Fine Tuning of Aperiodic Ordered Structures for Speech Intelligibility

Karaiskou, Antigoni; Turrin, Michela; Tenpierik, Martin

Publication date
2020

Document Version
Final published version

Published in
Proceedings of the Symposium on Simulation for Architecture and Urban Design (SimAUD 2020)

Citation (APA)
Karaiskou, A., Turrin, M., & Tenpierik, M. (2020). Fine Tuning of Aperiodic Ordered Structures for Speech Intelligibility. In A. Chronis, G. Wurzer, W. E. Lorenz, C. M. Herr, U. Pont, D. Cupkova, & G. Wainer (Eds.), *Proceedings of the Symposium on Simulation for Architecture and Urban Design (SimAUD 2020)* (pp. 319-326). Society for Computer Simulation International (SCS).

SYMPOSIUM ON SIMULATION IN ARCHITECTURE + URBAN DESIGN
SimAUD 2020

Fine Tuning of Aperiodic Ordered Structures for Speech Intelligibility

Antigoni Karaiskou[1], Martin Tenpierik[2] and Michela Turrin[3]

[1]Buro Happold
Bristol, United Kingdom
anti.kara91@gmail.com

[2] TU Delft
Delft, The Netherlands
M.J.Tenpierik@tudelft.nl

[3] TU Delft
Delft, The Netherlands
M.Turrin@tudelft.nl

ABSTRACT

Speech intelligibility is crucial in many spaces, yet designers often fail to predict the acoustic shortcomings of certain design choices. This paper builds on the potential of hybrid surface treatments showcasing low-frequency absorption to control background noise levels and high-frequency diffusion to improve speech-in-noise perception to introduce a workflow that encodes this information in a format easily perceived by designers. After patterns are being classified based on periodicity into partly periodic, non-periodic or aperiodic, a matrix serves as a rule of thumb communicating to non-experts the critical variables for high-frequency diffusion, such as well depth sequence, scale and profile. These become inputs of a computational process that generates variations to tailor patterns for speech intelligibility. Lastly, plotted graphs that visualize quantitative figures obtained from simulations are marked by a bounding box relative to the effective frequency range for designers to evaluate examined patterns during the process of optioneering. This integrated workflow targets architects and designers that seek for visual feedback to support an iterative exploration of performance driven geometries, while recognizing the contribution of aperiodic order to uniformly distribute the flow of sound energy.

Author Keywords

Speech intelligibility; Surface tiling; Micro-geometry; Correlation scattering coefficient; Quasi-periodic symmetries;

1 INTRODUCTION

Advanced acoustical studies are mainly carried for performance venues rather than daily life environments as those require over-engineered solutions that raise the cost. At the same time, current computational tools are mostly focused on simulations that deliver numerical outputs that do not clearly correspond to geometrical equivalents. The novelty of this paper in the field of simulation lies in suggesting a coherent workflow that encodes complex quantitative results obtained from simulations in a format easily perceived by non-experts, thus greatly contributing to a transdisciplinary design approach to tune ordinary spaces.

Speech transmission in a multi-talker scenario is strongly influenced by the properties of a room requiring successful management of competing factors such as space size, proportion, geometry, material properties and surface details. In that respect, the relationship among sound and geometry is projected on both the spatial context and the surface properties. Nowadays the focus of acoustic simulations has been shifted from evaluating the performance of macro-geometry to obtaining coefficients for micro-geometries as it was proven that adjusting properties at a surface level can improve speech intelligibility for a given macro-geometry.

In the past, most efforts were focused on sound absorption, but over the last decade there has been a growing interest in improving sound performance in terms of scattering by generating complex micro-geometric surfaces through robotic fabrication methods. Most of these examples sought to avoid periodicity by increasing the complexity of the reflected sound field, thus generating complex surface patterns by means of computational resources based on randomness. According to recent findings, quasi-periodic symmetries show superior performance over the common diffusers due to their potential of eliminating periodicity [1]. Such structures seem promising for uniform sound energy dispersion avoiding the formation of bundled or looped reflections.

2 FRAMEWORK

Based on the findings of a MSc thesis for improving intelligibility for a typical absorptive classroom, this paper aims to contribute to the current debate by comparing spectral properties of highly ordered structures that are substantially nonperiodic, or aperiodic to partly periodic alternatives targeting the frequency range for speech intelligibility [2]. The study begins with a preschool environment as a problematic case study for speech intelligibility to define the targeted percentage of absorption and diffusion in the effective frequency range based on certain users' characteristics. The scope of the paper limits itself in tuning micro-geometric surfaces for high-frequency diffusion. Trying to investigate the effect of periodicity for a given pattern, it argues in favor of the theory of aperiodic order, suggesting mathematical structures that possess order without periodicity by regulating physical properties of spatial surfaces [3]. In that respect, it identifies a global set of critical geometrical properties that can influence the sound profile and utilizes Pachyderm2.0RC20 by plotting the

SimAUD 2020 May 25-27, Online

correlation scattering coefficient for comparison purposes. Discussing the results leads to a shift of the global set of properties to a local equivalent relatively to a pattern's periodicity classification.

The outcome if this, is a workflow that suggests a stepped process for tuning micro-geometric surfaces with a given amount of low-frequency absorption for high-frequency diffusion. In that respect, designers need to identify the effective frequency range per task and user group, define the amount of diffusion per frequency range and have it numerically manifested by giving a percentage (%), generate pattern iterations changing critical input parameters based on a local set of properties and compare the generated samples in terms of speech intelligibility by means of plotting the correlation scattering coefficient. Utilizing a computational workflow to quantify scattering seems critical for giving designers a visual feedback on the acoustic performance of their iterative explorations.

2.1 Speech Intelligibility in preschool environments

The first step lies in relating the targeted sound wavelengths for a given user group with the effective frequency range of both absorption and diffusion. To showcase this process, the example of a preschool environment serves as a challenging case study, as this dense and interactive environment poses a threat to intelligibility by running at a high occupancy rate, thus having an acoustic dynamic of high indoor ambient noise levels.

One of the most computationally demanding tasks for the brain is to recognize the message from the din since noise and speech are transmitted as a single stream. Speech-in-noise perception in a preschool environment is strongly related to the user's characteristics with neurological processes of encoding fundamental speech properties securing high signal-to-noise (SNR) ratio. Since cognitive and biological development are correlated, preschool children and those facing learning difficulties are two of the most vulnerable groups [4].

Four categories of uncomfortable sound can be recognized related to sound typology and source identification, namely, threatening sounds -screaming, crying, anger- , high frequency sounds -squeaking, creaking, scratching- , background sounds -fans, radiators, ventilators- and communication sounds [5].

2.2 Acoustic Requirements

Speech power comes from low frequency vowels (125-500Hz), whereas speech intelligibility is given by high frequency consonants (2000-6000HZ) [6]. Consonants consist of low intensity and short duration acoustic cues with a changing spectral content, whereas vowels are of higher amplitude, last longer and show an almost stable spectral content [7].

Harmonics enhance neural encoding by reinforcing the periodicity of a target speaker's fundamental frequency (F0) extracting relevant information from the auditory stream, thus allowing for speaker localization and analysis of the auditory scene [8]. Several studies proved that the response quality for high frequency acoustically dynamic speech cues, as well as harmonics, is degraded by noise, leaving them more susceptible to masking [7]. Early sound reflections, though beneficial, can affect timbre and localization phenomena if coming from nearby adjacent surfaces, resulting in listeners localizing the talker to another location than where (s)he is standing. Later reverberation is known to mask speech. In that respect, all reflections, but especially the ones arriving after 40 to 50 ms, can be considered a form of noise correlated to the signal [9].

Relevant acoustic measures

Speech intelligibility correlates with various measures, such as reverberation time and signal-to-noise ratio (SNR) to estimate the combined effect of room acoustics and background noise. Either too short or too long reverberation time will decrease speech audibility and speech intelligibility respectively, thus one should consider both speech transmission index (STI) and mid-frequency (500 and 1000 Hz octave frequency bands) reverberation time (T_{30}) to estimate the effective frequency range for either absorption or diffusion.

Measures	Parameters		Comments
Signal to Noise Ratio	SNR [dB]	15	Remove excessive absorption
Reverberation Time	$T_{30[s]}$	0.4-0.6	If too low, SPL can be reduced
Intelligibility	STI	0.6-1	An alternative would be U_{50}
Noise Level	$L_{A,eq}$ dB(A)	< 60	Typical: 80 dB(A)

Table 1. Target values as given from literature

2.3 Effective Frequency Range

Speech intelligibility is related to more than the acoustic measures. The sound level and its characteristics are influenced also by room acoustics, total number of children, pedagogic methods applied, ventilation systems. Typical values of sound pressure levels (SPL) in preschools are in the range of 75-80 dB(A), with children being exposed to higher SPL than personnel, namely 85 dB(A) [5]. Important to note is that there is a correlation between high SPL and frequency spectrum, in that high rates are reached in sound frequencies of 1000-4000 Hz, namely the typical spectrum of children's voices.

Improving speech intelligibility for a preschool environment requires a hybrid treatment, as low frequency absorption prevents amplifying vowel sounds and removes first-order strong reflections, whereas high frequency diffusion delays and temporally diffuses early reflections. For absorption to prevent amplifying vowel sounds of active children, lower frequencies, especially those at 125 Hz, should have the shortest reverberation time possible, in order to approximate the reverberation graph of a forest, which is argued to achieve high intelligibility properties [10]. The exact amount of absorption and scattering per effective frequency bands is given in Table 2 and is based on the findings of the aforementioned MSc thesis assigning high values for low frequency absorption and mid-to-high values for high frequency diffusion after conducting a Geometric Acoustics Modelling and Simulation study [2].

	Absorption (%)		**Diffusion (%)**	
Frequency range	Low	High	Low	High
Effective %	**90**	25	25	**50**

Table 2. Effective values of absorption and diffusion per frequency range

3 FINE TUNING OF MICRO GEOMETRIES

After defining the effective frequency range based on the preschool case study, absorption and diffusion targets need to be mapped to equivalent design rules. Though various databases deducted from current literature allow designers to pick and choose among design rules for low-frequency absorption, there is no equivalent workflow for tuning micro-geometric surfaces for high-frequency diffusion. Thus, the study aims to utilize outputs closing this gap.

The most typical device for diffusion throughout history is Schroeder's Quadratic Residue Diffuser (QRD), a phase grating device composed of a periodic arrangement of wells of equal width varying the depths, whose sequence is based on number theory. However, this design is stigmatized by various setbacks, such as unattractive visual appearance, specular reflections at high frequencies when increasing the well width beyond a certain value and non-uniform distribution of the reflected sound field due to the periodic repeating sequence. Certain modulation schemes around this type allowed for both spatial and temporal dispersion, causing a complex reflected wave front, while achieving high absorption at low frequencies due to the resonance created by the deep well system. However, these diffusers still have the issue of periodicity.

3.1 Mitigating the Problem of Periodicity

Periodicity can be problematic for scattering directivity as it is dependent on incidence angle and frequency. Thus, changing the positions of the sound source or altering the effective frequency range based on user characteristics and functional requirements can cause problems.

The concept of randomness for useful scattering

To eliminate periodicity, random sequences are utilized generating random or pseudo-random designs by arranging elements in a non-repeating way [1]. Patterns that resulted from random sequences showed the potential to increase the frequency range of useful scattering [11]. However, at high frequencies the dispersion by a modulated array can often be worse than for a periodic arrangement, meaning that custom designs need to be tested for their diffusion performance [12]. Such random patterns are also hard to generate or predict concerning their performance, due to them lacking a degree of order that defines their physical properties making them cost prohibitive.

Spectral properties of aperiodic order

A promising alternative to current methods that mostly yield numeric performance indicators for estimating scattering performance, is to analyze the spectral properties of diffraction, which might be better suited for interpretation by non-experts.

The spectral measure of diffraction is given by autocorrelation, which is interpreted as a Fourier transform, namely a weighted sum of periodic functions representing the harmonic perception of sound. In that respect, the diffraction pattern can be critical for encoding information about the spatial autocorrelation, whereby point spectra indicate order, which can be measured by analyzing the contribution of each frequency to the autocorrelation [3].

Physical qualities of quasi-periodic formations

Another optimum solution for uniform scattering performance could be a single, long number sequence with good aperiodic autocorrelation, as it gives just a single period without repetition. In that respect, typologies that, though globally unstructured, show a high degree of regularity locally seem promising towards achieving non-repetitive sequences. Highly ordered structures that possess order without periodicity, hence being substantially non-periodic or aperiodic, exhibit surprising properties linking to many areas such as dynamical systems, harmonic analysis, spectral theory and number theory.

Recently, a study explored the effect of different properties, such as structural height, arrangement and profile shape on random- and normal- incidence scattering coefficients for Penrose tiling patterns. Further, it tested fractal order, an inherent property of quasi-periodic formations, which showed high scattering capacity for a wide frequency range as well as high uniformity of scattering directivity [13].

3.2 The Mathematical Model of Surface Tiling

Since recent literature argues in favor of random, non-periodic and quasi-periodic formations, this study tries to fit in this context by comparing tiling arrangements that fall under these categories.

Tiling is defined as a countable group of closed sets that covers the plane in a non-overlapping manner [14]. In a mathematical sense this is represented by a finite set of shapes arranged in a system that tessellates a surface via geometric patterning, whereby local rules give the constraints on the way neighboring tiles can fit together [15].

In terms of periodicity, a tiling is defined as periodic if there exist, among the symmetries of the tiling, at least two translations in non-parallel directions. Meaning that one can outline a region of the tiling and tile the plane by translating copies of that region without rotating or reflecting. When no translations can recreate the same region, a tiling is thought to be non-periodic. A set of prototiles that can never tile the plane periodically is said to be aperiodic, often referred to as tiling of unbounded spaces.

Comparing hierarchical structures of self-similar systems
A performance comparison among three tiling arrangements, as a true representative sample of the general population of those structures, serves to identify important physical properties per effective frequency range. For tessellating the plane, the discretization strategies of Penrose tiling, Voronoi diagram and periodic centroidal Voronoi were applied to parametrically define test samples of 1 m^2.

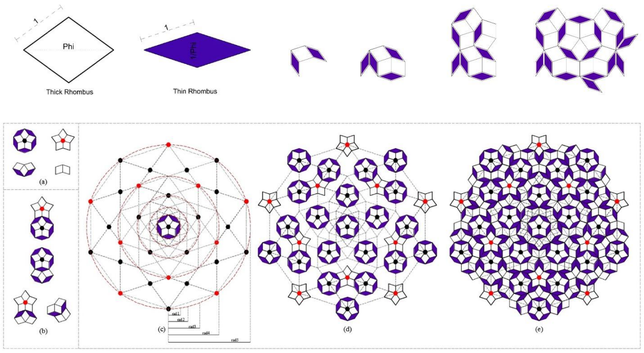

Figure 1. A framework of nested decagrams based on φ, serves as the underlying hidden grid for guiding the construction process of the quasi-periodic system.

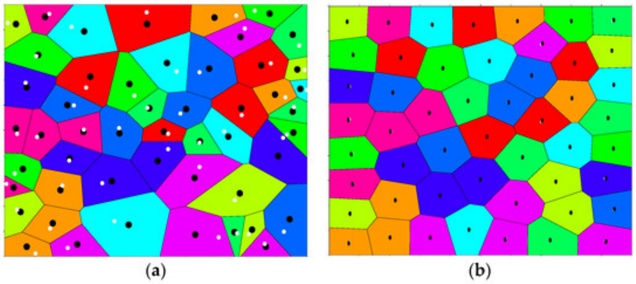

Figure 2. Random and centroidal Voronoi diagram: generators (white dots) and centroids (black dots): (a) random Voronoi diagram, and (b) centroidal Voronoi diagram.

The most famous aperiodic prototiles were invented by Roger Penrose in 1974. As shown in Figure 1, the so called "twin parallelograms" is an aperiodic tessellation of the plane by two prototiles without gaps or overlaps. The pair of rhombuses has equal sides, but their angles differ. The thick rhomb has angles of 72° and 108° and the thin rhomb 36° and 144° [13]. An interesting property is that the ratio of the two is the golden mean. Further properties involve self-similarity found mostly in fractals and finally a fivefold rotational symmetry due to quasi-periodic structure. Though Penrose tiling seems a chaotic sequence, it does represent a very regular local structure by having greater organizational depth [14].

The second typology, known as the Voronoi diagram achieves tessellation of a plane dealing with proximity to a countable set of sites P. The Voronoi region V(P) in the Euclidean plane consists of all the points at least as close to P as to any other site. As shown in Figure 2, the set of those Voronoi regions constitutes a plane tessellation denoted by Vor (P) and goes by Voronoi diagram generated by P. Following the rules for periodicity a Voronoi diagram of a non-periodic site set is a non-periodic tiling of the plane [14].

A special type of Voronoi known as periodic centroidal Voronoi tessellations (PCVTs) is shown in Figure 2, building the third typology for this study. In this case the generators of the Voronoi tessellations coincide with the mass centroids of the respective Voronoi regions and satisfy certain properties that enforce periodicity regarding some unit cells. The most common method for computing CVTs is the Lloyd algorithm [16].

Computational workflow for identifying design variations
The patterns were remapped on surfaces creating three-dimensional geometries based on certain properties. To identify whether a global set of critical properties would be applicable on all patterns whether aperiodic, non-periodic or partly periodic, a computational workflow was developed.

To ensure functional equivalency among the samples following rules were applied for generating the patters and deciding on the well sequence per diffusor. For the aperiodic sample of the Penrose tiling tessellation a grasshopper script in C# generating Penrose tiling was modified, whereby the thick rhombus represented the well of the diffusor. The non-periodic sample was based on Voronoi seeds that allowed for random seed generation to define the relative arrangement of the cells. The scale, namely the total amount of cells was set in respect to the proportions of the previous sample, whereby the 4-, 5- and 6-sided polygons were selected as the wells of the device. For the partly periodic sample, the centroidal Voronoi (CVT), scale and wells were similarly set relative to the non-periodic sample constrains. The test samples are shown in Figure 3.

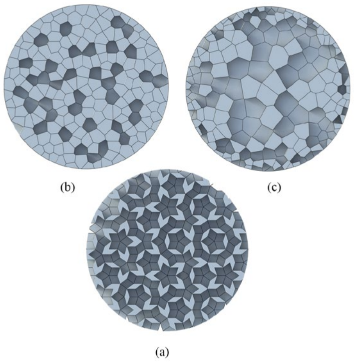

Figure 3. Test samples tessellations. Define wells and number of cells: (a) Penrose tiling, (b) Voronoi diagram and (c) Periodic Centroidal Voronoi

An overview of the simulation alternatives and their variables is given in Table 3. Fractal scale, geometric profile and well depth sequence were identified as global critical properties. The comparison distinguished among the following variables: a large or a small scale, an extruded or a tapered profile, two or various amount of well depths of either 20%, 50%, 150% or 200% depth-to-width ratio.

	Variables			
Critical Properties	Scale	Profile	Well depth sequence	
Aperiodic	Cells=2x Cells=x	Extruded Tapered	Two depths Various depths	(20/ 50/ 150/ 200) %
Non-periodic				
Partly periodic				

Table 3. Samples: physical properties and relevant variables

There are certain reasons behind evaluating this global set of properties. The scale serves to investigate whether the same scattering performance can be achieved with half the number of base elements, whereas the profile whether different angles could contribute to spatial dispersion of the sound field. Defining relevant well depths for comparison purposes is a challenging task, strongly related to the targeted frequency range. Varying among 20%, 50%, 150% and 200% depth-to-width ratio was decided based on the following. To achieve soft reflections a depth of 10-30 mm is efficient, whereas to eliminate echoes a greater depth of 50-90 mm is more appropriate [17]. The wavelength of sound (λ) equals the speed of sound divided by frequency ($\lambda = c/f$). A well depth that is given as ¼ of the wavelength λ, results in a 180° phase shift relative to a part of the surface without well. This procedure can determine the different depths relative to frequency ranges of 1 kHz - 4 kHz, due to the potential for local sound cancellation and complex reflection patterns [18].

3.3 Comparison Method for Iterative Design

Evaluating diffusion is complex and requires a more thorough investigation since (as absorption) too much or too little can result in acoustic aberrations. Achieving complete scattering at the design frequency and its multiples ensures that energy is not reflected in the specular direction but does not evaluate the quality of the produced dispersion. A diffuser apart from redirection needs to achieve spatial dispersion in order to reduce echoes without moving problems to a different place. Though energy dispersion is the most dominant approach for evaluating current diffusers, the phase in the polar response or the reflected impulse response are equally important. An ideal diffuser produces a polar response that remains constant when changing the angle of incidence and the frequency within its operational bandwidth.

Computational workflows that quantify scattering characteristics can serve designers get a visual feedback on the acoustic performance of their iterative explorations, thus allowing comparison of the scattering effect of the reflected wave front created by various output surfaces within a given room's macro-geometry.

Coefficients per band aperiodicity

The Schroeder Quadratic Residue Diffuser allowed for the first time to evaluate complete diffuse reflection due to periodic phase grating energy that caused grating loops [1]. After this, the most recognized methods for determining scattering coefficients can be summarized as follows: the standard method ISO 17497-1 performed in a reverberation room measuring random incidence values, a laboratory method in a rectangular room measuring normal-incidence values and a BEM-based numerical method in a free field measuring directional values [13]. However, such studies are complex and time-intensive, and their results can be interpreted only by experts.

Another method for evaluating a diffuser performance is estimating the correlation scattering coefficient from polar responses which was originally suggested by Mommertz [19]. The scattering coefficient in that case is given by the correlation of the scattered pressure polar responses from the tested surface and a flat surface. Hence, the measurement gives the dissimilarity between the test and flat surface scattering over a polar response, rather than the energy moved from the specular direction when the surface is moved. For randomly rough surfaces, the ISO scattering and correlation scattering coefficients will be similar, but for diffusers with distinct polar responses this is not the case [12].

Correlation scattering coefficient plots

The sample evaluation in this study utilized the software Pachyderm, version *Pachyderm2.0RC20* using the Finite Volume Method, which, though experimental for reliable quantitative predictions, is useful for comparison purposes of alternatives related to geometrical properties [17]. This is an open source code that recently incorporated a wave-based analysis of Finite Volume Method for estimating the correlation scattering coefficient as an input for Geometrical Acoustics software, although it only considers normal incidence.

For designers to support their iterative explorations with performance measures, the correlation scattering coefficient is thought to quickly visualize results per sample giving an indication of performance for comparison purposes among promising alternatives already checked for compliance if adhering to the rules previously defined as a critical set of global properties found in Table 3.

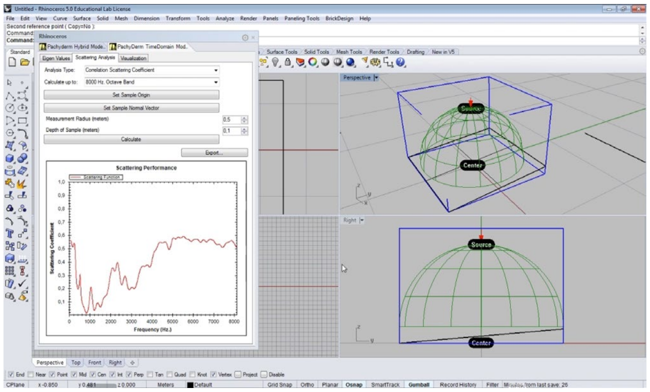

Figure 4. Coherent methodology for plotting the correlation scattering coefficient for comparison purposes

To minimize discrepancies on the obtained quantitative results a coherent methodology guided the various simulations. The samples were placed with their center at the origin (0,0,0) entirely below the given green sphere as show in Figure 4, while cleaning the model from any unnecessary geometry apart from the sample. Next, it was required to set a 'Measurement Radius' wide enough for a sphere of that radius to fully encompass the sample. Like the process followed in the scaled reverberation chamber measurements, the radius of the samples was set to r = 0.5 m with a circular perimeter.

4 VISUAL FEEDBACK

4.1 Rules for Compositional Pattern Producing Networks

The samples discussed in Section 3.2 utilized the global set of critical properties given by Table 3 to generate valuable alternatives, which were then fed into Pachyderm2.0RC20 that visualized the obtained quantitative results. As shown in Figure 5, a bounding box defines the relevant frequency range of the plotted graphs allowing for certain values of the correlation scattering coefficient plots. The relevant plot of the correlation scattering coefficient, as explained in Section 2.3, should be constrained within the range of 2000-7000 Hz obtaining values between 0.5-0.9.

For the well depth sequence of two depths, increasing the depth-to-width ratio up to 150% improved the performance of the samples only for the non-periodic sample, whereas increasing the scale has a positive impact for partly periodic ones. Choosing a well depth sequence of various depths of 200% depth-to-width ratio shows a better performance for the non-periodic and partly periodic samples, whereas the angled profile gives only a marginal improvement over the extruded in all tested cases**.**

Contributing to the discussion regarding the theory of aperiodic order, only one sample gave a scattering plot fully enclosed within the useful frequency range for speech intelligibility, namely the case of an aperiodic sample (cells=2x, extruded, two depths with a depth-to-width ratio=0.5). Though the correlation scattering coefficient is not enough to prove that the aperiodic samples perform superior to the non-periodic and partly periodic ones, this result is thought to be relevant arguing in favor of the theory of aperiodic order, given the 20 different configurations for assessing the critical properties for the three arrangement types.

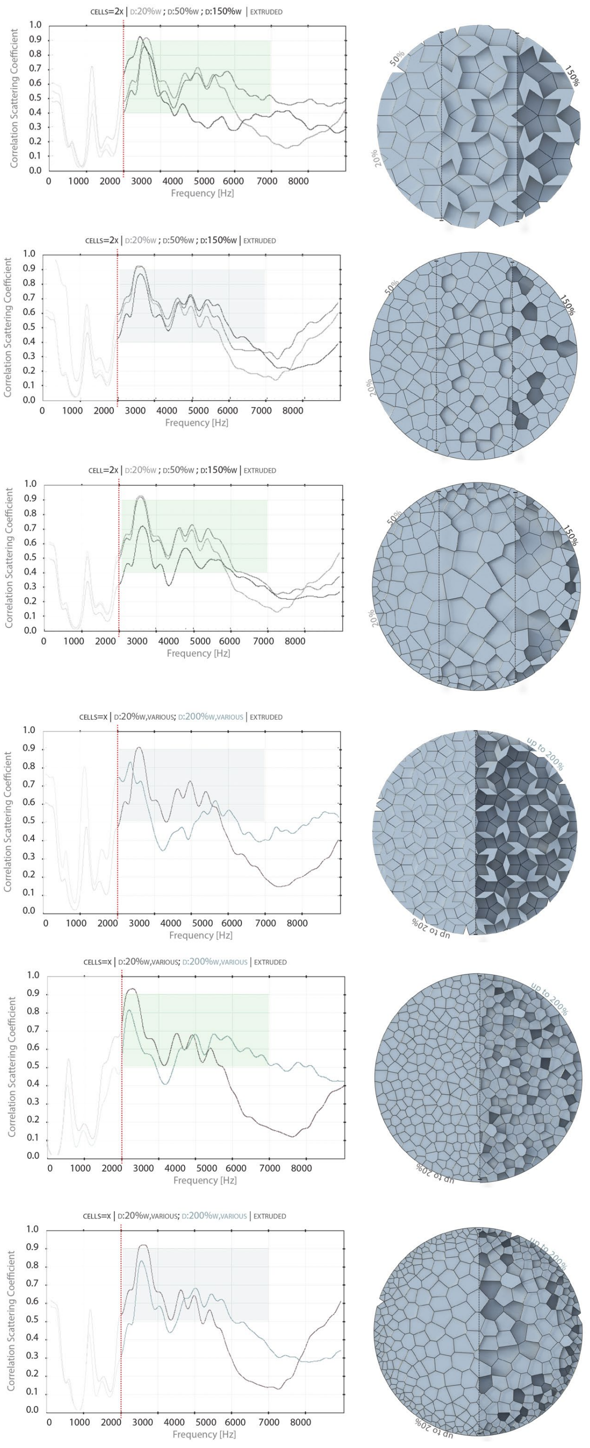

Figure 5. Iterative sample generation plotting the correlation scattering coefficient for comparison purposes

Guidelines based on the discussion of the results

The results obtained by this analysis as shown in Table 4 favor simplicity over complexity and are valid for the patterns tested for the purpose of this study, hence a generalization should be avoided. Nevertheless, the critical properties do change based on samples being aperiodic, non-periodic or partly periodic but whether the suggested variables are applicable to all patterns that fall under those categories would require further testing of examples that fall under these classes.

	Variables			
Critical Properties	Scale	Profile	Well depth sequence	
Aperiodic	Cells =2x	Extruded	Two depths	depth-to-width = 0.5
Non-periodic	Cells =2x	Extruded	Various depths	depth-to-width = 2
Partly periodic	Cells =2x	Extruded	Various depths	depth-to-width = 0.5

Table 4. Matrix providing optimum variables per case study

However, there is a clear shift from a global set of properties to a local equivalent based on each pattern's periodicity classification. In that respect the matrix proposed in Table 4 serves in identifying the local set of critical properties for generating valuable design alternatives per pattern. Further guidelines for the digital evolution of compositional patterns followed by designers could serve a performance-related approach for structures that comply with the concept of aperiodic order.

1. Based on a pattern's periodicity classification, the optimum depth-to-width ratio needs to be defined, without exceeding a certain threshold since deeper valleys could potentially increase absorption. Note that the design frequency per device cannot be shifted relative to changing the well depth for normal incidence, as utilized by Pachyderm2.0RC20.
2. The complexity and the number of elements should be decreased by avoiding various depths and increasing the scale where possible.
3. Different geometry profiles are encouraged to be investigated, while being aware that small scale specular reflection is expected for angled or curved surfaces at high frequencies.

4.2 Limitations and Suggestions

The suggested workflow examined the effect of physical properties of aperiodic mathematical structures compared to partly-periodic and non-periodic only on normal-incidence scattering coefficient, as it was found that the scattering coefficient for Penrose-tiling-type diffusers are largely independent from incidence angle [13]. However, further compatible workflows should as well as simulate random incidence scattering coefficients, while testing the uniformity of scattering directivity, given that these properties are critical to evaluate the performance of the reflected sound field.

Towards diffuser optimization the diffusion coefficient, which is frequency dependent, is of great importance, complementary to the scattering coefficient, providing an index to measure its quality. To avoid confusion due to edge diffraction at low frequencies, the normalized diffusion coefficient should be considered evaluating the level of uniform spatial reflections [12].

As far as the patterns are concerned, quasi-periodic formations seem promising for estimating further acoustic properties. Fractal order, which gives higher uniformity into the polar distribution was not considered for this paper but is a critical property especially if considering hierarchical structures of self-similar systems. Structures that allow self-similar systems to emerge offer a possibility to broaden the effective frequency range. Further, utilizing three-dimensional quasi-periodic sequences for well depths seems promising, investigating space-filling rather than plane-filling geometries, such as Ammann's tiles, rhombohedra etc.

5 CONCLUSION

Engineering sound propagation as a function of spatial volume and surface properties can influence the way in which an emitted sound is heard after being projected back into the space. Best practice considers both the macro-geometry of a space, including curved, flat or intersected walls, as well as fine-tuning the micro-geometry of various surface patterns. Certain geometrical properties can allow design products to act as acoustic filters, concentrating and/or dispersing sound in temporal and frequency domains [14]. Modern parametric modeling allows the quick iteration of many design alternatives, supporting a generative design workflow to create variations based on critical properties. To evaluate those based on performance measures, simulations that are strongly dependent on geometry, rather than material properties are required. In that respect, the correlation scattering coefficient can be useful as a comparison method for non-experts to visualize the acoustic performance of their design iterations. As opposed to the assumption that in general more complex surfaces are expected to yield greater scattering, this study argues that a lower level of complexity can still yield a complex wave front if hierarchical structures that exhibit aperiodic order are utilized. The suggested design-oriented workflow identifies the critical properties of those structures and allows designers to run iterations creating and testing different configurations in respect to uniform scattering across a broad spectrum to ensure intelligibility of everyday spaces.

REFERENCES

1. Ajlouni, R., *Quasi-periodic Geometry for Architectural Acoustics.* ENQ Enquiry A Journal for Architectural Research, 2018. **15**(1): p. 42-61.
2. Karaiskou, A., *Bricks as Spatial Sound Modulators: Towards tuning the geometry.* 2018.
3. Baake, M., D. Damanik, and U. Grimm, *Aperiodic order and spectral properties.* 2017.
4. Thompson, E.C., et al., *Individual differences in speech-in-noise perception parallel neural speech processing and attention in preschoolers.* Hearing Research, 2017. **344**(44): p. 148-157.
5. Waye, K.P., *Sound, mind and emotion research and aspects.* 2009.
6. D'Antonio, P., *Optimizing the signal to noise ratio in speech rooms using passive acoustics.* Proc. Meet. Acoust. Proceedings of Meetings on Acoustics, 2013. **19**.
7. White-Schwoch, T., et al., *Auditory-neurophysiological responses to speech during early childhood: Effects of background noise.* Hearing research, 2015. **328**: p. 34-47.
8. Kraus, N. and T. White-Schwoch, *Neurobiology of Everyday Communication: What Have We Learned from Music?* Neuroscientist, 2017. **23**(3): p. 287-298.
9. Charles, M., *Acoustics : architecture, engineering, the environment*. 1998, San Francisco, CA: William Stout Publishers.
10. Minna, H., et al., *Child & Noise : How does the child percieve the sound environment?* 2017.
11. Reinhardt, D., *The sound of space in 3 robotic prototypes: Introducing 6-axis robotic fabrication to shape macroand micro-geometries for acoustic performance.* AZ A/Z : ITU journal of Faculty of Architecture, 2018. **15**(1): p. 79-92.
12. Cox, T.J. and P. D'Antonio, *Acoustic Absorbers and Diffusers, Third Edition: Theory, Design and Application*. 2016, Boca Raton; Florence: CRC Press: LLC Taylor & Francis Group
13. Hyojin, L., T. Yuzo, and S. Tetsuya, *Acoustic scattering characteristics of Penrose-tiling-type diffusers.* APAC Applied Acoustics, 2018. **130**: p. 168-176.
14. Cáceres, J. and A. Márquez, *An aperiodic tiles machine.* 2002.
15. Ostwald, M.J., *Architecture and Mathematics from Antiquity to the Future Volume II: The 1500s to the Future.* 2015.
16. Zhang, J., Q. Du, and M. Emelianenko, *Periodic centroidal voronoi tessellations.* Int. J. Numer. Anal. Model. International Journal of Numerical Analysis and Modeling, 2012. **9**(4): p. 950-969.
17. Rahm, P., M. Ramsgaard Thomsen, and M. Nguyen, *Humanizing Digital Reality Design Modelling Symposium Paris 2017.* 2018.
18. Reinhardt, D., et al., *Robotic Fabrication in Architecture, Art and Design 2016 / Dagmar Reinhardt, Rob Saunders, Jane Burry, Editors; Foreword by Sigrid Brell-Çokcan and Johannes Braumann, Association for Robots in Architecture; with contributions by Marjo Niemelä*. 2016, Springer: Switzerland.
19. Vorlander, M. and E. Mommertz, *Definition and measurement of random-incidence scattering coefficients.* Applied acoustics. Acoustique appliqué. Angewandte Akustik., 2000. **60**(2): p. 187-199.