Sustainable design of vegetated structures: Building freshness

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Abstract. City revegetation strategies seem appealing to mitigate urban heat island effects through shading and transpirational cooling. Moreover, other potential benefits that may derive, e.g. biodiversity enhancement, the reduction in buildings energy consumption, stormwater management, acoustic insulation or air purification, earned them the designation ‘no-regrets approaches’ for adapting to climate change. However, the lack of understanding and quantification of green infrastructures’ environmental impacts prevents urban planning policies to be consistent and to turn attractive initiatives to effective implementations. The monitoring of existing green infrastructures is required to evaluate their cooling effect. For this purpose, an elastic gridshell in composite materials has been designed as a support for climbing plants at École des Ponts ParisTech (Champs-sur-Marne, France). The life cycle assessment of the vegetated structure is performed in order to develop sustainable design strategies. Based on an energy balance approach, the collected thermo-hydric data can be used to determine which mechanisms are the most suitable for urban vegetation to enhance outdoor thermal comfort.

1. Introduction
City revegetation strategies seem appealing to contribute to urban heat island mitigation in a sustainable manner. However, current technical solutions employed to green dense urban areas are rarely adaptable to existing buildings and need major works to be carried out, as in the case of extensive green roofs. Supports of vegetation that are lightweight, cost-effective and compatible to various urban configurations are lacking. Moreover, the cooling effects provided by different types of urban vegetation are not yet properly understood and quantified, which prevents an effective implementation of green infrastructures in the townscape.

2. Vegetated structures

2.1. Elastic gridshells with composite materials
Given the constraints specific to dense cities, vegetated elastic gridshells (see figure 1) may represent an interesting type of green structure or furniture for enhancing thermal comfort on public spaces. Elastic gridshells aim at simplifying the construction of freeform structures and reducing the amount of material needed to cover large spans. Frequently, the fabrication process consists of assembling straight and slender beams into a flat regular grid. During the erection process, the elements are elastically bent so that the grid becomes doubly-curved. Once the desired geometry is obtained, it is
braced to keep this final shape. Large-scale elastic gridshells that contributed to the reputation of active-bending structures were mainly manufactured out of timber, like the Mannheim Multihalle in 1975, the Weald and Downland Museum in 2002 and the Savill Garden in 2005. During the past, elastic gridshells used steel, aluminum, bamboo, cardboard and more recently carbon fiber reinforced polymers (CFRPs) and glass fiber reinforced polymers (GFRPs) [1].

Based on Ashby charts [2], Douthe [3, 4] showed that technical composites were perfect candidates for gridshell applications. In particular, pultruded pipes in composite materials display better results than timber laths when their respective mechanic properties (i.e., deformability, stiffness, toughness) are compared and GFRPs stand out from CFRPs when cost and embodied energy are considered. However, the environmental impacts due to materials and fabrication processes are expected to be greater for GFRP elements than for timber ones. As GFRPs exhibit a good resistance to many kinds of chemical attacks, the relevance of GFRP gridshells is thus amplified by the harshness of the environment. For example, GFRP gridshells are well-suited to any long-term outdoor exposition whereas timber gridshells would need regular maintenance operations under continental climatic conditions, hence increasing (environmental) costs. As the energetic content index in Ashby’s method only reflects partly the environmental footprint of a material, life cycle assessments (LCAs) of the whole system are preferred to have a comprehensive mapping of its environmental impacts. More details on the LCA of GFRP rods are given in section 3.

Figure 1. Vegetated “tree-shaped” gridshells. [credits: Théo Mondot]

2.2. Climbing plants

The choice of the plant species depends on biological criteria (hardiness with respect to the climate, soil, growth rate, competition between species), esthetical criteria (shape, flowering, fructification, integration in the surrounding landscape), technical criteria (maintenance, stresses exerted on the structure), etc. According to gardeners working for the City of Paris, a mix comprising about two-thirds of deciduous trees and one-third of perennial ones is adopted in the parks and streets of the city to ensure shade in summer without blocking the incoming sunlight in winter. As the pots depicted in figure 1 contain one cubic metre of substrate, it has been decided to plant three climbers per pot in the same proportions. Possible candidates for the climbers in the Paris region are vines (e.g., Vitis coignetiae, Parthenocissus quinquefolia, Parthenocissus tricuspidata), clematis (e.g., Clematis armandii, Clematis montana, Clematis 'Jackmanii'), honeysuckles (e.g., Lonicera japonica, Lonicera caprifolium), hops (e.g., Humulus lupulus ‘Aureus’), passifloras (e.g., Passiflora caerulea), jasmine (Jasminum officinale) or false jasmine (Trachelospermum jasminoides). Some of these climbing plants have been studied recently for green facades in Reading [5] and in Berlin [6] and demonstrated cooling potential through transpiration and shading.

2.3. Prototype
An experimental vegetated gridshell has been designed (see figure 2(a)) and will be built at Ecole des Ponts ParisTech in Champs-sur-Marne to assess the cooling effect provided by such structures. The grid comprises 32 pultruded composite rods made from vinylester resin and glass fiber, each rod having a length of 6m and a diameter of 18mm. The rods are assembled every meter with polyamide connections (see figure 2(b)) that are designed to let the rods rotate freely along their longitudinal axis. As the rods are initially straight and have equal principal moments of inertia, this free-rotation condition at the nodes and the supports ensures that the rods are not subjected to torsional stresses [3]. The stress level in the rods is capped at 25% of their limit stress to minimize creep and comply with recommendations for long-term mechanical performance of GFRP rods in actively-bent structures [7]. The gridshell is braced by 3mm-diameter steel cables at the top and the middle and by a steel sheet at the bottom. This metal cylinder envelops a pot containing three climbing plants, the substrate, pozzolan for drainage and a water reserve.

![Figure 2](image-url)  
**Figure 2.** (a) Perspective view of the experimental prototype; (b) connection between two rods; (c) assembling of the rods into a flat grid; (d) closing of the grid into a cylinder; and (e) bending of the rods before bracing the grid.

The structure is 4.5m high, 1m wide at the base and 7m wide at the top, hence covering a projected area of circa 40m². The mass of the gridshell alone is 100kg. The whole vegetated structure weighs
approximately 500kg when the water reserve is empty. A few pictures illustrating the main construction steps are shown in figure 2.

3. Life-cycle assessment

3.1. Description of the system

Processes are modelled with OpenLCA v.1.7.4. Ecoinvent 3.2 database is used for the life cycle inventory (LCI). The life cycle impact assessment (LCIA) method is based on NF EN 15804 [8] and NF EN 15804/CN [9] standards that apply to construction products. French national complement NF EN 15804/CN is employed to characterize air and water pollution. The nine impact categories proposed by NF EN 15804/CN are considered: acidification of soils and water (kg SO$_2$ eq.), ozone depletion (kg CFC-11 eq.), eutrophication (kg PO$_4$$^3-$ eq.), photochemical ozone formation (kg ethylene eq.), air pollution (m$^3$), water pollution (m$^3$), global warming (kg CO$_2$ eq.), mineral and fossil resource depletion (MJ), and non-fossil resource depletion (kg Sb eq.). The model graph of the processes considered in the analysis is shown in figure 3. Each process is detailed below.

![Figure 3. Flowchart of the system.](image)

The LCI for similar glass fibre reinforced polyester resin composite elements has been performed previously [10]. It accounts for energy consumption, material consumption, types of packaging and transport, wastes related to production (such as raw material wastes) and the treatment of the latter. It does not consider the end of life of the end product. As vinylester resin is not yet available in ecoinvent 3.2 database, the process polyester resin, unsaturated | polyester resin production, unsaturated – RER used in [10] is kept to model the LCI of GFRP rods.

Gridshell connections are made in glass fibre reinforced polyamide and weigh 90g each. The process injection moulding | injection moulding – RER is employed. The mould is modelled as a 100kg-low-alloy-steel element with average metal working (metal working, average for steel product manufacturing | metal working, average for steel product manufacturing) and 800km aircraft transport pending further information from the manufacturer. According to the manufacturer, one million connections can be fabricated with this mould. Hence, an amortization of the mould is considered.

The braces (3mm-diameter steel cables with cable clamps) and the 40kg pot are modelled as low-alloy steel elements with average metal working.

The gridshell fabrication needs the production of 96kg of GFRP rods, 112 connections, 35m of braces and one pot. Transport from the production sites is not yet taken into account because of a lack of information.

In a first approach, waiting experimental results, the water consumption (i.e., irrigation) is estimated to 200L per plant per year. Based on [11], the potential productivity per plant is estimated to 4kg of dry matter per year. Assuming a carbon content of 50%, each plant stores 2kg of carbon per year, which corresponds to 7.3kg of carbon dioxide used for photosynthesis. Thus, each plant is
modelled in OpenLCA by a single process that uses 200L tap water for irrigation as an input and avoids 7.3kg of carbon dioxide yearly. These figures consist in rough approximations and will be refined later experimentally (see sub-section 4.2). Processes used for the production and transport of the soil, sand and pozzolan are not considered at this time. The data will be collected and analyzed when the prototype is built.

Finally, a vegetated gridshell comprises the production of one gridshell and three plants as modelled above. The lifetime of the plants is estimated to 30 years but the service life of the structure is expected to be larger based on durability studies carried out on GFRP rods [7]; the treatment or reuse of the structural elements is beyond the scope of this study.

3.2. Results

The potential impacts due to the gridshell production alone and to the vegetated gridshell after 30 years are given in table 1. As the plants only need tap water for irrigation in this model, the differences in the impacts of the gridshell and the vegetated gridshell are very limited, except for the global warming potential. This is due to the amount of carbon dioxide removed by the plants in their surroundings because of their growth. However, this carbon is stored temporarily and will be released sooner or later depending on the end of life of the plants: they may be burnt at the recycling centre to serve as fuel for heating the district, shredded to be used as mulch, decomposed by composting, etc. These scenarios will be considered in future works.

Table 1. Impacts of the gridshell production and of the vegetated gridshell (the results are shown for a lifetime of 30 years).

| Impact category                                  | Gridshell | Vegetated gridshell |
|-------------------------------------------------|-----------|---------------------|
| Acidification of soils and water (kg SO₂ eq.)   | 2.9       | 3.0                 |
| Ozone depletion (kg CFC-11 eq.)                 | 6.3·10⁻⁵  | 6.3·10⁻⁵            |
| Eutrophication (kg PO₄³⁻ eq.)                   | 0.46      | 0.47                |
| Photochemical ozone formation (kg ethylene eq.) | 0.17      | 0.17                |
| Air pollution (m³)                              | 1700      | 1700                |
| Water pollution (m³)                            | 4.9·10⁵   | 4.9·10⁵             |
| Global warming (kg CO₂ eq.)                     | 690       | 40                  |
| Mineral and fossil resource depletion (MJ)      | 1.0·10⁴   | 1.0·10⁴             |
| Non-fossil resource depletion (kg Sb eq.)       | 1.4·10⁻⁸  | 1.4·10⁻⁸            |

Figure 4 shows how the GFRP rods, the connections, the pot and the braces contribute to the environmental impacts caused by the gridshell production. The graph indicates that in this case, the share among the four processes follows a similar pattern for all the impact categories. The impacts due to the production of the GFRP rods accounts for approximately two-thirds of the total, which suggests that future designs should aim at decreasing this material quantity. For the gridshell to keep a similar global structural behaviour, this could be achieved with a denser grid of rods of smaller diameter (at the cost of a greater number of connections) or with GFRP tubes (i.e., hollow instead of solid rods). Natural fibre reinforced polymers (NFRPs) could also be utilized to reduce the amount of glass fibre in the structure. However, this may lead to mechanical long-term issues [7] and one has to ensure that their industrial production does not require more polluting processes. This has still to be assessed.
Figure 4. Relative contribution of each element production to the total environmental impacts of the gridshell production.

Table 1 shows the interest that urban vegetation could play in terms of climate change mitigation, as it temporarily stores carbon, but other potential benefits, such as cooling effects, are not reflected by the LCA. This is discussed in the following section.

4. Evaluation of the cooling effect at a local scale

4.1. Cooling mechanisms

Oke [12] proposed in 1982 a sound theoretical framework to advance knowledge in the field of urban meteorology and overcome the mere description of urban heat island effects. His approach popularized the use of surface energy balance models for predicting the thermal response of cities to various urban forms and environmental conditions. Since, numerous works have attempted to improve the modelling of energy, mass and momentum exchanges at stake in the energy balance. A general way to write the energy balance at the interface between the urban area and the atmosphere is given by Offerle [13]:

\[ Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A + S \]  

in which \( Q^* \) is the net all-wave radiation, \( Q_F \) the anthropogenic heat flux, \( Q_H \) the sensible heat flux, \( Q_E \) the latent heat flux, \( \Delta Q_S \) the heat storage, \( \Delta Q_A \) the net advected flux and \( S \) all other heat sources or sinks. All these terms are homogeneous to heat flux densities and are expressed in W.m\(^{-2}\). The rationale of this approach is detailed in many works, e.g. in [14]. Neglecting anthropogenic and advected fluxes, and in the absence of heat sources and sinks, equation (1) may be rewritten as per Masson [15] to highlight the dynamics of the energy exchanges:

\[ eC \frac{dT_s}{dt} = Q^* - Q_H - Q_E - Q_G \]  

in which \( e \) is the layer thickness (in meters), \( C \) the heat capacity (in J.m\(^{-3}\).K\(^{-1}\)), \( T_s \) the temperature of the surface and of the layer (in kelvins) and \( Q_G \) the conduction heat flux between the surface layer and the underlying layer (in W.m\(^{-2}\)). The terms used in equation (2) may be written as:

\[ Q^* = (S_\lambda - S_s) + (L_\lambda - L_s) = (1 - \alpha)S_\lambda + L_\lambda - \varepsilon \sigma T_s^4 \]  

\[ Q_H = h_{ch}(T_s - T_{air}) \]  

\[ Q_E = LE = Lh_{sw}(p_{sw}(T_s) - p_w) \]
$Q_G = -\lambda \left( \frac{\partial T_z}{\partial z} \right)_{z=e}$

where $S_\downarrow$ and $S_\uparrow$ are the downward and upward short-wave radiations (in W.m\(^{-2}\)), $L_\downarrow$ and $L_\uparrow$ the downward and upward long-wave radiations (in W.m\(^{-2}\)), $\alpha$ and $\varepsilon$ the surface albedo and emissivity, $\sigma$ the Stefan-Boltzmann constant ($\sigma=5.67 \cdot 10^{-8}$ W.m\(^{-2}\).K\(^{-4}\)), $h_c$ the convective heat transfer coefficient (in W.m\(^{-2}\).K\(^{-1}\)), $T_{air}$ the air temperature (in kelvins), $L$ the specific latent heat of vaporization of water (in J.kg\(^{-1}\)), $E$ the evaporation rate (in kg.m\(^{-2}\).s\(^{-1}\)), $h_{cm}$ the convective mass transfer coefficient (in s.m\(^{-1}\)), $p_{sat}$ the partial pressure of water vapour in the air (in pascals) and $\lambda$ the thermal conductivity of the layer material (in W.m\(^{-1}\).K\(^{-1}\)). Equation (2) may be used to model the temperature evolution of the substrate, of the ground under the gridshell shade or of one leaf, irrespective of the surface area. However, the area of the surface under consideration may play an important role in terms of fluxes repartition, as smaller objects have greater heat transfer coefficients according to Sakai [16]. Note that “surface” often denotes a control volume with homogeneous properties that could represent a large urban area (e.g., [14]) or a crop canopy (e.g., [17]). The energy balance of a thin layer as described above is graphically summarized in figure 5.

**Figure 5.** Energy balance for a thin layer of material.

The quantification of these energy exchanges enables to predict the urban surfaces temperature evolution and to better understand by which means heat island effects could be mitigated by vegetation. As trees transpire, they cool down their leaves, which then cool down the air by convection if their temperature is lower than that of the air (i.e., $Q_H < 0$). This is not always the case, as demonstrated by measurements of tree crown temperatures in Basel that were found to exceed air temperature by 5 K [18]. Recently, Manickathan [19] showed with computational fluid dynamics (CFD) simulations based on leaf energy balances that the top of a tree crown could warm the air (even if the transpiration is high) whereas cooling occurs at the bottom of the tree where the absorbed radiation is low. This small amount of direct cooling caused by trees agrees with previous CFD simulations [20, 21]. As the amount of air cooling seems to be limited based on a meta-analysis on the cooling effect provided by parks and green spaces [22], the main impact of urban trees upon thermal comfort is attributed to their shade as reported by Armson [23]. Based on equation (2), shading an artificial surface (i.e., lower $S_\downarrow$) decreases its surface temperature, hence reducing the convection of heat to the air (i.e., lower $Q_H$) and the radiation towards pedestrians and other surfaces (i.e., lower $L_\uparrow$). Decreasing absorbed radiation also reduces thermal storage in materials and release of the heat during the night [24]. Moreover, during summer trees may be able to keep a foliage temperature closer to the
air temperature compared to surrounding artificial surfaces thanks to their numerous small leaves [16]. Hence, they would act as a radiative screen for pedestrians. This agrees with studies assessing the human comfort in outdoor environments based on the Universal Thermal Climate Index (UTCI) [19, 25].

4.2. Instrumentation

The gridshell prototype described in section 2 will be instrumented to assess the cooling effects due to air cooling and surface shading. Load cells will be placed under the pot to measure the evapotranspiration (i.e., the mass of evaporated water), as with a lysimeter. This data will also be used to measure the water needed for irrigation and refine the plant growth model. The radiation balance is measured with pyrgeometers and pyranometers. Temperature sensors are employed to get the temperature of the air, of the substrate and of the ground. Leaf temperature is obtained by a thermal imaging camera. These experimental results will permit to have a deeper understanding of the dynamics of heat exchanges around an isolated vegetated structure and to compare their cooling efficiency with other species of climbing plants [5, 6] and other types of landscape strategies (e.g., [26]).

5. Conclusions and perspectives

An innovative 40m²-gridshell in composite materials has been designed as a support for climbing plants in order to provide shade in urban areas. A life cycle assessment of this structure has been performed to evaluate the environmental impacts due to its construction. Modelling the end of life of both the materials and the plants is still needed to develop sustainable solutions that may contribute to heat island mitigation. Experimental results are also required to assess the cooling effects and the maintenance costs provided by this vegetated urban furniture and by urban vegetation in general. This will allow to derive indicators describing the cooling performance of various landscape strategies and to establish trade-offs between outdoor thermal comfort and resource use, e.g. materials utilized for the structure and water needed for irrigation.

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