest DL_2 values have the absorption of the ceiling maximized closest to receivers 02 and 03. We found this to be one indication that the distribution of absorption given by the optimization, is dependent on the acoustic parameter being optimized and its method of measurement. Figuring out the exact relation between the used calculation method, applied parameters and the outcomes subsequently produced by the optimization process requires more in-depth scrutiny of the data.

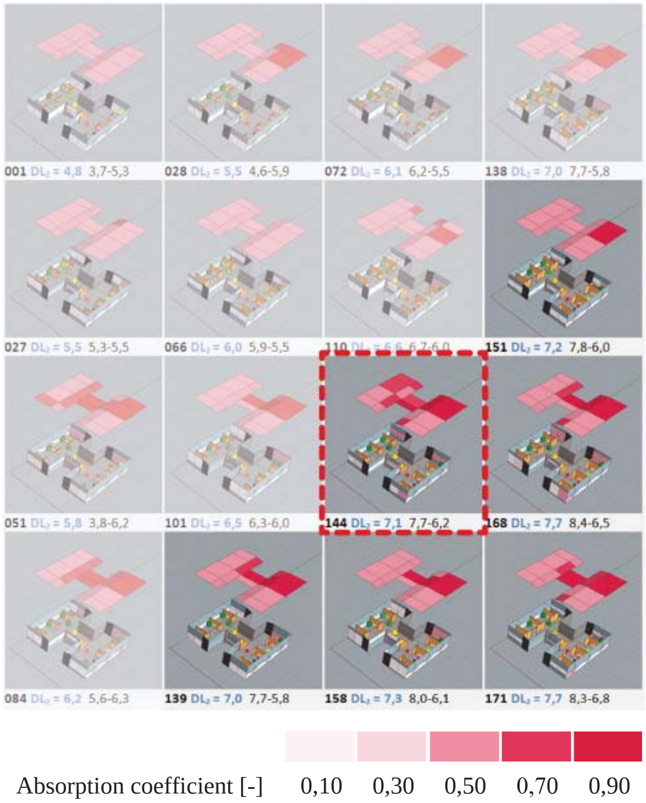


Figure 10. Configurations of sampled solutions sorted going from the least amount of absorption and screens (top left) to the acoustically best performing solution (bottom right)

One design alternative is finally selected for purposes of feedback and validation. As illustrated in *figures 9-10,* most of the given solutions do not reach the ISO-standard target value of DL_2; $D_{2,S} \geq 7$dB. For the final selection the solution is chosen which barely satisfies this criterion, with the smallest amount of screen area obstructing sightlines: this gives us 'solution 144'. Said configuration is firstly characterized by a screen height of h = 1,5 m. Keeping in mind that the source and receivers are placed at a height of h = 1,2 m; increasing the screen heights further (to 1,8 m) leads to configurations that outperform solution 144, although not by much. The effect of this increase is for instance far less evident than the same increase made between 1,2 m to 1,5 m screen height.

DISCUSSION

The developed ray tracing algorithm is a very simple implementation of acoustic analysis with parameterization capabilities and provides a basic framework that can and should be built further upon. In its current form sound pressure levels (and other parameters derived from SPL) can be analyzed in a given closed space. Through alteration of geometric entities and material properties, measured sound levels can be lowered, which should bluntly equate to an improvement of acoustic quality in the space.

The current model is still in its infancy and requires further development on several points. Key areas of improvement include increasing the reliability of the script and its results, making the definition faster in terms of calculation time and streamlining its use through the creation of a more intuitive user interface. First, evolving the script from a pure ray tracer into a hybrid model should prove to be beneficial for the accuracy of the results. Second, the current implementation could be made more efficient in a few ways. Due to the workings of the Grasshopper definition, the ray tracing process always starts over if any of the input variables are changed. This is however not necessary when only material properties are altered and room geometry stays the same. Furthermore, Grasshopper does not innately recognize cases in which two model instances with different inputs produce similar geometry. As a result, several evaluated configurations may look alike and thus return rather insignificant differences in terms of acoustic performance. In some cases a solution might even be evaluated twice or more. Calculation time can be greatly reduced if such unnecessary operations are taken out of the equation. Especially in parametric search, where multiple model configurations are assessed, increasing calculation speed is of paramount importance. Altogether, a more fundamental question is raised of whether evolutionary algorithms will ever be suitable in a practical application of acoustic optimization. As it stands, solutions returned by the optimization process are primarily presented by their individual performance in regard to the objectives. Comparing the visual and parametric characteristics of each solution is however done manually. This naturally constrains the amount of alternatives that can be inspected within any reasonable time frame and, in a sense, defeats the purpose of generating many design instances in the first place. An integrated form of statistical analysis could help to uncover relevant relationships between geometric or material alterations, and subsequent acoustic performance.

The optimization process in this study was performed with a measurement setup using a single stationary source at a time. Offices are however multi-talker environments: noise in the workplace is produced by several employees, whom are seated at different places in the room, who tend to move around and may speak simultaneously. An efficient measurement method that is more representative for this natural situation has yet to be developed.

CONCLUSION

Within this study it is observed that the computational optimization of open office environments is possible by integrating principles of acoustic simulation in a parametric model. Said model needs further development to become a viable and accessible tool in the arsenal of an architect or building physics consultant. Besides making improvements to the simulation algorithm itself, we have identified the necessity of including graphical post-processing features, so the results of the optimization process can be interpreted more effectively.

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