Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf, Jacqueline Pauli, Walter Kaufmann (eds.)

A bio-based falsework system for the circular construction of shell structures

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Abstract
Ongoing research regarding the design of shells and spatial structures frequently focuses on the efficiency of the structure itself to reduce the amount of material required, but often, it negates the potentially significant environmental impact of the construction system required to realise them. As a result, shell structures typically need bespoke, disposable, and wasteful formworks. Mycelium-bound composites (MBCs) are circular, compostable, bio-based materials that, when pressed, attain an increased load-bearing capacity. They can be produced from locally sourced waste streams, which both helps to close waste loops in the region of production and to reduce the need to import materials for construction. Although their use as the main structural material for shells and spatial structures is still in the early stages of research, MBCs can be a sustainable alternative for the construction of formworks and temporary supporting structures where requirements such as fire resistance, resilience, and durability are less demanding. This paper offers an overview of the structural properties of MBCs and presents an innovative and circular use of dense MBCs to construct dry-fit waffle-like structures that can be used as falsework during the construction of shells and other geometrically driven structures. The benefits of these materials are demonstrated by performing a literature-based LCA to show the potential of dense MBCs as a valid alternative to standard materials such as oriented strand board (OSB) in construction.

Keywords: Mycelium-bound composites, MBC, bio-based, waste, falsework, formwork, circularity, shell structures, spatial structures

1. Introduction
The construction industry accounts for approximately 50% of the demand for raw materials (OECD [1]) as well as for 36% of the generation of waste (eurostat [2]) in the EU. This is due to the long-established linear flow of construction materials, which are largely produced using non-renewable resources and whose end-of-life entails their incineration or transportation to a landfill. This is the case for materials such as engineered wood products like oriented strand board (OSB) or medium density fibreboard (MDF) and plywood even though there is ongoing research to address this challenge (Shahjadi et al. [3]). As the demand for construction is projected to exponentially increase (IEA [4]) the industry faces an urgency to lower its environmental impact and reliance on non-renewable resources. This has resulted in initiatives across the industry to shift from these linear-type approaches to more efficient and circular practices.

Shell and spatial structure research has been a part of this shift by proposing structures that utilise materials efficiently. However, the geometries of these structures can be complex, thus requiring custom and oftentimes temporary formworks and falseworks (See Figure 1). These falseworks are typically constructed from materials such as OSB or MDF which lack an established circular life cycle. OSB and MDF lose performance when recycled (Nguyen [5]) and therefore can only be downcycled, making it more cost-effective for these materials to go to landfill or be incinerated. One approach is to optimise the formwork to efficiently use traditional materials; however, in this paper we instead propose to construct the formwork using a circular compostable material.

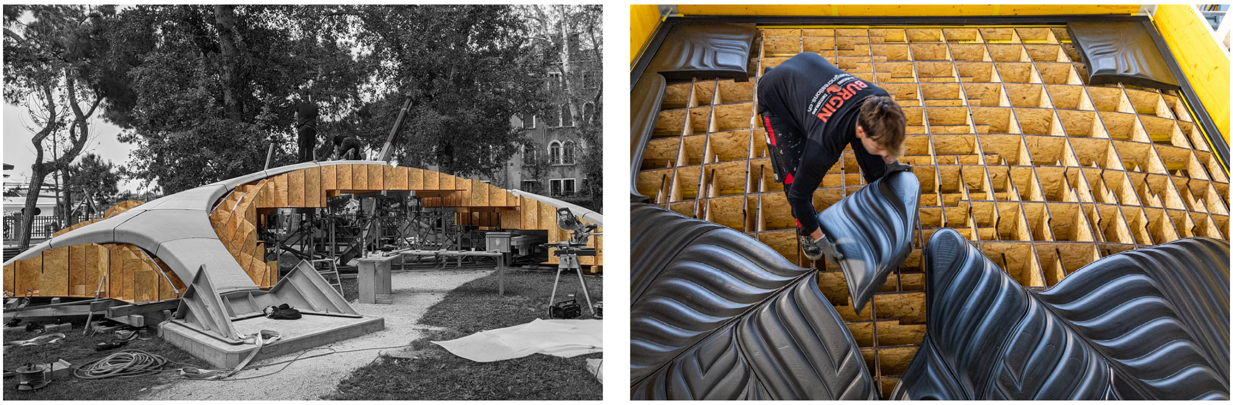

Figure 1: Examples of dry-fit falsework systems in the construction of the Striatus bridge (left, Image Author: Tom Van Mele) and NEST HiLo Slab B (right, Image Author: Georgia Chousou).

Mycelium-based materials are a class of bio-based materials which have recently gained momentum in the field of material research and development for the construction industry (Bitting et al. [6], Girometta et al. [7], Attias et al. [8]). Mycelium refers to the root system of fungi (Islam [9], Bartnicki-Garcia [10]) which degrades and binds as it grows. This property of binding is utilised by combining a fungal strain with a lignocellulosic substrate in a controlled environment (humidity, temperature, light) and later transferring this mixture into moulds. Through this process substrates such as agricultural waste or industrial waste free from chemical additives can be valorised and transformed into construction materials (Sisti et al [11], Jones [12], Elsacker et al [13]). The result is a circular and compostable foam-like mycelium-bound composite (MBC) with good acoustic (Pelletier et al [14]) and thermal properties (Elsacker [15], Yang [16]). Optionally, MBCs can be post-processed by cold- or heat-pressing (CP- or HP-MBC) to yield a densified material with increased structural performance (Chan et al. [17], Appels et al. [18]). The materials used in shell construction are required to meet certain structural and fire resistance criteria; however, dense MBC lacks the relevant standards required to validate their performance to safely implement them in such applications. Alternatively, temporary structures are subjected to lower criteria which creates an opportunity to explore the use of dense MBC in falsework construction.

In this paper, we first review the structural performance and material characteristics of dense MBCs in comparison with the engineered wood alternatives OSB and MDF. Based on this the scenario of a dry-fit waffle-type falsework is used to demonstrate the applicability and benefits of dense MBCs in falsework construction. A simplified life-cycle analysis (LCA) from literature is conducted to approximate the environmental impact of these three materials in the categories of climate change, acidification, and eutrophication for the functional unit of 1 cubic metre. The methodology and findings are subsequently critiqued, with key steps for future improvement identified in the biofabrication and environmental impact assessment of mycelium-based materials.

2. Materials and Methods

2.1. Structural Performance

The structural characteristics of several dense MBCs are presented in Table 1 alongside technical data for conventional OSB and MDF boards sourced from the SWISS KRONO website [19]. While MBCs can be pressed into boards of comparable size and thickness to OSB or MDF, the dimensions of the dense MBC boards listed in Table 1 are thinner and smaller. The range in values for dense MBC can be attributed to several factors, including variations in the substrate and fungal strain used, as well as the post-processing techniques.

Two distinct trends are evident that impact the performance of dense MBC: cold- versus heat-pressing, and increasing the density. Each trend improves the young's modulus as well as the flexural strength demonstrating the impact of the biofabrication process on the final material performance. Although the values in Table 1 serve as a reference point, HP-MBC emerges as the most promising alternative for falsework construction. However, it is important to note that the young's modulus remains approximately 2-5 times lower than that of OSB or MDF. Nevertheless, the existing research indicates that further investigation and refinement of the biofabrication process can narrow the performance gap between dense MBCs and engineered woods.

Material Familiy	**Material**	**Reference**	**Average Density (kg/m^3)**	**Average E-modulus Tension (Gpa)**	**Average Flexural Strength (Mpa)**	*Notes*
MBC	CP-MBC	Appels et al. [18]	240	0.008	0.2	
	HP-MBC	Appels et al. [18]	370	0.05	0.8	
	HP-MBC	Chan et al. [17]	954	0.7	2.7	
Engineered Wood	OSB	SWISS KRONO [19]	650	3.5	20	*major axis*
				1.4	10	*lateral axis*
	MDF	SWISS KRONO [19]	760	2.5	22	

Table 1: Structural performance values for MBC and engineered wood materials.

From an assembly standpoint, a dry-fit falsework system is selected to exclude the impacts of fasteners and glues. These systems are also simple to design and deconstruct but generate a significant amount of waste. Therefore, when constructed from dense MBC they can be disassembled and either composted or broken down and used to regrow new material without contamination. Two such systems are shown in the falsework technique used in the assembly of a discretised 3D-printed concrete bridge (Striatus, Figure 1 left) or for the casting of in-situ concrete vaulted floors ("Floor B" of the NEST HiLo unit, Figure 1 right). Yet to be addressed is assessment of the environmental impact resulting from the potential substitution of engineered woods with dense MBC.

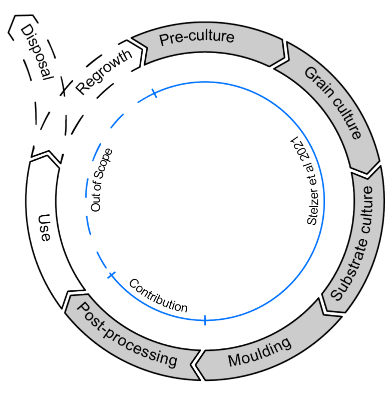

Figure 2: Steps of material life cycle cited from literature and steps contributed by this paper through energy measurement.

2.2. Environmental Impact

At the time of writing this paper there is no published LCA for dense MBC; therefore, a strategy was developed for elaborating upon the published cradle-to-gate LCA data for non-pressed MBC to approximate the impact of dense MBC (shown in Figure 2). Blocks of the same functional unit size used in the LCA for non-pressed MBC published by Stelzer et al. [20] were grown and then pressed in a Zschokke Laborpresse 4000kN by Imex Technik AG. The pressing times, temperatures, and pressures from Chan et al

[17] were replicated and the energy consumption measured, although CP-MBC were pressed without heating the pressing plates. The final step in the biofabrication process is to bake the pressed boards. The energy associated with this step was determined by using a Volcraft SEM6000 CH smartplug and running the oven at 60°C for 24 hours. The number of samples which can fit into the oven is calculated, and the energy consumption divided accordingly. As a last step, the final impact numbers are scaled up to represent a functional unit of a cubic metre to allow for a direct comparison to OSB and MDF.

To conduct a meaningful comparison between published LCAs, key parameters were identified from the LCA for non-pressed MBC as a guide for selecting published LCAs of OSB and MDF. The final reference needed to have the following qualities:

- be conducted in Europe,
- have a similar system model, and
- utilise the same life-cycle impact analysis (LCIA) methods.

The LCA published by Diedrichs [21] is the closest match in parameters to that of Stelzer et al. [20]. It is conducted for Germany, has a scope of cradle-to-gate, and utilises CML 2001 [22]. While there are newer LCAs separately for OSB and MDF which utilise CML 2016 [22], Diedrichs [21]was chosen for consistency as it investigates both materials. The categories included in the LCA are climate change, acidification, and eutrophication, and are based on which categories overlapped between Diedrichs [21] and Stelzer et al. [20].

3. Results

During the evaluation of the LCA results, the difference between CP- and HP-MBC was observed to be larger than originally anticipated. As shown in Table 2, the embodied carbon of CP-MBC is approximately 16% lower than that of HP-MBC, 14% lower than OSB, and 33% lower than MDF. Surprisingly, the energy associated with heat-pressing increases the embodied carbon of HP-MBC to exceed that of OSB, yet it is still 20% lower than MDF. In the category of acidification, the dense MBC materials achieve a lower impact; however, in the eutrophication category they are decidedly higher. These results indicate that further research and optimisation of the biofabrication of dense MBCs has the potential to further decrease the margin of impact, however the largest potential from an environmental impact standpoint lies in CP-MBC.

Material	FU	Climate Change* (kg CO2 eq.)	Acidification* (kg CO2 eq.)	Eutrophication* (kg CO2 eq.)
CP-MBC	1 m^3	272 ●	0.57 ●	0.39 ●
HP-MBC	1 m^3	325 ●	0.82 ●	0.62 ●
OSB	1 m^3	318 ●	1.06 ●	0.15 ●
MDF	1 m^3	406 ●	1.10 ●	0.30 ●
**LCIA Method : CML [20]*				

Table 2: LCA results of dense MBC material in comparison to the engineered wood alternatives.

The largest contributor to the impact of MBC is the electricity used throughout the biofabrication process, while the substrate and grain mix are the next largest contributors across different impact categories (Stelzer et al. [20]). Optimising the process for pressing dense MBC from a life-cycle impact standpoint could result in a reduction of the impact. This can be done, for example, by identifying the shortest amount of time and least amount of force required to achieve specific structural properties. Furthermore, the impact of the substrate and grain mix can be reduced through the grinding up of used dense MBC as substrate for growing new mycelium-based materials, thereby reducing the demand for fresh substrate. These two approaches have the potential to decrease the environmental impacts of dense

MBCs even further than shown in Table 2, which, similarly to Table 1, should be regarded as a guide upon which improvements can be made.

4. Conclusion and Discussion

In conducting this comparison between dense MBCs and engineered woods, a number of assumptions were made to ensure the evaluation was straightforward, quick, and easily replicable. However, these assumptions also led to a sharply limited scope. Key steps in the biofabrication process and in the definition and execution of the LCA are highlighted in this section as crucial areas for future researchers to address. These steps aim at bridging the gaps in material performance and environmental impact evaluation observed in this study.

4.1. Performance-driven Biofabrication

As introduced in the results section, the final impact of dense MBC is highly influenced by the associated biofabrication process. In particular, the energy associated with each step. Each lab which produces MBC has its own unique protocols which affect the final properties of the material. As challenging as this variability is, it is also an opportunity. For example, the final drying process may not be required for CP-MBC as air-drying may prove sufficient. Similarly, the force and duration of pressing can be optimised based on the target performance, resulting in dense MBCs with minimal and efficient energy usage. Additionally, the pressing machine used for this paper is dated and therefore may have a higher energy consumption than modern press machines. As the energy usage in the biofabrication process is most influential, the combination of these changes could highly influence the results to be reduced even further.

Additionally, there is the possibility to grind old MBCs at the end of their life cycle in order to serve as substrate for growing new MBC material. This has the potential to offset the impact associated with fresh substrate, while in turn reducing the demand for raw materials and generation of waste. Combining these optimisation strategies can serve as a foundation, with additional strategies emerging as the biofabrication methodology is refined with a performance-driven environmental impact approach

Although CP-MBC demonstrates the greatest environmental benefits, its structural performance is currently limited and less promising in comparison to HP-MBC. As a result, future research should focus on optimising HP-MBC with the aforementioned performance-driven impact approach, by reducing energy consumption throughout the biofabrication process. While HP-MBC also currently lacks the structural capacity to be implemented in falsework construction, the modification of steps in the biofabrication process shows potential to bridge this performance gap.

4.2. Cradle-to-Cradle LCA for Biomaterials

While the region, system model, and LCIA methods between Stelzer et al. [20] and Diedrichs [21] match, there are some key discrepancies to address. As previously mentioned, the LCIA methods are the same, but Diedrichs was published eleven years before Stelzer. While it is likely that new policies and methods during this period have influenced both the primary data and impact calculation methods, the extent of this influence remains uncertain. Therefore, it is recommended to reconstruct both LCAs using the LCI (life-cycle inventory) and primary data. This ensures consistency in scope and source between the materials being compared, as well as allows for the inclusion of key impact categories such as land use.

Another aspect of LCA not addressed in this paper is biogenic carbon. While Livne et al. [23] conducted a biogenic carbon LCA for MBC, it was excluded from this study due to the need for comparable data for OSB and MDF, which was unavailable at the time. However, biogenic carbon can significantly affect the results and is another element of the biofabrication process which can be optimised.

For example, Livne et al. found that MBC can be carbon negative when grown for 2 weeks but carbon positive after 3 weeks. Future LCAs should therefore include biogenic carbon to better evaluate engineered woods and compare substrate options. Additionally, expanding the LCA scope to cradle-to-cradle is recommended to capture the full circular life cycle of MBCs. Identifying specific use-cases within this framework can reduce the speculation often associated with expanding the scope and allow for the inclusion of MBCs' key benefits, such as their biodegradability and potential for multiple regrowth cycles, which are key advantages for their application in construction.

This LCA was based on a standard quantity of one cubic metre of material, which does not account for the varying structural characteristics of dense MBCs compared to engineered woods (see Table 1). A performance-based redesign of the dry-fit falsework system could provide a more rigorous comparison metric by optimising the falsework system based on material performance. This approach is similar to LCAs conducted for thermal materials, where a target R-value or lambda guides the material selection and comparison (Carcassi et al. [24]). By focusing on material efficiency and design optimisation, even materials with a larger environmental footprint can achieve a reduced impact. This performance-driven metric thereby offers a method for a more equitable comparison between materials with different structural capabilities.

In conclusion, this paper calls on researchers and practitioners to expand their focus from traditional natural materials to innovative biomaterials such as dense MBCs. While the quantification of their impact and benefits is still in its early stages, this study has outlined promising methods for further reducing their environmental footprint and improving their performance evaluation. High-waste applications, such as falsework in construction, present opportunities for these circular materials to minimise waste generation and close production loops. By refining the biofabrication process, there is significant potential for mycelium-based materials to not only achieve target performance values but also foster more circular practices across the construction industry. While we are only at the beginning of exploring their full potential, the key steps identified here represent the foundation of a roadmap for developing high-performance, low-impact solutions for future applications.

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