Robotic 3D Printing of Recycled Wood – Mycelium Mixtures Promoting Circularity in Architectural Production

Advancing the integration of Wood Waste in Sustainable Design Applications

Miran Calmanovici[1], Achiya Livne[2] and Shany Barath[3]
[1,3]Technion - Israel Institute of Technology
[2]Ben Gurion university of the Negev
[1]miran.c@campus.technion.ac.il, 0009-0005-1761-6391
[2]achiyali@post.bgu.ac.il, 0000-0001-8289-7410
[3]barathshany@technion.ac.il, 0000-0003-0776-7389

ABSTRACT

This study addresses the potential circularity of wood waste in architecture through the development of a Recycled Wood and Mycelium Mixture (RWMM) for use in Liquid Deposition Modeling (LDM) to produce sustainable, scalable architectural components. The research aims to optimize material formulations and assess the printability of a bio-based material for self-supporting models and mycelium growth. Local wood waste, specifically beech wood sourced from carpenters, was 3D printed using mycelium as a natural binder. In the first experiment, wood particles (1.6–2.0 mm) were combined with psyllium husk as a gelling agent and *Ganoderma lucidum* spawn to evaluate printability. The second experiment explored the use of unprocessed wood waste with particle sizes ranging from 1.0–30.0 mm for printing self-supporting cylindrical elements. The third experiment scaled up to a thermal block model, using a zig-zag toolpath to enhance surface area and promote mycelium growth. The results demonstrated the feasibility of large-scale RWMM printing, confirming its potential for sustainable construction. This research offers innovative solutions for integrating waste streams into additive manufacturing, contributing to the development of bio-based materials for architectural applications.

KEYWORDS

3D wood printing; wood waste; mycelium-based composites; additive manufacturing; bio-based materials; circular construction.

SESSION

ADAPT TO CLIMATE & PERFORM

1. INTRODUCTION

The acceleration of urban development, driven by global population growth, has placed enormous pressure on the construction sector to meet rising demands. This has positioned the architecture, engineering, and construction (AEC) industry as a major consumer of resources, accounting for over 30% of global material use (Orhon and Altin, 2020). Such levels of consumption underscore an urgent need for sustainable practices that prioritize the reduction of raw material usage and the incorporation of recycled resources. Among these opportunities, wood waste stands out as a valuable resource for advancing a more circular approach to construction by integrating recycled bio-based materials into building practices.

Although wood is widely recognized as a renewable and bio-based construction material, inefficiencies in its fabrication processes lead to substantial waste. Additionally, the frequent use of synthetic binders in wood-based products poses significant environmental and health risks (Kumar and Leggate, 2022). These challenges highlight the need to rethink the use of wood in construction to minimize waste and reduce reliance on harmful chemicals.

The combination of wood waste with natural binders, such as mycelium—the vegetative growth of fungi—offers a promising way toward sustainable material innovation. While conventional techniques, such as casting wood and mycelium mixtures in formworks, have successfully achieved specific performance benefits like improved acoustic and thermal properties, they are often resource-intensive and result in considerable waste. Formworks, for example, are typically discarded after use, contributing to landfill burden (Ghazvinian and Gursoy, 2022).

This context calls for innovative, waste-minimizing approaches to develop bio-based, circular solutions in the AEC industry. By leveraging wood waste and mycelium as sustainable material components, it is possible to significantly reduce environmental impact while advancing environmentally conscious construction practices that align with the principles of circularity.

2. BACKGROUND

2.1 WOOD WASTE

In Europe alone, approximately 50 million tons of wood waste are generated each year. (CORDIS,*2024*). Given the substantial amount of wood waste produced and the fact that wood is a bio-based resource, there is increasing interest in exploring ways to utilize wood waste. One promising approach is using sawdust from industrial processes, in additive manufacturing (AM). Research has shown that wood-based materials in AM can replicate several of the key properties of natural wood, such as compressive strength, acoustic performance, and thermal insulation (Buschmann et al., 2023; Das et al., 2021). This makes wood-based AM a sustainable alternative for architectural applications. When combined with a binder, wood waste becomes an extrudable material that can be printed layer by layer (Bierach et al., 2023; Rosenthal et al., 2022).

2.2 WOOD PERFORMANCE

Wood has gained recognition as an effective insulation material. Its natural structure traps air, minimizing heat transfer and providing excellent thermal insulation (Jelle, 2011). Processed wood waste, such as fibreboards and wood chip, demonstrates low thermal conductivity, making it a sustainable and practical choice for insulation. Studies by Oluyamo et al. and Mawardi et al. show that both wood type and particle size play a crucial role in thermal conductivity, with processed wood often outperforming bulk material.(Mawardi et al., 2022; Oluyamo et al., 2017)

Beyond thermal properties, wood's potential as a sound absorber has also been extensively studied, offering a renewable alternative to conventional materials like glass and mineral fibres. Key factors influencing sound absorption include porosity—the fraction of air within the material—and thickness (Wassilieff, 1996). For example, Boubel et al. found that beech wood grounded to particle sizes between 0.63 and 2.5 mm exhibited significantly better sound absorption than larger particles exceeding 16 mm (Boubel et al., 2021). These findings highlight the importance of optimizing particle size to maximize both thermal and acoustic performance in wood-based materials.

2.3 MYCELIUM PERFORMANCE

Mycelium has emerged as a promising bio-based binder due to its ability to bind organic matter through a network of hyphal microfilaments in a natural biological process (Pelletier et al., 2013). Research by Bruscato et al. demonstrated the potential of mycelium bio-foam as a sustainable alternative to expanded polystyrene, commonly used in packaging and building insulation (Bruscato et al., 2019). A study by Elsacker et al. that investigated the mechanical, physical, and chemical properties of mycelium-based composites with different types of lignocellulosic substrates found that although the mechanical properties such as compressive strength are not optimal, mycelium-composites can fulfill the requirements of thermal insulation (Elsacker et al., 2019). Furthermore, a study by Livne et al. reported that mycelium bio-composites can grow at ambient temperature conditions without harming their thermal or mechanical properties. The mycelium materials produced in this study had a thermal conductivity as low as 0.026 W/m·K, which is lower than standard commercial insulating materials (Livne et al., 2024).

In addition to thermal properties, mycelium-based materials exhibit notable acoustic performance. Pelletier et al. evaluated acoustic absorbers grown on agricultural by-product substrates, highlighting mycelium's efficiency as a binder and its strong acoustic and thermal properties compared to synthetic materials (Pelletier et al., 2019). Gezer and Kuştaş further explored mycelium-based insulation produced from disilicate wheat straw, finding that these boards achieved acoustic absorption coefficients of 87–99% at 1,000 Hz and sound transmission losses ranging from 46.4 to 59.7 dBA (Gezer and Kuştaş, 2024). These studies underscore mycelium's potential as a sustainable binder and promote good thermal and acoustic performance.

2.4 ADDITIVE MANUFACTURING TOOL PATH DESIGN FOR ENHANCED PERFORMANCES

AM has gained attention for its potential to enhance sustainability, with studies suggesting it can reduce environmental impact by up to 50% compared to traditional manufacturing methods (Cohen et al., 2024). Among extrusion-based technologies, Liquid Deposition Modeling (LDM) has emerged as a promising method for 3D printing wood pastes (Cohen et al., 2024), achieving wood content as high as 89 wt% (Rosenthal et al., 2018). LDM also supports mycelium growth by offering a higher surface-to-volume ratio compared to traditional molding processes, enabling innovative applications in sustainable material production (Elsacker et al., 2022).

Wood waste is valuable for producing sustainable, cost-effective 3D-printed components with minimal material loss. In conventional AM, wood is often blended with thermoplastics like PLA, PVA, or ABS, but these composites are typically limited to wood content below 40 wt% (Kariz et al., 2018; Krapež Tomec and Kariž, 2022). LDM overcomes this limitation, enabling significantly higher wood content while accommodating paste-like materials such as clay, concrete, and wood-based formulations. Recent studies have explored the potential for large-scale 3D printing of mycelium-based materials using beechwood particles, testing various gelling agents to optimize printability (Elsacker et al., 2022). Additional research has examined the influence of geometry and toolpaths on the growth and mechanical properties of 3D-printed mycelium composites, revealing the critical role of design in enhancing material performance (Gomaa et al., 2024).

The relationship between material properties and toolpath design is essential for achieving specific performance goals, such as acoustic absorption, acoustic scattering, and thermal conductivity (Cohen and Barath, 2023; Piccioni et al., 2023) . LDM research has focused on using tool paths as a design medium and developing computational methods for optimizing structural efficiency and material utilization (Breseghello and Naboni, 2022; Westerlind, 2021). These modifications not only inform geometric design that can be customized to enhance the acoustic and thermal performance of recycled wood and mycelium mixtures (RWMM) but also demonstrate the potential of LDM in sustainable architectural manufacturing.

3. METHODOLOGY

This study adopted a structured, three-phase experimental approach to develop and test RWMM for 3D printing. The first experiment identified local wood waste and evaluated its printability using a mycelium-based binder and a natural gelling agent. The second experiment involved printing and assessing self-supporting elements using wood particles of different sizes. Finally, the third experiment focused on scaling up the optimized formulation for large-scale 3D printing, exploring customization of toolpath design for architectural scales (figure 1).

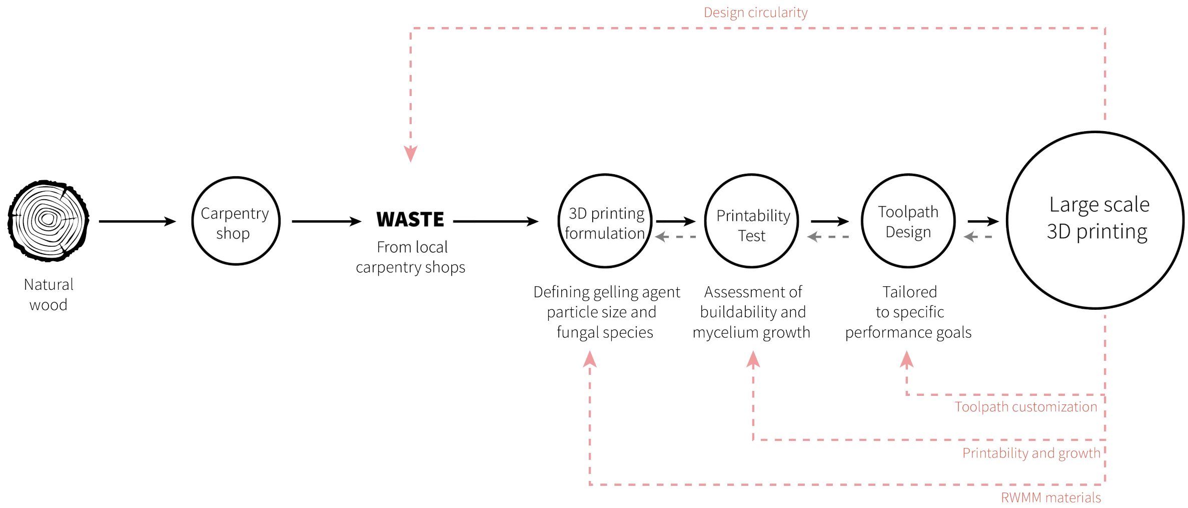

Figure 1 – A methodological production workflow outlining the iterative circularity of the fabrication process.

Across all experiments, tools and work areas were sterilized with 98% ethanol, while gelling agents and wood particles were sterilized in a pressure cooker to maintain optimal conditions for mycelium growth. For the 3D printing tasks, a UR5e robotic arm (Universal Robots. Denmark) equipped with a WASP LDM extruder (3D-printed PLA 10mm nozzle) (WASP, Italy) was used. After printing, the models were monitored for up to 18 days before being air-dried for 72 hours.

3.1 IDENTIFYING LOCAL WOOD WASTE AND TESTING PRINTABILITY

The first experiment involved two key steps. Initially, local wood waste was sourced from carpenters, representing a regional waste stream. The sourcing of local wood waste from carpenters identified beech wood as the selected wood type for the study. A review of commonly available wood waste types in Europe supported this selection, highlighting the dominance of beech wood in regional waste streams (Pramreiter and Grabner, 2023). The wood waste was ground and sieved to a particle size of 1.6–2.0 mm and sterilized in a pressure cooker. The grounded wood was then tested for printability using a formulation that included *Ganoderma lucidum* spawn (grown on hemp shives, Lambert Spawn, Netherlands) as a bio-based binder and a natural gelling agent identified from the literature (Elsacker et al., 2022). The mixture contained 15 wt% psyllium, 15 wt% wood particles, 10 wt% *G. lucidum* spawn, and 60 wt% water. The test print used a cylindrical toolpath with a diameter of 100 mm and a height of 100 mm. The printed model was stored in sterilized, sealed plastic containers for 14 days to support mycelium growth. Afterward, it was air-dried for 72 hours.

3.2 EVALUATING WOOD PARTICLE SIZES IN 3D PRINTED SELF-SUPPORTING ELEMENTS

The second experiment examined the impact of wood particle size on the printability and structural integrity of self-supporting 3D-printed elements. Two particle size ranges were tested: grounded particles of 1.6–2.0 mm and unprocessed wood waste with sizes ranging from 1.0–30.0 mm. To enable the printing of self-supporting elements, cornstarch was added as a secondary gelling agent, resulting in a modified formulation containing 7.5 wt% psyllium, 7.5 wt% cornstarch, 15 wt% wood particles, 10 wt% G. lucidum spawn, and 60 wt% water (Calmanovici et al., 2025). Cylindrical models of 100 mm diameter x 100 mm height were printed and stored in sterilized, sealed plastic containers for 14 days to support mycelium growth. Afterward, they were air-dried for 72 hours. Visual evaluation of the models focused on the internal mycelium growth throughout the structure, assessed by sectioning the dried samples. Printability criteria and mycelium integration were used to identify the optimal particle size for further research.

3.3 PARTICLE SIZE AND GELLING AGENT FORMULATION FOR LARGE-SCALE 3D PRINTING

The third experiment explored the scalability of the selected particle size and formulation for large-scale 3D printing. A typical printing toolpath of a thermal block model 150 mm wide, 300 mm long, and 170 mm high (figure 2) was selected from the literature (Piccioni et al., 2023). This experiment aimed to refine the formulation and printing variables to evaluate the materials potential to utilize toolpath design associated with performance properties such as thermal conductivity and strength for architectural applications.

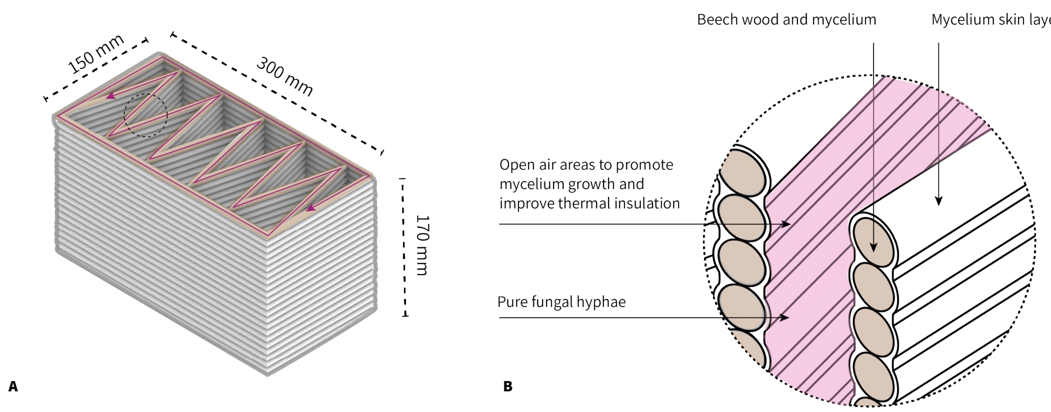

Figure 2 – **(A)** The 3D printed model highlighting the thermal toolpath design. **(B)** Explanation of the open areas within the model, created by the toolpath, which enlarge the surface area and promote mycelium growth.

4. RESULTS

4.1 IDENTIFYING LOCAL WOOD WASTE AND TESTING PRINTABILITY

The results of the first experiment, which evaluated the printability of beech wood in the RWMM, demonstrated the successful 3D printing of this mixture. During the printability test of the formulation using a cylinder model (100 mm diameter x 100 mm height) with a wood particle size of 1.6–2.0 mm and psyllium husk as the gelling agent (figure 3), the formulation demonstrated promising characteristics, including adequate buildability, consistent extrusion, and strong layer adhesion for the first four layers. However, similar to observations reported by Elsacker et al., the cylinder began collapsing after the fourth layer. Observations revealed that the geometry retained its collapsed shape during both the growth phase and the drying process.

Different from Elsacker et al., who proposed using raw beech wood material as an internal support structure (Elsacker et al., 2022), it was decided for the next experiment to adjust the gelling agent composition to achieve self-supporting prints without requiring additional internal supports. To enable the printing of self-supporting elements (figure 3), cornstarch was added as a secondary gelling agent, resulting in a modified formulation containing 7.5 wt% psyllium, 7.5 wt% cornstarch, 15 wt% wood particles, 10 wt% G. *lucidum* spawn, and 60 wt% water.

Figure 3 – **(A)** First print attempt using the original printing formulation. **(B)** The print after adjustment of the formulation.

4.2 EVALUATING WOOD PARTICLE SIZES IN 3D PRINTED SELF-SUPPORTING ELEMENTS

Results from the second experiment, which evaluated wood particle sizes in 3D-printed cylinder shape models as a self-supporting element, demonstrated that the adjusted formulation—incorporating corn starch as a gelling agent alongside psyllium husk—significantly enhanced the printability and buildability of the models. A complete cylinder model with 10 layers was successfully printed without collapse. Both grounded particles of 1.6–2.0 mm and unprocessed wood waste with sizes ranging from 1.0–30.0 mm, were printed successfully. However, when using the larger particle size range, a slight adjustment to the formulation was necessary, involving the addition of a small amount of water to improve pumpability. The formulation included 6.25 wt% psyllium, 6.25 wt% cornstarch, 15 wt% wood particles, 10 wt% *G. lucidum* spawn, and 62.5 wt% water. After drying, the cylinders were sectioned into two pieces for evaluation. A comparison of the initial mycelium growth within the two models revealed that the size of the wood particles had no significant effect on the internal growth of the mycelium (figure 4).

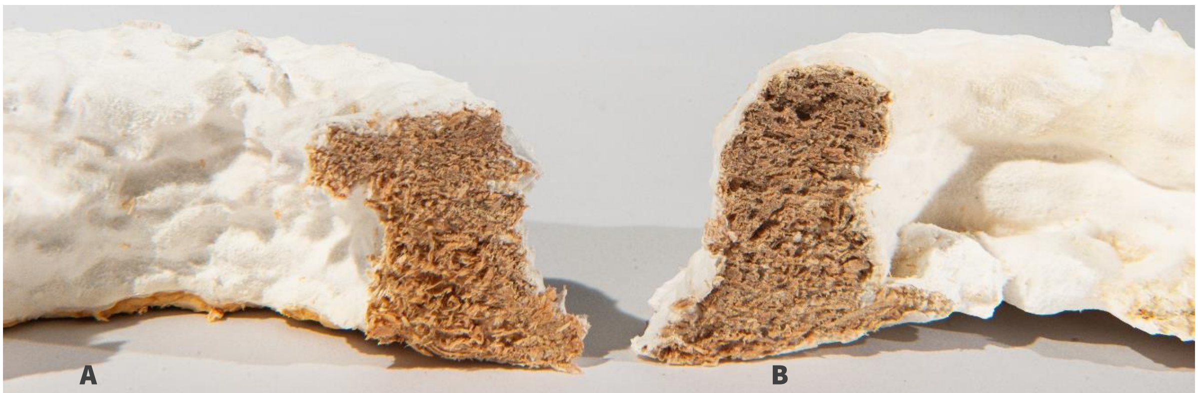

Figure 4 -**(A)** A section of a 3D-printed cylindrical model using unprocessed beech wood particles (1.0–30.0 mm). **(B)** A section of a 3D-printed cylindrical model using ground wood particles (1.6–2.0 mm)

Consistent with observations in the first experiment, the geometry of the 3D-printed models remained intact during both the growth phase and the drying process. The successful 3D printing of the RWMM formulation using the unprocessed particle size range was due to two key factors: the ability to print the cylinder without additional support and the elimination of processing time and energy required for grinding the beech wood into a precise particle size. These benefits led to the selection of this particle size range for further experimentation.

4.3 EVALUATING LARGE WOOD PARTICLE SIZES FOR LARGE SCALE 3D PRINTING

The case study thermal block, utilizing a zig-zag toolpath, was printed successfully using the unprocessed beech wood particle range. The design of the toolpath increased the material's surface area creating better conditions for mycelium growth and binding. This approach demonstrates the potential for printing porous, self-supporting structures and integrating biologically informed computational design methods. Future toolpath planning can incorporate morphological optimization to increase surface area while adhering to printing constraints (Armaly et al., 2023). The print reached a height of 105 mm without displaying deformation or challenges in printing buildability (Figure 5) before stopping due to the WASP tank's maximum material capacity (4.5 kg) . Despite this limitation, the process demonstrated feasibility for the scalability of self-supporting components with the unprocessed beech wood waste mixture. This material shortage underscores the importance of precise material quantity planning, which will be addressed in future trials. After the full mycelium growth period, observations revealed a well-developed fungal skin covering the printed model, with thicker aerial hyphae forming in the open spaces created by the zig-zag toolpath design. The thicker growth of aerial hyphae in the cavities suggests that with an optimized toolpath the aerial hyphae could extend and interconnect into a foam, tapping air inside effectively. This structure holds significant potential for improving the material's insulation properties.

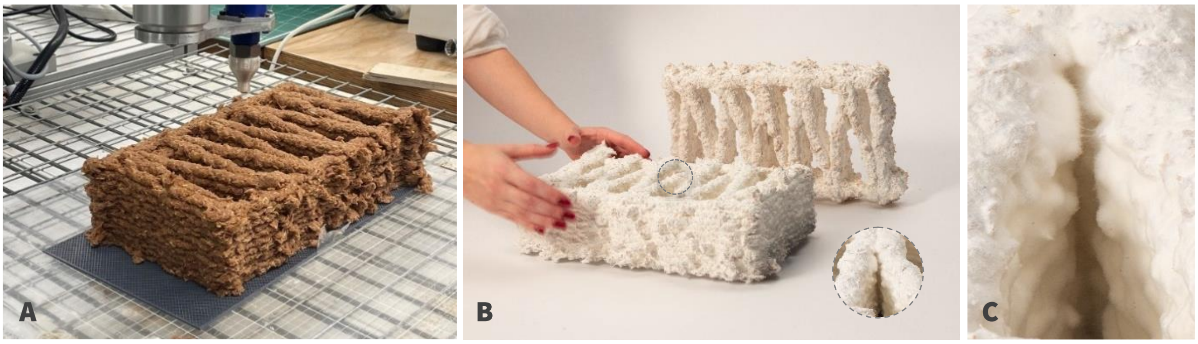

Figure 5 – **(A)** The 3D printed thermal block immediately after printing. **(B)** The same model after full fungal inoculation and drying. **(C)** Aerial hyphae growth within the open spaces.

Following the three experiments, next steps will focus on toolpath design experimentation for performance customization with a focus on thermal insulation and acoustic absorption properties. This will include developing a better understanding of the trade-offs between geometry complexity and toolpath printing parameters for both biological (i.e. increasing mycelium growth) and architectural requirements (i.e. improving heat dissipation, minimizing sound reflection, and maximizing absorption). These advancements aim to further establish the material's suitability for architectural and environmental applications.

5. CONCLUSIONS

This paper presented the feasibility for integrating wood waste in the 3D printing of self-supporting architectural components with RWMMs, demonstrating strong results in printability, buildability and mycelium growth. The findings highlight the importance of material formulations and particle size selection in printing self-supporting structures without additional scaffoldings. Additionally, the use of unprocessed beech wood particles minimized processing time and energy, promoting the upcycling of materials and advancing circularity in the AEC industry.

The results underscore RWMM's potential as a sustainable and versatile material for architectural applications. Future research should prioritize computational design and optimization of toolpaths and geometry to support thermal insulation and acoustic properties, including absorption and scattering. A deeper understanding of the relationship between wood particle size, internal mycelium growth, and their combined influence on acoustic and thermal performance is critical and should be empirically tested. Exploring advanced toolpath strategies and their impact on structural strength, as well as the role of geometry in improving material efficiency, will further expand the application potential.

Furthermore, studies on the effect of fungal species on acoustic performance and thermal properties highlight the need for comparative investigations to identify the most suitable types for specific requirements such as acoustic and strength (Gezer and Kuştaş, 2024). With a large-scale fabrication workflow now established, the next steps should involve refining material formulations to meet targeted acoustic and thermal performance criteria, paving the way for RWMM to contribute effectively to sustainable, high-performance architectural solutions.

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