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Life Cycle Design and efficiency principles for membrane architecture: towards a new set of eco-design strategies

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Abstract

The typical membranes for building are polymer-based materials, which have origin from fossil fuel. Nevertheless, they are supposed to become very lightweight building components, compared with other typical ones, and, due to their lightness, involve fewer stiffening structural materials (bio-based or not) than other traditional massive components. The need of understanding their real potentials and limits in terms of eco-efficiency is declared. The paper presents the research results about the eco-efficiency principles in the field of membrane architecture, based on the application of Life Cycle Assessment methodology to membrane structures. The paper presents a systematic review of the state of the art, with the aim to demonstrate the advantages of the Life Cycle Design strategy answering to the environmental sustainability. A comparison matrix about existing environmental data on membranes (environmental impacts, EPD, Recycling and up-cycling processes) and the LCA studies are part of the shown research output. On the need of harmonization of the research about the availability of LCA data for membranes and on the basis of the collected information, a first set of eco-design principles for membranes structures is proposed. Concluding, the authors reveal the current gap between the research studies and the real praxis in architectural design referred to a specific context and envisage further improvements of the application of the eco-efficiency principles starting from the early design phases.

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Keywords: Membrane skins; Eco-efficiency; Time; Environmental Impacts; Life Cycle Assessment, Lightweight Buildings

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1. Introduction

Designers more and more appreciate membrane materials: they are increasingly using them both for aesthetical purposes, and for retrofitting or refurbishment, as ultra lightweight wrapping envelope or façade cladding systems into permanent buildings (fig.1). Targeting their environmental efficiency, the organic shape, the minimum weight, the high flexibility, the translucency, the fast installation and low maintenance are pivotal aspects to be considered and assessed. They exploit minimal amounts of material to cover a space, compared to the common covering materials, thanks also to the ability to be tensioned, by shaping themselves to the forces ways, without additional components.

European interest in lightweight textile structures is clearly evinced by the explicit reference [1] to possible uses of advanced textiles in the coordinated calls for proposals on the cross-cutting themes of nanotechnologies (NMP) and the energy efficiency of buildings (E2B), where new lightweight building solutions are examined as potential replacements for the current accepted options that only seek energy efficiency through mass. Moreover the information, the research advances and the knowledge about membranes is somewhat fragmented and still sporadic. A powerful effort to outmatch the fragmentation is on-going by the activity of the TensiNet [2] and by the exchange and sharing of research's, companies' and firms' experiences into the COST Action TU 1303 – '*Novel structural skins: Improving sustainability and efficiency through new structural textile materials and designs*' [3]. These activities aim to harmonize the research on membrane and foil structural skins, to standardise testing and analysis approaches within Europe, and, by sharing the state of the art, to orientate the innovation and development of new and energy efficient structural skin products and applications.

Academic research activities are focusing several topics, in which structural membranes and advanced textiles are the pivotal elements of the eco-innovation processes. First of all, the eco-efficiency of membrane structures has been investigated, achieving the awareness of the generated embodied energy for lightweight materials and building systems during the design phase: most of the scientific results strongly underline to focus on the final eco-performance properties rather than on the individual material one [4] [5]. When increasing the level of energy performance of buildings in the operational phase, embodied energy in materials may represent a high percentage of the energy spent in the whole life cycle of a building. This means that the environmental quality of the products does not necessarily correspond to their eco-efficiency into a specific construction. Therefore designers and suppliers need to know the environmental profile of the products, together with thermal, acoustic, resistance performances, as a choice factor in the design phase. Consequently the producers and suppliers of membranes and the relative building components and structures are driving in this direction, developing new products, bio-based polymers and building components, designing lightweight structures, closing the production chain, controlling the (less or more) hazardous emissions looking for 'nearly zero dangerous emissions', pushing the improvement of the technologies for the recycling of materials and outputted substances and for closed production environments [6] [7] [8] [9].

2. Aim of the paper

The paper presents the research results on the eco-efficiency principles in the field of membrane architecture; it offers the collected information on the state of the art on the eco-efficiency and Life Cycle Assessment methodology applied to the membrane structures. The state of the art was organized by the categories of their application in construction. The aim of this research is to elaborate those concepts and to systematize the actual obtained results, demonstrating the advantages of the Life Cycle Design strategy answering to the environmental sustainability. A comparison matrix about existing environmental data on membranes (environmental impacts, EPD, Recycling and up-cycling processes) and the LCA studies are part of the shown research output. On the need of harmonization of the research about the availability of LCA data for membranes and on the basis of the collected information, a first draft of eco-design principles for membranes structures is proposed.

3. State of the art of the application of the LCA on membrane building systems

The LCA is a methodology which support the thesis of the increasingly need to follow the criteria of the efficient use of all materials embedded in the construction. The approach of the LCA comparison between different materials and technical elements allows, on one hand, to check the environmental impacts generated during the production of the materials and, on the other hand, to deepen the incidence eco-profile of the chosen technical solution and, consequently, on the sizing of the structures system, through the comparison of the weight of the materials, which are transformed into technical elements.

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

a. Life cycle of matter - Focusing on the more than 10 years rooted use of the methodology in building construction sector, the LCA application analyses 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 cradle), to the phase of packaging and transporting products to the building site (to gate). In this case the LCA is supporting the industry in order 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, in order 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 the technical systems. The investigation at the scale of building component takes into to account the choice of the qualitatively and quantitatively more efficient building system and convenient construction technique, based on the structural and thermo-physic and acoustic performances, as well as on the costs. However, the performance of environmental impacts can increasingly influence the choice of the building products, in a LC perspective of circularity of flows and closing the loops, with the aim to select sustainable products and strategies for the future of our ecosystem.

3.1. The stakeholders of the LCA of membranes

In the road map of the eco-efficiency of membranes, different stakeholders can be associated to the Life Cycle steps.

a. Life cycle of matter - New components of recent technologies for the building envelope require a high level of the testing of material properties and construction technology of the system in most of the projects. Where the LCA is applied to fields of experimental investigation, the experimental project has the manufacturing and production phase as a reference. Then the stakeholders of the outcomes of the first phase of investigation of the case study are: the chemical industry and the producers of polymeric films, yarns and fabrics, on one side, and the supply companies of tailoring and assembly of the membrane components for the architecture to the other. The first ones are committed to meet the regulatory requirements to reduce fuel consumption and harmful emissions to the environment in their supply chain, the seconds to provide safe, efficient and competitive technical systems with those already present in the building sector.

In the raising process of primary data in the LCI, the inventory phase of the LCA methodology, the industry is able to deliver the precise input and output resources and energies in order to edit an Environmental Product Declarations (EPD), and to deepen the environmental impacts recycling and up-cycling processes. The expected data about the environmental profile of membrane materials would be an average picture of the production chains' impact of the same family of products, as happened for other building products.

b. Life Cycle of building components - The comparative LCA between different types of building system solutions has as stakeholders designers, who are increasingly called upon to pay attention to the performance and the physical-technical materials chosen, from the early stages of the project, to forecast of consumption matter and energy before the construction of the building, added to the strategies for energy saving in the use phase of the building. In these cases LCA is useful in order to guide the designer to the most appropriate and eco-efficient solution for a specific context and the expected performance of the project.

This comparison approach is achievable thanks to the Inventory of the input and output data about the membrane materials' production chain: if they do not exist, their definition is needed by the LC analysts, expected to be rough and imprecise as the data edited by the industry. In this phase the designers could compute the compared impact of the building technical solution by the use of the already existing LCA calculating tools.

3.2. Studies on environmental impact of textiles and films

The considered scientific sources on the Environmental Impact Assessment of textile and finishing industries, clearly show that the investigation of the environmental impacts of the textile industry for clothing, furniture cladding and internal architecture have been started some decades ago, while the interest of the environmental burden of coated membranes and films for architecture starts recently. The studies deal with some specific stages of the chain that can be related or similar to the same procedures in the production chain for membranes and can suggest the risky phases of the production. Some of them are comparative with other similar products or procedures.

Assessment at the material and product level (materials related with the membranes for architecture): the American Fiber Manufacturers started to explore the ways to evaluate and improve the environmental impact of the fiber manufacturing process and manufactured fiber products related to the cloth sector, finding out an LCI for the manufacturing, use and disposal stages of the garment [10]. It evaluates a specific stage of the textile manufacturing chain, collecting data from each of the sources in a large amount of time (circa 8 months). The Eco-efficiency analysis has been used to compare the eco-effectiveness of PVC plastisol with two commercially accepted coating agents (polyacrylate and polyurethane) for textile fabrics [11, 42] and this study suggest interesting results useful for the membrane field.

Assessment at the material level and in the textile field (not directly related with the membranes for architecture) that represent samples of the methodological approaches: the Institute of Textiles and Clothing of The Hong Kong Polytechnic University reported in a paper the development of a unique model to quantify the environmental impact made by various textile fibers (organic cotton, flax, viscose, polyester, polypropylene, acrylic, nylon) and positioned them in terms of ecological sustainability [12]; The study on the environmental profile of textile wet processing in Finland [13] was carried out in order to define the eco-efficiency of the major Finnish textile companies for wet processing of knitted or woven fabrics, as a part of drafting the Best Available Technique Reference documents for the European IPPC Bureau. It focuses on the manufacturing stage of the fabrics, whose approach can be considered similar /comparable to the manufacturing of technical textiles for architecture. It is a transparent initiative of the companies to understand their environmental burdens' limits. In 2004 a research on LCA Methodology Issues for Textile Products (for furniture wrapping functions) was conducted in Swedish Chalmers University of Technology [14], trying to find out the most important problems of the application of the LCA to the textile sector and to contribute to the adaptation of the methodology to the sector specificities, identifying, from case studies, the basis for a simplified model intended for use in textile companies. In the years 2001-2004 a dedicated EU COST Action 628 on the theme of the life cycle assessment (LCA) of textile products, eco-efficiency and definition of best available technology (BAT) of textile processing was established to produce first hand, industrial environmental data of textiles in Europe, as well as to suggest tools for comparisons of present technologies and practices with cleaner applications, including the economic effects. The Action network also suggested criteria for ISO (Type III) Environmental Product Declaration (EPD) standards [15].

Assessment at the building system level (as sample of the comparative approach of the LCA in the building sector comparison to define the alternative construction solutions - benchmarking): in architecture and the building sector the comparative LCA is, from approximately a decay, an established approach in order to understand the contributes of the environmental impacts of alternative building systems and to help the design choices. The reports of studies with application of a comparative LCA of alternative building systems or components, are more: such as a the study of a comparative assessment of life cycle impacts of curtain wall mullions [16] (it consider the pre-use phase till the installation in buildings, with a deepened LCI with primary data), the comparative life cycle assessment of a transparent composite facade system and a glass curtain wall system [17] (it consider the pre-use phase, the use phase in terms of operational phase and the processes of dismantling, transporting and disposing of the components), the comparative environmental Life Cycle assessment of green roofs [18] (it consider the pre-use phase till the transport to the building site).

In the specific field of structural membranes the scientific literature show that LCA studies have been deepen, on one hand, the eco-efficiency of the fluoropolymeric film ETFE (ethylene tetrafluoroethylene) compared with traditional transparent building materials (typically glass [19] or PVC crystal, Policarbonate [20]) and traditional building roof or facade systems [21]; on the other hand the eco-efficiency of the Polyester fabric Polyvinylchloride coated PES/PVC, which is the most common textile materials for structural membranes, ,compared with other finishing components for façade [22].

The status of the conducted and studies on the eco-efficiency of membranes in architecture do not contemplate a whole life cycle as limit for the LCA: most of them are focused on environmental impacts of the pre-use phase of membrane materials and on the inventory of the components for such membrane systems, and they computed the impacts in terms of energy consumption for the manufacturing (embodied energy) showing the contribute of the membrane materials themselves and of their supporting systems (typically made in steel, aluminum and some plastic/rubber elements) [4, 20, 22]. In [21] the LCA shows the impacts of the pre-use phase and of the transports of the components from the industry to the building site. Most of these studies highlight how in the LCA of membrane materials, typically synthetized materials from the cracking of fossil fuel, is preeminent to assess the impacts (and compare them with the impacts of traditional building materials) per weight of components (i.e. kg/m^2 of building component) instead of a simple comparison per unit of material weight (i.e. kg of building material). So the lightness advantages emerge.

A recent study [23] conducted an LCA of a pneumatic structure built with ETFE cushions, which needs energy to maintain the inside pressure of cushions during the use after the installation, and, for the first time in the sector, considered the impacts of the operational phase (the energy consumption for the air pumps), in comparison with the pre-use phase, in terms of the environmental indicators considered in EPD standard.

All these mentioned studies are the output of scientific researches and the data for the inventory of membrane materials of the manufacturing phase were developed by scarce primary data implemented in processes of databases, stating some rough assumptions. Although the rough data assumptions of the membranes materials' LCI (with an estimation of 20% error, that not influence significantly the results of an LCA of a tensile façade system, see [21]), the real needed harmonization in the field of LCA of membranes (so far as in general in the LCA od building systems) is the use of a common procedure and principally the transparency of the information about the scope and the objective of the analysis, the system boundaries, the sources of the data, in order to make comparable the LCA results.

The table I, performed and edited by the authors, aimed to collect the existing environmental data and information of the life cycle phases the most used textiles and films for architecture (pre-use with available quantifications of Embodied Energy and Global Warming Potential; use phase with indications regarding the maintenance; end of life with active recycling and up-cycling processes by the textiles and foils manufacturing industries). The need of harmonization of the data is an opportunity to be shared and has to be leaded by the plastic industries that produce materials (pellets) and textiles and foils. The obtained data then are the basis for the LCA.

The need for future LCA research studies on membranes is to enlarge in the computation of the system limits of the environmental impacts from the only pre-use phase to the whole life cycle, with use phase impacts (operation, maintenance and substitution) and end of life impacts: in the case of tensile structures the use phase is characterized principally by the maintenance; in the case of pneumatic structures the use phase is characterized by the energy consumption of the pumping plant for the maintenance of inside pressure. A step forward could emerge from the cooperation of industries and LCA research centers, in order to catch the primary data about the input/outputs during the manufacturing chain of membrane materials (PES/PVC, ETFE, PTFE fabric, GLASS FIBERS/PTFE) and to elaborate their LCI data (for the industries as stakeholders), as common basis for preparing and developing the LCAs of various structural membranes (ones that have the designers as stakeholders). From the membrane industry side, there is a growing interest to qualify the environmental data regarding the pre-use phase, quantifying precisely the environmental impacts, and to edit the Environmental Product Declarations of the products, in order to be competitive on the market.

Table 1. A comparison matrix of the existing environmental data and information of the life cycle phases of textiles and films used in architecture (Elaboration of the authors)

		Types of membranes			
		PES/PVC	Fiber Glass/PTFE	PTFE fabric	ETFE foil
Pre-use	EE [MJ/kg]	96÷113,3 [33, 34, 35, 36, 32, 21]	295 (1)	295 (1)	26÷337,3 [19, 38, 39, 20, 27]
Pre-use	EE [MJ/m²]	54÷68 [33, 34, 35, 36, 32, 21]	-	-	315 for a 5-layer cushion [20] 326,2 for a 3-layer cushion [27]
Pre-use	GWP [$CO2_{eq.}$/kg]	4,6÷6,13 [33, 34, 35, 36, 32, 21]	-	-	89 [20] 170 for a 3layer cushion [27]
Pre-use	GWP [$CO2_{eq.}/m^2$]	2,2÷4,1 [33, 34, 35, 36, 32, 21]	-	-	137 for a 5-layer cushion [20]
Use	Durability of material (yrs)	10, till 30 [25]	25 [28]	15 industry warranty 25+ expected lifespan [29]	up to 50 [26]
Use	Life span of the construction system (yrs)	15 [26]			30 [26], 25 [27, 30], 20 [30,31]
Use	Mantainance	Periodical and planned controls are needed to search possible damages to be as quik as possible repaired	Anti-adhesivity propriety, self cleaning by rain Periodical and planned controls are needed to search possible damages to be as quik as possible repaired	Anti-adhesivity propriety, self cleaning by rain Periodical and planned controls are needed to search possible damages to be as quik as possible repaired	Anti-adhesivity propriety, self cleaning by rain. Inspection of the holes generated by birds [37] Periodical and planned controls are needed: a. to verify the dirty deposition on the edges and on the frame alu profiles; b. to search possible damages to be as quik as possible repaired
End of life	On going practices of recycling	Composite material, non omogeneus - Reuse and Recycling (down cycling) [32]	Composite material, non omogeneus - Recycling PTFE [24] up cycling	Composite material, non omogeneus - Recycling PTFE [24] up cycling	Omogeneous material, dry assembled system, easy to be disassembled and separated - R down cycling [20]

(1) Datus derived from the Eco-Invent database assessed by the method EPD2007 with the SimaPro 8.1: it seems to refear to the production phase to obtain the pellets of TFE

4. A proposal of Eco-efficiency design strategies in the field of membranes

Starting from the global needs of sustainability and reduction of non-renewable energy and material consumption, the quantification of the weight of the building is becoming a basic requirement in the design process, in order to be aware of the consequences in terms of environmental impacts of the design choices [40]. The shape optimization of lighter architectures that use materials in a rational and functional way and balance the relationship 'form and structure' is a need to renew the balance between nature and built environment. In this framework, the *Lightness* becomes a paradigm to reduce the environmental impacts starting from the design process till the manufacturing ones. The architectural design becomes an opportunity for searching the natural essentiality, highlighting how the natural cycles close the loop without wasting anything. The lightness paradigm is meaningful in a double level: high shape efficiency on one side and high matter efficiency on the other one. The correct combination of both aspects is the best feasible outcome from a design process, while the reversible perspective of the construction process has great influence to the environmental context [41].

Looking for lighter architecture means to enlarge the research into materials, reducing the thickness of components, optimizing the sections of the construction. If in the past materials suggested their own most appropriate use, today designers mould and define materials to cater to the project's requirements, no longer with any limits. Designed materials such as polymers have a characteristic that traditional materials do not: reduced weight for the same volume (density). This is paramount if the objective is to pursue savings in materials and energy, although it must also be assessed in terms of the other stages of the life cycle. Thus, the main aspects to be assessed during the design phase of a membrane structure are the embodied energy of components and the systems, the reuse/recycling of membrane materials, the lifespan of the temporary and removable buildings, their easy removal after the useful life and their end of life treatment.

The following topics can be conceived as strategies for the membrane structures' eco-efficient design.

a. *Doing more with less* - Minimal structures in nature only use the raw material needed in relation to the duration foreseen for the system. The design and study of new minimal structural components plays a key role in the definition of lightweight constructions as well as in the qualification of the built environment;

b. *Time-based structures* - The durability of membranes and foils employed to build up structural skins is object of analysis considering *time* as a key function in all the decision-making processes in design;

c. *Closing the loop* - New technology seeks to integrate polymeric waste in the production cycle of new structural materials (down- or up-cycling) and to find a new life for old, dismantled membrane structures (reuse or recycling). The analysis of the recycle/reuse scenarios is part of the Life Cycle design approach;

d. Life Cycle design - The Life Cycle Analysis methodology plays a fundamental role to obtain more sustainable procedures in design, building and renovation. It means to consider the strategies mentioned before into the life cycle stages of a designed structural membrane.

Focusing on the *pre-use phase*, in the Life Cycle Analysis strictly connected with the *post–use phase*, the resource efficiency of structural membranes and the design for their full life have to be examined:

- to obtain the resource efficiency of structural membranes means looking for a balance between shape, materials/components and the manufacturing and building up processes. In other words it means to effort by intelligent design and structure reducing materials to the needed quantity (link with the *strategy a.*); a direct correlation concretizes between the environmental efficiency, material characterisation and advanced simulation of membrane and foil materials and advanced simulation of their structural application.
- to design for the full life cycle means, at the material level, to predict the durability of membranes and foils (link *with* the *strategy b.*) and to investigate the technological possibilities of recycling and up-cycling of membrane materials (link with the *strategy c.*); and means, at the building system level, to foresee the lifespan of temporary and removable buildings (link with the *strategy b.*) and to provide the easy demount ability/re-usability/recycling of structure by appropriate engineering (link with the *strategy c.*); a direct correlation concretizes with the researches on new concepts and optimization of novel shapes.

Focusing on the *use phase*, the energy efficiency of membrane architecture has to be improved by the research advancements in term of high performative envelopes, daylighting strategies, passive and active solar technologies, innovative materials and coatings (like low-E coatings), other innovative components (like thermal broke clamp profiles), crating a direct correlation between the topic of the optimization of novel architectural and structural shapes and their thermo-physic behaviour..

5. A proposal of principles for an optimized LCA approach in the field of membrane structures

Looking on the world of professional design and construction is perceived a great difficulty to disentangle in structured, often divergent requirements to be fulfilled, and specifically in application a LCA methodology during the project. Admittedly we have valuable tools to support the design for eco-efficiency of the buildings, but at the same time we do not even glimpse a practice where having under control all the information, needed to make effective and efficient choices for a prolonged life cycle span. On one hand, the research assumes, however, the task of contemplating exhaustively the eco-environmental performance of structural membranes, despite the extreme complexity and richness of different aspects, and contrasting biased and simplistic approaches. On the other hand the operative attitudes of the design field are various: presumably, with a view to Life cycle thinking, the completeness of the systemic problem is not embrace, however reveal an approach to extremes design, focusing with the design technical choices partially on the optimization of individual lifecycle phases, with valuable results.

5.1. The approaches of designers towards the membrane buildings seen from the eco-efficiency point of view

According to a methodological approach for the environmental impact assessment, it is essential that the designer defines and delimits the scope, its object of study, the contextual problems and the more stringent best technique for dealing with. Analysing some examples of building projects that use membranes as envelope component exploiting the paradigm of lightness, it emerges how in some cases the design phase, choosing the membrane role in the building systems, focuses on the optimization of one specific phase of the building life cycle.

In the Aura House di F.O.B.A, Tokyo, Giappone (1998), where the entire wrapping envelope is PTFE coated- fiberglass membranes, the material choice is interpreted focusing on the pre-use phase optimization by the reduction of the consumed material, energy and resources, due to the thinness and the lightness of the membrane skin: the choice probably do not ensure the same efficiency in the use phase with the energy consumption for the conditioning, although the need electrical consumption for lighting during the days should be reduced thanks to the translucency of the membrane - strategy of *Doing more with less* [40].

The Modern Tea House of Kengo Kuma, Frankfurt am Main, Germany (2007) is an example of integrated design, with a formal and structural optimization, together with that of the pre-use phase; the ultra lightweight solution reduces the consumed materials energy and resources for envelope (Tenara membrane as finishing layers and air as structural material– an air supply plants) and represents an optimal balance of the design choices (form + materials + life span of the building) related with the specific temporary function of the building – strategies of *Doing more with less* and of *Time-based structures* [40].

The Wall House di FAR Frohn & Rojas, Santiago del Cile, Cile (2007) is an example of integration of lightweight materials (optimizing the pre-use phase) and energy efficiency attention by building's thermal control (optimizing the use phase), by an open mesh textile for the façade cladding/shading; the reversibility of the building system shows the attention also to the maintenance, in the use phase, and the possible reuse/recycling after the end of life - strategies of *Time-based structures* and of *Closing the loop* [40].

The concept of the London Aquatic Centre, a temporary building for the Olympic Games of London in 2012, focused on the optimization of the end of life phase, from the design phase and by the building technology choices: the building wings were completely dismantled in two mounts, the flexibility and lightness of the membrane cladding allowed compact storage and reduced spatial requirement, thereby optimising transport through the Texyloop recycling network located in Ferrara, Italy [26]; an LCA study by a membrane supplier demonstrated a 50% reduction in environmental impacts and the production of second generation raw materials [43] – strategies of *Doing more with less* and *Closing the loop*.

Considering the permanent or temporary nature of structural membranes (fig.2), from a lifestyle thinking approach (fig.1), design strategies may be identified, in order to orientate the technical and material choices:

For "permanent" ones, more attention must be paid to the operational phase (energy requirements for heating and cooling, for pumping, ordinary or extra maintenance), including the need for more envelope insulation, greater mass, more materials, and consequently a greater environmental impact during the production processes; consideration of what material and technological solutions to choose and their environmental impacts takes place subsequently.

For "temporary" ones, the role of the impact of building components remains prominent, considering that in some situations energy heating and cooling plants and consumption during the service phase are not required; at the design stage, the expected life span, which is almost always known and definable, is extremely important. One option is to use construction elements characterized by a high environmental impact, high-embodied energy and good durability: their impact may be absorbed over forty, fifty or sixty years. A second option is for the materials chosen to provide low energy content if the lifetime is short, or else good durability despite their high environmental impact so that they may be reused/recycled: in this way the total impact is sub-divided into multiple life cycle loops.

In the field of lightweight materials and membranes, materials used for temporary functions can be used also for permanent functions and vice versa: at the design stage it is important to define precisely the building's function, to be aware of its context and to establish the expected life cycle span of the building.

5.2. Definition of LCA statements starting from the research advancements

The LCA applications and the research experience on the sustainability of structural membrane, effort by the authors in the last six years, find out specific principles as reference to set up the LCA of membrane structures. Their verification during the LCA procedure of structural membranes helps to point out advantages and disadvantages and the needed correct exploitation of the proprieties of membrane materials.

1st principle: verification of the ratio Frame Perimeter/Covered Surface (in the case of structural membranes for roofs or entire building envelope) [4,20]: aiming to assess the eco-efficiency of a defined surface to be closed/covered, the wider area of a membrane "panel" correspond to the less perimeter length of frames, reducing the materials for their production and consequently the environmental impacts (*Doing more with less*).

2nd principle: verification of the ratio Fixing System (or Primary Structure)/Membrane (in the case of structural membranes for façades) [20, 21]: aiming to asses the LC impact of the membranes for façade cladding and the efficacy of their choice, it is needed the verification of the quantity of the elements of the fixing systems and understand their real need in terms of structural loads and of stiffness: they support ultra light thin materials instead of rigid (less or more) lightweight panels, that have to work in tension but not compulsorily framed as panels (*Doing more with less*) .

3rd principle: verification of the ratio Membrane Structure/Mechanical Load of the Structure considering steel or wood as main structural materials involved in the field of membranes: optimizing the mechanical and structural behaviours of a membrane structure, and the form, means to improve the correct use of membranes and the correct interpretation of their embodied proprieties (*Time-based structures, Life Cycle Design*).

The optimization of these ratios means the good exploitation of the characteristics and behaviours of the membranes with respect to other, less flexible and lightweight, traditional building materials.

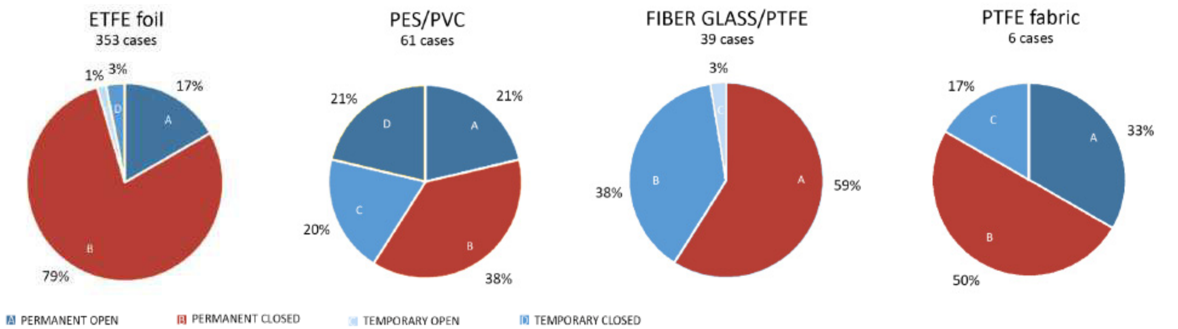

Fig. 1. After an analysis of several case studies built with different types of membranes, the graphs represent the distribution of the uses of membranes in different architectural configurations: the red areas highlight the diffusion of membrane architecture with permanent functions (more than 30 years) and close shaped buildings. (Elaboration of the authors)

6. Conclusion

In this paper, according to the research experiences of the authors, key points regarding the application of the LCA methodology in the field of structural membranes for architecture have been pointed out. The framework highlights the dimension *time* as a supporting paradigm to orientate the level of detail in the application of the LCA to the design. The existing gap between the research approach, which aims to contemplate exhaustively the environmental performance, and the operative attitudes of the designers, answering to the requirements of eco-efficiency, has been deepen. 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 emerged results, globally, are the first steps towards the establishment of criteria for application of the LCA to evaluate membrane structures in the building life cycle.

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References

[1] ERC Sectors: PE8 Products and process engineering - Lightweight construction, textile technology, http://erc.europa.eu (visited on 20.01.2015).
[2] www.tensinet.com.
[3] www.novelstructuralskins.eu - COST Action TU1303 Novel structural skins: Improving sustainability and efficiency through new structural textile materials and designs (2013-2017).
[4] Chilton J., Pezeshkzadeh S. A., Afrin S., *Embodied energy in ETFE foil construction*, In: H. Bogner-Balz, M. Mollaert, E. Pusat (ed) *[RE]THINKING Lightweight Structures*, Tensinet Syposium Proceedings (2013), pp. 457-466.
[5] Monticelli C., Zanelli A., Campioli A., *Life cycle assessment of textile facades, beyond the current cladding systems*, In: H. Bogner-Balz, M. Mollaert, E. Pusat (ed) *[RE]THINKING Lightweight Structures*, Tensinet Syposium Proceedings (2013), pp. 467-476.
[6] Fournier F., *LCA of PRECONTRAINT composite membranes & TEXYLOOP recycling cases studies*, In: H. Bogner-Balz, M. Mollaert, E. Pusat (ed) *[RE]THINKING Lightweight Structures*, Tensinet Syposium Proceedings (2013), pp. 487-496.

[7] Maywald C., *Vector Foiltec's activities in the field of sustainability and the experience of the EPD*, presentation in the COST ACTION 1303 meeting in Brussel on 29.09.2014.
[8] Dyneon 3M, *New Dyneon Emulsifier Eliminates APFO from Production of Fluoropolymers*, Technical communication of the Company (2008).
[9] Dyneon 3M, *Leading the way with sustainable production*, Technical communication of the Company (2014).
[10] Smith. G. G., Barker R. H. (1995), *Life Cycle analysis of a polyester garment*, in *Resources, Conservation and Recycling,* n.14, pp. 233-249.
[11] Bidoki S.M., Wittlinger R. (2010), *Environmental and economical acceptance of polyviniyl chloride (PVC) coating agent*, in *Journal of Cleaner Production*, n. 18, pp. 219-225.
[12] Subramanian Senthilkannan M., Hu J.Y., Mok P.Y. (2012), *Quantification of environmental impact and ecological sustainability for textile fibres*, in *Ecological Indicators*, n. 13, pp. 66-74.
[13] Kalliala E., Talvenmaa P. (2000), *Environmental profile of textile wet processing in Finland* (Tampere University of Technology, Finland), in *Journal of Cleaner Production*, n. 8, 2000, pp. 143-154.
[14] Dahllöf L. (2004), *LCA Methodology Issues for Textile Products*, Technical report n. 2004:8, ISSN 1404-8167, Environmental Systems Analysis, Chalmers University of Technology, Göteborg, Sweden.
[15] Nieminen E., Linke M., Tobler M., Van Der Beke B. (2007), *EU COST Action 628: life cycle assessment (LCA) of textile products, eco-efficiency and definition of best available technology (BAT) of textile processing*, in *Journal of Cleaner Production*, n. 15, pp. 1259-1270.
[16] Azari N. R., Kim Y. W. (2012), *Comparative assessment of life cycle impacts of curtain wall mullions*, in *Building and Environment*, n. 48, pp. 135-145.
[17] Kim K. H. (2011), *The comparative life cycle assessment of a transparent composite facade system and a glass curtain wall system*, in *Energy and Buildings*, n. 43, pp. 3436-3445.
[18] Kosareo L., Ries R. (2007), *The comparative environmental Life Cycle assessment of green roofs*, in *Building and Environment*, n. 42, pp. 2606-2613.
[19] Robinson-Gayle S., Kolokotroni M., Cripps A., Tanno S. (2001), *ETFE foil cushions in roofs and atria*, in *Construction and Building Materials*, n.15, pp. 323-327.
[20] Monticelli C. (2010), *Environmental assessment of ultralight roof structures built with new materials: the case of the ETFE cushions*, in Vegh L. (eds.) *Environmentally compatible structures and structural materials* (ECS), Czech Technical University, Praga, 24-25/09/2009, p. 28-37, ISBN/ISSN: 9788001045060.
[21] Monticelli C. (2013), Zanelli A., Campioli A., *Life cycle assessment of textile facades, beyond the current cladding systems*, in H. Bogner-Balz, M. Mollaert, E. Pusat (eds.), *[RE]Thinking Lightweight Structures*, TensiNet, Istanbul, Tensinet Symposium. 08-10/05/2013, pp. 467- 476, Istanbul, ISBN 9789072325068.
[22] Cremers J. (2014), *Environmental impact of membrane and foil materials and structures – status quo and future outlook*, in *Technical Transactions Architecture*, 7-a/2014, Poland.
[23] Maywald C. (2014), *Vector Foiltec's activities in the field of sustainability and the experience of the EPD*, presentation and contribute, EU COST 1303, Bruxelles meeting, sept. 2014.
[24] Wißler C. (2010), "New Process for Recycling of Fluoropolymers", in CHEManager International 4 Oct., Patent CN000102216246A, http://www.invertec-ev.de/en/projects/environmental-care/ptfe-recycling/; Dyneon 3M, Leading the way with sustainable production Technical communication of the Company (2014).
[25] Llorens I. (2014), *Report of the Nineteenth International Workshop Textile Roof 2014*, 26-28 May 2014, Berlin, Germany, p. 10.
[26] Zeh M. (2009), "Aging of membrane materials. How to keep membrane materials looking new over time", in *Fabric Architecture* n.11.
[27] Environmental Product Declaration in accordance with ISO 14025 TEXLON® System - Vector Foiltec, Nowofol, Dyneon - Declaration number EPD-VND-2011111-E.
[28] Saint Gobain Sherfill www.sherfill.com (consulted in March 2016).
[29] Report "Comparison of PTFE Glass vs TENARA Fabric" article in http://www.sefar.com/es/573/News-Detail.pdf?Article=2443749 (consulted in March 2016).
[30] Cremers J. (2014), "Environmental impact of membrane and foil materials and structures – status quo and future outlook", in *Technical Transactions Architecture*, 7-a/2014, Poland.
[31] Cremers J. (2014), "High Performance Lightweight Building Envelopes Made of Foils and Textiles", in 2015, Zanelli A., Spinelli M.L., Monticelli C, Pedrali P., *Lightweight Landscape*, Polimi – SpringerBriefs.
[32] Laratte B. ,Le Pochat S., Meurville E., PéchenartE. (2009), "LCA of a technical PVC textile including an original recycling process", in Ecochem 2009 Chemistry & Ecodesign, Montpellier, France.
[33] EVEA and SERGE FERRARI (2008), *Etude AVC de la Batyline in accordance with ISO 14040*.
[34] EVEA and SERGE FERRARI (2009), *Life Cycle Assessment of PRECONTRAINT® 502 (GB) in accordance with ISO 14040*.
[35] EVEA and SERGE FERRARI (2009), *Life Cycle Assessment of PRECONTRAINT® 1002 S in accordance with ISO 14040*.
[36] Laratte B., Pechenart E. and other (2008), *Étude ACV de la Batyline – analyse de Cycle de Vie réalisée selon ISO 14040*, Nantes.
[37] Escoffier A., Albrecht A., Consigny F. (2013), "Nice Stadium: Design of a flat single layer", in in H. Bogner-Balz, M. Mollaert, E. Pusat (eds.), *[RE]Thinking Lightweight Structures, TensiNet, Istanbul, Tensinet Symposium.* 08-10/05/2013, pp. 467- 476, Istanbul.
[38] Ashby M., *Materials engineering, science, processing and design*, Elsevier, Oxford, 2007, p. 167.
[39] Fernandez J. (2006), *Materials Architecture. Emergent materials for innovative buildings and ecological construction*, Elsevier, Oxford, p. 6.
[40] Monticelli C. (2013), *Life Cycle Design in Architecture*, Maggioli, Santarcangelo di Romagna, ISBN 9788838762499.
[41] Drew P. (2000), *Touch This Earth Lightly: Glenn Murcutt in His Own Words*, Duffy & Snellgrove, ISBN 1875989463.
[42] Fournier F (2009), *PVC Composites: Life Cycle Analysis & Recycling including an Australian case study*, in *Proceedings of Lightweight Structures Association of Australasia LSAA 2009 Conference Technology & Sustainability Applications*, Melbourne.
[43] http://en.sergeferrari.com/lightweight-architecture/recycling-a-promise-is-kept (consulted in February 2016).