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RESEARCH ARTICLE

Using nature in architecture: Building a living house with mycelium and trees

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Substrate

Abstract
This study proposed the development of a house with the following characteristics: grows, builds, and repairs itself; changes with the seasons; uses the forces of nature and is in harmony with its environment; favors biodiversity and natural equilibrium; low cost and does not require considerable workforce or industrial material; carbon free and waste free; returns to nature when no longer in use; enables sustainable and balanced mankind development. The use of living architecture to decrease or nullify the environmental costs of structure materials was also investigated. Furthermore, the use of living architecture techniques to comply with the current living and construction style with as little change as possible was analyzed. A new envelope material with little to no carbon impact was scientifically explored, and the use of this material to create a sustainable house was technically examined. Findings demonstrate that such a house is not only feasible but also rational and beneficial from the economic and environmental perspectives.

1. Living construction history

Living architecture is defined as the use of forces and possibilities given by natural living organisms to help and build low-cost and sustainable construction. Living architecture is not a new concept as it has been used for centuries.

The first popular examples of living architecture are bridges across Asia. Three vine bridges (Figure 1) have been built in Japan across the Iya Valley; these bridges use the strength and properties of *Wisteria floribunda* to hold wooden slabs of bridges of up to 43 m long. Similar bridges can be found in Indonesia (Jembatan Akar bridge) and India (Rangthylliang and Umshiang bridges in Figure 2). The local Indian tribe called War-Khasis used *Ficus elastica* with aerial roots that develop on the tree trunk and then reach the soil.

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Figure 1 Vine bridge in the Iya Valley, Japan (*photo from* Funzug.com).

Figure 2 Rangthylliang bridge (photo from P. A. Rogers, 2015).

Figure 3 "Chêne Chapelle" in Allouville-Bellefosse (*photo from "pintandaport"*).

By guiding roots in a hollowed branch across the river and pushing them into reaching the soil on the other side, the tribe naturally built bridges up to 50 m long in a 10- to 15-year process.

Figure 4 "Oak Chapel" in Jovac (*photo from Mrka*).

Figure 5 "Wee house" (photo from Sarah Grote).

Similar old and living constructions can be found in France (Figure 3) and Serbia (Figure 4), where an ancient hollowed oak was used as walls to build chapels.

At the present, many "tree houses" are grown around the world. Such houses use living trees as a structure but use industrial materials for building the living space: this practice is the first step toward the real "living architecture" aim of the present study. Striking examples of the said structures are the "Wee house" built in 2013 by Dave Herrle (Wolf, 2006) in the Westbrook forest (Connecticut, USA – Figure 5) and "Teresa and David's tree house" built in 2011 in the United States (Wolf, 2006).

However, achieving real "living architecture" requires not only using nature as it is but also shaping it to the required form. This process was pioneered by John Krubsack, who realized the first "living chair" in 1914 (Figure 6). The chair was entirely built by shaping living trees as they were growing (Wisconsin, 1922). John Krubsack took 11 years and 32 young seedlings to build the chair, and his

Figure 6 John Krubsack's growing chair, 1919 (*photo from* treeshapers.net).

Figure 7 "Basket tree" by Axel Erlandson in his "Tree Circus" (*photo from* atlasobscura.com).

achievement encouraged other "tree shapers," such as Axel Erlandson (Figure 7) who started shaping trees in 1925. After 20 years, Axel Erlandson opened his famous "Tree Circus" in California where he displayed more than 70 "tree sculptures." Tree shaping has continued growing and has been carried out by shapers, such as Richard Reames who was the founder of the "Arborsmith Studio" and crafter of the term "arborsculpture" and who wrote reference books on the subject (Reames et al., 1995; Reames, 2002); this shaper has inspired many architects, such as Konstantin Kirsch, Laura Spector, and Aharon Naveh.

Figure 8 Auerworld Palace (Auerstedt, Germany).

Figure 9 Evolution of the Baubotanik Tower (*photo from the Baubotanic research group*).

These significant contributions have initiated the modern living architecture. Marcel Kalberer and his "Sanfte Strukturen" team built the Auerworld Palace (Figure 8) in less than a month in 1998; this palace is a living one made only from living, bent, and shaped willows (Rocca, 2009). More than 10,000 living willow constructions were erected on this base in Germany (e.g., those in schools, private gardens, or public spaces).

In 2005, Oliver Storz, Ferdinand Ludwig, and Hannes Schwertfeger started building what they called "Baubotanik buildings" (Ludwig, 2012). The idea was to use an industrial structure to guide trees to develop following the desired shape and thus obtain the desired structure (Figure 9). Using this technique, they built an 8 m-high tower (i.e., the "Baubotanik Tower" completed in 2009) and a three story-high cubic building in a dense urban environment (i.e., the "Plane-Tree-Cube Nagold" completed in 2012 in Nagold). The latter building has been awarded the "Special Prize for Innovation" at "Holzbaupreis Baden-Württemberg 2012."

Mitchell (2006) notably contributed in the field by considering an entire house made entirely from living materials. The tree structure would be shaped similar to an igloo using the shaping techniques developed by Reames (Reames, 2002) on several living trees. He then explored the possibility to add a vineyard to create a mesh between

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the different parts of the tree structure, and the said part would be filled by clay and straw. Some parts would be emptied and filled with a soya-based plastic sheet to create windows. Furthermore, he presented solutions on ventilation, overheat protection (i.e., vegetal from the house would absorb solar radiation via photosynthesis), and rainwater collection (Figure 10).

These imagined new ways of living and new cities have potential to be built at present, and the artists behind them have inspired several builders, researchers, and architects. French architect Vincent Callebaut depicted his utopic vision of a city (Figure 11) with depolluting towers, vertical farms, and considerable utilization of living vegetal.

Belgian architect and painter Luc Schuiten also showed what he explains to be "a possible future" for our cities. He envisioned fully natural houses bore by living trees ("habitarbres" in Figure 12) with a translucent wall material and would use the forces of nature to sustainably develop (Schuiten, 2010).

In the current study, a research project on the use of mycelium for providing envelope on a tree house structure was presented on the basis of the knowledge and experience of the above-mentioned architects and innovators.

2. Methodology: creating a house structure with living trees

A family living house usually has two parts with two different functions. One is the structure, which is the part that enables the house to stand against environmental solicitation as well as its own dead load. The other is the envelope, which creates a closed cover that protects its inhabitants mainly from wind, coldness, and wild animals. Nature offers many interesting ways to create the two elements.

The first solution is to create an artificial hollow tree (Wilkin, 1999) (Figure 7). An artificial hollow tree can grow successfully using inosculation: this process is a natural one and allows merging of two branches from the same or different trees if one of the branches can tightly hold the other (Ludwig, 2012). Many different techniques can be used to induce inosculation, such as rope bonding, cable bonding, or screw bonding. The results depend mainly on the tree species to be inosculated (Table 1). To achieve the said goal, the house plan should be drawn on the ground first and then two rows of seeds should be planted (i.e., one in each side) on the plan lines. During the growth of the seeds, they should be intertwined to induce inosculation.

Figure 10 Fab Tree House, South Elevation, Terreform One (Mitchell, 2006).

Figure 12 "Habitarbre" from a living tree (Schuiten, 2010).

Figure 11 Vision of Paris in 2050 by Vincent Callebaut (Vincent.callebaut.org).

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Table 1 Comparison of tree shaping methods.

	Instant tree shaping	Gradual tree shaping	Aeroponic root shaping
Work time	Low	High	Low
Completion time	Low to medium	High	Medium
Implementation complexity	Low	Low	Low
Shaping possibilities	Few	Some	Many
Success odds	Low	High	Medium to high
Reproducibility	None to low	High	Medium
Implemented constructions	Yes	Yes	Few, of small envergure
Industrial application	None	Possible	Possible (TreeNovation)
Optimal specie	Poplar, willow	All upon specificities	Ficus, eucalyptus, acacia, and fruit trees (e.g., lemon tree, fig tree, and plum tree)

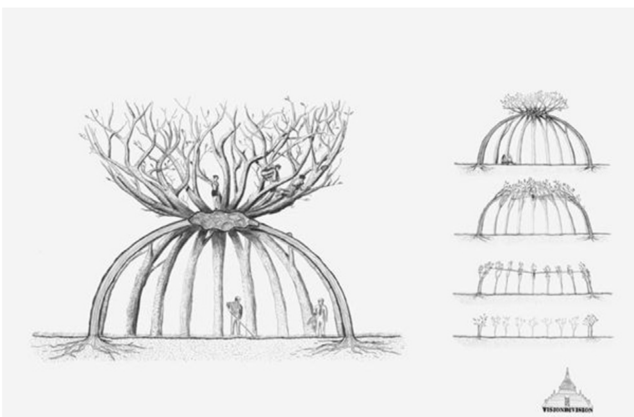

Figure 13 Tree structure built during a workshop at the Politechnico Milano (*picture from VisionDivision*).

The process can be repeated with the merged plant obtained until all the trees are merged into one (Figure 13). The top part should be inosculated in the central point to create the "roof," thereby creating a large hollow tree suitable for habitation. This method can take up to 10 years (Wilkin, 1999).

A method is proposed to decrease the time needed for the growth of a living house, that is, using trees only for the structure and other living materials for the envelope. Similar to the artificial hollow tree method, this method uses few trees and induces inosculation only in the central point on the top part. The aim is to create an igloo-like structure with strong living trees and leave empty spaces to be filled with other materials. Such structure have already been imagined (Mitchell, 2006) or built (Rocca, 2009) and can be made using three main techniques.

- Instant tree shaping is a widely used method and uses young 2–4 m thin trees, which are pruned and bent to the desired shape. A device (e.g., rope or tutor) is then used to maintain the trees in their position until they get used to it. This method takes several years depending on the tree species. The method is easy but presents many drawbacks, such as the response of the tree to the solicitation is long and difficult to forecast (Reames and Delbol, 1995).

- Gradual tree shaping is a method mainly popularized by Peter Cook and Becky Northey (Cook and Northey, 2010). This method is used to establish a "growing plan" of a tree and relies on constant and progressive guiding of the different branches of a tree, from the seedling to the mature tree. Only the apex branch of each sibling is kept most of the time to ease the process and avoid much stress on the plant, and the desired branching is realized by inosculating other seedlings. This method is predictable but takes much time and varies significantly depending on the growing specifications of the chosen species.
- Aeroponic tree shaping (Figure 14) is a method developed by Yaël Stav (Golan, 2008; James, 2016). The roots rather than the branches are shaped in this method. The method can only be used with compliant trees species such as *Ficus benjamina* of fast growing and flexible roots. The idea is to plant seedlings in an aeroponic box, which is exposed to more light than darkness and wherein nutrients are regularly vaporized for a year until the roots grow sufficiently long for the desired application. The tree is then taken out of the box, and the roots are shaped and planted on the site. Within a few years, the roots will lignify and become as hard and thick as the branches.

Every technique offers advantages and drawbacks as well as its optimal tree species (Table 1).

The most promising species for the said techniques are listed and compared in Table 2 (Martens-Mullaly and Waters, 2005). The results show that aeroponic root shaping should be used in tropical or warm regions where *Ficus benjamina* grows. Meanwhile, gradual tree shaping or aeroponic root shaping should be used in tempered regions where *Platanus acerifolia* or *Salix babylonica* grow.

The time and efforts required to mold a living tree to the minimum needs are high. However, many examples and solutions with carefully designed structure prove this

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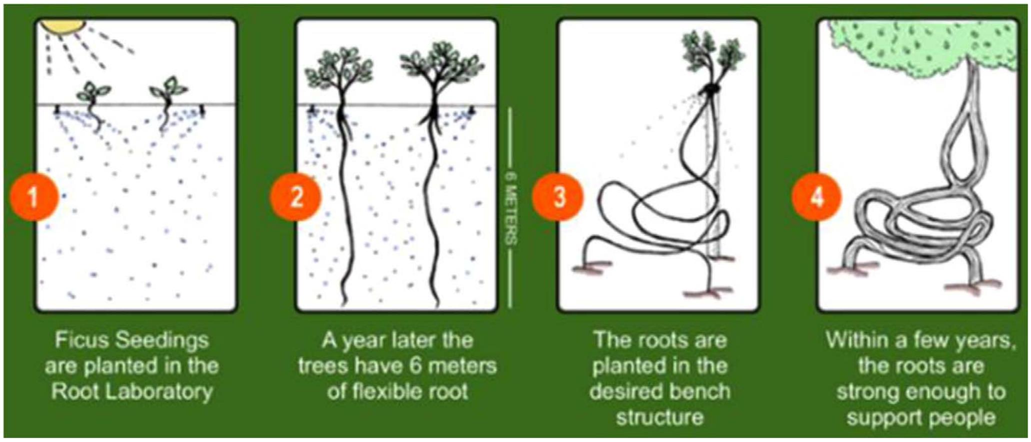

Figure 14 Developing roots in aeropony (image from TreeNovation).

assertion incorrect. Such a structure can be achieved by workers with little or no botanical experience, as demonstrated in the Politechnico Milano's workshop by Vision-Division (Figure 13). In this workshop, students successfully created an arborescent structure. However, the growth of the structure took some time. Whether work time is a concern is unclear. As stated by Mitchell Joachim in his speech at Catalonia's Institute for Advanced Architecture (Mitchell, 2015), "*If we can wait years to age a bourbon, why couldn't we wait years to create a vegetal city?*" Therefore, if a few years are extremely long for a single house, then this situation is untrue for an entire city. New fully vegetal cities can be grown all at once in a few years because the growth process requires very little human care after the setup.

If planning an entire village growth cannot be considered, then house farms can be built to comply with industrial speed requirements. Indeed, the final customer need not bear the entire growth time. Instead, arborescent structures with various shapes can be easily grown in bulk in "house farms" and then sold and transplanted on the given sites when they reached the desired growth.

3. Experimental approach

3.1. Creating an envelope with mycelium

After building the structure, the envelope for protecting inhabitants of the living house should be developed. Mycelium is a promising material for envelopes. As it is composed of thin filaments running without specific direction, mycelium may be solid and insulating. Mycelium is a highly and fast renewable resource, is entirely natural, and can grow on any given shape; some species are very lasting and offer a good fire reaction (Stamets, 2005). In 2007, Ecovative started to commercialize mycelium-based product, such as chipboards wherein glue is replaced by mycelium, insulation or packaging mycelium foam, or even a do-it-yourself kit to grow mycelium (www.ecovativedesign.com). Many artists used this kit to create sculptures or lamps. "The Living," an Autodesk funded lab, used this kit to create mycelium bricks by growing mycelium in molds and baking it once grown. They used these bricks to build the "Hy-Fi Project," a 13 m-high tower in New York. Creating a tower out of these bricks still require industrial operations, transportation, and energy, thereby requiring high financial and environmental costs. In this study, mycelium was grown in situ to create an envelope without neither industrial operations nor transportation.

To be useful for construction, mycelium should be carefully selected on the basis of the following criteria:

1. Saprophytic or mycorrhizal mycelium, as a parasitic one would endanger the living tree used for the construction;
2. Hyphal system, which is related to the final resistance;
3. Monomitic (i.e., possessing one hyphae type) mycelium, which is soft; dimitic and trimitic mycelia, which are strong owing to skeletal and binding hyphae (Stamets, 2005).

Other parameters should be considered, such as the optimum growing temperature and mycelium origin. The former parameter should be as close as possible to environmental temperature on site. On the basis of the said criteria, *Ganoderma applanatum* was used in this study to test the feasibility of mycelium construction (Table 3).

Given that mycelium can form a dense structure by colonizing a substrate, a simple way to use mycelium in architecture was proposed. First, the desired envelope should be realized out of cardboard in the tree structure. Then, cardboard should be inoculated by mycelium, which will be colonized using the cellulose on the cardboard to enable growth toward the desired shape until a solid and compact mycelium envelope is obtained. Finally, mycelium should be dried by hot air projection to kill the growth process while maintaining cell cohesion. The above-mentioned process will develop a whole mycelium envelope of low financial and environmental costs from a simple cardboard structure.

The success of the method enables Ecovative to develop a large-scale commercial use of mycelium; Ecovative is currently creating millions of mycelium packaging a year, including those for Ikea (Dell, Crate & Barrel (Bechet, 2016), and ecovativedesign.com).

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Table 2 Comparison of different tree types.

	Plane tree (*Platanus acerifolia*)	Willow (*Salix babylonica*)	Ficus (*Ficus benjamina*)	Beech tree (*Fagus sylvatica*)	Ash (*Fraxinus excelsior*)
Structural resistance	Very High	Low to medium	Medium	Very High	High
Growth speed	Medium to fast	Fast	Medium to fast	Slow to medium	Medium to high
Inosculation possibility	Very high	Medium	Very high	Very High	Very high (screw bond)
Bending and "tree shaping" possibilities	High	Very High	High	Medium	Very High
Origin	Hybrid, common in Europe	Australia	Asia	Europe	Europe and occidental Asia
Scarcity	Common	Common	Common	Common	Common
Additional advantage		Less sensible to diseases and parasites			Less sensible to diseases and parasites

3.2. Experimentation with mycelium

An experimental program was conducted to check whether a tiny *Ganoderma applanatum* sample (i.e., low inoculation rate) alone could colonize the cardboard. Sterilized 20×20 cm cardboard sheets were stored in sterile environment, and a tiny amount of mycelia growing on agar were placed between two cardboard sheets. The obtained structure was then preserved in a sealed bag to avoid contamination and was grown for a few weeks. However, the mycelium fails to properly colonize the cardboard. Thus, a large amount of mycelium should be used.

A second experimental program was performed with mycelium growing in a substrate jar stored in petri box. Four jars were filled with 1) sawdust, 2) 60% sawdust and 40% rye flour, 3) 60% rye flour and 40% sawdust, and 4) rye flour. All these jars were then sterilized by autoclaving, weighted, and added with distilled water to approach 50% moisture following the method in (Stamets, 1993). Then, in sterile environment and using only flame-sterilized instruments, mycelium was added in two points in each jar with low inoculation rate, and jars were shaken to prevent aggregate formation. Finally, every jar was sealed with parafilm and rubber band, and placed in a room with no direct sunlight with a temperature of 21 ± 2 °C and a relative humidity of 60% $\pm$ 10% for a few weeks (Stamets and Chilton, 1983). After 67 days, mycelium growth in jars cannot be detected except from the sawdust jar where it has grown rapidly because of the low inoculation rate. Sawdust is the most adequate substrate for growing *Ganoderma applanatum*.

The colonized substrate can be used to grow mycelium sheets with high inoculation rates (Figure 15). The growth on cardboard with high inoculation rate was tested using three different colonized substrates: colonized sawdust, colonized rye grain, and liquid mycelium. First, 20 cm $\times$ 20 cm cardboard sheets were sterilized by autoclaving. Then, some of the cardboard sheets were created with a hole which would be later filled by PVC pipe to represent window framing. In sterile environment with flame-sterilized instruments, two-layer sheets were built; each layer was composed of colonized substrate between two cardboard sheets dampened with distilled water.

These sheets were then stored in sealed bags in non-controlled environment to grow mycelium in situ. The sealed bag kept the moisture inside, thereby enabling mycelium to continue growing. When taken out of the bag, mycelium in the sheet quickly dries and its growth stops. Using a high inoculation rate grants impressive and quick results; sheets with sawdust and rye grain are fully colonized in 9 days to 17 days. However, liquid mycelium fails to colonize the cardboard.

Colonized sheets becomes quite resistant. A view of how mycelium degrades the cardboard to create a new material is shown in Figure 16.

Sheets were dried to increase resistance and thus stop the mycelium and fruit growth. Both 100 °C heating in oven under natural drying for 30 min and 1 week show the same results. In particular, the growth has stopped and the resistance is highly increased. However, some sheets that had been placed in high relative humidity ($T = 21 \pm 0.5$ °C

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Table 3 *Ganoderma applanatum* criteria validation.

Ganoderma applanatum		Criteria validation
Origin	Europe and North America (Kuo, 2004)	✓
Hyphal system	Trimitic (Phillips, 2002)	✓
Growth process	Saprophytic and does not endanger living trees (Schwarze and Ferner, 2003)	✓
Optimum growing temperature	25–30 °C (Castillo et al., 2004)	✓

Figure 15 Cross section of mycelium sheet.

and $H=60\pm10\%$) exhibit signs of superficial moldiness. This problem can be avoided even in high moisture environments by applying waterproof coating, such as pine tar.

Small-scale housing prototypes were produced to test the applicability of these sheets for construction (Figure 17). These prototypes were very simple in shaped and composed of a cubic 10 cm × 10 cm wood frame structure with small fitting mycelium sheets for its envelope. The sheets were grown using the previous method but were taken out of the sealed bag prior to being fully colonized to be glued on the structure. Once glued, vaporized water was applied every two days to maintain the growth on the structure. These prototypes are successful (Figure 17) even if the mycelium has dried prior to full colonization because of the absence of the sealed bag. The brown aspect is due to the application of pine tar.

These experiments allow defining a process for creating mycelium sheets (Figure 18).

Performance tests on mycelium sheets were conducted to understand their applicability in architecture. Material density was measured by weighting a sample and determining its volume by water displacement: $d=0.315$, which confirms potential thermal insulation properties around 0.1 W/M·K, which is close to that of autoclaved aerated concrete. Water absorption degree was also measured using the glass pipe method (RILEM-25 PEM) (Table 4). The results show that mycelium sheets are waterproof (with and without pine tar coating). The sheets have a good reaction to fire, as they can stay on a Bunsen flame for several seconds with no significant alteration prior to finally carbonizing without flame and with or without pine tar coating.

4. Methodology for building a living house

A rational methodology for building a house using living tree structures and mycelium envelope was proposed as shown in Figure 19. First, a tree structure should be creased using aeroponic root shaping with *Ficus benjamina* or gradual tree shaping with *Platanus acerifolia*. Gradual tree shaping is a time-consuming technique but allows the creation of a secondary structure for inducing the attachment of mycelium sheets. A substrate (preferably sawdust) should be inoculated with *Ganoderma applanatum* mycelium to obtain a high quantity of colonized substrate. Meanwhile, cardboard sheets should be prepared to create the desired shape for the envelope. Holes should be created in the sheets for placing doors and windows. These sheets can be soaked into liquid starch to induce mycelium growth. Then, the sheets should be sterilized, inoculated with the colonized substrate, placed on the tree structure, and covered with plastic canvas sheet for preventing drying during mycelium growth. Doors and windows should also be placed at this time and maintained by props as long as the mycelium growth continues. Once the mycelium colonized the whole envelope, it should be dried in free air or using hot air projection system. Finally, a coating such as pine tar should be applied to prevent superficial moldiness and insect attacks.

Although mycelium growth is stopped by drying, the whole building envelope has grown in situ, thereby resulting in no waste of the living arborescent structure, no transport or industrial processing, no carbon cost, and less human work. Such advantages are attributed to the living

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properties of the material and cannot be obtained with classic construction materials.

5. Conclusion and perspectives

Living architecture can be used in building a living house. This study aimed to facilitate sustainable development that enables people to build low-cost and sustainable houses while preventing nature destruction and waste emissions. Developing living architecture will play a significant role in a transition to an harmonious world wherein constructions respect nature and people. However, living architecture should be used in combination with traditional architecture, as an entirely living house still needs prototypes and

Figure 17 Colonized blocks with mycelium.

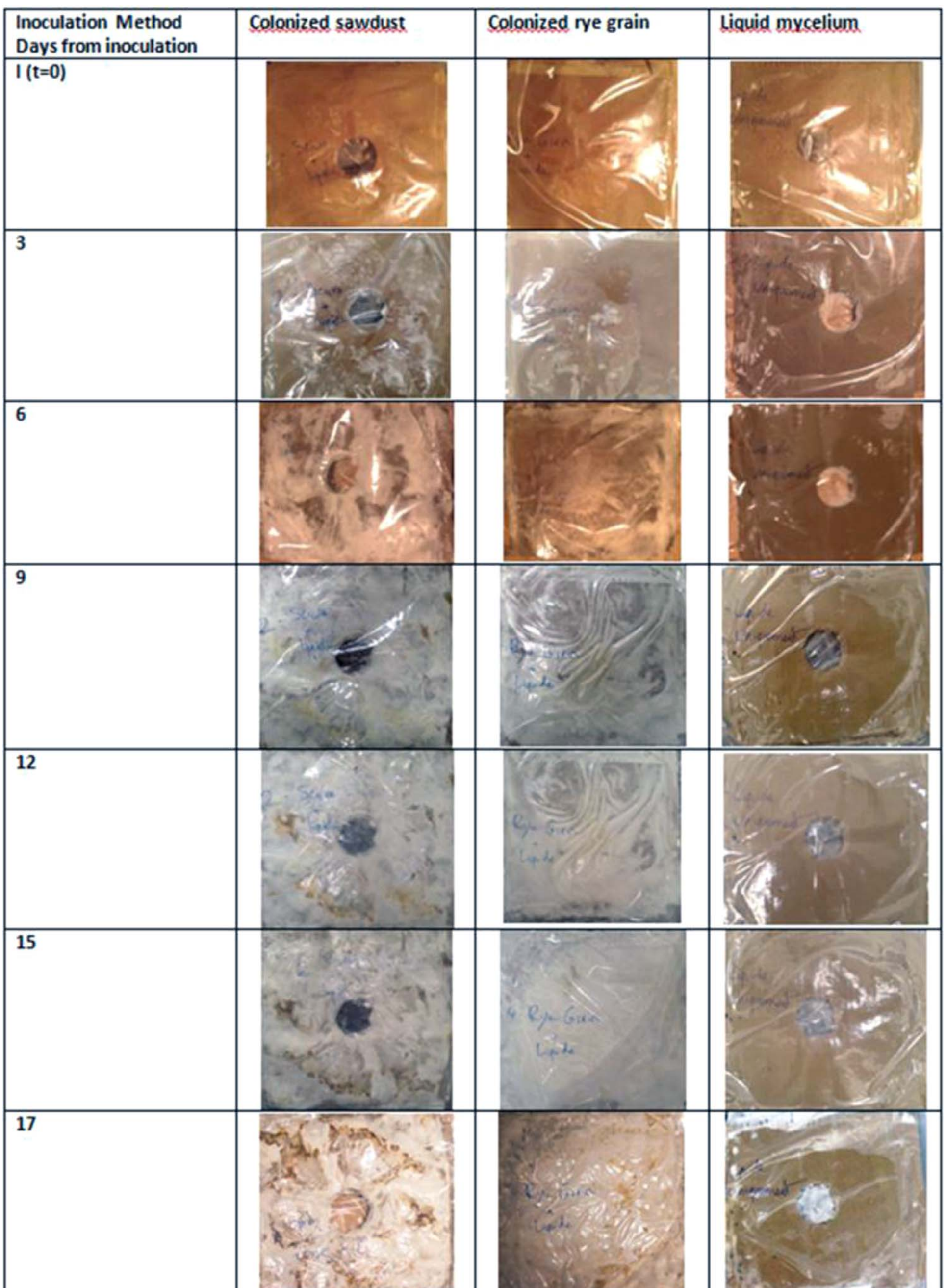

Figure 16 Mycelium growth monitoring.

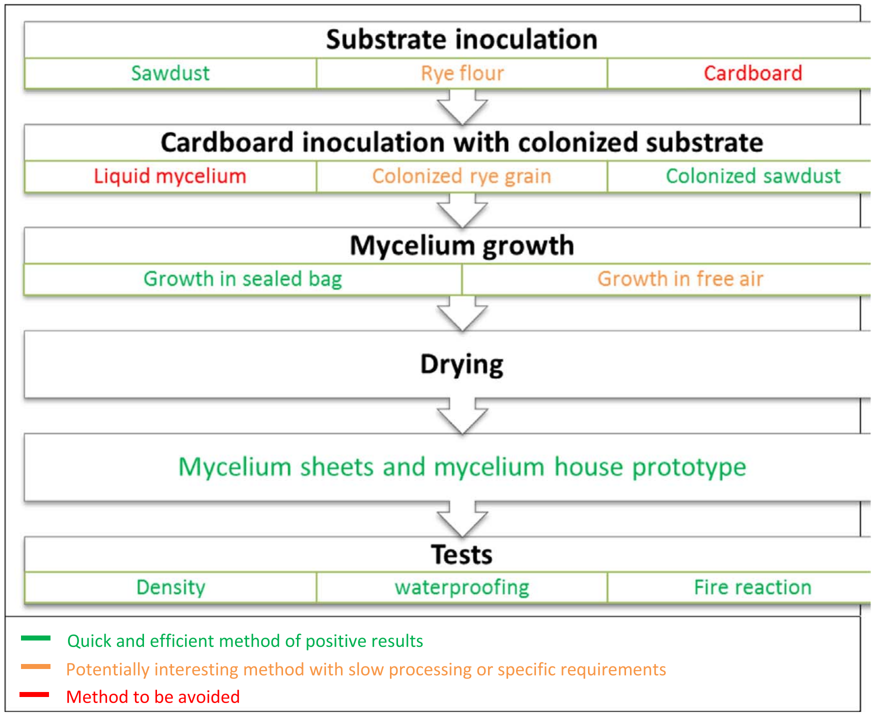

Figure 18 Process for creating sheets colonized by mycelium.

Table 4 Water absorption of colonized sheets with and without coating.

Absorption (mL)						
	Without pine tar coating			With pine tar coating		
Test nr	1	2	3	4	5	6
Sample orientation	Horizontal	Horizontal	Vertical	Horizontal	Horizontal	Vertical
After 5 min	0	0	0	Total	0	0
After 10 min	0	0	0	-	0	0
After 15 min	0	0	0	-	0	0

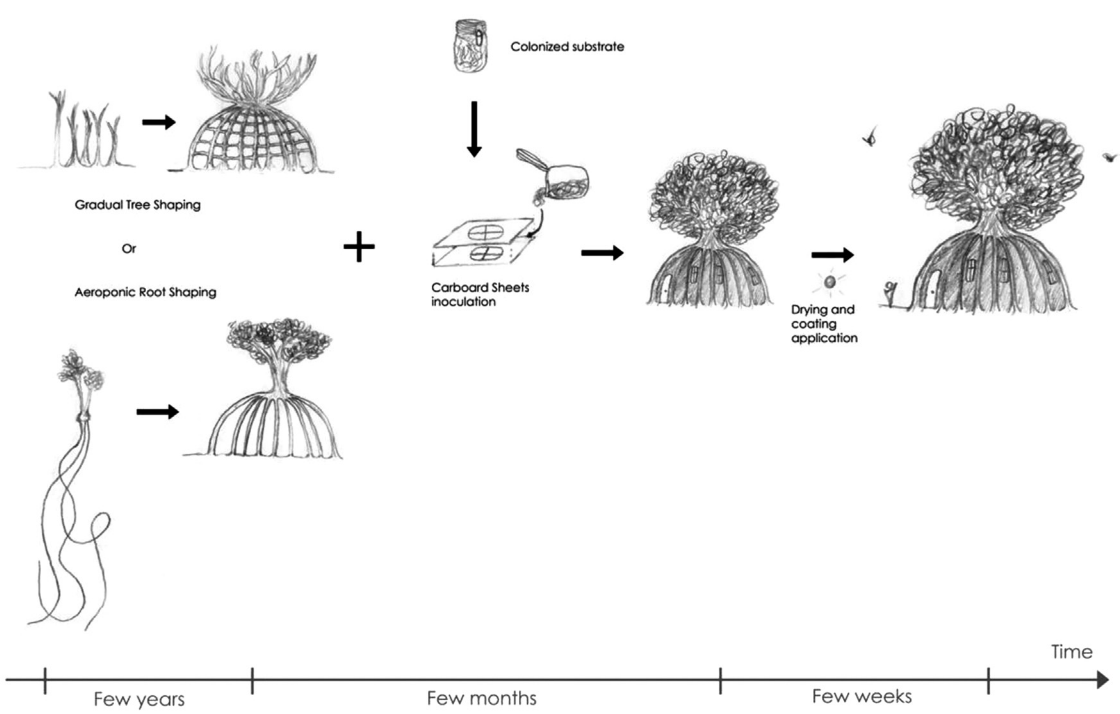

Figure 19 Methodology process for building a “living” house.

experimentation to be economically profitable. Living alongside with the nature without harming it and reducing impact at the minimum in a sustainable way is a vision shared by some people to grant a user community that wishes to live in a living house.

In the future, the number of people sharing this vision will grow rapidly with research and living buildings until living architecture becomes the main architecture of the future.

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