

Life Cycle Design for Lightweight Skin



Carol Monticelli

Abstract The typical membranes for building are polymer-based and have origin from fossil fuel but become very lightweight building components, compared with other typical ones. Structural elements stiffen them (bio-based or not) and, due to the lightness, involve fewer structural materials than other components. Through a multidisciplinary experimental design path—focused on the weight factor at the level of the constructive system and the efficiency factor at the level of primary material—it is possible to enhance the efficiency and the aesthetic of lightweight skins and distill the eco-design concepts which can be transferable to the whole construction sector. In other words, the author tries to demonstrate the impacts of reducing weight firstly in textile skins and also other lightweight and hybrid architectures. Coming from this significant weight awareness through experimental knowledge, the author discusses the opportunity to apply multidisciplinary design approaches to reduce energy consumption and environmental loads during the life cycle. This chapter aims to elaborate on those concepts and systematize the obtained results demonstrating the advantages of the Life Cycle Design strategy in the environmental sustainability of novel lightweight skins.

Keywords Life cycle assessment · Comparison · Eco-efficiency · Environmental impacts

1 Life Cycle Principles Applied to Lightweight Building Systems

Thinking of lighter architecture means enlarging the research into materials, reducing the thickness of components, and optimizing the construction sections. Due to the environmental sustainability's constraints, the main aspects to being assessed during the design phase become more and more: (a) the embodied energy of components

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and the whole building system; (b) the reusability/recyclability of each material embedded in the whole construction; and (c) the expected lifespan of a building, which is closely linked to the way of managing connection details for installation, maintenance, and final dismantle. The following topics can be conceived as strategies for the membrane structures' eco-efficient design (Cost Action TU1303 2017).

Suppose the future of membranes is to become permanent space enclosures. In that case, it is essential to improve the durability of light materials and performances during the use phase (like mechanical resistance and thermal insulation). But for enhancing thermal performance during use, the membrane layer in permanent buildings is increasingly complex.

One of the most critical challenges of tensile structures is to improve their internal environmental qualities. In the past, the temporary use of membranes made introducing insulating layers in their envelope unnecessary. Today, on the contrary, the great diffusion of lightweight structures for permanent use calls for new technical solutions for building optimized envelopes. The skill of previewing and controlling the thermal, acoustic, and light conditions becomes an urgent requirement for architects and engineers.

After a further two decades of production and manufacturing advances, full of relevant achievements both in terms of local regulatory standards (Forster and Mollaert 2004) and their harmonization (Mollaert et al. 2016), textile materials for architecture are considered reliable and durable, either used in the form of a flexible membrane, suitably coated, or used as soft formwork of rigid concrete-based (i.e., textile Beton) or resin shells (i.e., GFRP), and both for temporary and permanent constructions (Monticelli and Zanelli 2020).

The tensile structures' inherent properties of lightness and flexibility need the research of non-conventional solutions to apply advanced insulating materials in the textile envelopes without modifying their aesthetic aspect.

Consumers, stakeholders, end-users, and designers demand information about the environmental loads' implications of lightweight building skins and their construction activities. This kind of information about technical textiles and innovative films for tensile structures is still limited, and the common idea of the petrol-based solutions and the polymeric nature of membrane materials has to be overcome deepening the total quantities involved at the scale of buildings (and the related environmental impact) compared to other building systems solutions.

Life Cycle Assessment (LCA) application on lightweight and ultra-lightweight building skins has been a crucial part of the research efforts by the author in the last decay. LCA procedure applied on lightweight and ultra-lightweight materials for skins, with a specific focus on membrane building materials, helps to point out advantages and disadvantages and the needed correct exploitation of the properties of the materials. Nevertheless, a comprehensive description of the environmental performance of building materials, and even more the membrane materials (coated textiles and films), typically comes up from a massive volume of data, which the designers hardly manage in a routine design process, where the deepen aspects on the project are many. Specialists in this field can interpret the typical results of a Life

Cycle Assessment, and, sometimes, the results of different LCA studies are not easy to compare and understand.

A starting point for collecting environmental data is to support a program of development of environmental product declaration (EPD), defining data quality requirements into Product Category Rules (PCR) documents for membranes (COST Action 2017). Environmental impacts of materials can be objectively compared when adequate guidelines are followed. ISO 14025 (2006) describes the procedures required to acquire type III environmental product declaration (EPD). This allows comparability of environmental performance between products. The EPD is based on the principle of developing Product Category Rules (PCR), which specify how the information from an LCA needs to be used to formulate the EPD. An EPD is a transparent and objective report based on LCA, a systematic analysis of the potential environmental impacts of products or services during their entire life cycle. It also includes the upstream and the downstream.

The EPDs developed in Europe, related to skins materials, are primarily based on the PCR for the materials' categories (e.g., PCRs for wood materials, for rubber and plastic products, for flat glass products, for ceramic tiles): For the membrane materials, there are no specific PCRs and the more related ones are c-PCR-004 Resilient, textile, and laminate floor coverings, that are not well-fitting with membranes for building skins. PCR outlines five environmental impacts: global warming potential, acidification potential, eutrophication potential, smog potential (photochemical oxidation), and ozone depletion potential (ozone layer depletion).

A natural step in delivering the kind of information that is standardized through a group of similar-in-function products or materials, as an integral part of generating an environmental product declaration, is the Product Category Rules (PCR). PCR is handy where the environmental impacts of products within a category group are to be compared—perhaps as part of a product specification process.

The EPD is becoming more and more meaningful. In the last ten years, the EPD as voluntary product declaration was not sufficiently taken into account, probably because of a lack of good marketing or because the business was too young and the market was not ready yet to accept it. Since some aspects are not considered yet, it is impossible to compare different products, and two EPD cannot be compared. Especially, since the values are still too far from the shared knowledge of the building sector and, therefore, taken as they are, it is difficult to understand their meaning and possible use to evaluate at first glance.

Nevertheless, in a life cycle thinking perspective, the necessity of increasing the designers' awareness of lightweight and flexible materials and their performances is the priority. Consequently, the most effective life cycle-based design methodology, which will support designers during their daily work, is the need the author foresees, not as a theoretical analysis for scientists and environmental specialists.

Based on this background and the identified needs, a meaningful eco-design approach for textile architecture has still been under definition and evaluation (Monticelli et al. 2016), and three main design principles for the weight reduction and the efficiency of form-structure of both tensile membrane skins and pneumatic cushion envelope have been defined. Their verification before an integral LCA of

building skins and structural membranes helps to point out advantages and disadvantages (lightness) and the needed correct exploitation of the properties of membrane materials.

The *first principle* states that designers have to verify the ratio frame perimeter/covered surface in the case of structural membranes for roofs or entire building envelopes. Following the general minimization criterion of the doing more with less, this principle assesses the eco-efficiency of a defined surface to be closed/covered. The broader area of a membrane “panel” corresponds to reducing the perimeter length (otherwise the size of frames), reducing the involved materials for their production and consequently the related environmental impacts.

The *second principle* is verifying the ratio fixing system (or primary structure)/membrane, and it seems mainly relevant in designing structural membrane façades. The Life Cycle impact of the membranes for façade cladding and the efficacy of their choice seem straightly linkable to the quantity of the elements of the fixing systems; thus, understanding their real need in terms of structural loads and of stiffness and the choice of ultra-light thin supports instead of rigid ones are meaningful.

The *third principle* states that the designers have to verify the ratio membrane structure/mechanical load of the structure considering steel or wood as the primary structural materials involved in the field of membranes: optimizing the mechanical and structural behavior of a membrane structure and the form means to improve the correct use of membranes and the correct interpretation of their embodied properties (time-based systems, Life Cycle Design).

The optimization of these ratios means the excellent exploitation of the characteristics and behavior of the membranes concerning other, less flexible, and lightweight, traditional building materials.

The current stage focuses on enlarging the mapping of case studies by the application ex-post of two eco-efficiency principles to verify their validity and efficacy.

The expected next step is their introduction to the best practices for membrane design and their verification of the specific project during the design process of a membrane system.

These eco-efficiency principles aim to be considered a verification stage in the early design stage, quite similar to the bioclimatic principles that have to be considered to improve the well-being and energy efficiency of the buildings. They verify the design choices from the point of view of the environmental loads, concerning the building shape, the correct exploitation of the potentials of the membranes as lightweight materials. They represent a preliminary assessment, for a consequent optimization, of the environmental performance (due to the quantities of involved materials), before an eventual specific and deep Life Cycle Assessment.

To test the three principles on the field, built examples of textile envelopes and pneumatic cushions in buildings have been analyzed (Monticelli and Zanelli 2020) to verify the reliability of the mentioned eco-design principles of membrane structures Fig. 1. Here, the measuring of environmental impacts seems to be the leading research focus concerning their weight, which is the meaning of their optimization, even

though the awareness of textiles' performances is crucial to making the difference in disruptive design solutions.



Fig. 1 Building textile envelope solutions and their dimensions as case studies for applying two eco-efficiency principles. Reproduced from (Monticelli and Zanelli 2020)

The reading of the results Fig. 2 indicates that lightweight technologies allow designers a high degree of freedom in shaping geometries and shapes. At the same time, only their optimization will ensure effective LCA sustainability results. This optimization process can be effectively achieved by a broad surface development (principle 1) and by a balanced ratio of the weight of the support structure concerning the envelope (principle 2).

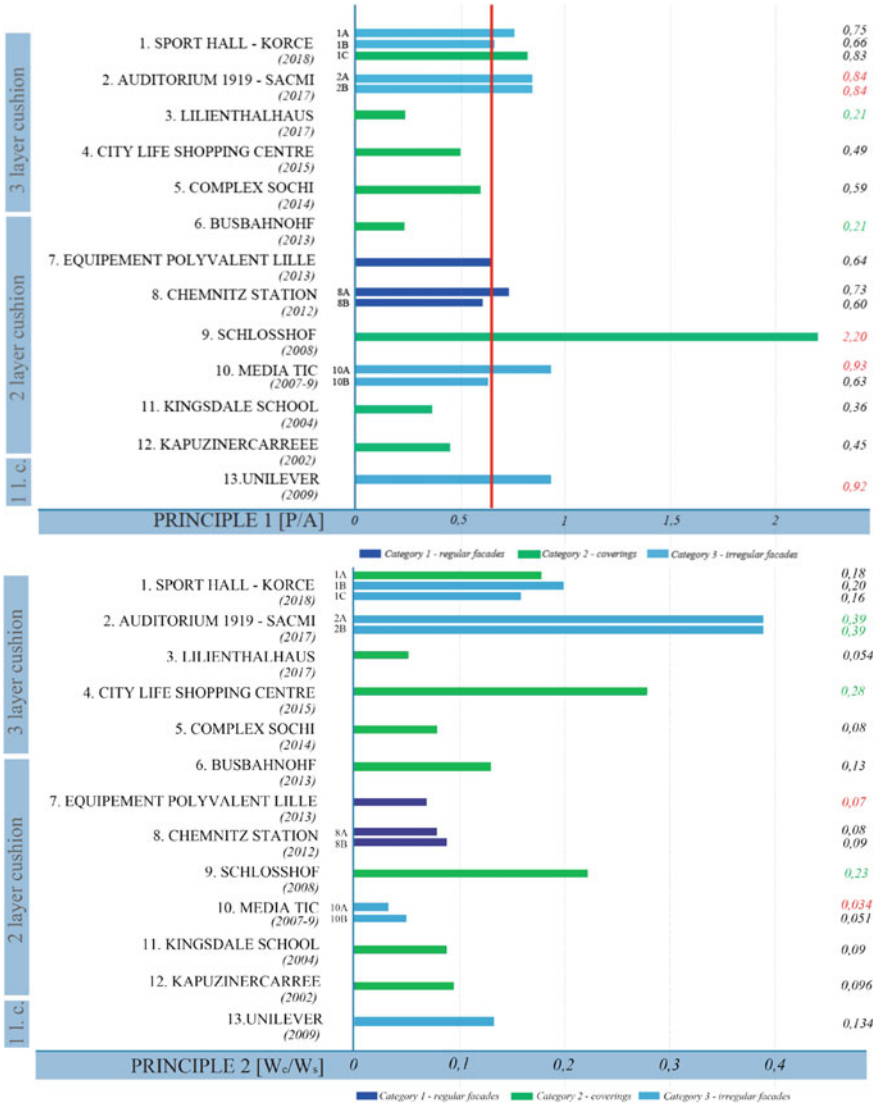


Fig. 2 Results of the 1st and 2nd principles. Reproduced from (Monticelli and Zanelli 2020)

In terms of environmental impact analysis of the lightweight technical solutions, after the first verification of the eco-efficiency principles, the designers could better construe the validness of their design choices or the possible re-orientations thanks to the principles' results. The step further is the LCA of the optimized technical solution to quantify the environmental impacts related to the environmental damages. And in this case, a comparative analysis is advantageous.

2 Comparative LCA on Membrane Skins

The application of a comparative LCA in the lightweight and the membrane architectures is the appropriate procedure to quantify and compare the environmental impacts and the consumption of materials and energy throughout the whole life cycle, within the following levels:

a. Life cycle of matter—Focusing on more than ten years rooted use of the methodology in the building construction sector, the LCA application analyzes the environmental impacts caused by the production chain of the manufacturing industry, with the system boundaries ranging from the phase of obtaining raw materials (from the cradle) to the phase of packaging and transporting products to the building site (to the gate) (supporting the industry to review all processes of the production chain of woven and non-woven textiles, coated textiles, and laminated foils, identifying which processes need to be optimized, to save energy and reduce harmful emissions).

b. Life cycle of building components—After the specific survey regarding the eco-profile of materials (i.e., ETFE foil or PES/PVC textile or PTFE fabric in the field of membranes), the next step of the LCA is the comparison of the environmental impacts of different building components and their technical systems. The investigation at the scale of building components considers the choice of the qualitatively and quantitatively more efficient building system and convenient construction technique, based on the structural and thermo-physic, acoustic performances, and the costs. However, the performance of environmental impacts can increasingly influence the choice of the building products, in an LC perspective of circularity of flows and closing the loops, to select sustainable products and strategies for the future of our ecosystem.

2.1 *An Environmental Load of Ultra-Lightweight Materials and the Nonlinear Relation with Their Weight*

It is provided to the reader a comparison of the life cycle of an ultra-lightweight new material—the fluor polymer material ETFE—and its building system, contributing to the increasing literature by assessing new material (Monticelli 2010).

The comparison helps to understand the importance of selecting environmentally efficient building technologies and structural systems based on embodied energy, reducing the number of materials and emissions in the atmosphere, water, and soil. And it highlights the importance of considering all the environmental impact categories to state the eco-compatibility of building technical solutions. The glazing roof is disadvantaged compared to the ETFE cushions, considering only the embodied energy indicator and adding the global warming potential indicator. Therefore, the LCA application defines the potentials and possible limits of alternative technological solutions thanks to a global view about the impact contribution in the life cycle. And from the LCA point of view, it highlights too how the relationship between the weight and the amount of the impact is not linear: “The heavier the material, the more it pollutes” is not the rule, but the production process history and the analysis of the environmental impact indicators, beyond the embodied energy.

It is essential to analyze the environmental impacts’ values per gravity of materials and their building components on the one hand and then to analyze the values when the suitable functional unit is the covered area by these roofing materials on the other hand. In architecture, the design for the construction is based on the design of building systems made of materials; consequently, it is relevant to assess the role of the materials in specific building systems.

Environmental impacts of two different building components for transparent roof systems have been assessed. The compared components fulfill the same function, transparency: extruded ETFE films for the cushion system and tempered glass sheets for a double-glazing system roof. In the following analysis, the system boundary is the pre-use phase (from cradle to gate). The functional unit is the quantity of material necessary to cover one square meter area and, consequently, build a component for the roofing system corresponding with the current building technology characteristics (Fig. 3).

The design shape of the compared components is different, the quantity of involved materials gives different results, and consequently, impact results change. The multi-layer etfe cushion involves less energy (1596 MJ/m²) than the other roof system (7395 MJ/m²), due to its lightweight and fewer used materials’ quantity. The glazing manufacturing causes dangerous output, influencing the acidification and eutrophication of air, water, and soil (regional, local environmental damages): It depends from the manufacturing process to obtain the float glass. The etfe system shows as result a great impact bond with the global warming potential and the ozone depletion


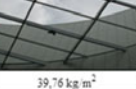
| TYPOLOGIES and WEIGHTS | | IMPACT CATEGORIES | | | COMPONENT IMPACT | | | |
|---|---|----------------------|-----------------|--------|---------------------|-----------------------------|--------|--------|
| ETFE (d = 1750 kg m ⁻³) | GLASS (d = 2500 kg m ⁻³) | unit kg | ETFE | GLASS | unit m ² | ETFE | GLASS | |
|  |  | Global warming pot. | kg CO2 eq kg | 88,91 | 0,85 | kg CO2 eq m ² | 67,57 | 33,80 |
| | | Ozone depletion pot. | g CFC-11 eq kg | 3,56 | 0,0001 | g CFC-11 eq m ² | 2,706 | 0,004 |
| | | Photochemical oxid. | kg C2H4 kg | 7,67 | 0,56 | kg C2H4 m ² | 5,83 | 22,27 |
| | | Acidification | kg SO2 eq kg | 102,00 | 10,60 | kg SO2 eq m ² | 77,52 | 421,46 |
| | | Eutrophication | kg PO4--- eq kg | 3,12 | 0,85 | kg PO4--- eq m ² | 2,37 | 33,80 |
| | | Embodied energy | MJ eq kg | 210,00 | 18,60 | MJ eq m ² | 159,60 | 739,54 |
| 0,76 kg m ² | 39,76 kg m ² | | | | | | | |

Fig. 3 LCA comparison results of glass and etfe as transparent roofing materials. Reproduced from (Monticelli 2010)

(global environmental problems), caused by the emissions and energy content of each product, due to the chemical industry manufacturing chain during the polymerization of monomers to create the granulates. The results point out the importance to assess these light technical solutions not only considering the material stage (relating to their own specific gravity), but also the involved materials in the roof subsystems and, even better, their role in the building.

From the point of view of the Life Cycle Analysis, as shown in Figs. 4 and 5, this comparison of glass/fluoropolimeric plastic highlights how the relation between the weight and the amount of the impact is not linear: “The heavier the material, the more it pollutes” is not the rule, but the production process history and the analysis of the environmental impact indicators, beyond the embodied energy.

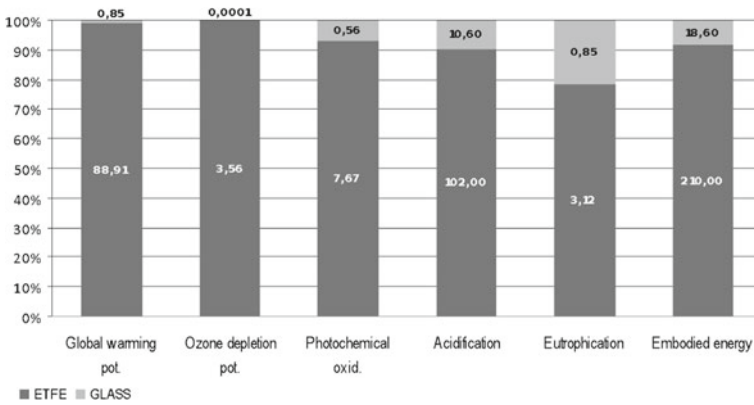


Fig. 4 Results of environmental impacts per kg of materials. Reproduced from (Monticelli 2010)

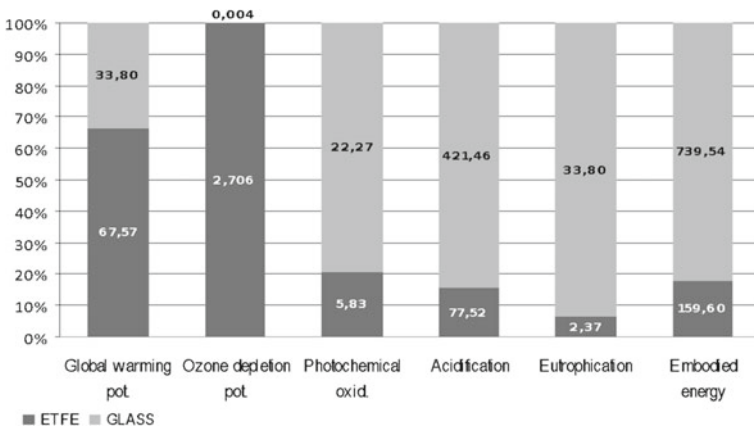


Fig. 5 Results of environmental impacts per m² of components. Reproduced from (Monticelli 2010)

2.2 *The Ratio of the Environmental Loads Between Different Façade Cladding Systems and Their Structure*

An additional comparative Life Cycle Assessment of the environmental impacts between three lightweight textile facade systems and two standard translucent systems currently on the market (U-Glass and Polycarbonate), designed for the retrofitting project of a social housing building placed in Milan, has been carried out, to show the potential of analysis during the design stage for a conscious selection for materials and building components. The designers should think during the envelope and façade modularity design to improve the benefits of lightweight membranes as a new kind of free-form façade, overcoming the current cladding modularity and optimizing the ratio between fabric panels and supporting elements (Monticelli et al. 2013). The main goal of the LCA application has been the investigation of the environmental impact of five translucent cladding technologies, selected as possible alternative finishing layers of a retrofitting external thermal insulation on an existing wall of a social housing dwelling building placed in the Rationalist district Lorenteggio (1938–1944) in the south-west area of Milan: a U-Glass system, a Polycarbonate system, and three different textile systems on the market. This LCA has been conducted from the point of view of the building sector, and its application between five other cladding systems aims primarily to understand the ratio between the environmental impacts of the fixing tools of each design and these of the cladding layers (Fig. 6).

The results of the analysis of the pre-use phase—from cradle to gate—consisted in the contribution of each façade system to the impact categories, which are environmental emissions and embodied energy. The meaningful comparison is between B, C, D, E, and F; the A is the retrofitted existing wall with the ETICS, a base case (Figs. 7, 8).

Their comparison depicts that the (F) Tex3 with the punching effect has the lowest contribution to all the environmental impacts. It is also the lightest technical solution,

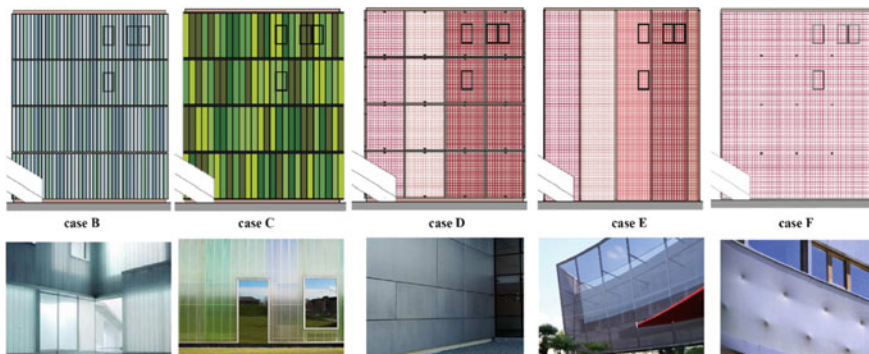


Fig. 6 The façade design of the different cladding system. Reproduced from (Monticelli et al. 2013)

| Impact Category | Unit | (A) | (B) | (C) | (D) | (E) | (F) |
|------------------|-------------------------------------|-----------|-----------|-----------|------------------|-----------|-----------|
| Global warming | kg CO ₂ eq | 23159,79 | 34056,49 | 35477,68 | 39318,45 | 31825,89 | 28517,26 |
| Ozone depletion | kg CFC-11 eq | 0,0020 | 0,0029 | 0,0025 | 0,0030 | 0,0025 | 0,0023 |
| Photochem. oxid. | kg C ₂ H ₄ eq | 15,55 | 22,23 | 23,41 | 25,51 | 20,80 | 18,79 |
| Acidification | kg SO ₂ eq | 58,57 | 113,04 | 102,60 | 122,77 | 93,00 | 79,77 |
| Eutrophication | kg PO ₄ ---eq | 18,81 | 38,29 | 34,10 | 47,61 | 33,63 | 27,88 |
| Embodied Energy | MJ eq | 258420,47 | 429854,29 | 429821,96 | 490432,30 | 380091,09 | 334509,85 |

Fig. 7 Pre-use phase—total environmental impacts (emissions and embodied energy) of the six cladding façade systems. Reproduced from (Monticelli et al. 2013)

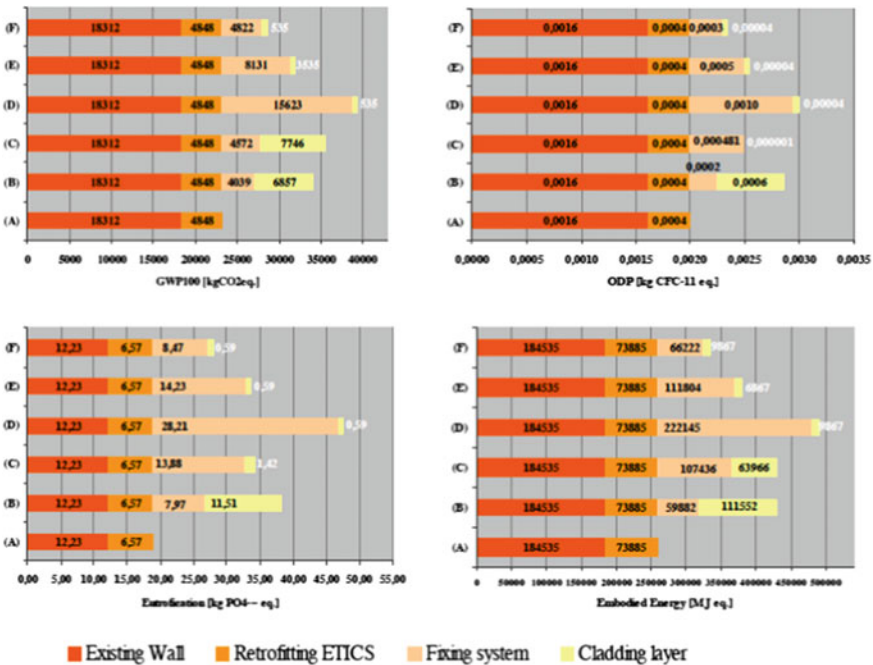


Fig. 8 Pre-use phase—contribution of each part of the compared wall systems to environmental impact categories. Reproduced from (Monticelli et al. 2013)

consistent with the (D) Tex 1, representing the most significant environmental impact contribution. The relation between weight/quantities of materials and impact results is not always so correspondent as said in Sect. 2.2: The (B) U-Glass system is the heaviest but not the most pollutant, and the (D) is the second one in weight but the most pollutant, considering the high quantity of aluminum in the façade system technology, which generates high environmental burdens in manufacturing processes.

Consideration from a building point of view, which also considers the environmental impact analysis, has to be done: Solution A satisfies the renovation, and the

thermal retrofitting of the walls and their impacts is shown in the Table in the Fig. 7. With the choice of an aesthetical improvement by claddings systems (an optional), the environmental burdens grow thanks to the additional materials and components: (B) U-Glass, (C) PC, (D) Tex1, and (F) Tex3 have, respectively, 166, 166, 190, and 129% more contribution to embodied energy than A; the same appends for the other impact categories. It means that awareness of the designers regarding the environmental performances of their choices has to be expected. The (B) U-glass cladding layer weighs more than the fixing elements (ratio 6:1). Consequently, the environmental impacts of the cladding layer are higher than these of the fixing elements. The weight of (C) PC cladding layer is the same as the fixing elements (1:1). The impacts do not follow this ratio, as shown in Fig. 1; d. (D) Tex1, (E) Tex2, and (F) Tex3 show a considerable difference in weight between the ultra-light textile and the relatively massive weight of the fixing systems, an observable tendency in Fig. 1. The three textile systems show a consistent difference in the results, as a consequence of the design of the façade and the cladding technology system: The (D) seems to be the most pre-fabricated, modular, and adaptable system on the market, and nevertheless, it employs considerable quantities of Al profiles, rendering the technology similar to an assembly of standard rigid panels; the (E) and (F) solutions offer different designs of that façade, improving the textile technology, reducing the profiles, then the amount of material, and at the same time enhancing the actual function of the textile cladding layer, compared to the other rigid cladding layers. All three textile technologies offer the same post-tension of the textile cladding, ensuring good resistance to the wind loads.

The nature of textile cladding layers suggests their application for a curtain wall, made of one foil of material instead of panels, exploiting all their potentials and significantly enhancing the ratio “frame/covered area” by avoiding the use of lightweight fabric with a high weight of the structure, which penalizes the environmental performance.

2.3 The Influence of the Materials and Components Upcycling in the Life Cycle of Lightweight Skins

The research compares an experimental path of measuring the environmental impacts of a temporary textile pavilion built with recycled materials and supplied within 100 km of distance from the building site and its comparison with the same design solution buildable with new materials. The Nuage pavilion was an ephemeral architecture designed and built by students in July 2013, using recycled PES/PVC textiles to create two toroid pneumatic rings and other recycled materials for shaping the whole supporting system (Fig. 9). Unsold stocks and production wastes of building materials and components (i.e., cardboard tubes, wooden pallets, polyethylene pipes, textiles) have been considered helpful for the short life span of the pavilion, i.e., a maximum of four years. As reuse is often done at a local level scale, due to economic

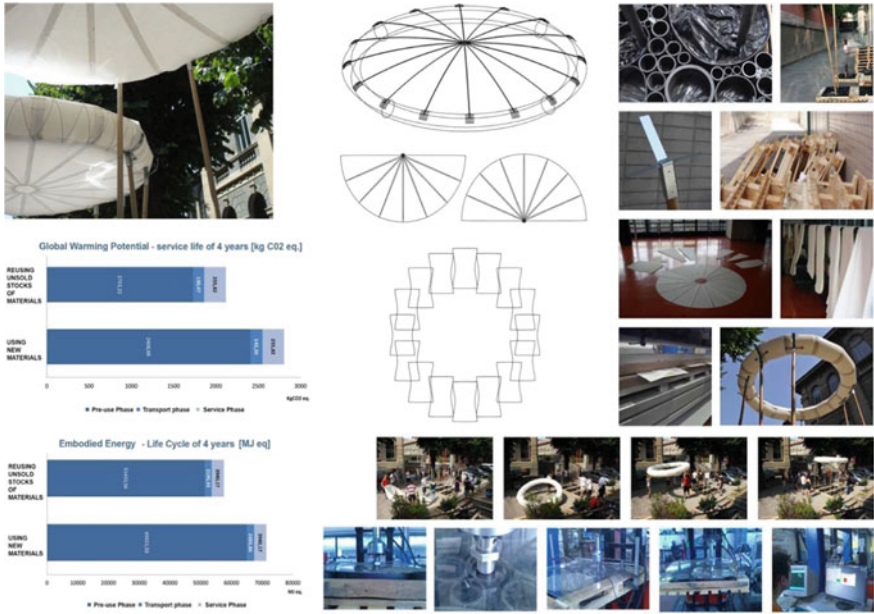


Fig. 9 Views of Nuage pavilion installation, an ephemeral architecture made of recycled construction materials, as textiles, cardboard, and plastic tubes, wooden pallets and plexiglas sheet and schematic results of their LCA inventory concerning their storage site. Reproduced from (Monticelli et al. 2013)

savings and energy and emissions savings during the transportation of materials, the study considers the area as much as bounded concerning the building site. The environmental impact assessment was based on the Life Cycle Assessment (ISO 14040) methodology to test the closing loop’s virtuous potentialities and optimize products’ life. The impacts of manufacturing, installation, and short service life of Nuage pavilion were measured, getting more profound knowledge and outlooks of considering the reuse/upcycling design approach in terms of avoiding impacting processes for our common hearth.

3 Conclusions

The existing gap between the research approach, which aims to contemplate the environmental performance exhaustively, and the operative attitudes of the designers, answering the eco-efficiency requirements is the step to be overcome. The importance of the definition of the life span of the building and its function, from the first steps of the design process, emerges and has to be considered between the first

design requirements. The author envisages further improvements in applying the eco-efficiency principles starting from the early design phases.

The advantage of the lightweight structure is also demonstrated from the point of view of the environmental impacts, thanks to the reduced involved material amount compared to other technical solutions. The importance of the environmental impact assessment (and the comparison) of light technical solutions is suggested at the material stage, but especially at the building system stage and even better at a building scale. The weight of a building system and its life span, concerning the temporariness or extended use, is crucial to evaluate the effectiveness of the design choices. An important aspect to consider and not underestimate is the relation between the weight of a component and its environmental load: It is not linear and proportional, as shown in the reported case studied (Sects. 2.1 and 2.2).

Concerning the Sect. 2.3 last but not least, consideration is related to the end-of-life scenario: The membrane materials are petrol-based, although the global quantities produced in the membrane building sector are limited compared to other sectors. In any case, the membrane architecture sector is deepening the problem of the end of life and the scenarios “post-use.” Interests might be oriented toward upcycling, reuse (where possible), and remanufacturing as compatible solutions, waiting for the sector’s development toward new sorts of bio-based materials or components made of renewable raw materials and sources.

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