ACOUSTIC APPLICATIONS FOR ADDITIVE MANUFACTURING IN CONSTRUCTION - A REVIEW ON PROCESSES, MATERIALS, DIGITAL METHODS AND FUTURE POTENTIAL IN ROOM ACOUSTICS

Christin M. Gandyra
David Fluss
Eslem Boynuzuun
Alexander Wolf
Ulrich Knaack

This study reviews the state of the art in room acoustics, focusing on current practices and the potential of digital technologies to enhance the implementation of acoustic measures in building projects. It briefly summarizes acoustic basics and existing regulations and examines commonly used materials, digital manufacturing and design processes for acoustically effective geometries. In particular, the study explores the opportunities provided by performance-based design and additive manufacturing to expand the applications of acoustics in construction. Despite widespread knowledge of the negative effects of poor acoustics on well-being, productivity, and health, room acoustics remain underprioritized compared to building acoustics in teaching and standardization and consequently the realization of projects. Current solutions, while effective, are limited in design flexibility. The review identifies three key parameters for efficient acoustic design: performance-based design (I), materials (II), and digital fabrication (III). Additive manufacturing, in particular, is promising for enhancing both design freedom and customization, enabling tailored acoustic panels that meet specific project requirements. Clay and paper are identified as highly suitable materials for these applications, combining sustainability with acoustic effectiveness. This research highlights the significant potential of integrating digital fabrication and advanced manufacturing techniques in room acoustics to promote healthier and more adaptable built environments.

INTRODUCTION

Performance-based design (PBD) integrates analytical and generative methods to optimize acoustics through iterative feedback loops [1]. Unlike traditional design approaches, PBD prioritizes functionality, based on predefined acoustic parameters. Efficiency improves with numerical simulations and AI-driven methods.

Conventional materials may limit customization in geometry, performance, and aesthetics. Digital fabrication, however, promises a precise structural and volumetric design, creating engineered materials with enhanced acoustic properties [2]. Advances in additive and subtractive manufacturing have expanded research in acoustic materials, moving beyond monolithic materials toward optimized, application-specific solutions.

This paper explores how digital technologies may improve room acoustics by tailoring material geometries based on space usage. It reviews recent developments in engineered acoustic materials, focusing on three key areas: acoustics, additive manufacturing, and materials in building acoustics. The study considers works published between 2010 and 2024, coinciding with the rise of digital fabrication following the expiration of the Fused Deposition Modeling patent in 2009 [3].

Relevant articles were identified through searches for the keywords *acoustics, additive manufacturing, noise reduction, sound absorption, and 3D-printed materials in* *construction*. The primary focus is interior spaces, but also studies on outdoor soundscapes are included. Only English- and German-language papers with full online access were considered.

ARCHITECTURAL ACOUSTICS

Physical basics

Sound waves are produced by longitudinal pressure differences by a moving source and characterized by the waves' speed, frequency, phase and amplitude as well as the wavelength, which is central to how sound interacts with objects [4].

If a sound wave with power P_i as shown in Figure 1 hits a surface relatively big compared to its wavelength then it is divided into parts that are reflected/ diffracted/ scattered (P_r), transmitted (P_t), passed through the material (P_f) or absorbed (P_a) [5]:

(1)

$$P_i = P_r + P_t + P_f + P_a$$

All of these sound paths can be used to work on speech intelligibility, enhancing the perception of music or suppressing noise. The science of achieving good sound within the built environment is called architectural acoustics, a subfield of acoustical engineering. Acoustics in architecture is further differentiated in inter-space noise control (building acoustics) and interior or exterior space acoustics (room acoustics) (see Figure 2). While the first finds measures to shield a room from noise transmission from another space, room acoustics is the science of sound propagation within spaces focusing on absorption and reflexion to achieve favorable sound environments for the intended use of a room.

Building acoustics primarily address sound transmission between rooms and are common in everyday projects, whereas room acoustics focus on optimizing reverberation and clarity within a space but are rarely regulated [6]. Room design must balance absorption, diffusion, and reflection to prevent adverse acoustic conditions. Room acoustics significantly impact clarity in venues such as concert halls and parliaments but are often overlooked in everyday buildings negatively effecting sound in offices, schools, or urban areas. Here, insufficient absorption exacerbates unwanted effects like the *Lombard effect*, where increasing background noise forces speakers to raise their voices, further deteriorating intelligibility. The reverberation distance r_H, which defines the point where direct and diffuse sound levels equalize, depends on absorption area and sound source distribution. Positioning speakers near reflective surfaces or employing directional loudspeakers can enhance intelligibility, but in multi-speaker environments, low-frequency buildup masks critical speech frequencies. Mitigating this requires deep-frequency absorbers down to at least 63 Hz, preferably 50 Hz, particularly in smaller rooms [5]. In environments with weakly absorbing surfaces ($\alpha < 0.2$), excessive reflections degrade sound localization, music clarity, and speech intelligibility, affecting musicians, sound engineers, and office workers. Even minor reflective surfaces can distort measurements, requiring targeted absorption when structural modifications are impractical (Fuchs, 2017).

Acoustically effective materials with sound-scattering or absorbing properties are common in construction to enhance interior acoustics. Customizing acoustic measures for specific projects is vital for efficiency but faces design and manufacturing challenges.

Acoustic Standards

Sound and acoustic design significantly influence room atmosphere, affecting perception, health, and well-being [7]. To ensure accountability and standardization, guidelines such as ISO standards, the International Building Code (IBC), the National Building Code of Canada (NBC), and the Eurocode (EC) provide regulations. In Germany, state-level regulations specify acoustic requirements, as summarized in Figure 3.

German building codes mandate minimum sound insulation based on usage, primarily outlined in DIN 4109 and DIN 12354. Stricter requirements, such as VDI 4100, may be applied upon request. While inter-room noise control is regulated, room acoustics—sound performance within a single space—lack mandatory codes. Instead, planners rely on general recommendations, including ISO 23591 for music venues and workplace guidelines such as VDI 2569 ("Office Acoustics"), DIN 18041 ("Room Acoustics"), and ASR A3.7 ("Noise"). DIN 18041 is particularly relevant for optimizing room acoustics.

Due to their non-mandatory status, these standards are rarely implemented, leading to a focus on sound insulation over intelligibility. As a result, classrooms, offices, and conference rooms often suffer from poor acoustic conditions, causing high sound pressure levels and communication difficulties (Nocke, 2019).

PERFORMANCE-BASED DESIGN

Nature exemplifies advanced acoustic optimization, as seen in moth wings that disrupt bat echolocation through sound absorption, echo reflection, and frequency alteration, effectively camouflaging them from predators [9]. These bioinspired principles offer new possibilities in acoustical engineering, achieving effects unattainable with conventional surfaces [10] and show the portential of precise adaptation to specific conditions in order to achieve effective sound control. Sullivan's principle of "Form Follows Function" (1896)

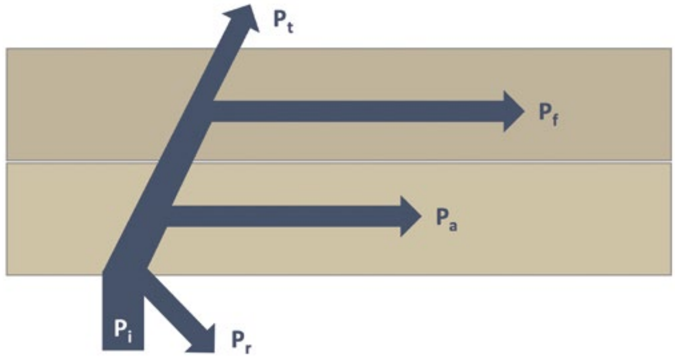

Figure 1: Interaction of sound and materials: possible sound paths.

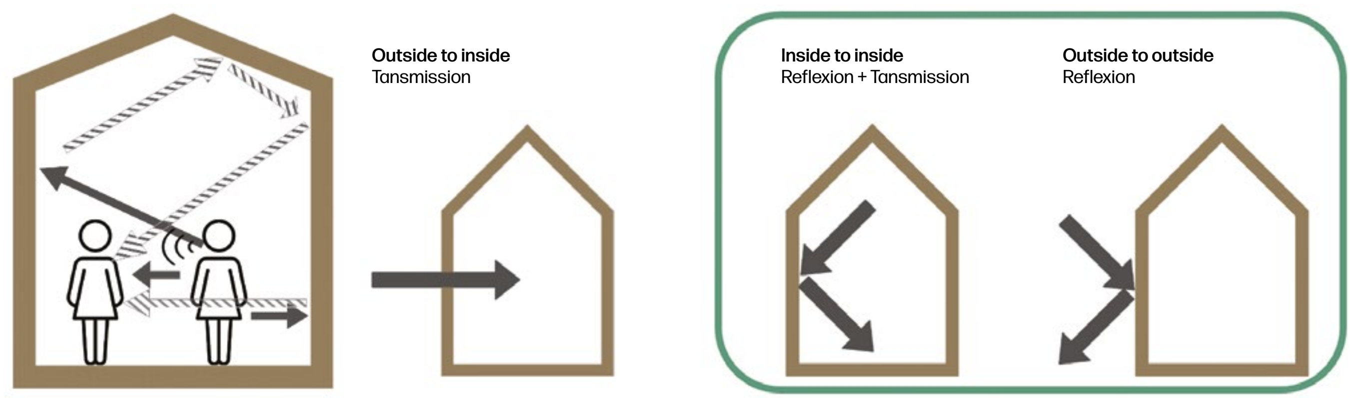

Figure 2: inter-space, interior and exterior acoustics (left)
and retroreflections within a space (right).

Calculation of reverberation time	Requirements for rooms
DIN EN ISO 12354-6 Absorption/Reverberation Time: 2004-04	DIN 18041 Audibility: 2016-03
	ASR 3.7 Noise: 2018-05
	VDI2569: 2019-10
Evaluation materials	**Experimental standards**
DIN EN ISO 11654 – Absorption Coefficient: 1997-07	DIN EN ISO 3382-1 Performance Spaces: 2009-10
ISO20189 – Soundabsorption: 2018:11	DIN EN ISO 3382-2 Ordinary Spaces: 2008-09
	DIN EN ISO 3382-2 Open Plan Offices: 2012-05
	DIN EN ISO 354 Lab. Sound Absorption: 2003-12

Table 1: Overview of German codes for interior space acoustics
(reproduced and modified from [8])

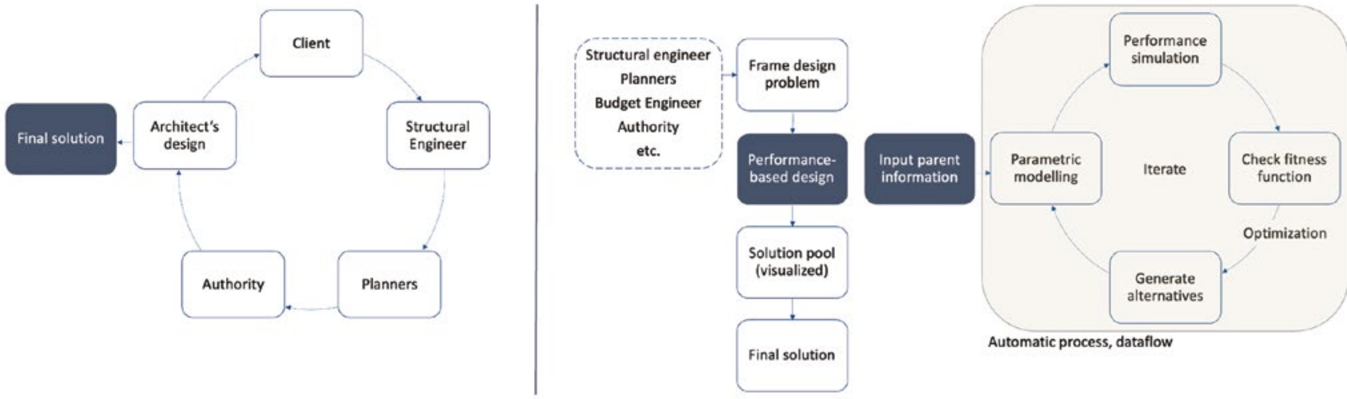

Table 2: Sound absorption coefficients of different common building materials [reproduced and modified from [41],[42]].

Material	Description	125 Hz	250 Hz	500 Hz	1kHz	2 kHz	4 kHz	Mean value
Clay	rammed earth (100 mm)	0,15	0,22	0,27	0,29	0,34	0,48	0,29
	rammed earth (100 mm) with clay plaster (7 mm)	0,05	0,05	0,09	0,09	0,09	0,14	0,09
Ceramic	brickwork, 10 mm flush pointing	0,08	0,09	0,12	0,16	0,22	0,24	0,15
	standard brickwork	0,05	0,04	0,02	0,04	0,05	0,05	0,04
	smooth brickwork, flush pointing	0,02	0,03	0,03	0,04	0,05	0,07	0,04
	ceramic tiles, smooth surface	0,01	0,01	0,01	0,02	0,02	0,02	0,02
Concrete	porous concrete blocks	0,05	0,05	0,05	0,08	0,14	0,2	0,10
	rough concrete	0,02	0,03	0,03	0,03	0,04	0,07	0,04
	smooth concrete, unpainted	0,01	0,01	0,02	0,02	0,02	0,05	0,02
	smooth concrete, painted	0,01	0,01	0,01	0,02	0,02	0,02	0,02
Plaster	gypsum plaster tiles, 17% perforated, 22 mm (ceiling)	0,45	0,7	0,8	0,8	0,65	0,45	0,64
	plasterboard on frame, 100 mm airspace	0,3	0,12	0,08	0,06	0,06	0,05	0,11
	plasterboard on cellular core partition	0,15	0	0,07	0	0,04	0,05	
								0,00
Wood	plywood, mounted solidly	0,05		0,05		0,05	0,05	0,03
	plywood, 12 mm, over 50 mm airgap	0,25	0,05	0,04	0,03	0,03	0,02	0,07
	plywood, hardwood panels, over 25 mm airspace, solid backing	0,3	0,2	0,15	0,1	0,1	0,05	0,15
Paper	sprayed cellulose fiber (16 mm on solid backing)	0,05	0,16	0,44	0,79	0,9	0,91	0,54
	sprayed cellulose fiber (75 mm on solid backing)	0,7	0,95	1	0,85	0,85	0,9	0,88
Glass	glass, 4 mm	0,3	0,2	0,1	0,07	0,05	0,02	0,12
	glass, 6 mm	0,1	0,06	0,04	0,03	0,02	0,02	0,05
	glass 2-3 mm, double glazing, 10 mm air gap	0,15	0,05	0,03	0,03	0,02	0,02	0,05
Metal	steel decking (floor)	0,13	0,09	0,08	0,09	0,11	0,11	0,10
	metal, 32% perforated, backed by 30 mm rockwool (ceiling)	0,12	0,45	0,87	0,98	1	1	0,74
	person, adult, standing	0,15	0,38	0,42	0,43	0,45	0,45	0,38
Other, in m^2 units	plastic chair, hard seat	0,07	0	0,14	0	0,14	0,14	0,08
	chair, cloth upholstery	0,44	0,6	0,77	0,89	0,82	0,7	0,70

Figure 4: Design workflow: traditional (left), performance-based design (right) [reproduced and modified from [12]].

highlights the importance of purpose-driven design in architecture. While not a new concept, advancements in digital modeling and manufacturing now enhance these aspirations. Despite the persistence of formalistic design trends, functional optimization tools are increasingly shaping architectural solutions [11].

Traditional design workflows remain time-consuming and imprecise, relying on iterative adjustments based on individual preferences. Performance-based design (PBD) similarly considers boundary conditions and desired characteristics but differs by automating output generation through logic-based modeling rather than direct design modeling [12]. As shown in Figure 4, the generated solutions are then evaluated by the project team to determine the optimal outcome.

Advances in digital modeling and manufacturing enable greater design complexity, facilitating new theoretical concepts and experimental validation [13]. With increasingly complex building requirements, performance-based design plays a central role.

Parametric software allows visualization of intricate geometries, enabling function-oriented material design across scales, known as architectural infrastructure materials. This approach adapts geometry to environmental conditions, space usage, and room shape while enabling rapid production of customized components. It is widely used in auditorium design to enhance acoustics for musicians and improve speech intelligibility [14–16]. The Smithsonian Museum's courtyard roof exemplifies how multiple factors—structural integrity, shading, and sound absorption—can be integrated [17].

Technological advances, particularly numerical simulations and parametric design, streamline feedback between generation, evaluation, and modification, making applications more accessible to planners [18]. Parametric modeling tools like Grasshopper for Rhinoceros support acoustic performance evaluation based on material and geometric properties, using programs such as Odeon [19], CATT-Acoustics [20], Treble [21], and Pachyderm Acoustics [22] . Pachyderm integrates design and analysis within Grasshopper, improving coordination [23]. Recent projects favor integrated design environments, reducing interoperability risks between visualization and simulation tools [12].

Grasshopper modules like the solvers Galapagos [24, 25] and Octopus [20] optimize predefined parameters, allowing automated incorporation of simulation results and algorithmic refinement for greater precision. [26] combined noise analysis, parametric design, and simulation to integrate acoustic benefits into landscape design. The study demonstrated potential noise reduction strategies for Munich Airport.

Metamaterials are high-performance structures with properties beyond natural materials, composed of periodic meta-atoms. Digital manufacturing advancements have led to their increased development. Metamaterials are classified into fields like nanophysics [27, 28], mechanical [29, 30], elastic [31, 32], and acoustic [33, 34]. Current construction research focuses on mechanical metamaterials [35] like auxetics to reduce earthquake damage [36] and composites for structural reinforcement [37]. Acoustic metamaterials manipulate sound waves through periodic meta-atoms, useful for noise reduction by redirecting sound via reflecting meta-surfaces [38, 39] propose acoustic metasurfaces with C-shaped meta-atoms for sound reflection adjustment whereas [40] suggest H-shaped meta-atoms. Both achieve a wide-angle sound reflection of up to 80°. Acoustic properties depend on material, geometry, and arrangement, suitable for noise control in urban areas, facades, and sound barriers at various sites.

MATERIAL CONSIDERATIONS

Common building materials include clay, ceramics, wood, concrete, steel, and glass. Especially in the field of architectural acoustics paper and gypsum need to be mentioned additionally. Depending on characteristics like its density a material's capacity for sound absorption varies (see Figure 5) making some a better option for certain applications than others.

While clay, plaster, and paper have rather positive sound absorption properties, dense materials like ceramics, metal or glass are for the most part reflective. The latter therefore need to be combined with high absorbent materials or can be used in room acoustics to transport sound. The material groups will subsequently be shortly reviewed in terms of their typical use and acoustic performance regarding their capacity for sound absorption. Furthermore, their use for AM in the built environment shall be briefly outlined.

Ceramics and Clay

Clay, one of the oldest building materials, still remains prevalent in construction due to its global availability [43]. It can be distinguished between dried (clay) and fired (ceramics) products.

Fired elements are classified as ceramics, typically composed of clay, loess, and clay marl [44]. Industrial processes allow for varying properties, including porosity, which influences sound absorption. While ceramics generally exhibit high reflectance, increased porosity enhances absorption. Particularly additives like charcoal, which burn during firing leave pores and thereby improve performance at higher frequencies [45, 46]. For applications requiring maximal reflection, surface roughness can be adjusted through glazing, engobing, or modifying porosity via sintering at higher kiln temperatures [44].

Dried elements are typically referred to as clay or loam. Loam, a mix of clay, sand, and silt, is traditionally used in rammed earth, clay bricks, and panels for non-load-bearing walls [47]. Unlike ceramics, unfired clay has a higher sound absorption coefficient, further enhanced by fiber additives. Rammed earth surfaces achieve frequency- and humidity-dependent absorption coefficients up to 0.58, significantly outperforming concrete and lime-cement plaster across a broader frequency range [41, 42]. Its sustainability, high thermal mass and hygric behavior are furtherly demonstrating the material's suitability for indoor applications.

In research in the built environment different technologies are already well established for the additive manufacturing with clay. While robotically rammed earth [48] produces sturdy structures, only simple large-scale structures are possible to realize, similar to automated sprayed earth, where the wet mixture is applied with high air pressure with a drone [49, 50]. On the contrary the base material for binder jetting is dry earth powder which is locally solidified a fluid ecological binder [51]. While it enables the fabrication of parts with larger bridges and overhangs, the production is rather time-consuming and has disadvantages regarding the process stability. Extrusion offers a compromise between printing speed and producing high-resolution objects that gain their stability not through their mass, but through internal stiffening.

Additive manufacturing techniques for shaping can be easily integrated into the process chain of structural ceramics [52]. In addition to the original Cartesian extrusion systems, systems with extended motion control, have increased the design possibilities for integrating additional functionalities through further degrees of freedom [53]. While additive manufacturing with loam can be used to print whole buildings [54], additively manufactured ceramic parts are usually limited in size by the kiln and include smaller scales. This aspect seems to make AM ceramic parts only suitable for a complementary use in the built environment, for example when it comes to restauration [87]. Nevertheless, when integrated into industrial processes larger pieces and numbers can easily be fired thereby also making it a good use case for CCA where bricks are additively arranged into structures [79].

Paper and Wood

Paper is an established acoustic absorber due to its low density and environmental benefits. Commercial products exist for sound insulation [55], while ongoing research explores room acoustical applications. Panels made from recycled egg trays and natural fibers (corn husk, sugar cane) highlight the potential of sustainable solutions [56]. Another approach optimizes cellulose-based multilayer composites for sound absorption [57].

Wood, though less absorbent, is commonly used in resonators. Hybrid materials, such as cork-wood combinations, have demonstrated superior absorption in impedance tube experiments, offering sustainable alternatives [58].

A number of researchers have already made use of the potential of those sustainable materials in additive manufacturing. The technology already found its way into the construction sector: Commercially available products are birdhouses or insect homes for biodiversity in green facades [59].

The base material for 3D paper printing usually consists of cellulose, carboxymethylcellulose, lecithin and a filler such as chalk or starch [60, 86]. Aside from the challenges in regards to humidity or shrinkage its characteristics make it a good fit for acoustic applications [60]. Just like paper also research on wood AM mainly focuses on extrusion with a similar mixture consisting of wood particles and a starch binder. A challenge for these materials is the slow drying and therefore low green strength and the forming of mold [61].

Concrete and Plaster

Common concrete consists of cement, water, and aggregates, including sand and gravel. Admixtures are often added to enhance workability, durability, or setting time. For acoustic applications, specialized concrete is used to reduce sound transmission. Lightweight aggregates like expanded clay or pumice create a more porous structure, improving sound absorption.

Plaster and gypsum-based materials are also widely used for walls, ceilings, and soundproofing. For the latter especially perforated ceiling tiles [62] are widely used, but also perforated wall elements or fiberboards are common. Gypsum is the primary ingredient, combined with water and additives like retarders, fibers, or perlite to improve strength and acoustic properties. Some products include mineral wool or foam fillers to enhance sound absorption.

While various materials have been explored in the past years, concrete remains the dominant choice for additive manufacturing [63]. Research in the field is steadily progressing and depending on the usage different suitable technologies are available. Concrete offers the advantage on effortlessly realizing prints on a large scale which means it is applicable to print houses in-situ or realize pre-fabricated parts. With a modular gantry printer even two story-buildings can be realized relatively fast using contour crafting, an extrusion process [64]. Shotcrete printing also offers the possibility of realizing large objects fast. The procedure applies concrete by compressed air with the compromise of a relatively lower resolution [49]. On the other hand, approaches like injection printing [65] so far are limited to smaller dimensions but come with the opportunity of working with an enlarged freedom of design because of the support that the surrounding gel offers distancing the technology from the common planar layers in additive manufacturing. Gypsum on the other hand is difficult to use in extrusion processes due to its long setting time. Though approaches tried to develop adjusted mixtures [66] additive manufacturing with gypsum mixtures is barely implemented.

Glass

The most prevalent glass types in the built environement are soda-lims slicate glass and borosilicate glass. Due to its closed surface and high-density glass of course has a very low sound absorption coefficient below 0.1 and is not common for acoustic measures. At the same time its importance in construction and high percentage in facades give it an extraordinarily high potential to improve room acoustics, especially outdoors in urban areas [67]. By carefully engineering the geometry of a glass façade the design can help diffusely scatter or relocate sound to reduce the sound pressure level in certain areas.

Because of its characteristics glass 3D-printing comes with a lot of challenges. As a material it has high strengths but is also brittle and needs high temperatures during processing. Nevertheless, in the past few years different reliable technologies have been developed that are able to meet the demands of the construction sector. For the common applications with soda-lime silicate glass Fused Deposition Modeling (FDM) has proven to be a good choice [68]. Another printing technology in the field that is being investigated is Direct Energy Deposition (DED) [69]. When it comes to facades, additive manufacturing is of use especially when it comes to shaping or modifying the flat planes and rethinking the way we work with them. Promising concepts include AM supports [88] in order to reduce the visuak imapact of joints, AM sealings of insulated glass units (IGU), stiffening of glass façades by adding AM ribs or simply aesthetic design applications within a building [89].

Steel

An even metal plane is highly reflective with sound absorption values of up to 0.1. Adjustments in the geometry like perforations and angles or the combination with absorbing materials significantly improved the acoustic performance of metal facades [70].

Regarding steel various applications for the built environment are possible from a high output to (in-situ) manufacture bridges [71, 72] to manufacturing fairly smooth surfaces. The majority of projects in the field of additive manufacturing with steel focus on the production of entirely printed elements like freeform columns [73] or nodes produced with Wire Arc Additive Manufacturing (WAAM) [74]. Since in facades freeform is becoming a key subject in recent projects involve the additive manufacturing of individualized nodes out of steel with smaller tolerances Directed Energy Deposition Laser Wire (DED-L)) [75] and the forming and stiffening of freeform steel sheet panels. The welded reinforcement not only helps in shaping and stiffening the sheets but also reduces production costs and saves material [76].

The variety in studies and research projects highlight the growing interest in additive manufacturing for the built environment and emphasize the need for further functional applications. Therefore, research in material optimization and process development is necessary, as well as sustainable solutions to address current limitations and expand commercial applications.

DIGITAL FABRICATION FOR ACOUSTIC APPLICATIONS

Digital manufacturing technologies are rapidly evolving across various fields, with additive manufacturing (AM) gaining prominence in construction due to its design flexibility and potential for complex (acoustic) applications. However, AM in architecture faces two key challenges: (1) large-scale geometries and (2) high material demands, including weather resistance, load-bearing capacity, and durability [77]. A wide range of AM technologies and materials are available, selected based on desired properties and functionality [78]. Research spans lab-scale experiments to full-scale demonstrators, with Robocasting favored for its high-speed production, meeting industry demands [79].

Digital technologies are transforming acoustic optimization in building design. Using computational design, simulation tools, and digital fabrication, architects and engineers create efficient and sustainable solutions. The focus is on controlling sound through scattering, absorption, and resonators to manage reflections and reverberation. Unlike traditional methods, digital fabrication allows for complex, custom acoustic elements, enhancing performance and aesthetics. The following section outlines Computerized Numerical Control (CNC) technologies relevant to acoustics and construction, emphasizing material feasibility and application scope.

Subtractive Technologies

Subtractive methods take away material to reach the final form, hence they are more similar to common conventional technologies than additive manufacturing. By combining digital design with robotics or CNC-milling complex structures can be derived.

An integral approach by Rossi et al. [16, 80] combines material, production method, form, acoustics and visual effect and examines their interdependencies. used brick elements for the acoustic modular design of interior spaces. They used robotic subtractive production using oscillating wire cutting produced clay blanks with complex individual geometries. In addition to their ability to micro-regulate sound through their porous texture, digital manufacturing technologies expand the possibilities of ceramic elements on a macro scale through function-based design [16, 80]. Giglio et al.[14] developed a workflow for the design of customized acoustic interior surfaces based on computational design and manufacturing processes (CNC milling). The aim was to combine optimized reflection, scattering and absorption properties in the final product.

Additive Technologies

Products that make use of diffuse scattering particularly benefit from the individualized mass production that digital methods offer due to the easy adaption of the dimensions of the reflecting structure related to the considered frequencies and the room's requirements [81].

Absorber systems effectively utilize digital technologies to reduce sound levels through passive destructive interference at specific frequencies [82]. Material and surface roughness significantly impact performance, with smoother surfaces enhancing effectiveness. Attempts to incorporate diffuse scattering by bending geometries were negligible in acoustic benefit and caused temperature stress buckling [83].

AM acoustic panels can further be improved by using natural fiber-reinforced polymer composites in FDM to enhance mechanical as well as acoustical properties [84].

Measures for the outside of a facade using digital technologies on the other hand are rare. A pre-study at TU Darmstadt included the development of an additively manufactured acoustically effective ceramic façade [85].

The idea behind the functionality of the design is visualized in Figure 6. The parabolically shaped elements direct sound waves into their interior. Thereby, the sound waves are deflected upwards. The upper parts of the system are designed with an infill structure to further scatter and absorb sound. Size, curvature and opening can be varied depending on the orientation of the sound source and the most dominant frequency range. Compared to the reference object with an even surface, a SPL reduction of up to 7 dB was demonstrated for the tested facades.

CONCLUSIONS

Additive Manufacturing (AM) offers significant advantages in acoustic material production, enabling precise control over design and fabrication. While clay may not match the acoustic performance of specialized foams, its excellent hygric properties and sustainability make it a viable alternative compared to other common materials in construction like concrete, glass, or metal. AM allows for the optimization of porosity and frequency response in clay-based acoustic elements, addressing limitations of conventional manufacturing. However, process-related variations, such as porosity inconsistencies and surface roughness, must be carefully managed to ensure reproducible mechanical properties.

Despite growing interest in clay 3D printing and its ecological benefits, current processes are constrained by coarse resolution and material variability. To facilitate its adoption in acoustic applications, further research is needed to refine material formulations, optimize process parameters, and establish reliable drying methods. Prefabrication of such components requires a systematic approach to ensure dimensional accuracy and structural integrity. Additionally, hybrid strategies—such as applying 3D-printed textures onto prefabricated panels—could enhance acoustic performance while enabling scalable production.

Digital fabrication presents new possibilities for performance-driven acoustic solutions, yet its application to natural materials like clay remains underexplored. Integrating computational design with AM can lead to tailored acoustic elements that improve interior soundscapes while maintaining environmental efficiency. Future research needs to focus on refining printing techniques, developing hybrid solutions, and deepening the understanding of material-process interactions to enable the reliable, scalable production of clay-based acoustic systems.

REFERENCES

[1] Oxman R (2009) Performative Design: A Performance-Based Model of Digital Architectural Design. Environ Plann B Plann Des 36:1026–1037. https://doi.org/10.1068/b34149

[2] Moini R (2023) Perspectives in architected infrastructure materials. RILEM Technical Letters 8:125–140. https://doi.org/10.21809/rilemtechlett.2023.183

[3] Crump SS (1992) Apparatus and method for creating three-dimensional objects

[4] Fuchs H (2010) Schallabsorber und Schalldämpfer. Springer Berlin Heidelberg, Berlin, Heidelberg

[5] Fuchs H V. (2017) Raum-Akustik und Lärm-Minderung. Springer Berlin Heidelberg, Berlin, Heidelberg

[6] Nocke C (2019) Raumakustik im Alltag. Fraunhofer IRB Verlag

[7] World Health Organization (2011) Burden of disease from environmental noise. Copenhagen

[8] Nocke C Eine Übersicht zur Hörsamkeit von Räumen

[9] Simon R, Dreissen A, Leroy H, et al (2023) Acoustic camouflage increases with body size and changes with bat echolocation frequency range in a community of nocturnally active Lepidoptera. Journal of Animal Ecology 92:2363–2372. https://doi.org/10.1111/1365-2656.14016

[10] Tian Z, Meng Y, Zhao S, et al (2025) Moth-wing-inspired metasurface for modulating sound amplitude and phase. Mech Syst Signal Process 223:111849. https://doi.org/10.1016/j.ymssp.2024.111849

Figure 5: Additively manufactured acoustically effective ceramic facade [85].

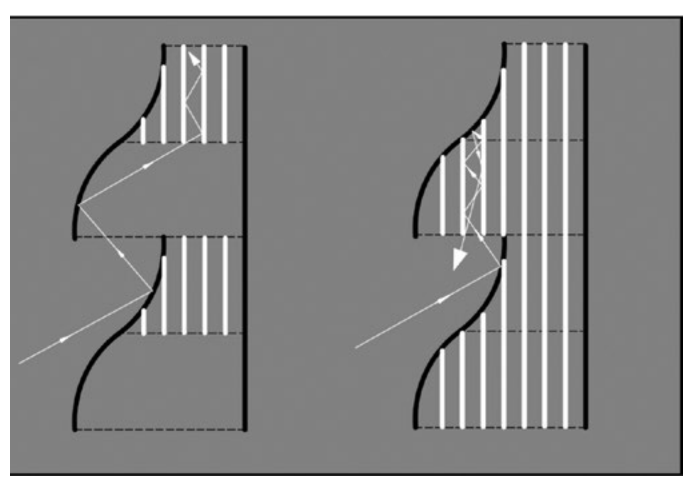

Figure 6: Soundpaths within the printed facade elements [85].

[11] Correa Zuluaga D (2024) Designing Material Architectures. In: AM PERSPECTIVES Research in additive manufacturing for architecture and construction. SOAP, pp 53–60
[12] Zhao S, de Angelis E (2019) Performance-based Generative Architecture Design: A Review on Design Problem Formulation and Software Utilization. Journal of Integrated Design and Process Science 22:55–76. https://doi.org/10.3233/JID190001
[13] Krushynska AO, Torrent D, Aragón AM, et al (2023) Emerging topics in nanophononics and elastic, acoustic, and mechanical metamaterials: An overview. Nanophotonics 12:659–686
[14] Giglio A, Paoletti I, Zheliazkova M (2020) Performance-based design approach for tailored acoustic surfaces. In: Research for Development. Springer, pp 137–148
[15] Hannouch A (2019) Acoustic Simulation and Conditioning in Vaulted Structures - Faceted Stereotomic Strategies for Multi-listener Spaces. pp 403–412
[16] Rossi G, Walker J, Søndergaard A, et al (2021) Design-to-Manufacture Workflows of Sound-Scattering Acoustic Brick Walls
[17] Peters B (2007) The Smithsonian Courtyard Enclosure: A Case-Study of Digital Design Processes. Expanding Bodies: Art ? Cities? Environment [Proceedings of the 27th Annual Conference of the Association for Computer Aided Design in Architecture / ISBN 978-0-9780978-6-8 74–83
[18] Badino E, Shtrepi L, Astolfi A (2020) Acoustic Performance -Based Design: A Brief Overview of the Opportunities and Limits in Current Practice. Acoustics 2:246–278
[19] Peters B (2010) Acoustic Performance as a Design Driver: Sound Simulation and Parametric Modeling Using SmartGeometry. International Journal of Architectural Computing 8:337–358. https://doi.org/10.1260/1478-0771.8.3.337
[20] Mirra G, Pignatelli E, Di Rosario S (2018) An automated design methodology for acoustic shells in outdoor concerts. In: Euronoise 2018
[21] Puzalowski P, Pedersen J, Jeong C-H (2024) Optimizing a small room for critical listening with Treble. INTER-NOISE and NOISE-CON Congress and Conference Proceedings 270:2317–2328. https://doi.org/10.3397/IN_2024_3165
[22] van der Harten A (2013) Pachyderm Acoustical Simulation: Towards Open-Source Sound Analysis. Architectural Design 83:138–139. https://doi.org/10.1002/ad.1570
[23] Peters B (2015) Integrating acoustic simulation in architectural design workflows: the FabPod meeting room prototype. Simulation 91:787–808. https://doi.org/10.1177/0037549715603480
[24] Bavister P (2013) Soundforms: The design, development and fabrication of a 1:1 scale mobile acoustic performance
[25] Foged IW, Pasold A, Jensen MB (2014) Evolution of an Instrumental Architecture. pp 365–372
[26] Bar-Sinai KL, Shaked T, Fettahoglu ES, et al (2023) Embedding Acoustic Analysis in Landscape Architecture Design Processes: A Case Study of Munich Airport. Buildings 13:143. https://doi.org/10.3390/buildings13010143
[27] Valuckas V, Paniagua-Domínguez R, Maimaiti A, et al (2019) Fabrication of Monodisperse Colloids of Resonant Spherical Silicon Nanoparticles: Applications in Optical Trapping and Printing. ACS Photonics 6:2141–2148. https://doi.org/10.1021/acsphotonics.9b00722
[28] Wang W, Iglesias J, Jin Y, et al (2021) Experimental realization of a pillared metasurface for flexural wave focusing. APL Mater 9:. https://doi.org/10.1063/5.0052278
[29] Mirzaali MJ, Caracciolo A, Pahlavani H, et al (2018) Multi-material 3D printed mechanical metamaterials: Rational design of elastic properties through spatial distribution of hard and soft phases. Appl Phys Lett 113:. https://doi.org/10.1063/1.5064864
[30] Li J, Slesarenko V, Rudykh S (2022) Emergence of instability-driven domains in soft stratified materials. NPJ Comput Mater 8:100. https://doi.org/10.1038/s41524-022-00783-x
[31] Iglesias Martínez JA, Groß MF, Chen Y, et al (2021) Experimental observation of roton-like dispersion relations in metamaterials. Sci Adv 7:. https://doi.org/10.1126/sciadv.abm2189
[32] Gliozzi AS, Miniaci M, Chiappone A, et al (2020) Tunable photo-responsive elastic metamaterials. Nat Commun 11:2576. https://doi.org/10.1038/s41467-020-16272-y
[33] Zhang T, Bok E, Tomoda M, et al (2022) Compact acoustic metamaterial based on the 3D Mie resonance of a maze ball with an octahedral structure. Appl Phys Lett 120:. https://doi.org/10.1063/5.0084030
[34] Xiao Z, Gao P, Wang D, et al (2021) Ventilated metamaterials for broadband sound insulation and tunable transmission at low frequency. Extreme Mech Lett 46:101348. https://doi.org/10.1016/j.eml.2021.101348
[35] Brûlé S, Enoch S, Guenneau S (2020) Emergence of seismic metamaterials: Current state and future perspectives. Phys Lett A 384:126034. https://doi.org/10.1016/j.physleta.2019.126034
[36] Mu D, Shu H, Zhao L, An S (2020) A Review of Research on Seismic Metamaterials. Adv Eng Mater 22:1901148. https://doi.org/10.1002/adem.201901148
[37] Spagnuolo M, Reccia E, Ciallella A, Cazzani A (2022) Matrix-embedded metamaterials: Applications for the architectural heritage. Mathematics and Mechanics of Solids 27:2275–2286. https://doi.org/10.1177/10812865221108372
[38] Deymier PA (2013) Acoustic Metamaterials and Phononic Crystals. Springer Berlin Heidelberg, Berlin, Heidelberg
[39] Chiang YK, Oberst S, Melnikov A, et al (2020) Reconfigurable Acoustic Metagrating for High-Efficiency Anomalous Reflection. Phys Rev Appl 13:064067. https://doi.org/10.1103/PhysRevApplied.13.064067
[40] Hou Z, Fang X, Li Y, Assouar B (2019) Highly Efficient Acoustic Metagrating with Strongly Coupled Surface Grooves. Phys Rev Appl 12:034021. https://doi.org/10.1103/PhysRevApplied.12.034021
[41] Blaschke KK, Schwickert S, Kob M (2022) Untersuchung der raumakustischen Eigenschaften von Lehmoberflächen. In: DAGA 2022 Stuttgart
[42] JCW Acoustic Supplies Absorption coefficients of common building materials and finishes. https://www.acoustic-supplies.com/absorption-coefficient-chart/. Accessed 21 Jan 2025
[43] Tiles and Bricks Europe AISBL (2022) Bricks and tiles -Industry, European Manufacturing. In: http://www.tiles-bricks.eu/industry
[44] Minke Gernot (2017) Handbuch Lehmbau : Baustoffkunde, Techniken, Lehmarchitektur , 9th ed. ökobuch, Staufen bei Freiburg
[45] Lawanwadeekul S, Otsuru T, Tomiku R, Nishiguchi H (2021) Effects of Surface Conditions of Porous Clay Bricks on Sound Absorption Charcteristics. In: Annual Congress of the International Institute of Acoustics and Vibration (IIAV)
[46] Lawanwadeekul S, Otsuru T, Tomiku R, Nishiguchi H (2019) Advanced investigation using the EApu method on the effect of quantitation and particle size of charcoal in clay bricks on sound absorption coefficient. In: International Congress on Acoustics. Aachen
[47] Dachverband Lehm (2023) Lehmbau Techniken
[48] Kloft H, Oechsler J, Loccarini F, et al (2019) Robotische Fabrikation von Bauteilen aus Stampflehm. Deutsche BauZeitschrift 54–59
[49] Hack N, Kloft H (2020) Shotcrete 3D Printing Technology for the Fabrication of Slender Fully Reinforced Freeform Concrete Elements with High Surface Quality: A Real-Scale Demonstrator. pp 1128–1137

[50] Chaltiel S, Bravo M, Veenendaal D, Sayers G (2020) Drone Spraying on Light Formwork for Mud Shells. In: Design Transactions. UCL Press, pp 150–157
[51] Mitterberger D, Derme T (2019) Soil 3D Printing. pp 586–595
[52] de Witte D (2022) Towards the fourth generation brickwork
[53] Wilfinger M, Knaack U, Strauß H, Fehlhaber T (2021) B Konstruktion · Bauausführung · Bauwerkserhaltung V Ziegel aus dem 3D-Drucker
[54] Schoof J (2021) Mutter Erde im 3D-Druck: Versuchsbau Tecla von Mario Cucinella Architects und WASP
[55] Wolf Bavaria PhoneStar Tri. https://www.wolf-bavaria.com/phonestar-tri/1008. Accessed 25 Sep 2024
[56] Kaamin M, Zaid N, Daud ME, et al (2019) Analysis on Absorption Sound Acoustic Panels from Egg Tray with Corn Husk and Sugar Cane. International Journal of Innovative Technology and Exploring Engineering 8:1426–1431. https://doi.org/10.35940/ijitee.I3304.0789S319
[57] Möhring R (2009) Baustoffkunde für Ausbildung und Praxis, 11th ed. Neuwied
[58] Zheliazkova M, Di Milano P, Giglio A, Paoletti I (2020) Acoustic characterisation of a novel wood/cork composite material for architectural applications
[59] omlab (2023) Nature-friendly starter home for house martin. https://www.omlab.nl/en/martin-starterhome/. Accessed 28 Jan 2025
[60] Abdullah Agha D (2024) 3D Paper Printing for the Built Environment. Springer Fachmedien Wiesbaden, Wiesbaden. https://doi.org/10.1007/978-3-658-45076-2
[61] Heinze L, Liebringshausen A, Eversmann P (2024) 3D printing with wood waste. In: Built Environment Additive Manufacturing . Darmstadt, pp 25–32
[62] rigips Saint-Gobain Akustikdecken von RIGIPS sorgen für optimale Raumakustik: Informationen, Bauteile und Systeme. https://www.rigips.de/loesungen-inspiration/raumakustik. Accessed 28 Jan 2025
[63] Tay YWD, Panda B, Paul SC, et al (2017) 3D printing trends in building and construction industry: a review. Virtual Phys Prototyp 12:261–276. https://doi.org/10.1080/17452759.2017.1326724
[64] Peri 3D Construction Europe's largest 3D-printed apartment building. https://www.peri3dconstruction.com/en/wallenhausen. Accessed 6 Jan 2025
[65] Hack N, Kloft H, Mai I, et al (2024) Injection 3D Concrete Printing: From Structural Geometry to Fabrication. Architectural Design 94:30–39. https://doi.org/10.1002/ad.3094
[66] Caetano DE, Alves JL, Neto RL, Duarte TP (2017) Development of Plaster Mixtures Formulations for Additive Manufacturing. pp 257–277
[67] Niesten J, Tenpierik MJ, Krimm J (2022) Sound predictions in an urban context. Building Acoustics 29:27–52. https://doi.org/10.1177/1351010X211034665
[68] Stern M, Townsend E, Massimino D, Becker K (2024) Advancing Sustainable 3D Printing: The Feasibility of Recycled Glass as a Building Material With Additive Manufacturing. https://doi.org/10.47982/cgc.9.583
[69] Fröhlich F, Hildebrand J, Bergmann JP (2022) Additive Manufacturing with Borosilicate Glass and Soda-Lime Glass. pp 151–164
[70] Krimm J (2018) Acoustically effective façades
[71] Gardner L, Kyvelou P, Herbert G, Buchanan C (2020) Testing and initial verification of the world's first metal 3D printed bridge. J Constr Steel Res 172:106233. https://doi.org/10.1016/j.jcsr.2020.106233
[72] Feucht T, Waldschmitt B, Lange J, Erven M (2021) 3D-Printing with Steel: Additive Manufacturing of a Bridge in situ. ce/papers 4:1695–1701. https://doi.org/10.1002/cepa.1475
[73] Waldschmitt B, Lange J (2023) Robot supported Wire Arc Additive Manufacturing of Steel Columns. ce/papers 6:696–701. https://doi.org/10.1002/cepa.2473
[74] Erven M, Lange J (2023) Material efficient WAAM Steel Construction Details. pp 543–551
[75] Oppe M, Tramontini L, Thieme S (2023) Additive Fertigung von freigeformten Stahl-Glas-Konstruktionen. In: Glasbau 2023. Wiley, pp 21–32
[76] Ojeda J (2023) Formlight. In: Rosendahl P, Gaudilliere-Jami N (eds) BE-AM 2023 SYMPOSIUM
[77] Henke K, Talke D, Buschmann B (2021) Einsatz von Holz bei der additiven Fertigung im Bauwesen. In: Proceedings of the 17th Rapid.Tech 3D Conference Erfurt, Germany, 22–23 June 2021. Carl Hanser Verlag GmbH & Co. KG, München, Germany, pp 177–187
[78] Mahmood A, Akram T, Chen H, Chen S (2022) On the Evolution of Additive Manufacturing (3D/4D Printing) Technologies: Materials, Applications, and Challenges. Polymers (Basel) 14
[79] Wolf A, Rosendahl PL, Knaack U (2022) Additive manufacturing of clay and ceramic building components. Autom Constr 133
[80] Rossi G, Walker J, Søndergaard A, et al (2021) Oscillating wire cutting and robotic assembly of bespoke acoustic tile systems. Construction Robotics 5:63–72. https://doi.org/10.1007/s41693-020-00051-8
[81] Vomhof M, Vasey L, Brauer S, et al (2014) Robotic Fabrication of Acoustic Brick Walls. pp 555–564
[82] Setaki F, Tenpierik M, Turrin M, van Timmeren A (2014) Acoustic absorbers by additive manufacturing. Build Environ 72:188–200. https://doi.org/10.1016/j.buildenv.2013.10.010
[83] Setaki F, Tian F, Turrin M, et al (2023) 3D-printed sound absorbers: compact and customisable at broadband frequencies. Architecture, Structures and Construction 3:205–215. https://doi.org/10.1007/s44150-023-00086-9
[84] Sekar V, Fouladi MH, Namasivayam SN, Sivanesan S (2019) Additive Manufacturing: A Novel Method for Developing an Acoustic Panel Made of Natural Fiber-Reinforced Composites with Enhanced Mechanical and Acoustical Properties. Journal of Engineering 2019:1–19. https://doi.org/10.1155/2019/4546863
[85] Fluß D (2023) Design and evaluation of additive manufactured ceramics in construction. TU Darmstadt
[86] Campos, T., Figueiredo, B., & Cruz, P. J. S. (2022). Exploration of natural materials in additive manufacturing in architecture: Use of cellulose-based pulps. Structures and Architecture A Viable Urban Perspective?, 663–670. https://doi.org/10.1201/9781003023555
[87] Wolf, A. (2025). Applied Additively Manufactured Ceramics for the Built Environment [Technical University Darmstadt]. https://doi.org/http://dx.doi.org/10.26083/tuprints-00029057
[88] Chhadeh, P. A., Sleiman, K., Hoffmann, H., Funke, N., Rettschlag, K., Jäschke, P., Baitinger, M., Knaack, U., Kaierle, S., & Seel, M. (2025). Design of additively manufactured glass components for glass point fixings. Glass Structures & Engineering, 10(1), 6. https://doi.org/10.1007/s40940-024-00290-z
[89] Seel, M., Chhadeh, P. A., Thiele, K., Akerboom, R., & Knaack, U. (2022). Additive Manufacturing of Glass for the Built Environment: Potential and Challenges. BE-AM | Built Environment Additive Manufacturing.