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Design, cultivation and acoustic analysis of a building-sized mycelium sculpture

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Abstract

This paper describes novel computational design, simulation and fabrication techniques employed in the production of a large sound-absorbing sculpture called Phoenix, made entirely from mycelium-composite materials (myco-materials). Myco-materials are composites made of lignocellulosic agricultural waste fibers bound by fungal mycelium and are produced at commercial scale as alternatives for plastics, insulation foam, or styrene. Mycelium composite materials have known acoustical properties that can be tuned according to variables such as growing time, substrate type, substrate size and density. The fabrication method for producing the Phoenix sculpture revisits how we build performative and formal complexity in the most economic and sustainable way. The results indicate the potential for grown materials to be used in retrofit projects, allowing rooms to be customized in various acoustical situations, such as music or speech.

Introduction

The notion that buildings must be permanent, high-energy investments is deeply imbedded, particularly in euro-centric cultures. The children's fairy tale "The Three little Pigs" (Brooke, 1904) teaches us that the smartest pig builds their house out of brick to withstand the forces of nature – or at least the wind. Between straw, sticks and bricks, all are extracted from natural resources, but only brick requires heat energy to manufacture. Do such energetic investments make a better building? What if the pigs' houses fell victim to fire or an earthquake? Brick construction collapses in fire due to weakness developed in mortar and due to brittleness in an earthquake. Bricks can be just as susceptible to collapse as straw or sticks. If the pigs were to re-build their houses, the pig who chose bricks would need to source new materials and new energy to re-manufacture them, whereas the pigs who chose straw and sticks could in a sense *re-grow* their houses.

An important reason we must grow buildings, is their lifespans are rapidly decreasing due to early demolition, which often contributes to unsustainable landfilling. Trends of shortened building lifespans have been documented through numerous studies tabulated by Anderson and Negendahl (2023). The lifespan of a house is around 60 years in the United States (Aktas and Bilec 2012), 65 years in Southeastern Europe (Novikova et al. 2018) and 25 years in Japan (Wuyts et al. 2019). Anderson and Negendahl (2023) studied buildings in Denmark and found that new buildings will have a *projected lifespan* 45% shorter than the average for that same building type. For example, new office buildings in Denmark have a projected lifespan of just 40 years, in contrast to office buildings built before 1960 that could have 80+ years remaining. In short-lived buildings, structural materials like concrete and steel account for more total emissions than replacement parts such as insulation and windows (Häfliger et al. 2017). Extending a building's lifespan by 50+ years through retrofitting has been simulated to give notable reductions in a buildings' embodied energy (Rauf and Crawford, 2015) and further improved after 30 years when operating energy accounts for most of the total lifecycle cost (Han et al., 2014). Building interiors such as commercial spaces and offices are also major producers of demolition waste. A study in Australia (Fini and Forsythe, 2020) found that 78% of fit-out waste from demolished office spaces is landfilled. This was attributed to fit-out elements often being produced for single-use with features that limit sustainable demolition. Another factor was the perception that demolition is more expeditious and cost-effective. In the United States construction and demolition waste amounts to 600 million tons each year, according to the Environmental Protection Agency (EPA, 2018). In an era when buildings are predicted to be demolished early, a first step toward addressing the issue of short building lifespans and the accumulation of waste from building materials is to adopt appropriate materials for specific purposes and to extend their lifespans through maintenance and retrofitting. The second step is to adopt local, low-energy and renewable materials that reduce transportation emissions and are designed for chemical recycling or biological disposal (such as composting). Particularly in the context of sculpture or interiors, where longevity may not be a primary concern, leveraging bio-based materials derived from waste, with significant degradation potential, offers distinct

Life

Death

Figure 1. Life and death of Monolito Micelio: a monolithic pavilion for a singing performance in May 2018. The structure was cultivated from a single colony of mycelium in a hemp substrate. After the performance, the structure was left to decay and eventually broken down, disposed and “fed” to compost. Photos by Jonathan Dessi-Olive.

advantages. Within the rapidly growing field of bio-based materials, fungi have stood out because they self-assemble into composite materials with tuneable architectural properties.

Mycelium composite materials (myco-materials) are lignocellulosic fibers bound by a biopolymer of fungal mycelium – the web-like vegetative filaments of fungi (Stamets, 2005), commonly from the phylum Basidiomycota. Myco-materials are an international enterprise and produced at commercial scale to make animal leather alternatives (Forager, 2023; Mycoworks, 2023) and packaging materials (Mushroom Packaging, Magical Mushroom Company). Using processes resembling mushroom farming, mycelia are cultivated under correct conditions until they have formed a biomass. In most applications, living biomass is dehydrated to stop the growth (Bayer and McIntyre, 2016) producing a lightweight and low-density material that resembles styrene foam that can be broken down and composted. Control over the density of the material and its properties is limited to the extent environmental conditions can be controlled across every stage of cultivation and desiccation. Different substrates and fungal strains can be combined to make biocomposites with varying properties of structural integrity, density, conductivity, moisture resistance and visual quality (Elsacker et al., 2019; Girometta et al., 2019; Appels et al. 2019; Sydor et al. 2022).

Access to greater quantities of myco-materials for research and teaching facilitated by companies like Ecovative (2023) has enabled the cultivation of pavilion structures demonstrate the potential of fungi to be used for building structures. At architecture scale, the most common approaches to fabrication with myco-materials are based on assemblies of bricks (Saporta et al. 2015), or blocks (Heisel et al. 2018), or large monolithic colonies grown in situ (Dessi-Olive, 2019). A recent review (Ghazvinian and Gursoy, 2022) documents 24 architectural projects utilizing mycelium. Some, including those mentioned above, featured self-supporting pavilions and prototypes that suggest that one could grow a building for a short-term function and later demolished and composted (Figure 1). Other examples demonstrate myco-materials applied to other functional scenarios, include cladding panels (The Growing Pavilion, 2023), thermal insulation (Mushroom Tiny House, 2023) and interior acoustical wall panels (Mogu Mycelium, 2023). While limited performance data are provided by Mogu, myco-materials have acoustical properties (Pelletier et al. 2013; Jones et al. 2020) and have undergone testing, summarized in a recent review paper (Gomez Mendez et al., 2023). In a previous study (Hsu and Dessi-Olive, 2021), the authors of this paper conducted impedance tube tests to ascertain the effect growing time has on the acoustical properties of myco-materials. While we saw granular acoustic differences for varying grow times, our more significant observation was that myco-materials have *limited promise for sound absorption*.

In this paper we present a case study of a building-scale sculptural installation made of myco-materials that addresses the issue of short building lifespans and unsustainable landfilling. Phoenix is a hanging sculpture comprised of lightweight sheets (myco-sheets), that was designed as a building retrofit to improve the acoustics of a large space used for events such as art exhibitions, musical performances and lectures. Our main area of inquiry explores how effectively the sculpture improves the acoustics of the space using ray tracing computer simulation to determine reverberation time (T20), clarity (C80) and speech intelligibility (STI). While exploring and designing with novel and sustainable materials is inherently intriguing and challenging, the acoustical function of Phoenix holds value by improving the acoustics of the space, pushing fabrication boundaries with renewable materials and contributing to interdisciplinary research.

Background and methods

Background and design of phoenix

The concept of Phoenix stemmed from a design and education collaboration called “The Mycelium Project” that imagined myco-materials as part of the contemporary construction industry. The team collaborated on a speculative residential commission to

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Figure 2. Processes and prototypes that preceded the design, cultivation and installation of Phoenix. On the left, bending living sheets guided by augmented reality for the Myco-Chandelier. On the right, cultivating non-rectangular sheets with flexible formwork for the hanging Myco-Pod. Photos by Jonathan Dessi-Olive.

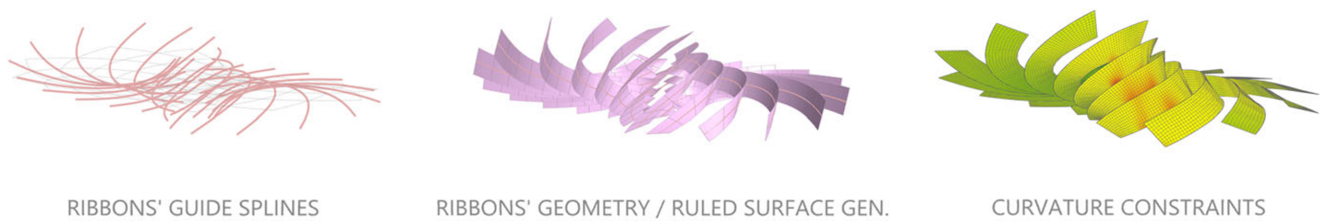

Figure 3. Analytical diagrams of formal steps for generating Phoenix. From left to Right: ribbon guide splines, preliminary ribbon geometry; and ribbon winding. Drawings by Omid Oliyan.

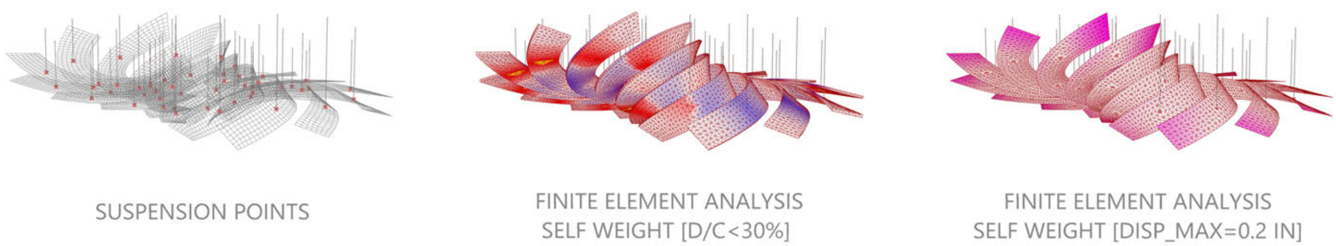

Figure 4. Analytical diagrams of structural issues. Left to Right: suspension points; hanging simulation of suspension lines and global stability; FEA self-weight; and FEA displacement. Drawings by Omid Oliyan.

renovate a conservatory space with a hanging structure made of myco-materials that improved sound. Through improvisational experiments (Dessi-Olive et al. 2022) that gave way to prototypes (Figure 2), the research team at MycoMatters Lab formalized the "hang-dry" fabrication method and in parallel developed an integrated computational design process, which is described in greater detail in a separate publication (Dessi-Olive et al., 2023). The design of Phoenix is composed of 16 uniquely shaped hanging myco-sheets that are generated based on a set of guiding splines, with consequent design constraints which requires fabrication from flat sheets. The geometries are ruled surfaces that can be translated into developable surfaces based on the degree of winding and unwinding (Figure 3). Our integrated computational approach reliably accommodates for complex geometric manipulations against a finite element analysis (FEA) solver which provided structural feedback, each sheet was analyzed for local stress at connection points, their global stability and deformations due to self-weight (Figure 4).

Cultivating myco-materials and hang-dry fabrication method

There are numerous challenges of cultivating myco-materials at architectural scale (Dessi-Olive, 2022a). Forming large-scale objects requires complex formworks or scaffolds, they highly susceptible to contamination during cultivation and drying large objects requires lengthy air-drying or access to large, energy-consuming ovens. This issue has been addressed through demonstrations of 3D printing myco-materials and have produced building elements such as stacked block columns (Blast Studio; Goidea et al. 2020). In another area of inquiry, researchers cultivate myco-materials into flexible textile formworks, leading to prototypes including columnar structures with basket woven exoskeletons (Dessi-Olive, 2022b; Adamatzky et al. 2019), shell structures (Gruber and Imhof, 2016; Søren, 2018) and tubular structures (Ratti 2019). A subset of the typology uses gravity to form myco-materials by hanging, which is exemplified by a recent project called BioKnit (Scott et al. 2022), a dome-like structure with a 3D knitted textile exoskeleton was cultivated by hanging and once fully cultivated and dried, the structure was flipped. Our "hang-dry" method facilitates the craft of expressive 3D curvatures into living myco-sheets during their intermediate stage of cultivation, by hanging them from precise support points, actively bending them and drying them in place. The technique benefits from augmented reality (AR) assistance using Fologram, an AR application which projects digital models to a fabricator's HoloLens (Microsoft's take on augmented reality). An illustrated

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Figure 5. In step 1, formwork is laid out on an impermeable membrane. Photos by Jonathan Dessi-Olive.

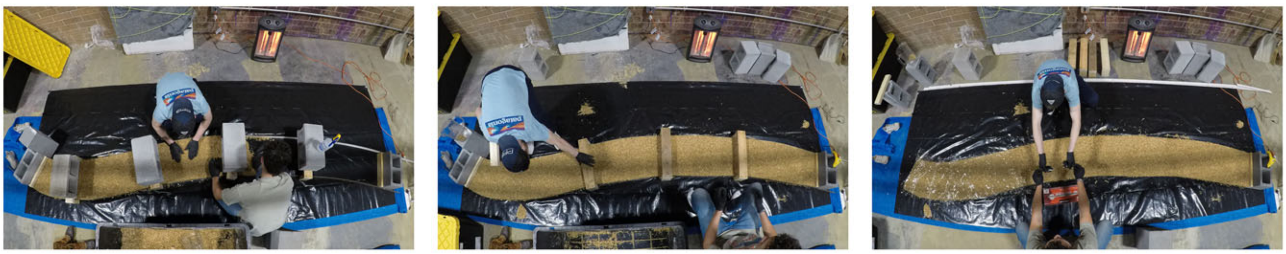

Figure 6. In step 2, the formwork is packed with living myco-materials. Photos by Jonathan Dessi-Olive.

Figure 7. In step 3, the cultivated sheets are hang-dried into their 3D form. Photos by Jonathan Dessi-Olive.

summary of the fabrication process is included below. In the first step, a reusable formwork system (wooden brackets, flexible splines and concrete blocks), is configured with AR on top of an impermeable membrane (Figure 5). In the second step (Figure 6), the formwork is packed tightly with 40 mm thickness of living fibers; the formwork was disassembled; the fibers covered with plastic film to preserve humidity and sterility, and a plastic tarp was placed to block light and trap heat. The 16 sheets were cultivated in a sequence that corresponded with the anticipated hanging sequence. In the third step (Figure 7), the cultivated myco-sheets were lifted and actively bent, guided by AR, shaping each sheet to its correct digitally generated 3D form.

Acoustic simulation methods

The acoustical simulations performed used computer simulated ray tracing methods to show the potential effectiveness of the Phoenix structure in different sized rooms across common acoustic design metrics. The tests involved theoretical absorption values for both the Phoenix sculpture and the room itself. This philosophy allows the results of this study to provide a target for acoustical metrics for the room, the material properties and the form of the structure.

Acoustic simulations were performed in AFMG's EASE 4.4 software. To minimize the variables for this project, three ideal absorption coefficients, equal across all frequencies, were tested for room surface materials, $\alpha = 0.20$, $\alpha = 0.50$ and $\alpha = 0.80$, representing low, moderate and high absorption surface situations. For the Phoenix, $\alpha = 0.70$ idealizes a moderately absorptive material. This allows the results to reflect only geometrical concerns, rather than potential factors of frequency-dependent surfaces. Additionally, to represent a possible real frequency-dependent scenario, gypsum was specified for the wall surfaces in the room. From EASE, an omnidirectional speaker is inserted in the middle of the front of the stage area. An audience area is specified at ear height in the room. Two room sizes are studied. The large room represent the real room that the Phoenix is installed in and is 18.3 m × 18.3 m ft. The small room represents the smallest room in which the Phoenix would fit and is 11.5 m × 11.5 m. Both rooms are 6m in height. The output variables of interest for this paper are reverberation time (T20), clarity for music (C80) and speech transmission index (STI) in the context of audience area coverage.

Average acoustical results are calculated for a location near the center of the room, and spatial maps of the values are created. Figure 8 shows an axonometric representation of these spatial mappings with the Phoenix show on the left, and with the Phoenix

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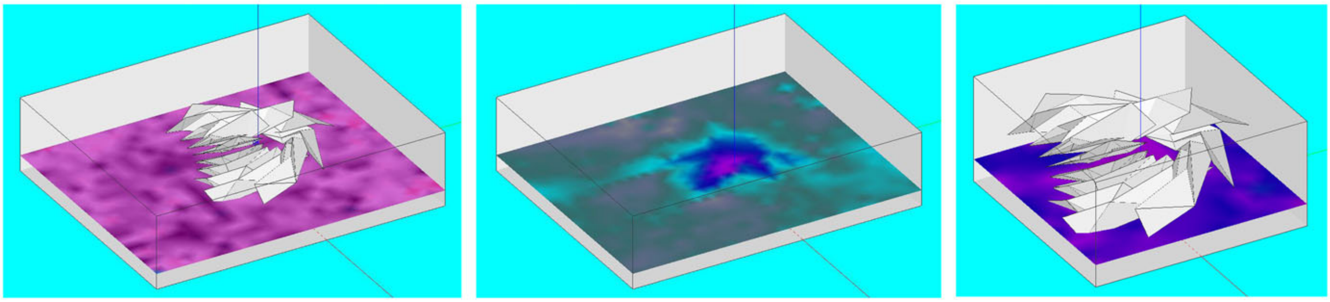

Figure 8. Axonometric view of spatial mappings of T20 with a visible Phoenix (left) and C80 with an invisible Phoenix (middle) in the larger room, and a visible Phoenix in the small room (right). Note the simulation plane represents "ear height" and not the floor of the space. Drawings by Timothy Hsu.

Figure 9. Oblique and side view of Phoenix with its sheets expressively winding and unwinding. Installed at the Charlotte Art League, North Carolina, USA, 2023. Photos by Jonathan Dessi-Olive.

now shown in the center. The mapping plane is set at ear height, with the speaker placed at (0,0) in the center of the space. For the results below, 2D plan mappings represent the plane that is shown in Figure 8. The plan view is more easily interpretable for design. Figure 8 also shows the small gypsum room with the Phoenix sculpture.

Results and discussion

Myco-fabrication results: phoenix

Phoenix (Figure 9) is composed of 16 uniquely shaped hanging myco-sheets made entirely from fungi-based materials. As they twist, wind and unwind through the space, the lightweight myco-sheets form two oculi at the heart of the sculpture in opposing directions. Phoenix was cultivated and installed on-site at an arts accelerator in North Carolina called the Charlotte Art League (CAL). The overall dimensions of Phoenix were 6.5 m × 6.5 m × 2 m – occupying the area of a small house. All 16 myco-sheets had unique shapes and lengths between 3.6 m and 5 m, totalling just over 1 cubic meter of living hemp substrate. The sheets were cultivated from a hemp-based "spawn" that was pre-inoculated with fungi from the phylum Basidiomycota procured from Ecovative (Grow. Bio, 2023). In addition to the usual challenges expected from cultivating large-scale structures, the production included several challenges. Space was a resource whose importance cannot be overstated. Another challenge was maintaining the proper growing environment during cold winter months. Ideal temperatures would range between 22 and 26°C, but on-site during cultivation, temperatures remained around 14–18°C despite active reinforcement from space heaters. While the expected grow time for each sheet was 12–15 days, the average grow time was 32 days. Another unanticipated challenge was the structure simulations assumed the stability of Phoenix after it had dried and turned rigid. However, the sheets were also hanging while they were heavy, wet and flexible, which meant several additional attachment points were required to minimize inaccuracies between connection points. Thanks to the visual reference in the Hololens, the fabricators could intuit and improvise additional connections needed to shape the living myco-sheets more accurately according to the digital form. Next, the sheets were left to dry for one week until they were lighter and rigid, and the extra attachment points could be removed. The "hang-dry" technique employed in the production of Phoenix demanded significant labor resources at all stages of the process. This was particularly true during the hanging stage, where the longest myco-sheets required up to 4 or 5 people to lift and support it while the connections were made to the hanging apparatus. While novel and efficient, the "hang-dry" technique is accompanied by numerous challenges that suggest it maybe not suitable for growing a whole building, and more for bespoke sculptural, and interior design applications like Phoenix.

Acoustic simulation results

The results shown here offer insight toward a notion of improvement with building-scale interventions. While growing a building still faces practical and scalability challenges, retrofitting existing buildings to meet modern and custom demands has current and near-future applications. The results below indicate the potential for grown materials to be used in retrofit projects,

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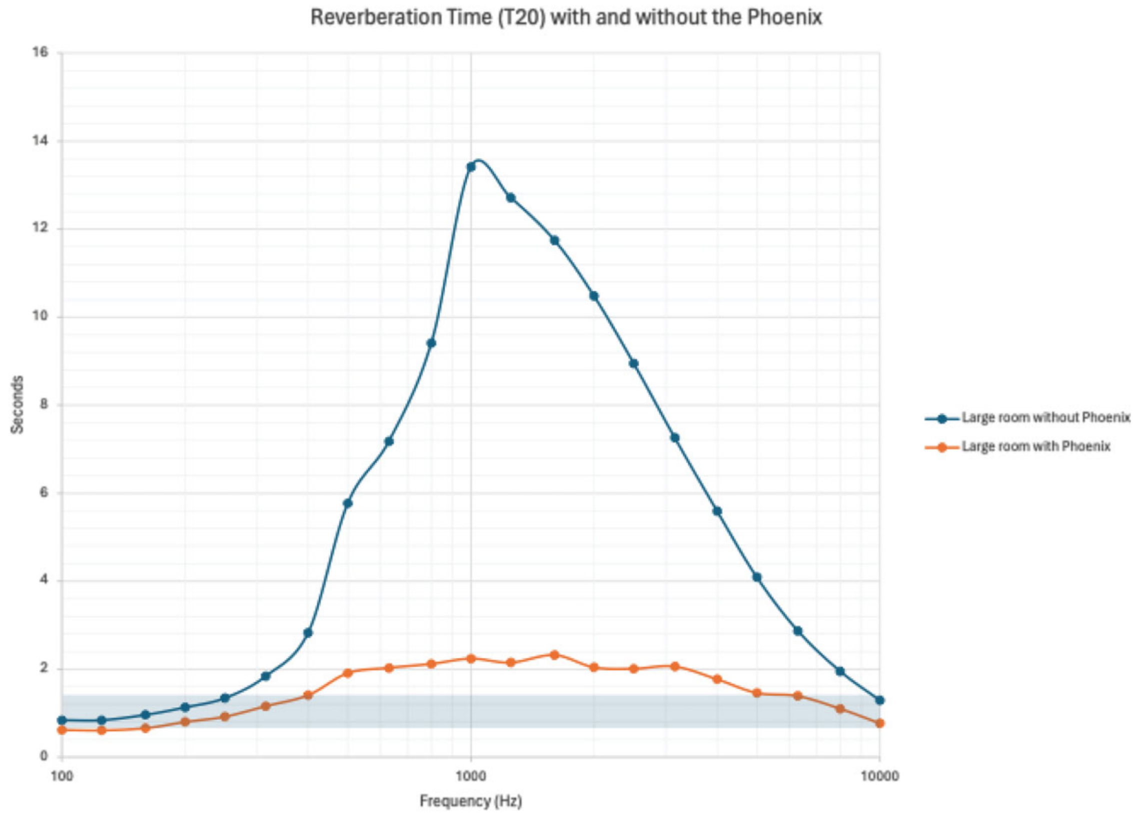

Figure 10. Comparison of T20 of the large gypsum room with and without the Phoenix. The blue box represents recommended reverberation times for rooms for speech and chamber music.

allowing rooms to be customized in various situations, such as music or speech.

T20 is used as the Phoenix structure is hypothesized to affect early reflections and create more changes to the early portion of the impulse response. For larger rooms used for speech and chamber music, the reverberation time can range between ~0.75 seconds and ~1.5 seconds. In rooms designed for music, C80 is a common metric to study clarity of experience listening to music, that is, the ease that fast notes can be distinctly distinguished from one another. In concert halls for western classical music, C80 ranges from approximately −1 dB to 3 dB (Gade, 2003). In rooms designed for the spoken word, speech intelligibility is one of the key metrics that can determine the functional success of a room (ANSI, 2010; Prodi and Visentin, 2019). Speech intelligibility measures how easy it is to understand speech (Long, 2014). The impact of speech intelligibility on human communication cannot be understated. In student learning outcomes (Bistafa and Bradley, 2000) and critical hospital communication (Ryherd et al. 2013), speech intelligibility is at the heart of the core functionality of these spaces. STI is one method used to predict intelligibility as it accounts for reverberation time, background noise and room distortion (ISO, 2012). STI values range from 0 to 1, where Barnett (1999) proposed that ratings of 0.75–1.0 equate too excellent intelligibility, 0.6–0.75 corresponds to good intelligibility, 0.45–0.6 represents fair intelligibility, 0.3–0.45 indicates poor intelligibility and 0.0–0.30 indicates bad intelligibility.

The simulated Phoenix structure, with $\alpha = 0.70$, reduces reverberation time in the gypsum room. Our simulations show that without the Phoenix, the broadband average T20 is 5.4 seconds. By comparison, the broadband average T20 is 1.5 seconds with the Phoenix. Additionally, the reverberation time comparison across 1/3 octave band frequencies is shown in Figure 10. Not only is reverberation time generally lower with Phoenix, but the spectrum is flatter, suppressing the higher reverberation time in frequencies between 500 and 5000 Hz. In Figure 11, the reverberation time across 1/3 octave band frequencies is shown comparing the reverberation time for the large and small gypsum room with the Phoenix installed. The large room has a higher reverberation time, due to the larger volume. Both rooms have reverberation times that would be suitable for musical applications. The smaller room would be ideal for speech settings.

Table 1 shows the average T20, C80 and STI values for the various combinations of large and small rooms with gypsum, $\alpha = 0.20$, $\alpha = 0.50$ and $\alpha = 0.80$ at a position near the center of the room under the Phoenix. In the large room, the volume of the room is the controlling factor for the acoustic metrics for the $\alpha = 0.20$ and gypsum scenarios, while the wall absorption is the controlling factor for $\alpha = 0.50$ and $\alpha = 0.80$ scenarios. The speech intelligibility equates to an excellent rating for all four materials. In the small room, for all scenarios, the values are similar. For the large room, the reverberation time would be appropriate for music for the gypsum and $\alpha = 0.20$ scenarios and the reverberation time would be appropriate for speech in the $\alpha = 0.50$ and $\alpha = 0.80$ scenarios. In the large room for all four materials, clarity and STI are considerably high. This implies that the early energy of a sound dominates and that speech would be easily understood. In the small room, all values would be consistent for a room appropriate for speech as all four materials show excellent STI ratings.

The average values hide the effect of Phoenix. A large room with this volume and low absorption would typically have much

Table 1. T20 (seconds), C80 (dB) and STI average results. C80 recommended values range from approximately −1 dB to 3 dB for Western classical music and STI values of 0.75–1.0 equate too excellent speech intelligibility, 0.6–0.75 corresponds to good speech intelligibility

	Average values at center of room		
	T20 (seconds)	C80 (dB)	STI
Large room gypsum	1.50	14.17	0.82
Large room 20% absorptive	1.52	14.18	0.82
Large room 50% absorptive	0.27	27.16	1.00
Large room 80% absorptive	0.26	27.19	1.00
Small room gypsum	0.55	18.64	0.89
Small room 20% absorptive	0.56	18.05	0.88
Small room 50% absorptive	0.54	17.34	0.88
Small room 80% absorptive	0.55	17.72	0.88

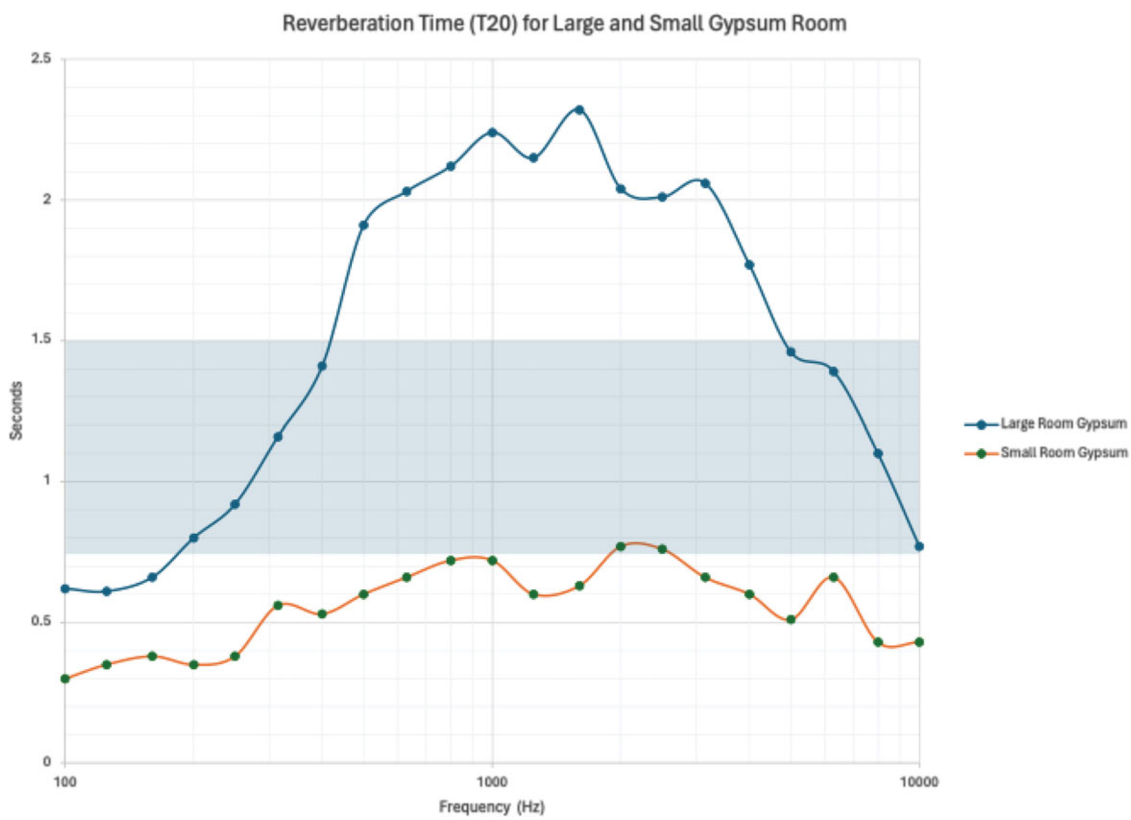

Figure 11. Reverberation time of large and small gypsum room with the Phoenix installed in both. The blue box represents recommended reverberation times for rooms for speech and chamber music.

higher reverberation time values, lower C80 and far reduced speech intelligibility. As seen in in Figure 10, the T20 without the Phoenix is higher than with Phoenix. To understand the acoustical effect of the sculpture, spatial mappings are needed to see how T20, clarity and speech intelligibility differ with respect to listening location in the space. Spatial mappings show that in the large room, areas under the Phoenix exhibit reduced T20, heightened clarity and better speech intelligibility, while areas not under the Phoenix suffer from poorer acoustics. To show a representation of vast differences between the clarity under the Phoenix as compared other areas in the room, Figures 12 and 13 show C80 in the large room for $\alpha = 0.20$ and $\alpha = 0.80$ scenarios. Particularly in Figure 12 with $\alpha = 0.20$ in the large room, areas under the Phoenix all exhibit positive clarity values. Areas to the side have lower and negative values, leading to less clarity. In Figure 13 with $\alpha = 0.80$, the same type of spatial distribution occurs, with less consequence because with high absorption, the areas not under the Phoenix have high clarity. However, this outcome shows that we can customize local audience areas to have specific sonic outcomes that do not affect other areas. This allows for designers and acousticians to retrofit spaces efficiently yet make custom interventions that affect certain performance or audience areas, rather apply a generic solution to the entire room.

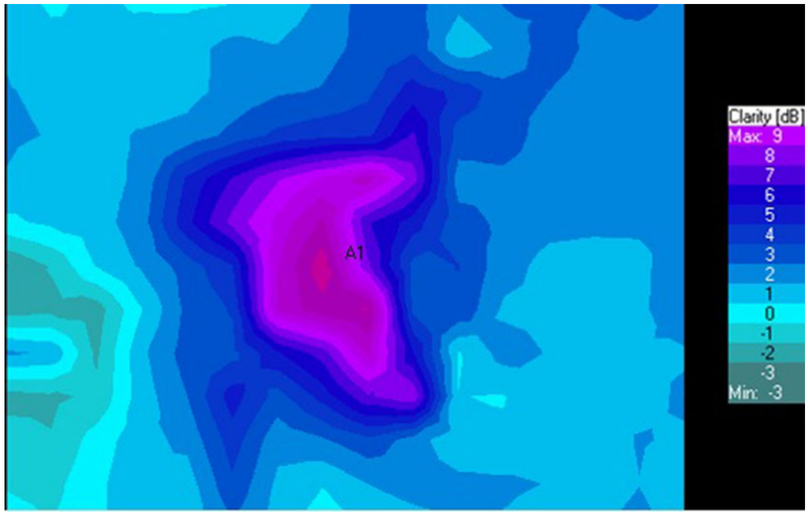

Figure 12. C80 for Large room at α = 0.20.

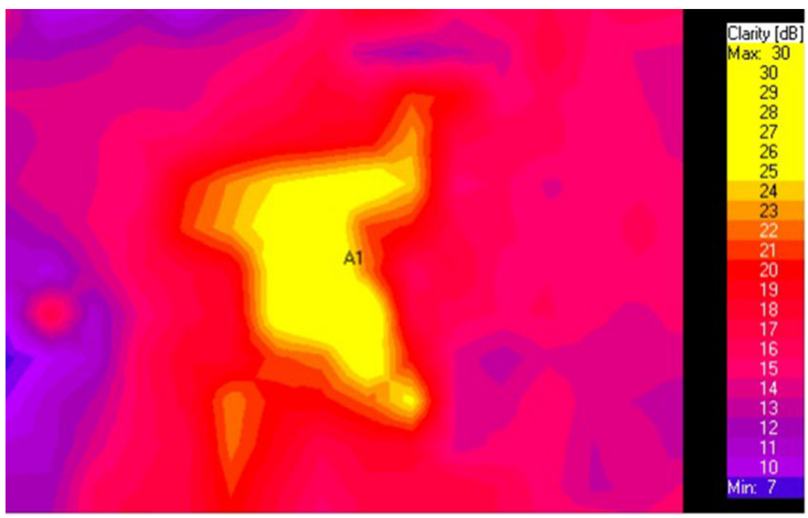

Figure 13. C80 for Large room at α = 0.80.

Acoustical panels have been used to control the reverberation time within rooms and there are some use cases where these panels have had sculptural functions in addition to their acoustical functions. Such hanging acoustical panels, often called “clouds,” have been used above orchestras in concert halls often have a design element, giving them an esthetic purpose in addition to controlling sound reflections. Examples include the orchestra clouds used at the Morton H. Meyerson Symphony Center in Dallas, or the Elbephilharmonie in Hamburg, Germany. Many sound sculptures found in museums or sculpture parks focus on controlling sound reflections or creating sound from nature. However, the Phoenix differs from these as it offers some level of sound absorption. Sound absorbing art examples include acoustic fins, covered acoustic panels and small-scale panels that focus on the visual design aspect. Acoustic absorbers that hang from the ceiling have grown more popular in public places, like offices and atriums. While often not custom in design, these hanging absorbers still possess some esthetic appeal. These suspended structures include lamp shades, drapes, colorful panels, decorative design elements and a variety of other products that shape acoustical foam into design elements. The Phoenix, existing at the intersection of design and functional acoustics, is unlike these examples mentioned. Here, the design and the acoustic function are fused and both specifications are essential for the success of the sculpture.

Conclusions

The ability to grow a building, has become a necessity, not just a wishful fantasy. We will continue to construct buildings whether we are replacing other previously demolished buildings, or to address a global housing crisis that will be caused by a dwindling supply of natural materials and resources, the mass movement of people because of geopolitical conflict and climate change (IOM, 2008). Single use building products and the perception that demolition and landfilling is cheaper are culturally and economically engrained into the building industry because sustainability is not considered a value-adding property. In this paper we have raised the issues of short building lifespans and the accumulation of landfill waste as further justification for why we need to grow a building and have proposed two major steps that can be taken to address these issues. First, to extend building lifespans through retrofitting and maintenance, and second, to adopting materials that are designed for chemical recycling or biological disposal. Mycelium materials have been proposed here as viable candidates for building materials that can be deployed using diverse fabrication methods to address different performative concerns. While fanciful, it is unlikely myco-materials will make a complete and permanent building system on their own and less likely that they will directly replace materials like bricks and concrete.

Can we grow a building? Almost. It depends what kind of building, and whether we are growing a whole building or just part of one. Limitations for building-scale deployments of myco-materials are foremost caused by the challenge of supply and access to commercial quantities of these materials. For myco-materials to succeed in building construction, they must remain in the current dialog of academic and professional contexts. Phoenix is a building-scale installation that demonstrates we can grow building retrofits that improve the quality and performance of existing buildings. In the production of Phoenix, we have demonstrated an integrated computational methodology that included the use of FEA simulation AR to validate design and to aid assembly. The "hang-dry" method is a powerful means of breaking away from brick or block assembly logics that suggests more suitable contexts in which myco-materials may be deployed acoustical treatments or scenography. Furthermore, from our acoustic simulations we observe the potential to leverage the hang-dry technique as a means of growing retrofit installations that are specific and customized to the acoustical needs of an existing space for various situations such as music or speech. This further emphasizes the importance of geometric design as a collaborative territory where acousticians and designers can creatively negotiate specific shapes and biomaterials with appropriate acoustical parameters, to customize acoustic outcomes in retrofit projects. Our future work on this topic will integrate acoustical criteria into our computational framework including the way the geometric form of an installation like Phoenix impacts the first sonic reflections, and how surface area reduces late reflections which cause ambient reverberations. This work will also continue to be carried out in academic settings where students have direct access to myco-materials at various stages of cultivation and with diverse fabrication methods. Their experience working on Phoenix was a vital means of apprenticeship and learning. Underpinning this research is the belief that community-scale biohybrid building systems must be explored, demonstrated and shared now if real impact is to be made immediately.

Data availability statement. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Ethics statement. Ethical approval of this research was not needed from the ethics committee of our university.

Connections references

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