A Method for Designing with Deadwood for Architectural Acoustics

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Abstract

This paper presents the investigation and proposition of how to analyse and design with deadwood as a material resource, and how it can be applied as advanced acoustic design in architecture. The study is focused on Poplar wood in progressed decay, where visual, structural and sound characteristics are analysed and discovered through material studies, prototype studies, computational studies and measurement studies. The research findings have environmental, technical and aesthetical consequences for how we understand and rethink material resources, their structural state and how we can understand biogenic material transformations as part of the design process. Processes lead to a better understanding of using the regenerative materials we have available on the planet. The specific research contributions are increased knowledge of poplar density variances from natural decay and how density variance impacts sound absorption properties of the material and spaces. Furthermore, a new method for descriptive and prescriptive acoustic design processes is presented, based on image-analysis methods. This research and its findings are argued to open novel pathways for material practices as an approach that engage with biogenic material agency, which in turn empowers architecture to address urgent questions of material scarcity and material-climatic relations driven by the built environment.

Keywords

Rethinking biogenic resources · Architectural acoustics · Digital design method · Deadwood

1 Introduction

The current trajectory of using materials in the built environment does not align with the available materials. This is seen even in countries with a highly developed built environment, such as in Denmark, where the planetary limits of societal material use are reached by March (Lin 2021). Hence, even in well-informed countries with resources to transition to a sustainable society, we spend four times the resources for a balanced annual cycle. In a global context, each person on the planet spent on average 33 kg every day, with a projected increase to 45 kg every day by 2060 (OECD 2019). The material usage growth is coupled with another problem, which is that

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the increase will be non-metallic mineral materials constituting the vast majority of the development (ibid). These materials, such as concrete, have a high environmental footprint in its making, transport and recycling processes. Current discussion in Western countries encircle the argument for a de-materialisation and reduction as general processes for transforming to a sustainable situation (ibid). This will be a necessary strategy for countries that already spend too much, but in contrast, BRIC countries (Brazil, Russia, India, China), including the dominant part of the world population and population growth, the expansion of the built environment is driven by mechanisms which enable people to have the same living standards that others have enjoyed for decades (OECD 2019). Thus, while local reductions must take place, a global dematerialization appear less realistic until global equality in built environment quality is constructed.

Environmental responsible materials and viable quantities of materials through better use are therefore necessary. In this effort, research and industry efforts accelerate biogenic material investigations and applications, with construction timber being at the strategic foreground. In contrast, concurrently, forests around the world are decreasing in scale (Brack 2018; Eurostat 2016) removing the basis for wood-based material growth of raw materials. At the current level, global forests are producing 3912 million m^3 (2020) of raw timber (United Nations 2019), which means a large gap to the current and projected demand for construction and transformation of existing structures.

Forests consist, however, of more than raw material for certified construction timber. Deadwood, that is both lying and standing wood in decay, is a significant part of global forests, amounting to 20% of the forest material (Russell et al. 2015). Deadwood has important roles in maintaining the forest ecology, as it decays and rematerialises the forest bed, providing nutrients and homes for insects, plants and animals (Seibold et al. 2021). Hence, a significant deadwood capacity is a direct indicator of forest health and an important element for sustainable ecologies.

Yet, deadwood from forests emits 115% of the global fossil fuel emissions (Seibold et al. 2021). Rethinking deadwood as a material resource presents two technical and practical potentials, namely, a utilisation of materials that is readily available now and at the same time an immediate blocking of releasing the sequestered CO_2 into the atmosphere.

2 Material Characterisation

The study and application of deadwood in the built environment may offer additional potentials than a mere technical resource rethinking through quantity-based substitution of materials. As deadwood enters a process of material decay, it transforms its physical characteristics. This is seen in the change of colour, the material porosity, brittleness and density. Expressive qualities can be deciphered by visual observation and tactile registrations, and which are traceable by the observer back to the transformation process induced by local environmental forces. The expressed causality between the emerging material, its transformation and environmental forces drives the characteristics of both technical and aesthetical definition, such as a tree's positive and negative growth structures (Fig. 1). When considering an architectural form’s articulation as a process of a materials response to a force, it is aligned with the theoretical notions of tectonics in architecture (Christiansen 2019; Foged & Hvejsel 2018; Frampton 1995; Hartoonian, 1994; Sekler 1965; Semper 1989). The advancement from common tectonic descriptions focusing on the articulation of gravitational forces is here based on environmental forces of wind, moisture, temperature and fungal growth processes. Hence, in material transformation processes, such as organic decay in the natural environment, a material and its form relation are at the same time structurally transformed and revealed. As an example, in the gradual decay of a tree, we can observe material distribution paths through

Fig. 1 Tree trunk in natural decay process revealing its inner structure and fibre composition

reversed growth processes combined with local environmental forces at play.

In this example, perceived material and form expression is the result of additive and subtractive formation forces. The material-environment processes undertake on-going articulations of structures beyond their initial state, where they become revealed through local, dynamic and complex force interactions. In such cases, a rethinking of materials as resources is based on a continuous understanding created by a temporal revealing of the relations between a material, a form and environmental forces (Foged 2015).

3 Material and Medium

Extending the position of environmental forces as drivers for new material practices in architecture, and as strategy for rethinking material resources, a force acts not only on the material, but also on the human. In the case of sound, an intimate and direct relation persists between the source of sound energy, a material form and the sound energy recipient. Sound is an environmental force manifested by pressure waves through air as the transfer medium (Cox & D'Antonio 2016; Long 2014). And while invisible, the perception of sound is formed by materials, when the pressure wave is either reflected, absorbed or transmitted by the material. Architectural theorist Steen-Eiler Rasmussen states:

> Can architecture be heard? Most people would probably say that as architecture does not produce sound, it cannot be heard. But neither does it radiate light and yet it can be seen. We see the light it reflects and thereby gain an impression of form and material. In the same way we hear the sounds it reflects and they, too, give us an impression of form and material. (Rasmussen, 1964).

Maybe less obvious than the visual, structurally expressed material-form convergence in a common tectonics discourse, material qualities and form definitions are captured and revealed by the sheer presence of a human, with sound being omnipresent, enveloping and partaking in defining the reading of a context.

4 Investigation

This study investigates how we can rethink resources by understanding, designing and applying naturally transformed wood by decay, both technically and aesthetically. This responds not only to a revealing of a material articulation, but also to a practical extension of wood's CO_2 cycle. Instead of organic material passing through a decomposing process, the uptake of CO_2 during its growth process, material and its embedded bonding of CO_2 is maintained as part of a carbon sink in the built environment. With the use of wood materials, which has entered a decay process, an explicit process of sustaining material for use, and CO_2 sequestering, resolves into a sustainable material discourse.

Specifically, the investigation explores and uncovers how a material in a decayed state, today considered non-usable, can be articulated with and for architectural acoustics, responding directly to the SDGs (11) sustainable cities and communities and (12) responsible consumption and production.

The paper presents experimental material-geometric studies using poplar wood in a progressed decay state. Through examination of the visually expressive material high density variance is discovered. This inhomogeneity is mapped and further investigated through acoustic impedance measurements to determine specific sound absorption coefficients. The knowledge derived from these studies are integrated into a computational design analysis model based on image-analysis techniques enabling the computing of highly specific acoustic properties when correlated with other findings in the literature and the impedance measurements, presenting a new method and model for material sound absorption estimation. Following the development of a full-scale cross-layered poplar prototype structure, room acoustic measurements are conducted in a testing space to understand the impact from experiential and aesthetic perspectives. The material-form and acoustic force findings are then presented, followed by a discussion and conclusion.

5 Methods and Materials

Studies are conducted through a mix-method approach with qualitative and quantitative investigations, including visual/tactile registrations of material samples, measurement of material properties, experimental prototype investigations, computational image-analysis with numerical filtering/mapping, absorption coefficient measurements, and room acoustic measurements and data analysis. As each sub-study includes specific methods and successive findings for progressive, experimental studies, some results are presented as a basis for following studies/methods description within this section.

6 Material Studies

The qualitative study of wood in a state of decay offers a direct decoding of the material condition. By opening the trunk by planar cuts along the grain, visual observation illustrates the process of fungal influence leading to spalting characterised by the noticeable black lines (Fig. 2). Spalting

Fig. 2 Piece of poplar with clear spalting patterns

occurs under specific environmental conditions, where fungi growth are provided by oxygen, moisture and temperatures between 20 and 40 degrees Celsius (Stange & Wagenführ, 2022). The pattern of fungi attack leaves the black colouring. The remaining wood is coloured in tones of yellow, brown, orange, green, white and light grey. Texture and patterns are particularly detectable close to the spalting, encircled by the dark lines. By touch, planned surface has varied smoothness, with brown and orange colour smoother and light yellow and dark-white-light grey with more rough surfaces. By pressing into the wood with a small blunt object, performing a sense-based Janka test of material hardness, brown-orange regions are significantly harder than the rest. A direct relation between hardness and smoothness appears to be correlated with visual decoding by colour of the material. A quantitative study determining material density characteristics is done by cutting smaller pieces from the plank, in dimensions 20 × 30 × 50 mm (Fig. 3).

The volume dimensions are found by analysing the wood for areas with consistent coloration/pattern, to create colour-based representative samples. 23 samples are made, which all are measured to 0.01 mm precision and weight with 0.001 g precision, Table 1. Densities, kg/m^3, for each sample is then calculated.

The study identifies a significant difference in material density within the samples, from the same plank of wood, ranging from 292 kg/m^3 to 521 kg/m^3. The common density description of Poplar is 350 kg/m^3 (Zhang et al., 2022). The deviation to the density norm and particularly between the samples studied indicates a material that is substantially transformed by the environment-driven decomposing and fungal decay process, when considering both its visual expressive character of colour, texture and pattern, and its physical properties of hardness and density.

7 Material Acoustic Studies

To further examine the material properties of the varied density of decay poplar wood, material acoustic measurements are conducted through Impedance Tube testing. The used instrument is a Brüel & Kjær Type 4206-T, with B&K LabShop signal generator, analysis and post-processing software, following the ISO 10534–2 testing standard. The impedance tube testing method is based on a specific instrument, using two different two-microphone procedures with small and large samples, Ø29 and Ø100 mm respectively (Fig. 4). Each measurement setup is based on calibrated microphones, noise-to-signal analysis and phase calibration through FFT analysis.

Fig. 3 Set of material samples that are examined for density variance, with lowest density in top left corner and highest density in lower right corner

Table 1 Material test sample measurements, weights and calculated densities

Sample	x	y	z	gr	mm^3	kg/m^3
1	29,49	19,82	49,97	9,917	29,207,05,525	339,5,412,484
2	29,2	21,78	49,95	10,872	31,767,0012	342,2,419,363
3	29,31	21,83	50,79	9,504	32,497,33,647	292,4,547,373
4	29,09	19,28	50,06	13,621	28,076,41,131	485,1,403,496
5	29,14	19,53	49,94	14,259	28,421,06,375	501,7,053,593
6	29,17	19,73	50,14	11,1	28,856,77,837	384,6,583,238
7	29,48	21,74	49,78	9,684	31,903,76,306	303,5,378,611
8	29,15	19,42	49,99	13,602	28,298,98,907	480,6,532,123
9	29,42	21,87	50,15	15,883	32,267,28,231	492,2,323,438
10	29,13	21,64	49,97	11,404	31,499,7488	362,0,346,331
11	29,22	21,76	49,98	16,044	31,778,64,346	504,8,673,655
12	28,97	21,43	50,24	15,616	31,190,3535	500,6,676,182
13	29,4	19,75	50,16	11,921	29,125,404	409,2,990,435
14	29,18	21,55	50,49	16,572	31,749,57,621	521,9,597,229
15	29,21	19,23	50,37	10,528	28,293,24,707	372,1,029,253
16	29,24	19,89	50,12	10,813	29,148,97,003	370,9,565,034
17	29,2	21,79	50,27	13,539	31,985,19,236	423,2,896,225
18	29,46	19,52	50,18	14,77	28,856,47,066	511,8,436,061
19	29,48	19,82	49,86	12,208	29,132,8789	419,0,454,381
20	28,97	21,84	49,95	13,55	31,603,60,476	428,748,559
21	29,19	21,71	50,13	12,97	31,768,12,794	408,2,708,312
22	29,27	21,77	49,86	12,572	31,771,18,589	395,7,044,613
23	28,8	21,74	49,9	14,195	31,242,9888	454,3,419,354

Fig. 4 Impedance Tubes testing instrument used for material acoustic analysis, including both large wide tube (low frequency analysis), small tube (middle and high frequency analysis), signal generator and specific computer/software for analysis, post-processing and export of results

Fig. 5 Material samples (29 mm) prepared for Impedance Tube testing, including Poplar, Paulownia, Oak and Douglas fir wood species

Material samples are positioned in a measurement chamber, which is coupled with the signal generator tube housing the loudspeaker for the analysis signal produced. Measurements from 50 to 1600 Hz uses Ø100 mm samples/large tube setup, and analysis between 200 and 6400 Hz uses Ø29 mm samples/small tube setup. Given the large inhomogeneity identified in the density material study above, 9 different poplar samples are tested from 50 to 6400 Hz. For comparative analysis additional wood species are analysed, including Oak, Paulownia and Douglas samples. All samples have a depth of 40 mm (Fig. 5).

8 Computational Studies

With the discovered correlation between material colour and material density of the poplar wood samples, image-based material analysis can be used to capture, analyse and map material characteristics of the highly inhomogeneous material. Adding absorption coefficient data from the above study provides a dataset correlating colour analysis, material density and material acoustic absorption properties.

Image analysis has a wide variety and use in scientific investigations and applications, from engineering (Liu et al. 2021), psychology (Fleming, 2014; Frantz, 2003), computer science (Tanaka & Horiuchi, 2015) and architecture (Fragkia et al. 2021) among others. Image analysis provides the possibility for qualitative investigations by the observer, such as through direct pattern registrations and by indirect analysis of digital analysed images using false colour and brightness analysis methods, and as training data for artificial intelligence and machine learning methods. From the same image, quantitative investigations by computational analysis are possible, such as analysis of individual pixel properties. With each digital image pixel hosting four numerical values such as Red, Green, Blue and Alpha (transparency), a single image captures and holds a large number of material data. This study uses RhinoGrasshopper software for image analysis, image mapping, geometric modelling and sound absorption estimation based on the developed material dataset. The integrated image-analysis module (Image Sampler) is restricted to analysis of 40.000 pixel at a time. This results in analysis of 160.000 data points (RGB, alpha values) for each image-analysis processing pass.

With an image paired with the material dataset developed, correlating material colour and material density, a direct calculation and mapping of estimated density and absorption characteristics is made. The colour to absorption calculation uses data from the literature, establishing a relation between density and absorption coefficient from other studies (Nandanwar et al. 2017; Smardzewski et al., 2013, 2014) and the absorption coefficient measurements conducted above. A method for fast material analysis, material characterisation and material sound absorption properties estimation are then established to evaluate the highly complex material and compute material sound absorption relations by use of images (Figs. 6 and 7).

9 Prototype Experiments

To expand the studies from material probe investigation to full-scale prototype with room acoustic impact studies, a large acoustic surface of wood requires assembly. Experiments with cross-layer joining of poplar planks and boards are done by a three-directional fibre (wood grain) orientation approach. By this method, large, deep poplar planks can be positioned vertically, while front and back board elements, relative to the centre placed planks, can be angled freely to increase cross-weaving of the wood grain (Figs. 8 and 9). In the first full-scale prototype (Fig. 8) crossing is done with 45-degrees, with the front cross based on a 70 mm board height, extruding 60 mm from the plank surface. This technique increases stiffness and stability of the assembly, and more importantly introduces a varied deep structure that scatters sound energy in relation to frequency (Cox & D'Antonio, 2016; Cox et al. 2006). The back board element cross is 20 mm high, extruding 10 mm from the plank surfaces. Both crosses are recessed 10 mm into a milled track of the vertical planks that are 40 mm thick, 2000 mm high and 300 mm wide.

The poplar planks are almost planar in the first prototype experiment, yet much of the poplar

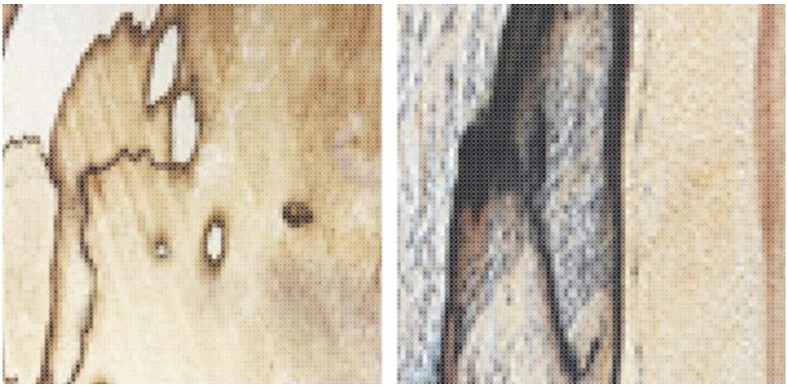
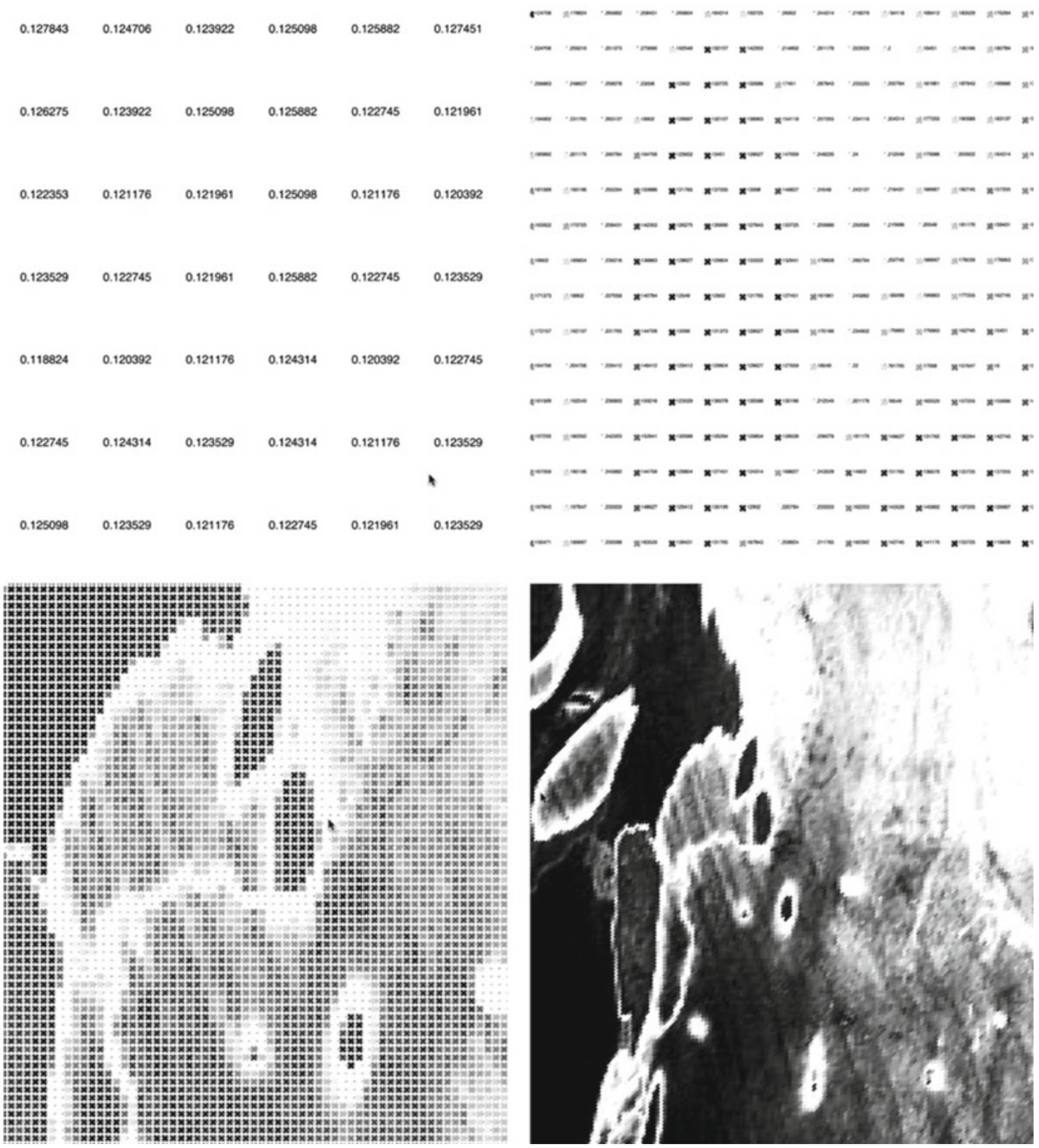


Fig. 6 Method for translating material visual character to material acoustic properties based on empirical studies of decay poplar wood



0.127843	0.124706	0.123922	0.125098	0.125882	0.127451
0.126275	0.123922	0.125098	0.125882	0.122745	0.121961
0.122353	0.121176	0.121961	0.125098	0.121176	0.120392
0.123529	0.122745	0.121961	0.125882	0.122745	0.123529
0.118824	0.120392	0.121176	0.124314	0.120392	0.122745
0.122745	0.124314	0.123529	0.124314	0.121176	0.123529
0.125098	0.123529	0.121176	0.122745	0.121961	0.123529

Fig. 7 Image analysis process showing the data resolution with a data point for each mm^2. Top left, zoomed in analysis (6 × 7 mm sample size), top right, zoomed in, pattern starts to be visible (15 × 16 mm sample size), bottom left, zoomed in, resolution and pattern is visible, but data points not visible, bottom right, pattern is clearly visible, data points not visible

Fig. 8 First full-scale cross-layer prototype with 45-degree crossing over two planks

wood has significant warping due to the moisture release process during drying of the anisotropic and highly inhomogeneous decayed material. The second full-scale prototype experiments with the assembly of three large planks (2000 × 400 × 400 mm) which warps more than 20 mm across the length of the plank (Fig. 9). The same three-directional fibre crossing method is applied, but with 60-degree angles to adapt to the large difference in local height differences between the planks. Using a deep front board element, as in the first prototype, the joining depth and structural overlay of the assembly elements are driven by the warping geometry's intersection with the crossing board. The same applies for the back crossing, albeit with the board being much lower in its protrusion height, relative to the plank surface.

Fig. 9 Second full-scale cross-layer prototype with 60-degree crossing over three planks

10 Room Acoustic Measurement Studies

The raw poplar planks and full-scale experimental prototypes of cross-structured poplar assemblies, with identified inhomogeneous material densities, are tested for material and room acoustic properties. The room used for measurements is a shoebox geometry, with dimensions 7.6 ×5.6x2.8 m. Ceiling and walls are in plaster and painted. Floor is hard linoleum. One wall is constructed from large glass panes. Three planar hardwood doors are placed in the room. The temperature is measured at 26 degrees Celsius and relative humidity is 55% during measurements. Prior to installing the prototypes for testing are 'clean' space test measurements conducted for comparison. Measurements are conducted with 6 measurement positions (averaged over 3 measurements at each position) and 1 source position, making a total of 18 measurements for each study (Figs. 10 and 11). Equipment used for measurements includes a calibrated Behringer 8000 measurement microphone and a Yamaha MSP5 active loudspeaker

Fig. 10 Room acoustic measurements with free standing poplar planks

Fig. 11 One of two positions of the prototypes placed in the measurement space

with a sound dispersion profile similar to human sound emitting patterns. Sound sweeping for impulse response is used with a 2 s period, and analysed from 125 Hz to 8 kHz, using Røde Fuzzmeasure software. The measurement setup complies to ISO3382-2 standard (ISO 2008). For analysis and results evaluation of the impulse response measurements, RT60 (T20 domain) and FTT Waterfall plots are produced and analysed.

11 Results

The findings from the investigations of rethinking resources using decay poplar wood for acoustic design propositions are outlined in categories of investigation.

Specifically

- Material and density

  Based on qualitative and quantitative investigations, the study finds that poplar in the decay state has significant density variance, ranging from 292–521 kg/m^3 in the specific study (Table 1).

- Material and sound absorption

  By quantitative investigations, the study finds that there is a direct, albeit complex material density relation with sound absorption qualities of the poplar wood studied (Fig. 12). In the graph including all material samples examined, two groups are identified. One group, based on higher material inhomogeneity (Poplar 1, Poplar 2, Poplar 3, Poplar 4, Poplar 6, Poplar 7, Poplar 9) as seen in the graph including all samples. Another group, based on the higher material homogeneity (Oak, Douglas, Poplar 5, Poplar 8) as seen in the graph with the four selected materials. As is documented, the Poplar 8 sample (200 kg/m^3) has significant higher absorption coefficient than Poplar 5 sample (528 kg/m^3).

- Material and Room Acoustics

  Based on quantitative investigations, the study finds that the poplar material and prototype assemblies have a significant impact on room acoustic properties and therefore the human perception of the material impact on experiential phenomena, with sound energy absorbed predominantly in the mid frequencies 250–1000Hz, and secondarily in the high frequencies 2000–8000Hz, dropping 0.5 and 0.3s in RT60, respectively (Fig. 13). This aligns with the material acoustic sample findings above.

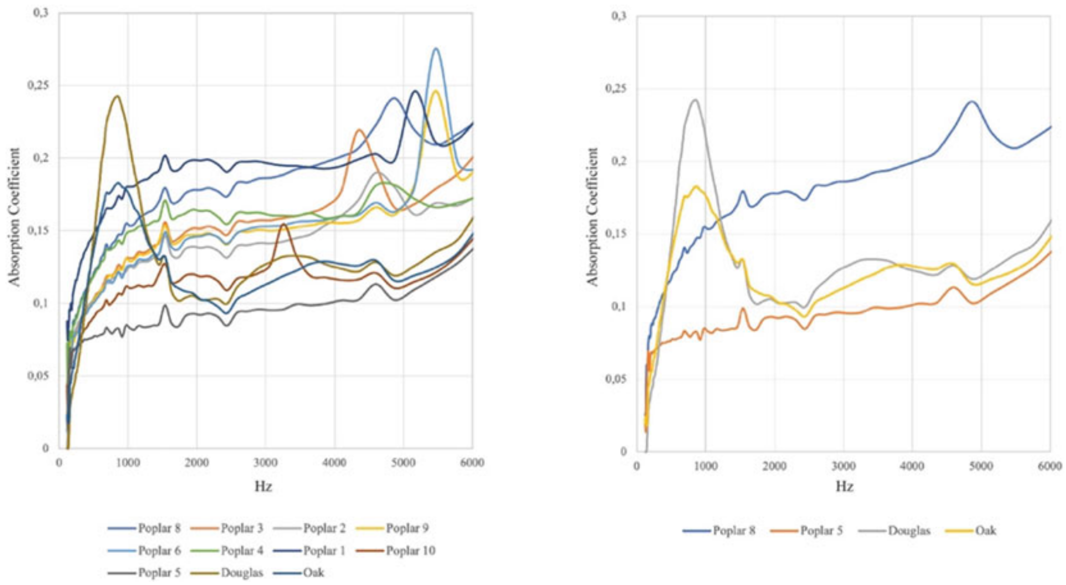


Fig. 12 Absorption coefficient results from impedance measurements. All samples to the left showing the absorption variance within the same material, and highlighted samples to the right showing the relation between density and absorption properties

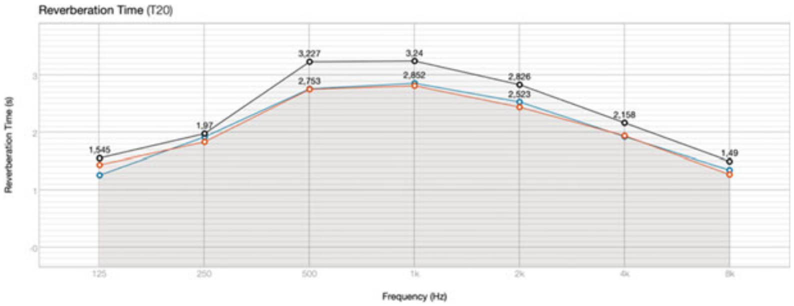


Fig. 13 Reverberation Time measurements with a ‘clean space’ (black line), prototypes against the wall (red line) and prototypes placed at an angle to one of the walls (blue line)

- Material and Design Analysis Method

As the density of a fibrous material has a direct correlation with sound absorption properties documented, and in alignment with the literature, the study presents a computational design and analysis method for acoustic properties based on image-analysis techniques. The presented method is scalable in resolution in direct relation to the resolution of the sample photo of the material and the specific analyser used. The method can be used to analyse and inform the assembly logic of material complex bespoke elements, guiding design decision for a holistic intended sound absorption profile of a combined structure. While the detection of density and related absorption characteristics is identified, method estimation inaccuracy can be found when the material surface colour/texture does not continue through the depth of the material, leading to a ‘uneven depth density’, resulting in a less accurate estimation of absorption behaviour from surface analysis.

- Material and the Rethinking of Articulated Resources

Through material, form, assembly and acoustic studies, synergetic relations between these aspects have been studied. The formative forces acting towards perceived visual and sound phenomena are driven by natural occurring and design-driven articulated material-environmental agencies. While structural integrity, assembly logic and

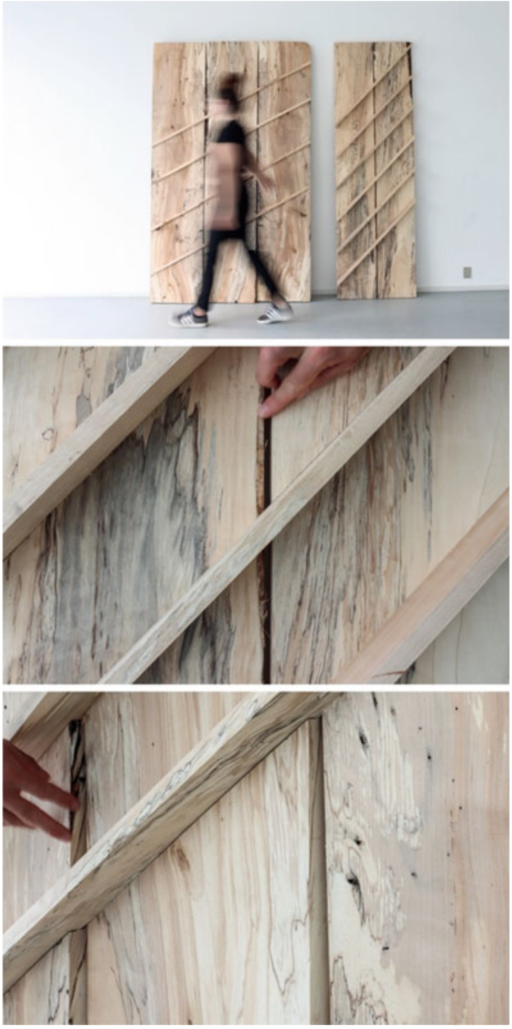


Fig. 14 Top: Poplar prototypes showing scale, back and front crossing. Centre: Detail of fibre crossing and gap between vertical planks. Bottom: Three-directions cross-structuring allowing highly warping elements to be joint through varied track/insertion depth

joining precision remain important, it is the revealing of material and form relations through visual-acoustic interactions that play the dominant part in the rethinking of resources, addressing environmental, technical and aesthetical aspects together. Rather than rejecting materials from structural inhomogeneity and high visual-acoustic variance, this study finds and demonstrates that material uncertainty can be considered and developed as a resource for unprecedented architectural articulations. As a result, this opens to a novel approach for studying and applying material resources that are in decay, uncertainty condition, or otherwise considered unusable in the built environment.

12 Discussion

This research expands the contemporary notion of material resources in architecture based on the idea and studies with poplar wood in a state of decay, specified for acoustic potentials and design. However, considering the importance of deadwood in the forest ecology, an expansive and unbalanced use of deadwood as a new material resource should be avoided, despite the presented potentials and findings. Instead, conventional timber and deadwood may go into a larger and systemic understanding and use of forests as providers of future biogenic material resources, following temporal material use structures that facilitate a more nuanced and potentially better relation between the building of forests and the building of architecture simultaneously.

13 Conclusion

Deadwood can become a new resource in architecture, with significant environmental, technical and aesthetical potentials. By rethinking material variance and material uncertainty as a resource for articulation, biogenic materials in decay offer novel potentials in general, and specifically in relation to acoustic design as findings in this study demonstrate.

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