Thermal Design with Highly Inhomogeneous Materials

A computational method for the thermal design of complex wood assemblies

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This research investigates how thermal composites can be analysed and designed by computational methods using highly inhomogeneous wood. This seeks to advance our understanding and ability to use biogenic materials considered non-usable and to enable these materials to become novel thermal structures for modulating thermal conditions for humans. The research design is based on computational and material studies, using thermography to analyse materials to develop new computational analysis and design procedures for composite design and applications. The computational methods are based on pixel proximity analysis, where the material dataset developed as part of the investigation is integrated for the calculations of thermal transfer shown directly in the design interface. This allows a designer to intuitively manipulate the material-geometric relations between elements to investigate and propose novel thermal composites from complex wood parts. The results show that the concept and developed computational design methods enable new thermal composite design.

Keywords: *Thermal Design, Poplar, Wood Assemblies, Computational Design.*

INTRODUCTION

We face increasing scientific evidence (IPCC, 2021, 2014), societal awareness and understanding of a world without infinite resources (Lin, 2021). This development highlights the issues of overuse and pollution driven by global expansive material-industrial processes (OECD, 2019). A development that emphasises the necessity for a fundamental shift to another material conceptualisation, design, analysis and use across the built environment. A focus on using more regenerative materials based on organic growth, such as trees and crops, presents a path ahead and a series of material complexities of anisotropic material behaviour and inhomogeneity in organic cellular structures. While the complexity and use of organic complex structures are not new, we have seen new development across the last ten years, with research projects pursuing geometric articulation based on anisotropic material characteristics (Correa et al., 2013; Foged, 2022; Foged and Pasold, 2019; Hensel and Menges, 2006; Menges and Reichert, 2015, 2012).

Focusing on materials as a primary driver of articulation is particularly relevant when investigating the dynamic properties of density across materials as they change based on growth processes and when these materials are exposed to environmental processes that force degradation and transformation. If we can understand and design with the complex dynamics of material density based on a

material's natural transformation, new potentials for material-driven information flows can be reached and activated for design compositions where the density properties are key parameters, such as in thermal and acoustic design.

Studies focused on the organisation and layering of materials for their thermal properties have been explored in material science and material and climate engineering (Mirabolghasemi et al., 2019), investigating among others electronic circuits design and building insulation barriers construction (Zaero-Polo and Anderson, 2021). In electronic devices, the thermal conductivity of materials is particularly important in relation to avoiding overheating of systems, while in building barriers, thermal conductivity and multilayer heat transfer are studied to minimise heat loss in buildings and reduce moisture development through condensation processes. In building design of responsive envelopes, the composition of plant fibrous for thermal form development and dynamic material-thermal properties have also been studied recently (Foged, 2022). In the domains of architecture, design and engineering, materials are typically considered homogenous and isotropic entities derived from industrial fabrication processes, such as plastics, metals and mineral-based compositions. While the explicitness, repeatability and homogeneity enable general descriptions and applications, such an approach also avoids, or limits, materials with higher levels of non-uniformity that may have unique characteristics and information traits for specific and new properties.

This study investigates how highly inhomogeneous wood elements can be analysed, understood and organised for novel thermal assemblies through computational design and analysis processes. The investigation is based on the wood species of Poplar in a state of material decay, which induces a natural material transformation process that modifies the density characteristics of the material due to decay processes, which may result in highly varied thermal conductivity properties across the material, as has been demonstrated for acoustic properties by analysing and designing through density characterisation of a material assembly (Foged, 2024).

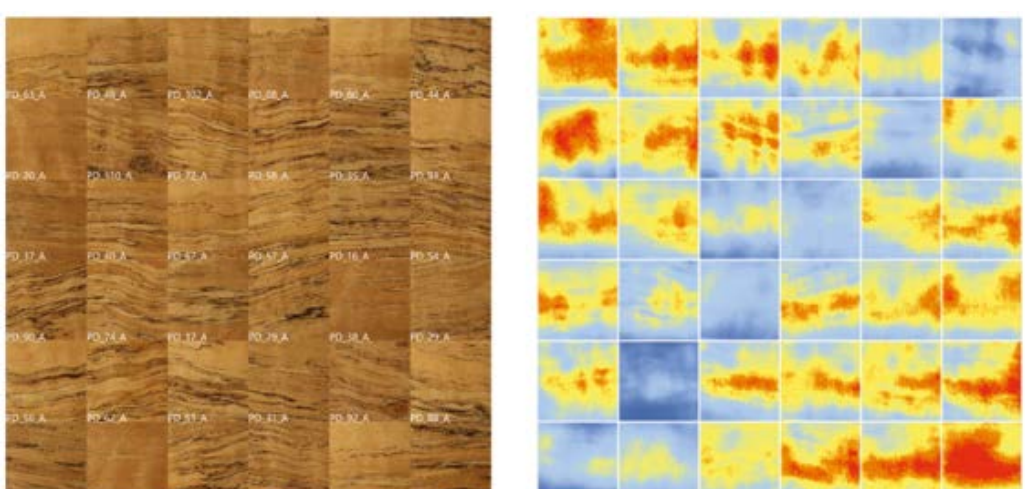

Figure 1
Studies of Poplar wood samples to the left and thermal imaging of samples to the right.

METHODS

The study applies a three-part investigation structure including data collection by material-thermal imagine (Figure 1) the development and exploration of a computational design model for the organisation of the analysed materials to create bespoke thermal composites, full-scale prototypes and a case study of testing and demonstrating the sorting and distribution of material elements in an existing building structure to minimise, neutralise or amplify thermal conditions. The information infrastructure of the analysis and design methodology is developed in three parts, including a) the measured material-thermal data and geometric properties of the materials, b) analysis processing of the dataset and c) activation of the analysed data into design processes for creating thermal composites based on the bespoke materials. Information between the three computational parts flows through feedback loops, particularly when material-geometric-thermal relations are investigated and explored towards design engagement. In the first part, a new material dataset is developed by Poplar samples (100x100x3mm) that are analysed for thermal variance across the material specimen through thermal stimuli and imaging analysis. Each sample is placed on a laboratory hotplate (Model: Cole-Palmar TP200), with the thermal camera (Model: Flir A700 Science) placed above the sample, pointing vertically down towards the sample. The hotplate is set to 50 degrees Celsius (ambient air and initiating sample temperature is 25C), to capture the temperature of the upper surface of the sample, revealing how heat transfers through the sample. This material-temperature data collection of the specific sample provides the variables needed to compute the heat flux and heat transfer equations (Lienhard and Lienhard, 2024). This constructs a 2-dimensional matrix of 380x380 temperature points, representing the thermal flux characteristics of the material with a physical resolution equal to the pixel count.

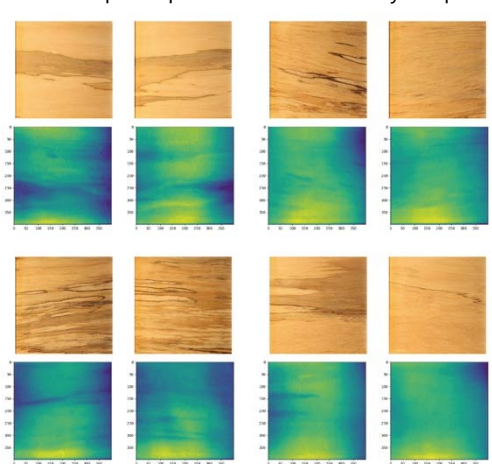

Figure 2
Material samples and computed thermal conductivity of samples based on thermal imaging analysis.

From the thermal imaging analysis, thermal conductivity maps of each of the samples are developed (Figure 2) by computing the heat transfer equations for each pixel, assuming in this case a 1-dimensional transfer condition due to the low thickness of the samples and the controlled thermal stimuli and thermal imaging procedure. The thermal conductivity maps of each material sample are stored in MS Excel for integration into the design model where multiple material elements can be combined to form a composite of varying material-thermal elements. To activate the development of the material-thermal dataset for design processes, computational analysis and design model is developed (using Rhinoceros3D as a platform) where geometries can be defined, combined and overlayed as a composite assembly, enabling the making of novel thermal structures when informed by the specific material characteristics of the geometry. The model works on all possible planar geometries but is explored with the geometries of the material samples.

In relation to the dataset, the thermal property of the assembled structure is presented as pixel grids (Figure 3). To improve the calculation speed of finding overlapping elements for intuitive

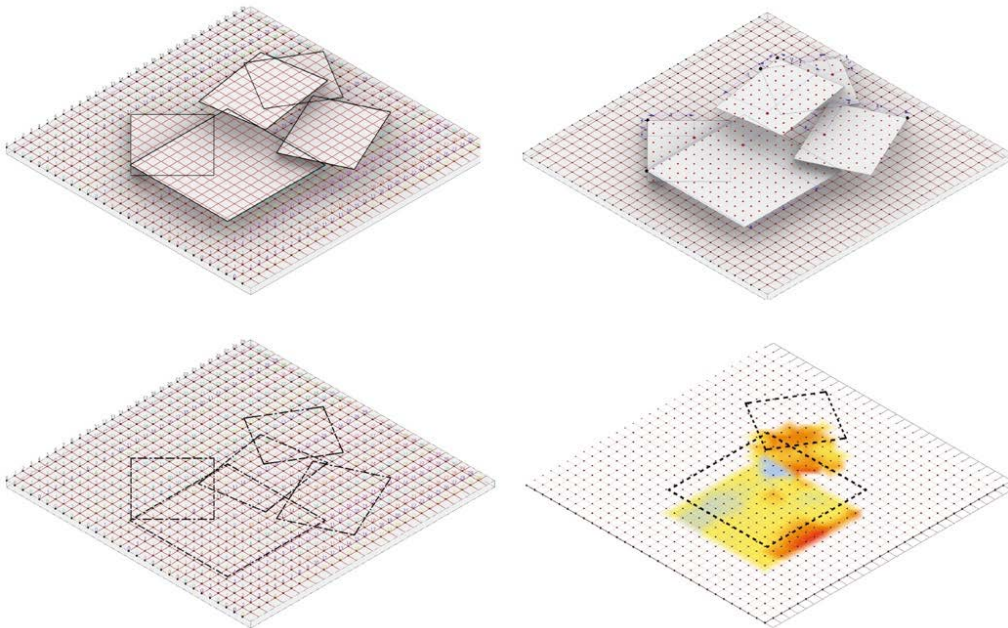

Figure 3
Studies with developed computational design model to organise geometric simple elements into thermally advanced composites

design operations, a method was developed to calculate a pixelized base structure to grab each pixel thermal data and define overlapping positions. The developed model analyses the structure based on pixel-proximity, where each pixel's overlaying geometry is found, then mapped to the material catalogue to call the material-temperature properties from the dataset, and then compute the combined thermal flux through the highly varied composite (Figure 3 and 4). The computational method developed and implemented allows for multi-layered structures with geometrically and materially complex elements, with the model using a material ID for generating and visualising thermal properties as coloured meshes each time the design is updated.

RESULTS

When observing the thermal results of an array of elements (Figure 4) advanced composites for thermal performances are possible to create by the proposed the method even with simple geometries. With the same material set available, as shown below, thermal variations can be created by rearrangement or sorting mechanism. In figure 4, three different results are achieved in the top row by distributing materials to form three different thermal effects of one-sided linear gradients (left), centre gradient (center) and two-sided linear gradients (right).

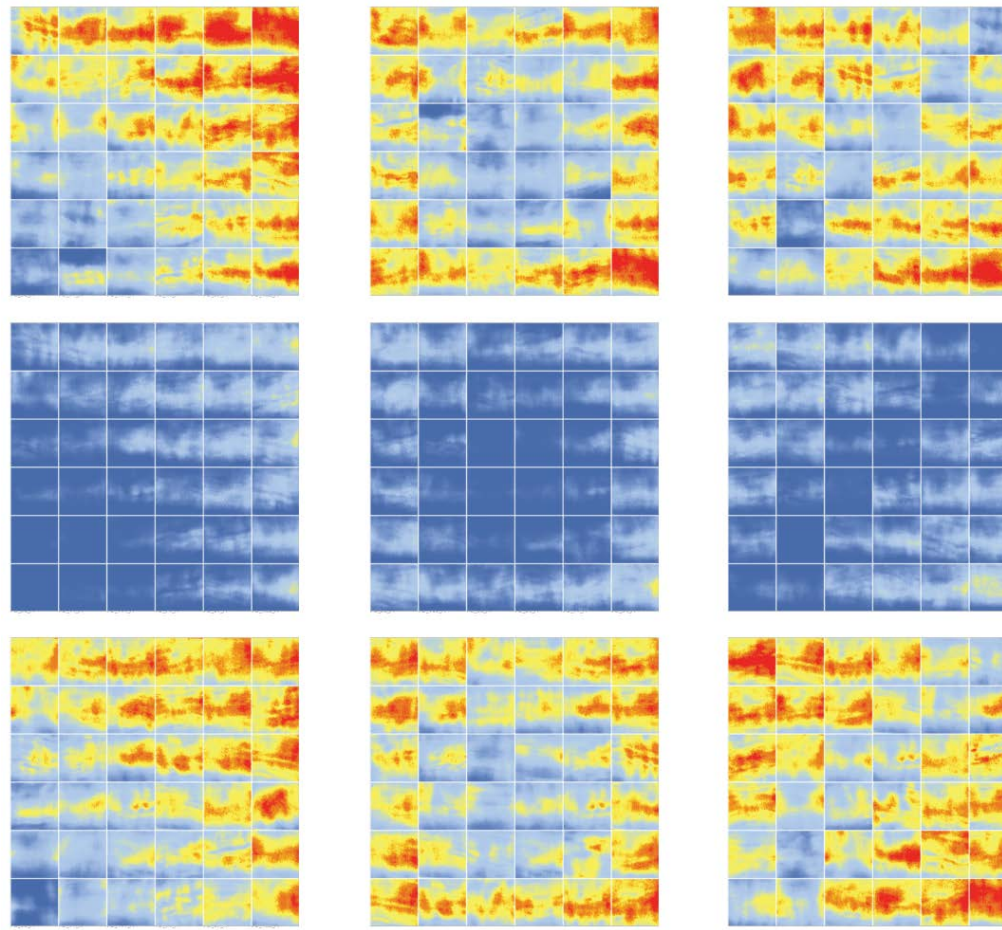

Figure 4
Computed organization of materials to create different thermal gradient composites.

The same is done for another three material sets (bottom row with three figures). The combination and results of the three top and three bottom sets are then shown in the center three composites, thereby creating a multilayer composite, with unique thermal profiles by organising the combination of the 2D arrays and stacking of these arrays.

A prototype test is done with 200x100x5mm elements, where the material assembly is steered to create a linear thermal conductivity from the left (high conductivity) to the right (low conductivity (Figure 5). The material array, as installed in an office setting, with the thermal imaging performance of the array shown above demonstrates the thermal characterization achieved.

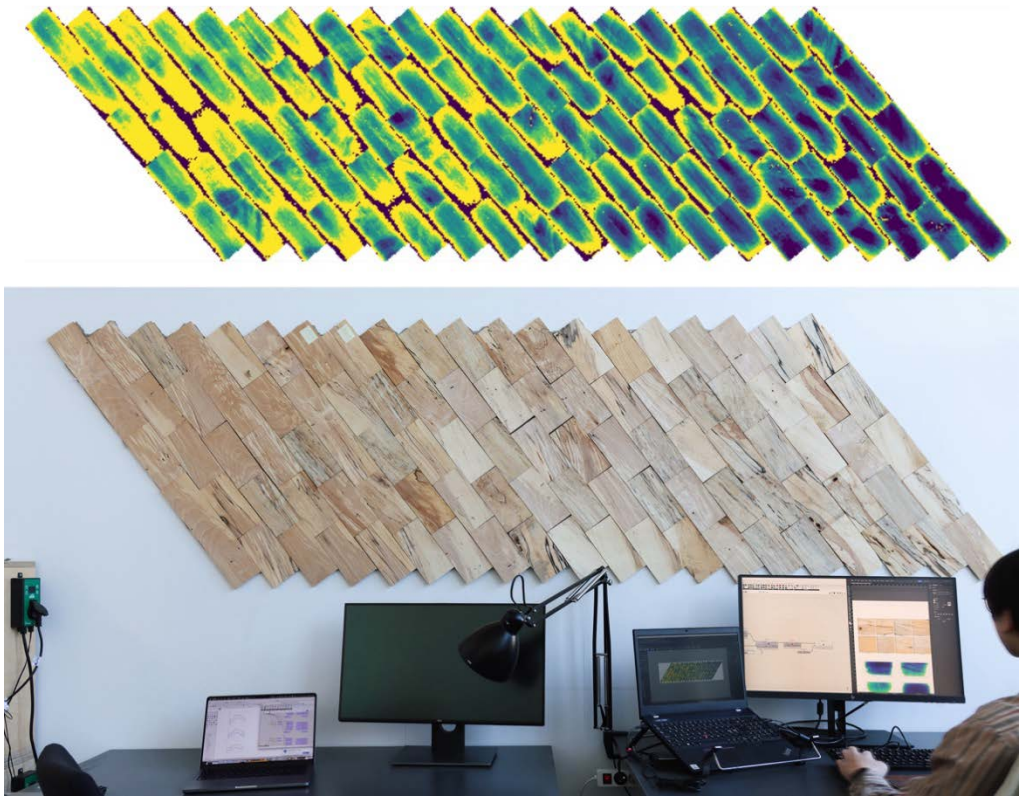

Figure 5
Full-scale prototype based on an array of elements to form a thermal composite structure with a linear thermal pattern.

When the computational analysis and design methods are exposed to the complex thermal conditions of an outer wall (Figure 6) the interrelations between highly specific material and thermal properties can be explored and designed from design intentions. In the case shown below, the contrasting radiant heat conditions are intended neutralised by the computationally distributing elements with different thermal properties resulting in a multilayered array of elements. The thermal imaging to the left show the thermal condition, with and without the window panes. In the two figures to the right, figure 6, we see how the thermal conductivity mapping of each element results in a targeted distribution across the wall. Areas with lower temperatures are applied with material with lower conductivity values to provide more insulation. In the two figures to the right, the heat resistance value is used to represent multiple material thicknesses and conductivity values. The top shows the first layer application of elements to counter the thermal resistance calculated and add an additional material layer, lower right figure, where the thermal resistance shows where another layer is applied to colder regions, resulting in higher heat resistance values.

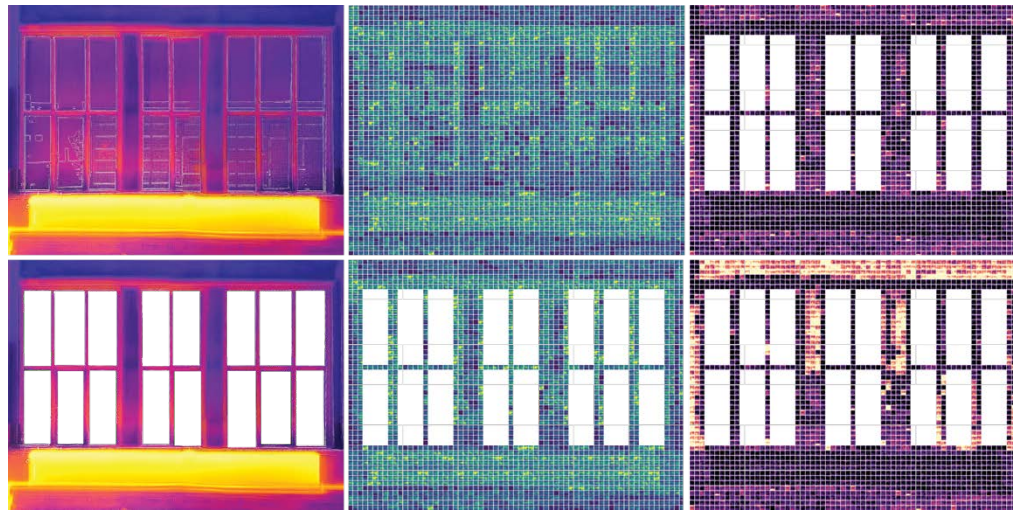

Figure 6
Method test case with poplar elements distributed across building envelope to decrease thermal bridges.

DISCUSSION

The methods presented are based on highly inhomogeneous wood samples, using Poplar in decay, and experimental results are therefore tied to the specific dataset developed as part of this investigation. The material singularity of the dataset in terms of wood species allows for increased analytical precision but also poses a limitation in directly transferring results to other, even similarly grained, species or samples. Other complex materials need to be studied to pass on results, yet the method presented to identity, analyse and design composites and thermal design interventions through these appears to be generalisable as an approach to advanced thermal composite design through computational design processes.

The material dataset developed and applied consists of 120 elements. Making detailed thermal imaging of each sample is a time-consuming procedure due to the heating and cooling of elements during thermography procedures and related post-imaging analysis. It may be practically unfeasible to make advanced thermal composites with these materials if each element requires a lengthy analysis process. New machine learning methods may take part in overcoming this problem, using a small high-resolution dataset to analyse and predict thermal properties of similar materials without a thermal imaging process required.

CONCLUSIONS

From the experimental computational and material studies a new methodology of creating thermal bespoke composites is presented. The results demonstrate how the proposed:

a) computational analysis and design methods can be used in design processes to create unique material design with articulated thermal composites not possible without this method.

b) computational analysis and design methods can aid a designer with investigation and application of highly inhomogenoues wood materials for advanced thermal design tasks, such as neutralising or amplifying constructions thermal properties and the results this have on thermal environments.

Future studies will focus on 1) the advancements of the dataset to include more wood species, 2) increase the precision of the experimental process capturing the thermal dynamics of areas with extraordinarily high inhomogeneity, 3) develop additional methods for sorting the wood elements into composites and 4) develop new wood analysis tools using machine learning techniques.

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