Integrating design, acoustic performance and fabrication: the case of the acoustic optimization of a meeting room

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Integrating design, acoustic performance and fabrication: the case of the acoustic optimization of a meeting room

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The integration of design, performance and fabrication has been object of continuous research in contemporary architecture. However, this integration is rather limited for the acoustic performance, which is commonly introduced at later stages of the design process. This paper aims to present the integrated design and fabrication of an acoustic performance-driven wooden structure in an existing meeting room. A complex double curved structure has been considered for the general shape of the design concept. It has been based on a "two-way joist shell" (waffle structure) realized through the repetition of a single reference module, embedding different acoustic properties: absorptive, reflective and diffusive. The room clarity and reverberation time have been considered as key performance indicators throughout the existing conditions measurements phase, simulations and optimization workflow. The paper gives an overview of the conception and implementation of a digital workflow that is applied at a first level for the integration of the design and acoustic performance, and at second level for the integration of the design and digital fabrication of a full-scale prototype and its practical execution. Finally, the work highlights the advantages of a process that incorporates interdisciplinary techniques and innovations in the built environment.

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INTRODUCTION

One of the defining characteristics of contemporary architectural design is the growing emphasis on integrating form, technology, and performance into cohesive and effective design solutions. [1] The Performance-Based Design (PBD) approach has emerged as a strategy to effectively address increasingly stringent functional and environmental requirements, shifting the focus from form-oriented to performance-driven architectural processes. Within this framework, a parametric workflow can be defined as a process that links geometric definition and performance evaluation through interdependent parameters and iterative simulation.[2]

Among the various physical phenomena that influence the interior comfort of buildings, acoustics is one of the most challenging for architects to include in the design workflow.[3] Traditionally, acoustic considerations are introduced at later design phases, typically managed by acoustic specialists after fundamental decisions regarding geometry and materials have already been made.[4] Such delayed integration often results in compromised acoustic performance, necessitating costly, less effective, and aesthetically intrusive corrective measures.

Introducing acoustic design considerations at the conceptual stage is therefore essential, particularly in spaces where acoustic quality directly influences functionality, such as meeting rooms, auditoriums, classrooms, and collaborative workspaces.[5] To effectively achieve this early integration, designers must be equipped with accessible computational tools capable of providing immediate insights into the relationships between initial design decisions (such as room geometry, spatial configuration, and material choices) and their acoustic outcomes.[6] Visual Programming Languages (VPL) represent a promising method for achieving this integration, enabling architects to intuitively explore and assess acoustic performance without extensive acoustic expertise or advanced computational methods.[7]

The effectiveness of such tools heavily depends on selecting appropriate acoustic parameters. Recent research highlights that while T_{30} and C_{50} effectively respond to variations in room geometry, layout, and distribution of absorptive and diffusive materials, STI exhibits low sensitivity to these factors unless substantial changes in background noise occur.[8] Although T_{30} and C_{50} are inversely correlated (as longer reverberation times reduce the early-to-late energy ratio) they describe complementary aspects of the same acoustic behavior, linking reverberation decay to perceived clarity.[9] Consequently, both the two parameters provide meaningful and sensitive feedback during iterative design exploration.

This paper investigates, the effectiveness of integrating parametric acoustic design methodologies through a detailed case study. This case study involves the design, computational simulation, and physical realization of a "two-way joist shell" (waffle structure) [10], employing a modular system that integrates acoustic absorption, reflection, and diffusion properties. Acoustic performance predictions from digital simulations are validated through measurements conducted before and after installation of the acoustic modular system, highlighting the potential and practical effectiveness of the proposed integrated design approach.

METHODOLOGY

The study is performed considering the case of a shoebox meeting room. First, acoustic measurements of the existing conditions were carried out and compared with simulation data to define baseline performance and identify critical issues. Based on these results, a custom acoustic intervention was developed through a parametric and iterative workflow, integrating early design intentions, formal and functional requirements, and fabrication constraints into a coherent structural and acoustic system.

A. CASE STUDY

The case study is a meeting room located within the Centro Studi PLINIVS at the University of Naples Federico II (Italy). The room was selected due to recurring reports of poor acoustic comfort by its regular users. It presents a typical shoebox configuration, with a rectangular plan, parallel walls, and a hard, reflective envelope. As shown in

Figure 1a, the space is furnished with a U-shaped table surrounded by chairs, and it is primarily used for presentations and meetings, often involving a single speaker addressing an audience in a frontal configuration.

Despite the room's intended use for speech-based activities, its design did not incorporate acoustic optimization. In fact, the shoebox geometry of the room, characterized by parallel walls and flat surfaces, causes repetitive sound reflections and excessive reverberation.

In addition, material finishes (including predominantly untreated plaster surfaces) contribute to excessive reverberation, compromising listener comfort and communication effectiveness. As shown in Figure 1c, acoustic absorption coefficients for all surfaces were identified and assigned, showing a predominance of acoustic reflective materials.

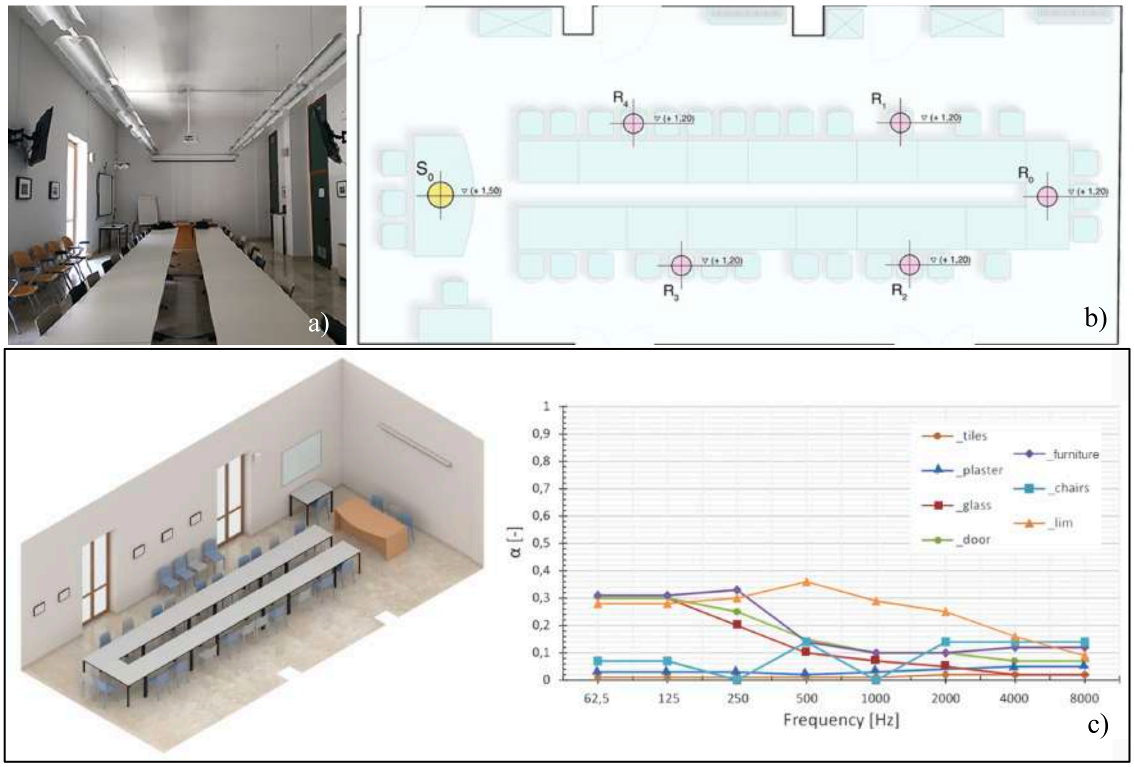

Figure 1. a) Photo of the pre-construction condition of the PLINIVS meeting room. b) Meeting room layout configuration. c) Tridimensional model of the PLINIVS meeting room and absorption coefficients identification.

B. PARAMETRIC APPROACH IN THE DESIGN WORKFLOW

The study aims to develop a fully integrated system in which spatial architectural definition, acoustic performance, and structural feasibility converge within a coherent architectural strategy. Rather than applying predefined solutions, the design process focuses on crafting a tailor-made intervention, where the ceiling becomes both an acoustic device and a spatial structure. The objective is to define a system that is formally expressive, acoustically effective, and feasible with self-building tools, a custom solution developed specifically for the space in question.

One of the fundamental challenges of this approach is the control of complex shapes in a multi-objective design process, where geometric, acoustic and manufacturing variables are simultaneously considered. As shown in Figure 2, the design workflow follows a structured and iterative process. It begins with the acoustic characterization of the existing room, providing essential data for defining configuration hypotheses. The development of these hypotheses is conducted in a parallel manner, with consideration given simultaneously to both the overall design of the structure and the panel design. Each of these hypotheses is informed by specific performance targets. Acoustic simulations support the acoustic evaluation step, enabling feedback loops and continuous adjustments between design and performance analysis. Once optimal conditions are reached, the process advances to final design, digital fabrication, and assembly, ensuring that all decisions are validated against both acoustic and manufacturing constraints.

The effectiveness of the configurations was assessed using a recursive algorithm. The study of the initial conditions represented a crucial step in identifying the necessary interventions to improve the room's functional performance. Based on a general understanding of established acoustic correction strategies, both macro-level transformations and punctual interventions (such as the development of customized panels) were explored within the same parametric and performance-driven framework.

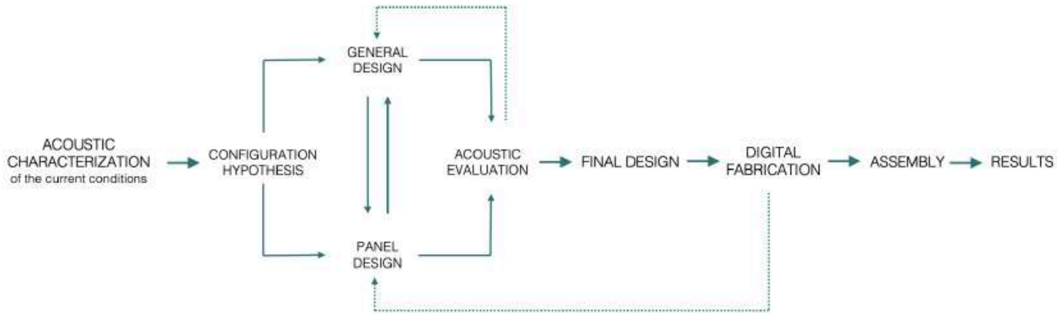

Figure 2. Design process workflow

I. ACOUSTIC PARAMETERS AND CHARACTERIZATION

The DIN 18041 standard defines optimal reverberation time values according to the different activities in a room for speech or music, the room volume, and the frequency in octave bands.[11] Initially, optimal acoustic performance targets were defined based on established acoustic standards. According to DIN 18041, the optimal reverberation time ($T_{opt,\,occ}$) for occupied speech-oriented rooms is calculated as follows:

$$T_{opt,occ} = 0.32 \log V - 0.17 \; [s]$$

where V is the room volume in cubic meters. Furthermore, the Italian standard UNI 11532-2 recommends that rooms dedicated to speech with volumes below 250 m³ should achieve clarity index values (C_{50}) greater than or equal to 2 dB in the frequency range of 0.5–2 kHz. [12]

The existing room was modeled in 3D using Rhinoceros (McNeel), and the acoustic simulations of reverberation time (T_{30}) and clarity (C_{50}) were then carried out in Grasshopper using the Pachyderm Acoustics[13] plugin. Moreover, a series of on-site acoustic measurements were conducted using accessible low-tech equipment (balloons as impulse sources and a smartphone microphone for recordings), analyzed with the Audacity's plugin Aurora to extract T_{30} and C_{50} values.[14] In each simulation and measurement, characteristic source and receiver positions were selected to reflect the top-down communication layout of the room, with a single speaker addressing a seated audience arranged in a frontal configuration (Figure 1b).

Figure 3a-b illustrate the comparative analysis between simulated results obtained with Pachyderm, T_{30} and C_{50}, respectively. T_{30} simulation results are compared with measured values, obtained through Aurora, in order to calibrate the simulation settings.

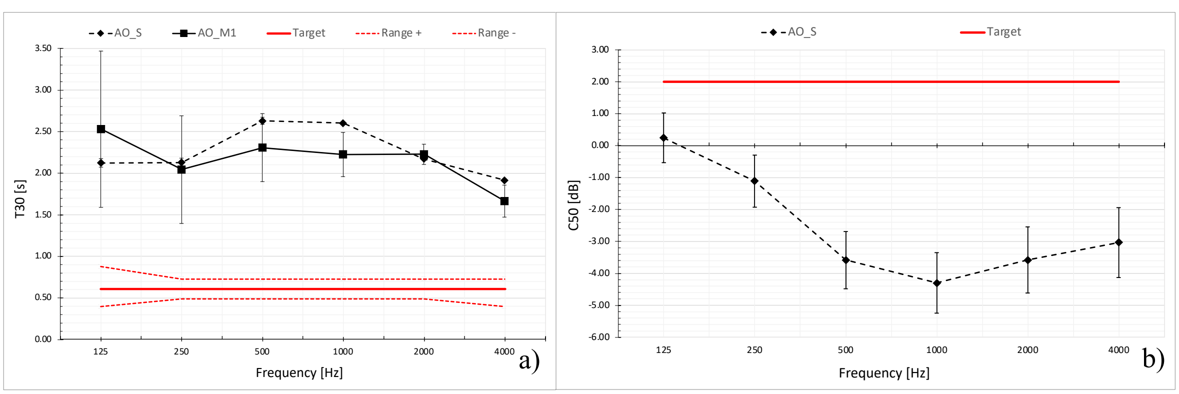

Figure 3. a) T_{30} simulation with Pachyderm Acoustics compared with pre-construction measurements in order to calibrate the simulation set-up. It is shown the optimal reverberation time calculated according to DIN 18041. b) C_{50} simulation with Pachyderm Acoustics. It is shown the target objective of 2 dB. AO_S: Pre-construction simulation; AO_M1: Pre-construction measurements with low-tech equipment.

C. CONFIGURATION HYPOTHESES

Other than T_{30} and C not meeting the optimal values, one of the most evident considerations that emerges from the pre-construction acoustic evaluations, is the spectral imbalance of T_{30} approximately 0.6 s between the 500–1000 Hz band and the rest of the spectrum, suggesting the need for a more uniform reverberation profile.

Regarding C_{50}, the overall curve trend suggests worst clarity in specific frequency bands. Another relevant observation is the significant variability between different receiver positions, as shown by the error bars in Figure 3a-b indicating uneven distribution of clarity and intelligibility across the room. Based on these considerations, the design objectives were defined as follows:

- Reduce reverberation time across all frequency bands.
- Flatten the reverberation response in the 125–2000 Hz range.
- Improve the spatial uniformity of sound clarity within the room.

As a first exploratory step, three configuration hypotheses were developed following DIN 18041 guidelines and tested through preliminary simulations. Considering that low frequency didn't show critical values in the pre-construction configuration, absorption coefficients of a commercial porous panel were used ($a_w = 0.6$). The configurations and resulting performance data are illustrated in the following Figure 4.

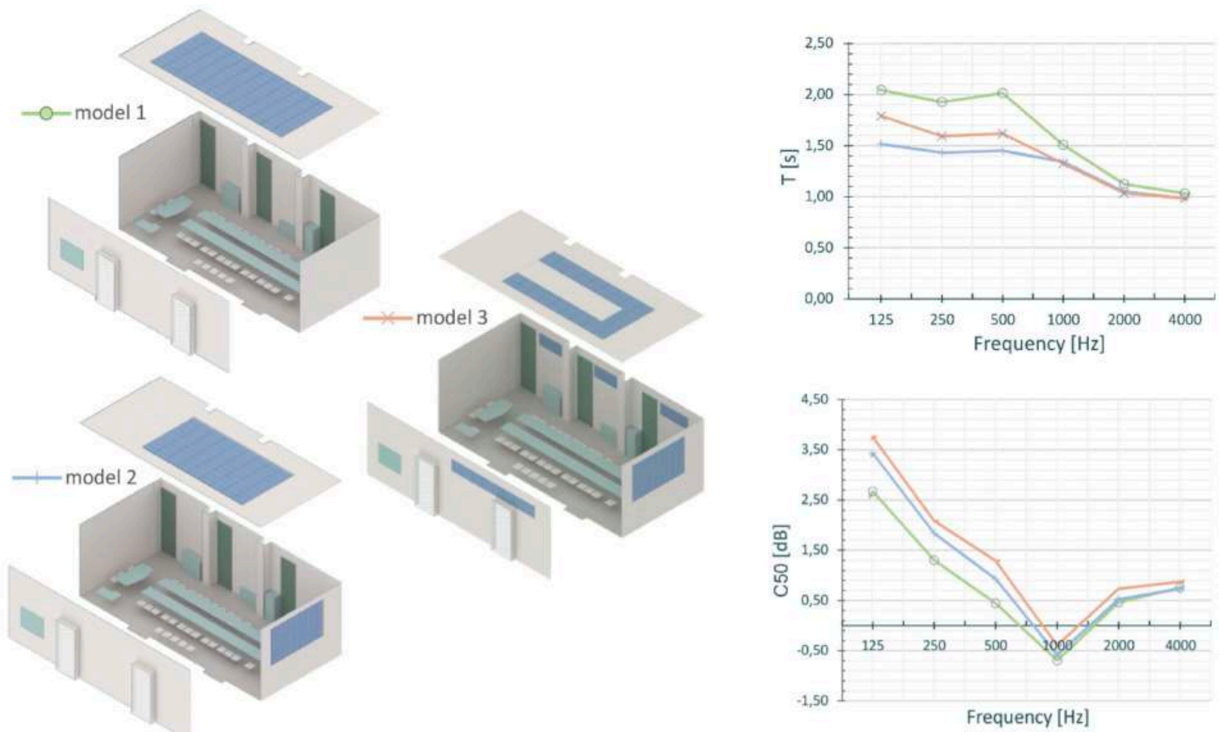

Figure 4. Simulated acoustic performance of three preliminary design configurations, evaluated in terms of reverberation time (T_{30}) and speech clarity (C_{50}). Model 1 includes 100% of the sound-absorbing panels on the ceiling. Model 2 distributes 70% of the panels on the ceiling and 30% on the rear wall. Model 3 adopts a more balanced approach, with 50% of the panels on the ceiling, 30% on the rear wall, and 20% on the lateral walls.

D. CONCEPT DESIGN

Due to constraints preventing changes to the room's layout, the concept idea focused exclusively on the ceiling, the largest unobstructed surface available for acoustic treatments. The furniture arrangement and usage context of the room guided the design toward a spatial subdivision that optimizes the acoustic experience for both speaker and listeners.

Based on the results of the preliminary simulations, the most effective configuration consists of a reflective zone above the speaker, an absorbent central ceiling area, and sound-absorbing treatment on the rear wall. In addition, in response to the observed unevenness in speech clarity across the room, the design was oriented toward the optimization of sound reflection and diffusion.

Figure 5 shows how the ceiling design addresses the room's acoustic requirements by dividing the structure into three distinct functional areas:

- The front area, acting as an overhead reflector positioned above the speaker, ensures strong and clear early reflections directed toward the audience, reinforcing top-down communication.
- The central portion incorporates sound-absorbing materials, thus reducing overall reverberation and enhancing clarity.
- The rear portion consists of a diffusive surface designed to distribute sound evenly across the room, support the last rows and minimize flutter echoes from the rear wall.

Additionally, acknowledging that diffusers are particularly effective in enhancing speech intelligibility, a vertical Schroeder diffuser is included on the rear wall.[15, 16, 17]

Overall, the idea behind the design solution is to optimize the acoustic performance (tuned particularly to address critical frequencies 125-2000 Hz), but also to introduce a visually dynamic element to the room, highlighting its spatial depth and height, thereby creating an engaging interior environment.

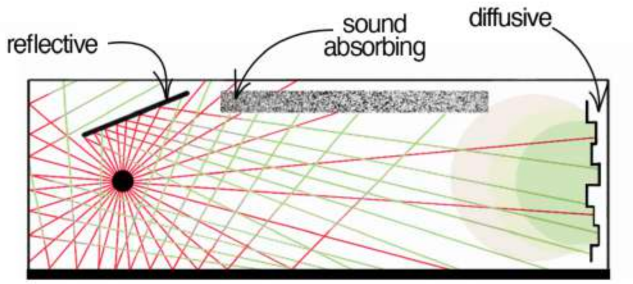

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Figure 5. Schematic section of a shoe-box room indicating the position of different types of acoustic treatments combined.

E. WAFFLE SYSTEM

The architectural and acoustic concept described materializes through a ceiling system based on a waffle structure. As Figure 6a shows, the system structurally consists of a modular grid of orthogonal beams—regularly spaced elements intersecting along two perpendicular axes—forming a continuous reticular geometry. This typology is well-established in architectural practice for its ability to combine mechanical stability and material efficiency through bidirectional load distribution.

The waffle grid is suspended from the existing ceiling and dimensioned to remain self-supporting within its modular framework. Its primary function is to provide a rigid and easily assembleable substructure that can host a range of acoustic treatments. As Figure 6b exemplifies, the subdivision into cells allows for a high-resolution spatial mapping of acoustic interventions, enabling each unit to perform a specific role (reflective, absorptive, or diffusive) depending on its position in the room.

The regular spacing of beams defines a clear set of constraints that informs both design and fabrication, ensuring consistency across geometric variation and manufacturing tolerances.

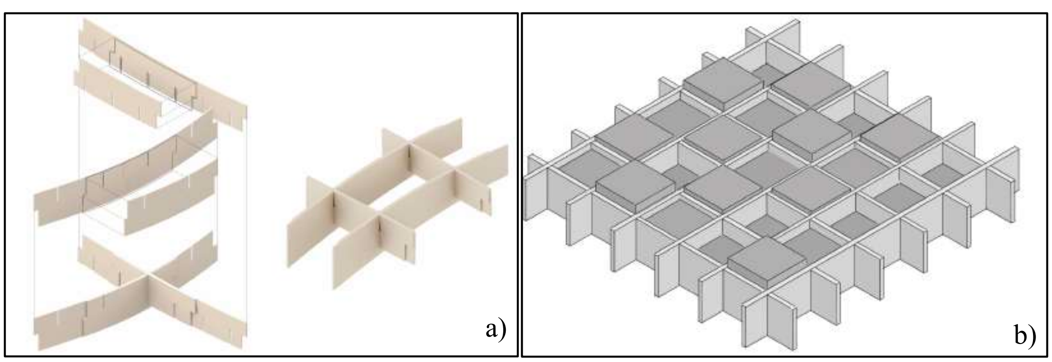

Figure 6. a) Detail of the construction system, based on half-wood joints and offset coupling of beam segments to form a single, continuous element. The intersection of longitudinal and transversal beams defines a modular grid capable of integrating acoustic and structural functions. b) Conceptual view of the grid structure designed to accommodate acoustic modules at varying depths, creating a diffusive surface inspired by quadratic periodic diffusers.

The waffle grid thus represents a dual-purpose framework: a mechanical skeleton and a topological matrix for acoustic optimization. Its geometric regularity offers both formal clarity and operational flexibility, preparing the ground for localized geometric manipulation and material integration discussed in the following section.

INTEGRATION OF ARCHITECTURAL FORM AND ACOUSTIC PERFORMANCE

A. PARAMETRIC MODELLING AND OPTIMIZATION

The definition of the ceiling system was managed through a parametric workflow enabling the integration of geometric, acoustic, and fabrication requirements within a unified digital environment. The model was developed in Rhinoceros using Grasshopper, with custom scripts and components allowing real-time manipulation of key design variables.

Rather than modeling a fixed geometry and adapting it to different performance conditions, the workflow was conceived as a generative engine: it builds and updates the form based on input from performance criteria and spatial constraints. The ceiling's global shape is controlled by a network of longitudinal and transverse curves, modifiable through parametric sliders. As shown in Figure 7a and b, this logic allows selective refinement of specific regions (front, center, rear) while maintaining consistency in global topology.

The model operates as a dynamic scaffold rather than a fixed object: structural spans, module spacing, and curvature intensity can be adapted in response to spatial needs and acoustic targets. Geometry is not isolated from performance; rather, it is structured to respond to acoustic feedback.

Acoustic simulations are integrated into this loop via external software tools and specific reflection paths, diffusion behavior, and absorption metrics are discussed in later sections

All components of the system—beams, panels, inserts—are designed for digital fabrication. Laser cutting constraints (e.g. sheet size, cutting tolerances, tool paths) are embedded in the definition from the early stages.

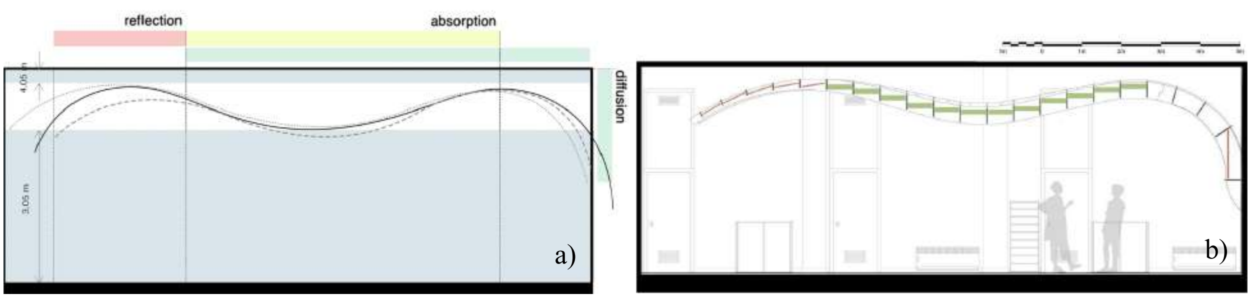

Figure 7. a) Geometric concept. A free form allows to optimize the curvature needed with the parametric software Grasshopper, in order to obtain the best acoustic performance. Not form finding, but form improvement. b) The selected strategy to integrate both geometric articulation and acoustic treatment is the use of a waffle structure, designed to host modular panels at varying depths. This configuration enhances the sound scattering effect, turning the ceiling into a large-scale diffusive surface.

B. SOUND REFLECTION

The first step in the acoustic modelling of the ceiling system focused on optimizing the shape and orientation of the reflective modules. To achieve this, the Image Source Method (ISM) was employed to guide the geometric definition of overhead surfaces based on early reflection paths. Within this approach, the optimal reflective geometry is derived by constructing an ellipsoid with its foci at the sound source (S_0), positioned at the speaker's location, and the farthest listener position (R_0) within the intended audience area (

Figure 1, Figure 8a and b).

Reflections were computed exclusively within this target area, allowing for the identification of inclined planes capable of directing early energy toward the audience. The intersection between these theoretical planes and the constraints imposed by the space (such as minimum ceiling height) defined the boundaries for the reflective region of the surface.

To generate a continuous base surface from these constraints, a net of longitudinal and transverse curves was constructed. Longitudinal curves were obtained by intersecting the reflector planes with three vertical sections parallel to the long walls (Figure 8b and c). Each curve was defined by fixed key points (determined via intersection and adjusted along the Z-axis) to create a spline that controlled the overall shape. While the optimal reflection points were fixed according to simulation, the remaining points were parametrically adjustable within a predefined vertical range to balance acoustic performance with spatial and perceptual comfort.

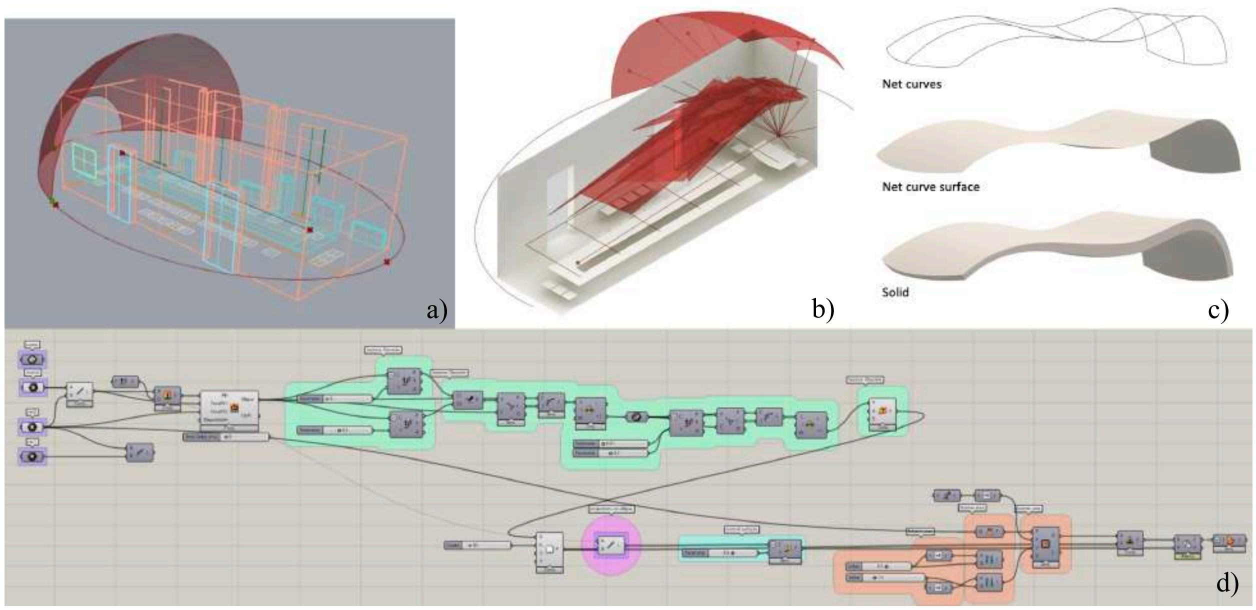

Figure 8. Geometric evolution of the reflective surface. a) Ellipsoid generated with foci at the sound source (S_0) and the farthest receiver point (R_0), used as a spatial constraint for identifying optimal reflection zones. b) Inclined reflector planes derived from acoustic targets. c) From the intersection curves between reflector planes and vertical sections parallel to the long walls to the generation of the solid volume. d) Grasshopper definition of the initial part of the net curve generation process.

C. SOUND DIFFUSION

To improve spatial uniformity in the back portion of the room, a diffusive surface was designed based on Schroeder diffuser principles. These devices are composed of wells of constant width and varying depth, with depth variation tuned to the design frequency to ensure optimal diffusion. For a room dedicated to speech, the target frequency band was identified between 250 and 4000 Hz.

The diffuser geometry was modeled in Grasshopper and refined using the Boundary Element Method (BEM) implemented in AFMG Reflex (Figure 9a). To integrate Reflex results into the parametric workflow, output data from the simulation (in .xlsx format) were linked back into the Grasshopper definition (Figure 9b and c). This connection enabled live updating of diffuser well depths in response to performance feedback, allowing for fine-tuned control of scattering behavior while maintaining geometric continuity with the overall waffle grid.

D. SOUND ABSORPTION

To address reverberation control and improve speech clarity in the central area of the ceiling, a series of modular sound-absorbing elements were introduced. Each module was configured as a rectangular box integrated within the waffle grid, designed to be adaptable in depth, perforation pattern, and internal material composition. The modular nature of the box configuration ensured compatibility with the overall digital model and enabled fabrication within the same pipeline as the other components. Each absorbing module was thus defined not only by geometric and structural constraints but also by acoustic targets, forming an integral part of the ceiling's multi-performance system.

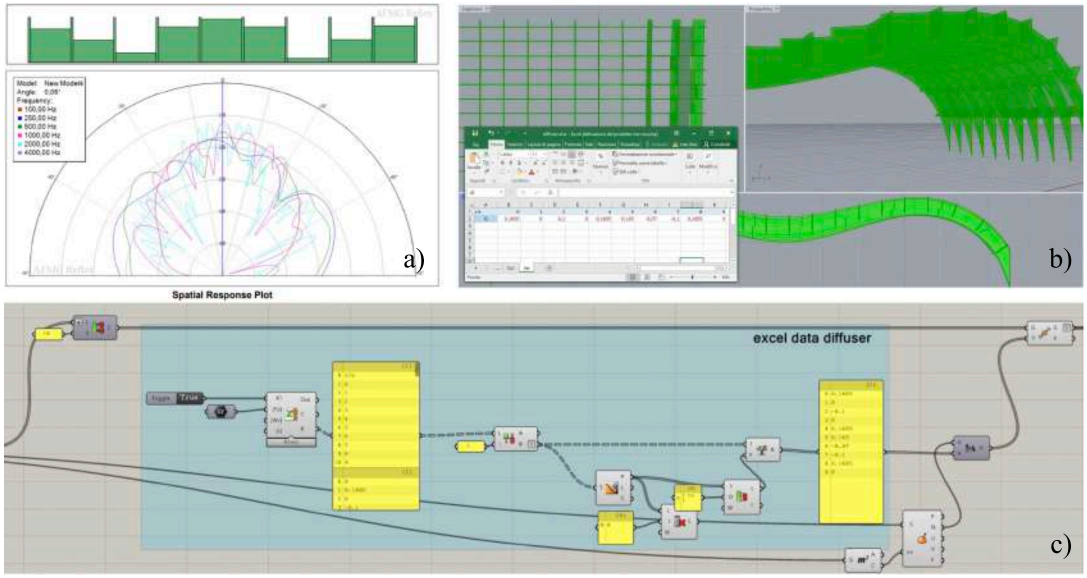

Figure 9. a) Frequency response of the Schroeder diffuser simulated with AFMG Reflex. b) Data interface between Rhino/Grasshopper and Excel for dynamic parameter exchange. c) Grasshopper definition managing geometry and integration with acoustic simulation results.

I. SOUND ABSORBING MODULAR UNIT

For the sound-absorbing component, the objective was to devise a perforated panel capable of effectively covering a broad frequency spectrum. This design leverages on: the resonant properties of a perforated panel in conjunction with a porous material; modularity of the box structure, facilitating fabrication, assembly, and secure attachment to the structural beams; airtightness through finger joints and a rigid wooden backing.

The overlapping perforations operate as a Helmholtz resonator;[18] slotted perforations act as the "neck" leading to the first cavity housing the circular holes; furthermore, the entire internal volume can be treated as the resonant cavity, with the "neck" formed by the double perforation (Figure 10). Perforations and volume dimensions were optimized in order to target 250 Hz octave band, since preliminary simulation data (Figure 4), indicated the need for increased absorption at low frequencies.

As the chosen porous material, a panel composed of natural hemp fibrous material was adopted. This panel is composed of 90% compressed hemp fibers combined with binding fibers sourced from an ecologically sustainable supply chain. Although primarily manufactured and marketed as thermal insulation, its physical characteristics render it a good sound-absorbing material.

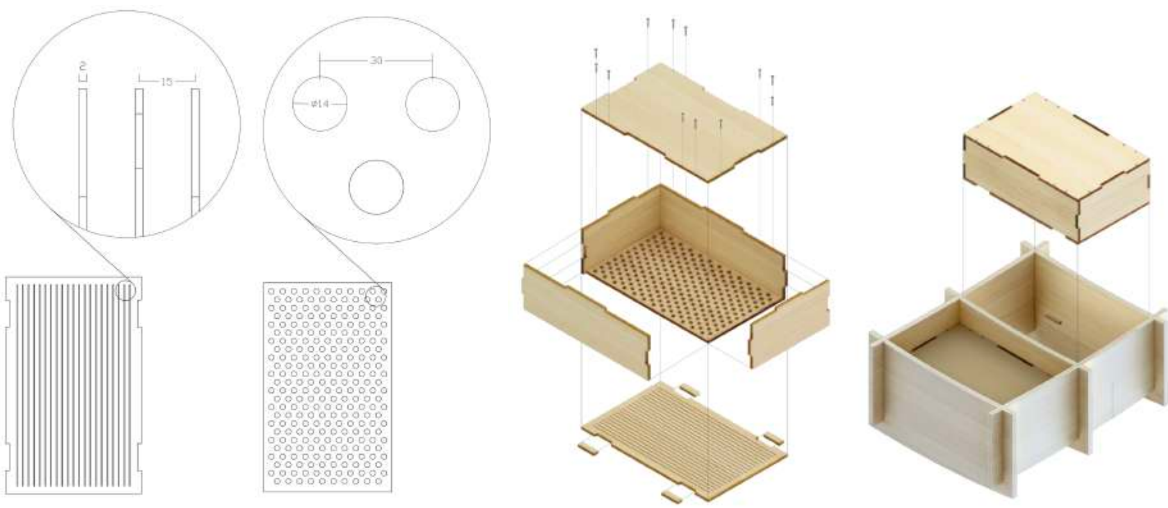

Figure 10. Sound-absorbing "box" module designed for integration within the waffle structure that fits into a single grid cell and is optimized to enhance frequency spectrum of porous material.

II. PROTOTYPING AND ACOUSTIC CHARACTERIZATION

The sound absorbing system prototype was realized through the laser cutting technique chosen to the realization of the whole structure. The laser cutting technique offers the advantage of fabricating unique pieces that match perfectly with each other, providing designers with complete control over their work and few limitations to their creativity.

In order to assess the performance of the acoustic absorption system, measurements were carried out in a controlled experimental environment within the reverberation room at Politecnico di Torino. The objective was to analyse various configurations of sound-absorbing panels and air gaps to understand how these factors influence the acoustic absorption characteristics of the panels, in order to choose the best combination.

The first step consisted in acoustically characterizing the porous material and the wooden box individually, obtaining the absorption curve of both the hemp fibre panel, the perforated panel and different combination of the first with the latter. After testing different possibilities, with and without the hemp, the configuration that exhibit the most significant performance is selected: wooden holed panel, high-density hemp fibre panels (100 kg/m³, thickness 50 mm) and 90 mm air gap. Figure 11 illustrates the absorption curve derived from measurements within a reverberation chamber. The chosen configuration displayed peaks between 150 and 250 Hz (30% more than the single hemp panel) making it an effective option for addressing low-frequency sound treatment, underscoring the significance of the air gap in determining acoustic performance at lower frequencies.

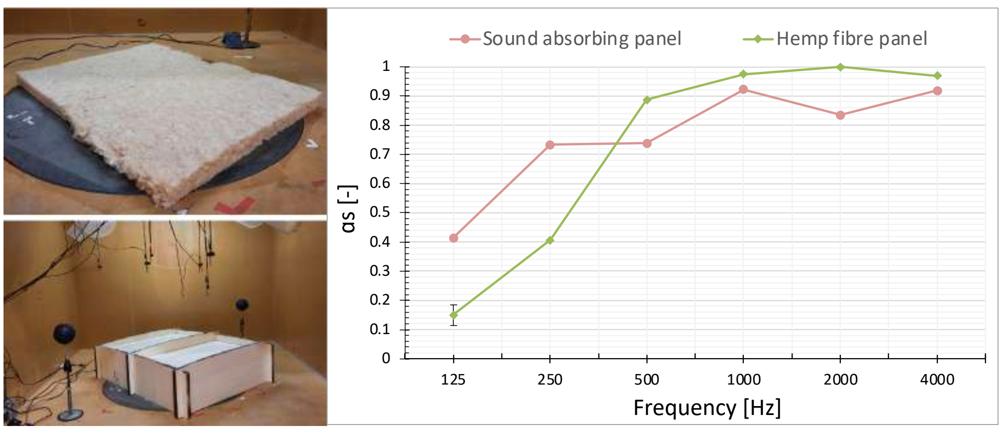

Figure 11. Absorption curve derived from measurements within a reverberation chamber of the single hemp panel compared to the whole sound absorption system.

E. ROOM ACOUSTIC SIMULATION

After defining all the design choices, obtaining the acoustic characterization of the chosen sound-absorbing system, and concurrently developing the three-dimensional model with Grasshopper, the final simulation is performed using Pachyderm Acoustics. The parametric workflow definition has two branches: one defines a detailed model of the project for digital fabrication, the other is designed for acoustic simulation. The latter lacks three-dimensional elements, consisting only of surface. Each element is grouped by material and associated with a Rhinoceros layer, to which the absorption coefficients obtained in the reverberation chamber are assigned through the Pachyderm interface. The simulation retains the same settings as the preliminary checks, with the Sound Pressure Level (SPL) of the source and the positions of the source and receivers remaining unchanged.

RESULTS

A. FABRICATION AND ASSEMBLY

During the fabrication process, each piece was pre-labeled by the laser cutter, classified, and systematically stocked. The sound-absorbing panels were assembled on-site, while the beams were partially pre-assembled to reduce material transportation to the PLINIVS meeting room. The longitudinal beams are 11 m long, which makes it impractical to transport them in full.

On site, the primary beams were fully assembled and then suspended using six steel hangers for each beam (Figure 12a) and then the secondary beams were fitted into the longitudinal beams through half-wood joints

(Figure 12b): the two sets aligned precisely with a tolerance of only 2 mm, demonstrating the precision achieved through a parametric workflow combined with digital fabrication. The reflective and sound-absorbing panels were inserted into the grid formed by the beam, supported by rectangular dowels, with each element seamlessly integrated into the structure. This level of assembly accuracy shows how digital fabrication enables a high degree of control over the transition from design to physical construction. The process minimizes deviations between the simulated performance and the built outcome, an essential condition in acoustically calibrated environments where geometric precision directly affects functional results.

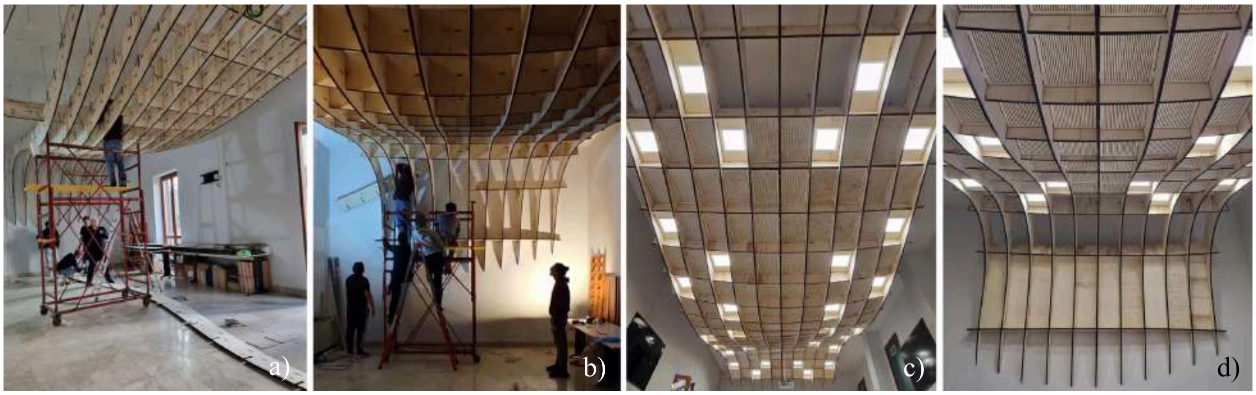

Figure 12. a) Installation of longitudinal beams. b) Fitting of transversal elements within the waffle grid. c) Completed structural framework. d) Realized Schroeder diffuser integrated into the rear section.

B. POST-CONSTRUCTION MEASUREMENT AND SIMULATION RESULTS COMPARISON

Following the assembly of the ceiling structure, a series of validation measurements were conducted using IR method measured with an NTi Audio XL2 sound level meter.

Figures 14a and 14b show the comparison between the post-construction simulation (PO_S) and the in-situ measurements (PO_M2). In terms of T_{30}, the simulation indicated a consistent reduction of approximately 1 s across all frequencies, along with a clear flattening of the response curve. The measured values confirmed and even exceeded these expectations, with T_{30} falling entirely within the target range defined during the design phase.

As highlighted by the post-construction simulation, C_{50} was defined as a key performance target, both in terms of spectral uniformity and spatial consistency across receiver positions. The measured results closely matched the simulation, with almost all receiver points falling within the acceptable performance range, as demonstrated by the position of error bars in the measured data.

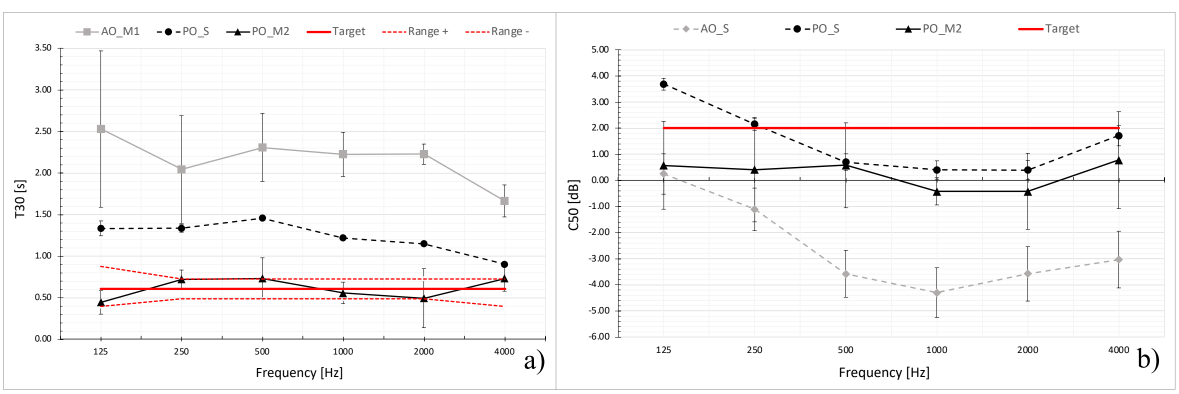

Figure 13. Results comparison from simulation with Pachyderm Acoustics and post-construction measurements. a) T_{30} b) C_{50} AO_S: Pre-construction simulation; AO_M: Pre-construction measurements; PO_S: Post-construction simulation; PO_M2: Post-construction measurements with sound level meters.

C. SUITABILITY OF THE RESULTING SPACE FOR MORE TYPICAL MEETING CONDITIONS

Although the acoustic design was tailored primarily to support frontal, speaker-oriented communication, the resulting space has proven to be highly adaptable to a broader range of uses. Following the installation of the ceiling system and the confirmed improvement in acoustic parameters, the room has been increasingly used as a co-working and study area. This functional shift was made possible by the enhanced acoustic comfort which now support interactions among multiple users in flexible spatial configurations.

FUTURE APPLICATION

The adopted approach was specifically developed to integrate multiple acoustic functions (reflection, absorption, and diffusion) into a single, coherent design strategy tailored to the specific spatial and functional constraints of the case study. However, its parametric nature makes it inherently adaptable, by modulating geometric parameters such as size, curvature, and position of the components. The same methodology and system can be extended to a variety of architectural typologies, such as lecture halls, multi-purpose auditoria, classrooms, and even acoustically sensitive public spaces such as restaurants or exhibition areas. The flexibility of the digital workflow enables designers to calibrate each intervention to the unique acoustic profile and functional requirements of the target environment.

CONCLUSION

The paper investigates an integrated and performance-driven design workflow, where spatial geometry, acoustic function, and structural logic are included within a single parametric framework. A case study based on the main function of a meeting room has been presented. This case study has involved the design, computational simulation, and physical realization of a waffle structure, employing a modular system that integrates acoustic absorption, reflection, and diffusion properties. Acoustic performance predictions from digital simulations.

From a fabrication standpoint, the system's precision was confirmed during on-site assembly. All components were pre-labeled and classified digitally, minimizing errors and ensuring fast, coordinated installation. The longitudinal and transversal beams, joined with minimum tolerance, formed a rigid and precise grid into which all acoustic elements were seamlessly integrated. This accuracy underscores the advantage of combining parametric design with digital production in contexts where performance precision—such as acoustic targeting—is critical.

Acoustic performance was validated through post-construction measurements and compared with simulation results. T_{30} values exceeded the expectations, falling within the target range and confirming the effectiveness of the acoustic strategy. In terms of C_{50}, both simulations and in-situ measurements demonstrated uniform and consistent results across the audience area, with all data points falling within the defined design targets. Moreover, following the installation of the ceiling system and the confirmed improvement in acoustic parameters, the room has been increasingly used as a co-working and study area.

Overall, the project shows that an integrated digital workflow can enable high-resolution acoustic control, formal coherence, and structural rationality—delivering not only a functional ceiling but an architecturally expressive system where form and performance evolve in unison.

Finally, this work shows that creating a clear workflow allows for the collaboration between experts, allowing for acoustics to act as a design driver in generating form and material patterns.

The fabrication has also highlighted a number of limitations: improved efficiency in assembly could be achieved going beyond the manual process as in this project. The digital workflow of this project is reasonably robust. However, many challenges around the tools available for a preliminary investigation of the acoustic performance from the scale of the material to the full acoustic device integrated in the environment is presented as a demanding task.

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REFERENCES

[1] X. Shi and W. Yang, "Performance-driven architectural design and optimization technique from a perspective of architects," *Autom. Constr.* 32, 125–135 (2013).

[2] S. Marble, "Digital Workflows in Architecture: Design-Assembly-Industry*",* Birkhauser*,* (2012).

[3] B. Peters, "Integrating acoustic simulation in architectural design workflows: the FabPod meeting room prototype," *Simul.* 91(9), 787–808 (2015).

[4] B. Peters, J. Nguyen, and R. Omar, "Parametric acoustics: design techniques that integrate modelling and simulation," *Proc. Euronoise Congr.* (2021).

[5] World Health Organization, "Environmental Noise Guidelines for the European Region*"* (2018). Available online: http://www.euro.who.int/en/publications/abstracts/environmental-noise-guidelines-for-the-european-region-2018

[6] C. Haan and F. Fricke, "Statistical investigation of geometrical parameters for the acoustic design of auditoria" *Appl. Acoust.* (35)2, 105-127 (1992).

[7] E. Badino, L. Shtrepi, and A. Astolfi, "Acoustic performance-based design: A brief overview of the opportunities and limits in current practice" *Acoustics* 2(2), 246-278 (2020).

[8] L. Labia, L. Shtrepi, and A. Astolfi, "Improved room acoustics quality in meeting rooms: Investigation on the optimal configurations of sound-absorptive and sound-diffusive panels," *Acoustics* 2, 451–473 (2020).

[9] Bradley, J. S., "Speech intelligibility studies in classrooms" *J. Acoust. Soc. Am.* 80, 846–854 (1986).

[10] S.E. Indrawan, "Design for environment and form findings through digital fabrication," *J. Archit. Built Environ.* 44(2), 171–178 (2016)

[11] DIN 18041, *Acoustics quality in rooms – Specification and instructions for the room acoustics design* (2016).

[12] UNI 11532-2, *Internal acoustical characteristics of confined spaces - Design methods and evaluation techniques - Part 2: Educational sector* (2020).

[13] A. Van der Harten, "Pachyderm acoustical simulation: Towards open-source sound analysis," *Archit. Des.* 83(2), 138–139 (2013).

[14] S. Campanini and A. Farina, "A new Audacity feature: room objective acoustical parameters calculation module." Available online: https://www.researchgate.net/publication/228756733

[15] A. Sanavi, B. Schäffer, K. Heutschi, and K. Eggenschwiler, "On the effect of an acoustic diffuser in comparison with an absorber on the subjectively perceived quality of speech in a meeting room," *Acta Acust. united Acust.* 103, 1037–1049 (2017).

[16] E. Arvidsson, E. Nilsson, D. Bard, and O. Karlsson, "Pattern and orientation of diffusers in rooms with absorbent ceiling," *Proc. Int. Conf. Acoust., 4th EAA Euroregio - ICA 2019* (2019).

[17] Y. Choi, "Effects of periodic type diffusers on classroom acoustics," *Appl. Acoust.* 74(5), 694–707 (2013).

[18] T. Cox and P. D'Antonio, "Acoustic Absorbers and Diffusers: Theory, Design and Application" CRC Press (2020).