Designing Urban Biodiversity:

Replicating Dead Tree Habitats Through 3D Printing of Bio-Based Materials

Michal Levitzky[1], Daniel Metcalfe[2] and Shany Barath[3]
[1,2,3] Technion - Israel institute of technology.
[1]michal-l@technion.ac.il, 0009-0002-2702-9201
[2]daniel.met@technion.ac.il, 0000-0002-3785-951921
[3]barathshany@technion.ac.il, 0000-0003-0776-7389

Abstract. This study addresses biodiversity loss in urban areas by recreating analogous dead tree habitats through 3D printing. By replicating the ecological functions of dead trees, which are critical to many species, the research aims to promote sustainable, artificial habitats using bio-based wood formulations and ceramics. Data from ecologists, field studies, and literature informed the parametric design process. Through iterative explorations, key habitat features like cavities, crevices, and textures were successfully integrated into 3D-printed structures. Wood-based formulations were tested for properties such as inclination and height, while ceramics provided reinforcement to enhance structural integrity. The results demonstrate that these hybrid habitats, combining wood and ceramic materials, have a potential to create customizable solutions for enhancing urban biodiversity. They are designed to mimic the morphological and material properties of dead trees, providing a novel approach to supporting species in urban environments. Future research will focus on implementing these artificial habitats in real-world conditions to assess their ecological performance, scalability, and adaptability to different climates and species needs. By doing so, this work will open up new possibilities for enhancing urban biodiversity through advanced design and manufacturing practices.

Keywords. 3D Printing, Wood-based Material, Multispecies Design, Urban Biodiversity, Dead Trees, Computational design.

1. Introduction

The global decline in biodiversity, driven by urbanization, habitat destruction, and resource overexploitation, is contributing to what is widely regarded as the sixth mass extinction (Cowie et al., 2022. Ceballos et al., 2015). These changes not only disrupt natural landscapes and ecosystems but also challenge the balance between human needs and environmental preservation. Biodiversity is essential for ecosystem resilience, providing crucial resources and services while enriching cultural, economic, and medicinal aspects of human life (Jonah, 2018). To mitigate this crisis, enhancing the ecological carrying capacity of human-dominated areas through multispecies design and computational approaches has been proposed (Haldrup et al., 2022; Weisser et al., 2022; Saroglou et al., 2024). Such approaches aim to support a diverse range of species while simultaneously addressing biodiversity loss and the increasing disconnection between humans and the natural world (Colléony and Shwartz, 2019; Beninde et al., 2015). Urban ecosystems, once overlooked by ecologists, are now recognized as vital for integrating nature into cities, enhancing human well-being, and biodiversity conservation (Wu, 2010).

1.1. DEAD TREES

Dead trees, also known as coarse woody debris (CWD), naturally serve as habitats for many species (Măciucă, and Roibu, 2012). Due to their significant ecological role, providing shelter, nesting sites, and food resources, they offer an excellent reference for designing habitats for plants, fungi, and animals. As a tree dies, its morphology and material compositions change, allowing various organisms to inhabit it in a process of ecological succession [ibid]. In urban environments, dead trees can be critical biodiversity hotspots, supporting species that might struggle to find suitable habitats in built-up areas.

Despite the widespread recognition of the ecological importance of CWD, these are often removed from urban environments for safety or aesthetic reasons (Fröhlich and Ciach, 2020). While promoting the management practice of leaving more CWD in urban areas is important, it is not always feasible in areas with high safety and aesthetic concerns. In such cases, an alternative approach could be to create synthetic habitats that mimic the ecological functions of dead trees, while also addressing human concerns.

1.2. DESIGN AND MANUFACTURING OF ARTIFICIAL HABITATS

Current computational design tools can aid in formulating complex geometries that mimic the porous nature and complex geometries of dead trees. Advanced manufacturing developments such as 3D printing, offer the ability to fabricate and customize morphological and material traits for such artificial habitats (Urban Reef, 2023). Specifically, 3D printing with ceramics has emerged as a promising method for creating artificial habitats for multispecies (Larikova et al., 2022). Known for their durability and adaptability, ceramic printing can mimic the natural textures and morphological complexity found in dead trees. Yet, they remain distinctly different in their material traits from decaying natural wood.

While 3D printing has been used with synthetic and natural materials for multispecies habitats (Oren et al., 2022), printing with natural wood compounds remains unexplored. Printing with wood-based pastes using liquid deposition modelling (LDM) has recently emerged as a promising extrusion-based technology integrating relatively large amounts of wood waste content (Rosenthal et al., 2018). This method holds the potential for creating habitats that closely resemble the material properties, natural processes and ecological functions of dead trees. Similar to decaying wood in nature, natural wood pastes can be subject to change, decomposition, and eventual breakdown over time, creating dynamic environments that mimic natural processes and offer an evolving habitat for diverse species.

This study aims to achieve two primary objectives: first, to identify the natural characteristics of dead trees and translate them into guiding principles for designing artificial habitats, and second, to develop a design-to-fabrication process for creating such habitats using printed wood and clay components. The integration of ceramics with wood-based pastes further enhances design flexibility, addressing key aspects such as structural integrity, morphological and material properties, aesthetics, and seamless integration into human environments. By examining and addressing the ecological role of dead trees, this research seeks to propose artificial prototypes that emulate natural habitats, potentially fostering biodiversity and promoting ecological resilience in urban settings.

2. Methods:

The research consisted of two main stages: 1) data collection, analysis and identification of ecological features, and 2) design-to-fabrication of artificial habitats.

2.1. DATA COLLECTION AND FEATURE IDENTIFICATION

Stage one of the research utilized a mixed-method approach to collect data and synthesize guiding features. Data was collected and processed through four field interviews with ecologists with relevant expertise. The field interviews took part in various natural settings in northern and central Israel and included observations and documentation of dead trees in their natural environments, along with contextualized, semi-structured interview questions aimed at understanding the interactions between material and morphological features of dead trees and different species. Interview 1 involved a forest management ecologist; Interview 2, an expert entomologist; Interview 3 an agronomist; and Interview 4 a herpetologist. The focus was on Mediterranean woodland trees, as their unique characteristics play a vital role in supporting species diversity in this region. The trees observed included oak, pine, olive, and charob, were of medium size, ranging between 3–4 meters in hight and had fallen to the ground between 10–50 years ago. The interviews were transcribed and coded to extract material and morphological features of dead trees that support multispecies habitation, taking into consideration the interactions among diverse species as well as their relationship with the dead tree and its surrounding environment. The data was systematically classified, detailing each phenomenon's name, description, characteristics, constrains and ecological function.

2.2. DESIGN EXPLORATION AND REFLECTION

Stage two employed a ‘Research Through Design’ methodology aimed at establishing working principles and creating a framework for a new artificial habitat system. The process included iterative design tests and the refinement of bio-based wood and clay formulations, integrating the identified ecological properties into a cohesive modular system. This comprised of three iterative design explorations, each with a specific objective: Design exploration 1: Testing Material Printing Properties and Limitations. The objective was to define the potential and limitations of clay and wood-based printing formulations for artificial habitats. The tests explored the clay and wood formulation's properties in terms of printing buildability, texturing, inclination, and overhangs. Design exploration 2 - Computational Design and Modelling of Individual Features. In this exploration, individual components were created, each representing one of the ecological principles identified in the dead tree analysis. A parametric model was developed in Rhino and Grasshopper to design and generate these individual features, ensuring flexibility for each part to faithfully embody its respective ecological function. These components served as the foundation for the subsequent exploration of modular integration and fabrication. Design Exploration 3 - Design-to-Fabrication tests of a modular habitat system. This exploration focused on creating elements of the modular system and exploring their integration. It involved iterative printing tests, model evaluation and refinement by exploring, for example, standard deviations of sizes and material shrinkage to achieve optimal results, while ensuring consistency with the printing parameters examined in the first exploration.

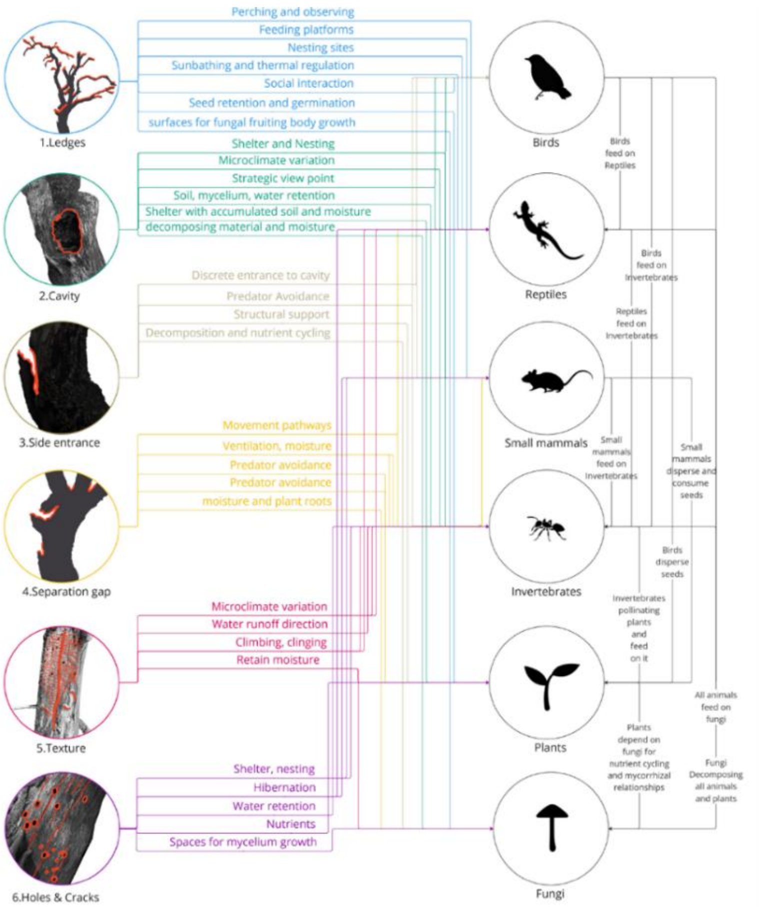

Figure 1 – interaction diagram between animals, plants, and fungi to ecological features provided by dead trees illustrates the connections between various species and the functions fulfilled by the trees, such as shelter, nesting sites, movement pathways, and resources.

3. Results and discussion:

The first stage resulted in the identification of six key artificial habitat features for the ecological function of dead trees (fig. 1) emerging from the interviews.

These include cavities, holes, ledges, textures, side entrances and separation gaps of varying sizes and material formations.

For each feature, specific morphological and material properties were defined, including size range, orientation, positioning, hardness, and composability (Table 1) as well as their relevance to different species (fig. 1).

Feature	Material properties	Morphological properties	Constraints	Ecological function	Source interview
1. Cavity	Hard shell from structural material (e.g. Ceramic or hardwood). Empty or containing a softer material (soil, mycelium, softwood)	Cavities of varying sizes and shapes. Max size 30*30*20 cm	Max cavity size	-Shelter and Nesting -Microclimate Variation -Soil, mycelium and water retention	All interviews
2.Side entrance	Hard structural material (e.g. Ceramic or hardwood).	A longitudinal opening leading to a cavity at a height of 1 - 10 cm	Max 10 cm height	-Discrete entrance to cavity -Predator Avoidance	Int. 2 and int. 4
3. Ledges	Hard structural material (e.g. Ceramic or hardwood).	1 - 20 cm in horizontal plane	Max 20 cm from the wall	-Perching and observing -Feeding Platforms -Nesting Sites -Sunbathing and thermal regulation -Social Interaction	Int. 1, int. 2 and int. 4
4.Separation gap	Negative space between the system units.	Variable	Structural constraints	-Movement Pathways -Ventilation and Moisture -Predator Avoidance	Int. 1, int. 2 and int. 4
5.Texture	Structural or soft material (Ceramic, hard or soft wood)	External texture of varying shapes and sizes	Max module size	-Microclimate Variation - Water runoff direction - Climbing and clinging - Roots and shoots attachment (plants)	All interviews
6.Holes & Cracks	Structural material (e.g. Ceramic or hardwood)	Diameter max sizes 0.4 - 3 cm	Max hard shell size	Microclimate Variation, Shelter, Nesting, Hibernation, Water retention	All interviews

Table 1 - Table of artificial habitat features relating to material properties, morphological properties, feature constraints and ecological functions as derived from expert interviews.

The second stage focused on three design explorations leading towards the definition of a modular system for artificial habitats based on the findings from stage one. These were designed while considering the potential and limitations (e.g., print buildability, texture, inclination, and overhangs) of two bio-based materials: clay and wood.

In the first design exploration, the wood formulation for 3D printing consisted of wood chips derived from industrial waste (grinded to size 400 microns), carboxymethyl cellulose powder as a natural binder, and water. The axial dimensions of the wooden parts were analysed by comparing the initial design dimensions with the final measurements after manufacturing and drying, revealing changes that require further investigation. For example, in the case of the oak wood printed cone (fig. 2), a computer model that was measured at a height of 130 mm reached a height of 113 mm after printing and drying; a bottom diameter of 100 mm in the model reached 108 mm after printing and drying; and a top diameter of 27 mm reached 36 mm after printing and drying. Unlike the wood, the clay model demonstrated higher compatibility with the computational model; Clay - The computer model that was measured at a height of 80 mm reached a height of 75 mm after printing, drying and burning; a bottom diameter of 80 mm in the model reached 76 mm after printing, drying and burning.

Figure 2- as part of the first design exploration additional components were investigated in the clay and wood-based materials 3D printing.

In the second design exploration, the focus was on developing the properties of the different features based on the insights from the interviews through iterative testing and refining a continuous printing code. The process allowed for fine-tuning and adaptation between the wood and clay features to ensure alignment with potential ecological and structural goals. Separate models were created, each of which demonstrates a specific characteristic (fig. 3). The printing of the ceramic parts highlighted that designs should prioritize continuous lines and closed shapes. Models featuring openings or walls with single-layer thickness were prone to collapsing and distorting during the printing process. Printing similar models in both materials revealed the discrepancies between the two material systems, suggesting these differences could serve as a potential design feature in the next exploration.

The third design exploration focused on connecting different parts that carried various ecological features into a modular system. This stacked modular system featured a central clay component to which 3D-printed wooden elements can be attached (fig. 4). This exploration focused on the connections between the components,

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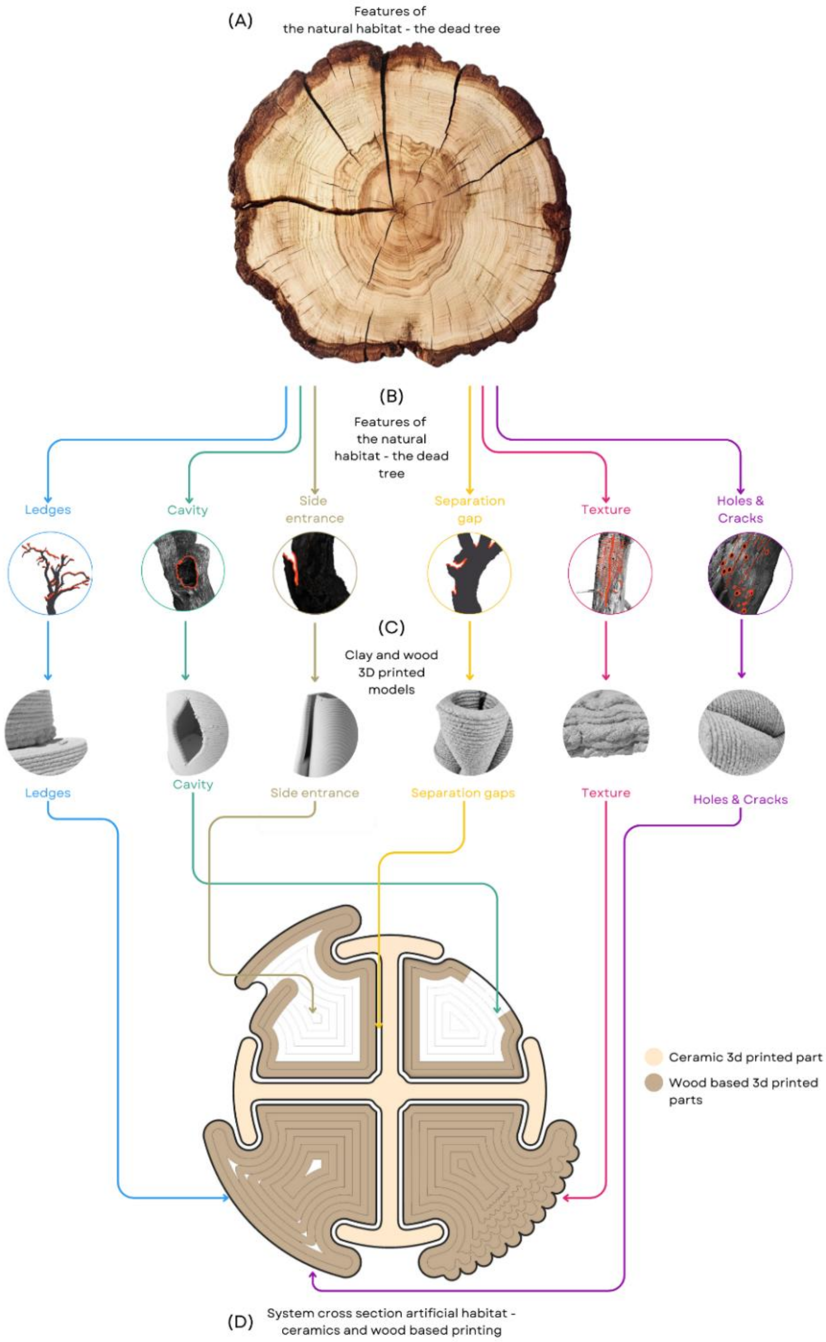

Figure 3 - From natural to artificial habitat, the translation of natural habitat features from dead trees into digitally designed and 3D-printed models using clay and wood-based materials.

regarding critical factors such as dimensional changes and shrinkage, while also evaluating the scalability of the design in terms of material requirements for the intended model size and the feasibility of larger-scale implementations. The central ceramic component was produced with a diameter of 380 mm, the model was printed to about 70% of the planned size with 4 kg of clay ,reaching a hight of 700 mm. To produce the wood-based parts, the same print head size of 6 mm was utilized; however, the layer height differed—3.6 mm for the ceramic material and 2.2 mm for the wooden material. Printing speed was adjusted based on the material viscosity and the regulation of air pressure.

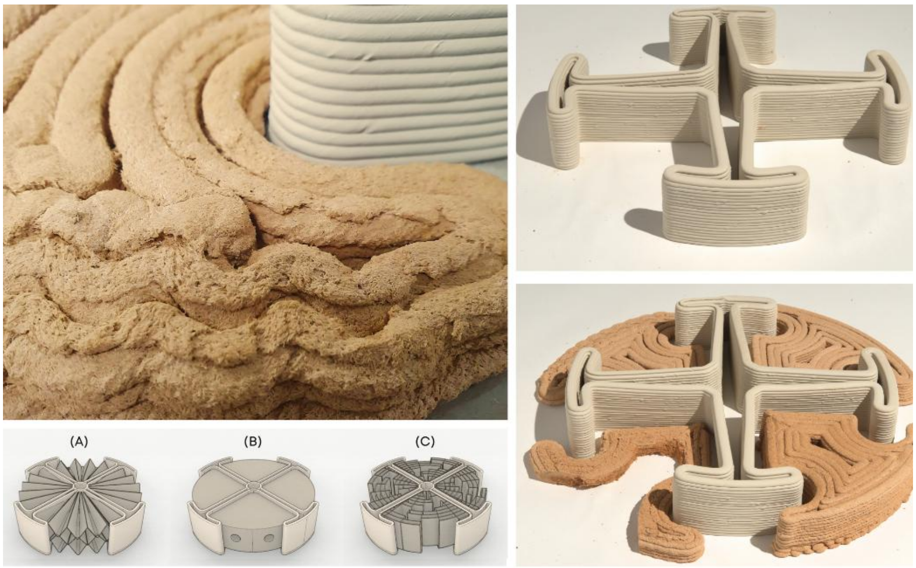

Figure 4 - 3D-printed models using clay and beech wood-based materials, cross-section first models of the integrated system. Initial exploration of the modular system with the different features-(A)holes and cracks,(B)cavity and (C)side entrance.

Overall, ceramic printing demonstrated precision, structural strength and minimal deformation of form, making it suitable for detailed texturing, structural elements and modules that require durability and protection, such as nesting holes for example. In contrast, wood printing resulted in a material less suited for intricate details or high precision but suited for components intended for decomposition and manipulation by colonising organisms. In the meeting point between the two materials, interesting features are created in the form of separation gaps. By combining the two materials it is possible to cater for different ecological functions while still controlling the structure and overall aesthetics of the artificial dead tree.

Alongside the technical insights regarding the production process, it became increasingly clear that the role of this habitat can also extend beyond its ecological function. Its modular design allows for adaptability to various scenarios and objectives. For example, in agricultural settings, the structure could be tailored to support ecosystem services such as biological pest control and pollination by bees. The high visibility of the structure can serve as a tool to foster dialogue and raise awareness among those who encounter it. By engaging with visitors, the habitat acts as an educational and outreach platform, promoting the importance of biodiversity and presenting innovative approaches to improving multi-species coexistence in shared environments.

4. Conclusion and future work

This research aims to contribute to the knowledge base on creating artificial habitats with the broader goal of promoting ecological diversity in urban environments. It highlights six key features of dead tree habitats that enable them to function as ecosystems supporting multiple species and proposes replicating these features using 3D printing with natural materials. This includes an understanding of manufacturing constraints and an exploration of various materials, shapes, and designs.

Following this process a prototypical cross section was developed of an initial full-scale habitat model, which will be developed into a freestanding vertically stacked structure. The proposed modular system uses a ceramic base structure for stability and durability with interchangeable wood-based inserts serving different ecological functions. This combination will allow for future customization of the system according to location and desired outcome as well as maintenance and replacement of the wood-based elements as they decompose and weather out.

In future stages of the research, which will include constructing a full-scale artificial habitat demonstrator, the focus will extend to refining the manufacturing of the components, developing efficient assembly techniques, and outlining processes for site placement and species monitoring to evaluate the development of ecological characteristics that promote biodiversity. Future iterations will involve the production of additional ceramic and wood components of the vertical structure, designed, for example, to house soil and climbing plants. These features will enhance the habitat by providing shade, retaining moisture, offering shelter, and enhancing ecological functions.

This research represents a significant step toward bridging the gap between ecological needs and urban development. By leveraging parametric design and 3D printing with natural materials, it provides a framework for creating artificial habitats that not only support biodiversity but also raise awareness of the importance of multi-species coexistence. By fostering greater understanding and advocacy, this work highlights the potential for integrative design approaches to promote ecological resilience within urban environments, paving the way for more sustainable and inclusive cities.

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