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Application and validation of eco-efficiency principles to assess the design of lightweight structures: case studies of ETFE building skins

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Abstract
Membrane and foil structural skins exploit minimal amounts of material to cover a space, compared to the common envelope materials, thanks also to the ability to be tensioned, by shaping themselves to the forces ways, with a few additional components. On the other hand, the environmental compatibility together with the thermal, optical, and acoustic performances are crucial factors during the designing phase. The paper aims to show the research updates on the Life Cycle Assessment (LCA) methodology applied to ETFE cushion building technology, with the final goal of validating a couple of design principles and sustainability criteria, which the authors stated after past research experiences on the membrane and foil structures evaluation in their building life cycle. The LCA design principles for those lightweight structures are: 1.Verification of the ratio Frame Perimeter/Covered Surface; 2.Verification of the ratio Fixing System (or Primary Structure)/Membrane; 3.Verification of the ratio Membrane Structure/Mechanical Load of the Structure. Their application will help to point out both advantages and disadvantages of membrane and foil structural skins and to correctly exploit the properties of those thin and flexible materials, during the design process. The aim of this work is to validate this sustainable design criteria and its repeatability through 5 different case studies of ETFE built structures, focusing mainly on the principles 1 and 2. Thanks to the results, benchmark range as designers' reference will be carried out.

Keywords: Eco-efficiency, criteria, LCA application, ratio perimeter/covered area, ratio fixing element weight/membrane weight, ETFE

1. Introduction
The environmental impacts of different membrane and foil structural skins have been assessed by different research studies, which are comparing both translucent and transparent design alternatives. A few comparative studies have been evaluating how use membranes in order to optimize their lightweight and strength and to push innovative designs beyond the current fixing techniques [1, 5]. Other research studies have been focusing on life cycle analysis of ETFE building components compared to common glass systems [2, 4] and even more widening the comparison to the polycarbonate transparent sheets [3].

All studies are converging to the necessity of increasing the designers' awareness of both lightweight and flexible materials and their performances, in a life cycle thinking perspective. Ambitious goals have been set for the energy efficiency of new buildings, which have to comply with the Nearly Zero Energy European standard by the end of 2020; furthermore the energy retrofit of existing buildings is a crucial strategy that must be implemented at a large scale to achieve the ambitious de-carbonisation goals that the European Union has set for 2050. A new generation of environmental responsive lightweight construction experts and designers will have a crucial role, rising the interest and need of innovative membrane and foil solutions, only if we can now demonstrate their lighter environmental impact than other rigid and massive structures.

The well-known advantages of ETFE and membrane materials in terms of pre-use phase LCA evaluations [1,2,3] are not more sufficient for leading innovative and sustainable design processes, while a more comprehensive LCA design methodology, specifically referred to membrane and foil structural skins has to be created and validated [6], with the final goal of supporting architectural and engineering designers to overcome a few disadvantages during the building service life. Those disadvantages can actually came through a lack of information on the thermal, optical, mechanical, acoustic behaviour of the most innovative lightweight building systems, as well as through a bad comprehension on how the tensile/pneumatic components are working into the whole structural and architectural building system. As there is no common Eurocode available for the design of ETFE membranes and structural glass, the basis of structural design for the projects in Europe are the Prospect for European Guidance for the Structural Design of Tensile Membrane Structures [10] and the Guidance for European Structural Design of Glass Components [11].

Inside that lightweight technology development perspective, the present paper aims to take open and updated the discussion on which would be the most effective life-cycle-based design methodology, which will be support designers during their daily work, and not as a mere theoretical analysis for scientists and environment specialists. This research need actually comes up from the networking between researchers and firms - both manufacturers tensile/pneumatic structures and membrane/foil producers - as well as engineering and architectural designers, which are all asking urgently to find a easier way to compare the eco-profile of lightweight material alternatives nowadays available on the global market [7].

The authors already found out and shared a first set of specific design principles for structural application of membranes and foils (roofs, facades whole envelopes), orienting a more sustainable, more comprehensive, whole life spanned lightweight technology's choice [6]. Those LCA design criteria are the following ones:

1st principle: verification of the ratio Frame Perimeter/Covered [2, 8]: 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 and Foil envelope [5, 8]: 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. Their verification before the LCA of structural membranes helps to point out advantages and disadvantages and the needed correct exploitation of the proprieties of membrane materials

2. Aim of the study

The aim of this study is the application of the first two principles, in order to validate them for the repeatability in the membrane design practice. The use of these principles is thought as a first preliminary verification of the eco-efficiency of the technological choices in the design of membrane architecture, before undertaking a LCA (Life Cycle Assessment – ISO 14040 [9]). Their application has to suggest to the designer and engineers a preliminary assessment of the optimization of form and quantity of used materials, aiming to reduce the whole environmental impact assessment of the designed solutions: if the form is optimized with respect to the ratios of the principles, less materials are involved in quantity and consequently embodied energy and environmental impact assessment are reduced. The application has been conducted on different alternative solutions of each case study, starting from the real existing façade and designing façades with different transparent technologies, as alternatives. The scope was to speculate the differences in terms of final results starting from the contemporary technological advancements and, consequently, in terms of different environmental impacts between the solutions.

In this study the application is *ex-post*, on existing buildings with facades or roofs made by the pneumatic system in ETFE, but, after a correct validation, it would aim to become a reference to be applied *ex-ante* during the design phase, from the first stages.

2. Case studies

Five meaningful case studies were selected for their morphological characteristics and also for some particular features listed as follow.

Case study A - The Kapuzinercarree in Aachen, Germany, is an interesting case study with a covered atrium by triple layer ETFE cushions, as a public space inside the court of an existing historical building (390 m^2). The trapezoidal atrium became an area exploitable all over the year and also a thermal buffer zone regulating the climate conditions between outdoor and indoor the old building. It is covered by the ETFE cushion system supported by a lightweight cable net structure, aiming to reduce at the minimum quantity the structural weights of the new structure on the existing building. The authors compared it (A1) with two hypothetic technical solutions: one made of glass roofing system (A2) and a second one made of a big unique ETFE cushion restrained by a steel cable net (A3) for supporting the snow load and hardening the system structural resistance.

Case study B - The atrium of the Kingsdale School in Dulwich, London, United Kingdom, is a huge rectangular and regular area (2.862 m^2) covered by three-layer ETFE cushions, themselves rectangular shaped. The role of this transparent roof is covering a big atrium between the buildings of the classrooms, made of traditional construction materials, for common activities between the school classes and for the playtime. It is a non-conditioned space, thanks to the role of the ETFE, as a greenhouse that catches the warm rays from the outside. In this case the ETFE system has a complex shading system which can regulate the entering radiation and light: the layers of each cushion are fritted with a checkered patterns and the intermediate layer of each cushion is movable by the different pressure inside the air chambers, going to be adherent to the upper or lower layer (with a negative pattern) and to close the transparent parts. The authors compared it (B1) at first with an alternative hypothetical solution designed with a glass roofing system (B2) and then with a different ETFE cushion configuration (B3), where the rectangular cushions are oriented transversally than the existing roof. In this last case the author's hypothesis aimed to verify the efficiency of the market target, which indicates as the optimized cushion's dimensions the span of three meters of the cushion in one direction and the longitudinal dimension as longest as possible. The three meters span is ensuring a correct snow load contrast.

Case study C - The Busbahnof in Aarau, Swiss, is an enormous cantilever roof, for the bus station with an organic curved shape (1.084 m^2). It is the most recent realization of the biggest double layer ETFE cushion, which covers the whole cantilever roof area, restrained by a complex system of steel cables, structurally designed in order to contain the curved surface of the cushion's upper and lower layer and to support snow loads on the big ETFE surface. The authors compared it (C1) with an alternative hypothetical solution designed with a spider glass roofing system (C2).

Case study D and E - The two facades with the ETFE cushions of the Media Tic building in Barcelona, Spain, are the last two cases considered in the present study. The Media Tic was designed as an energy producer and self-regulating to external stimuli. It is formally a cube representing the digital world, in order to host the activities of Information and Communication Technology. The envelope is a very personal combination of the architect Enric Ruiz-Geli with two facades coated by ETFE pneumatic cushions, attractive and functional at the same time for the self-regulation of the inside light and temperature. One facade is oriented to South-West (1108 m^2) and the cushions are rectangular, vertically oriented (D1). The other facade oriented to South-East is a composition of small triangular cushions (E1 - 1146 m^2). Both the facades were compared to solutions of transparent glass facades (D2 and E2), trying to reproduce a similar morphology. The first façade oriented to South-West was compared also with an optimized configuration of the ETFE cushions, designing bigger cushions, double in width than the real built solution, in order to understand the feasibility coupled with the upgrade of the area of the cushion and the reduction of the fixing systems (E3).

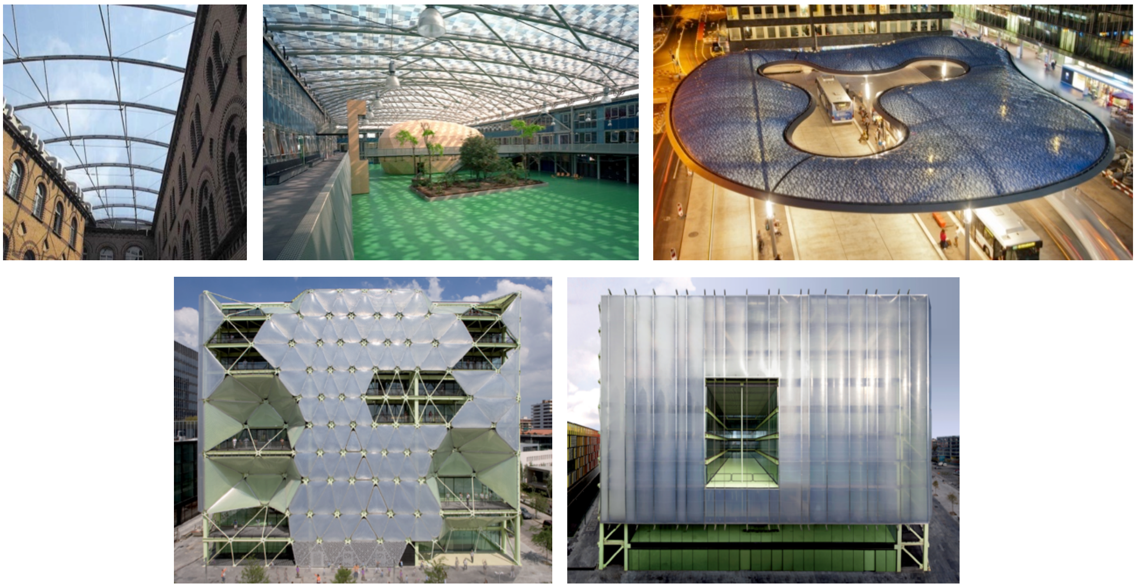


Figure 1: Roofs and facades for the comparison: top – left case 1 - the Kapuzinergraben in Aachen (Germany) [@Vector Foiltec], top – center case 2 - the Kingsdale School in in Dulwich, London (United Kingdom) [@Vector Foiltec], top – right case 3 – the Bus station in Aarau (Swiss) [@Vector Foiltec], bottom cases 4 and 5 – Media TIC in Barcelona (Spain) [@Cloud 9].

3. Methodology and computation

The requirements for the calculation of the first and second principles' ratios were - the dimensions of the covered area and - the perimeter of the profiles for the panels, - the quantities of material for the finishing layer (ETFE or glass) and – for the fixing system profiles (aluminium profiles both for the ETFE cushions and the glazing system). For each case study they were computed. The quantification was done at first for the real building. Then the design of alternative solutions made of glass and, in one case (A3), of a cushion as big as the whole roof area was speculated and defined, in order then to quantify, also in these cases, area, perimeter and the quantities of the involved materials. The quantification of the dimensions (area and perimeter) was based on precise information from the designers and the roofing/façade systems' producers, and from a redrawing of each case study roof or façade. The perimeter value is the sum of all length of the profiles around the edges of the envelope and the intermediate profiles. In the buildings designed as a composition of many panels, every one of these is sharing four or at least three edges with other ones: in these cases the profiles were considered one time in the calculations. Regarding the quantification of the weights of the technical elements (covering material and fixing system profiles) for each system the quantities, in terms of kilograms, for the profiles and the finishing layers were calculated starting from the perimeter multiplied for the section area of the profiles. Generally the quantities have some tolerances, caused by the rough estimation.

Regarding the fixing systems for ETFE cushions and in the design of the different compared solution, the typical specific aluminium keder profiles, mounted on an aluminium bar in connection with the main steel structure, were considered. Regarding the fixing systems for the glass solutions, the double safety glazing, fixed vertically or horizontally on main aluminium structure, with an ovoid section, by stainless steel fixed points, so called spiders, was the chosen option. The spider glass facade ensured the highest level of transparency and brightness of the glazing solutions actually on the market. In the ETFE technology of the biggest cushions, in order to avoid a consistent curvature of the cushion section and contrasting additional loads, a technical system made of profiles on the main edges and stiffening steel cable net was considered. In the systems with the glazing envelope, the authors speculated the recent advancements of the glazing industry, in order to design solutions with the biggest glazing panel, actually buildable by the floating glass industry: the maximum dimension is actually 3,2 by 16 meters. The ETFE inflated cushion systems can reach bigger dimensions of single cushions, thanks to the lightness of the foils, quite as big as the designer want, but the manufacturers advise not to exceed 200 square meters per pillow, as much larger cushions require more assembly difficulties and even more burdens in case of repairs. A static constraint, as well as a cost-effective dimension in terms of the economical efficiency of the system recommended by the manufacturers, is to consider a maximum distance of three meters between one profile and the other, in particular for the shells in order to safeguard the structure from the incidence of any snow load.

For each structure, both the weight of the profiles and the weight of the covering material were added, obtaining the total weight for each building (both existing and hypothesized). Finally, calculations were performed using the two principles. For the first principle, the perimeter of the profiles was divided for the area of the covering material (ratio between the perimeter and the covered area has to be minimized), while for the second principle the ratio of the covering material to the fixing systems indicated as a ratio comparing the weight of the covering material to the weight of the fixing system (as much as the value of the second ratio is higher, as the exploitation of the relative building technology is optimized; in other terms this ratio has to be maximized).

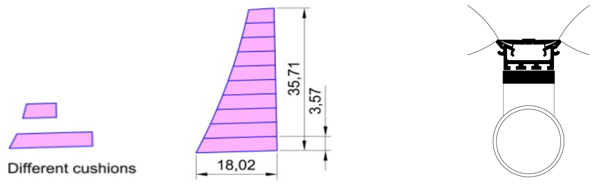
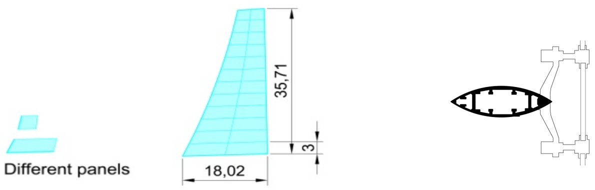
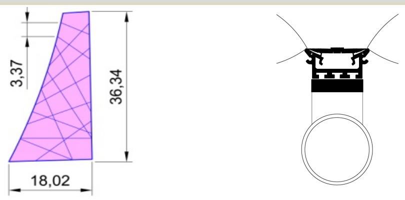
4. Results and comparison

The results of the comparison of the Membrane eco-efficiency principles carried out by the authors in the 5 case studies above mentioned enabled two main reading paths. Firstly the single case study's data can be internally and vertically compared, throughout the different design strategies the authors proposed as possible alternative design approaches to that original intention, which the designer really applied. On the other hand, the data allow the reader an enlightening interpretation on how differences building technologies seem to guarantee unvaried answers to the designers' needs, if only they respect the double sustainable principle of *doing more with less*. In other words, the reading of analysis data across different case study show that lightweight technologies allow the designers high degree of freedom in shaping geometries and forms, while only their optimized application will guarantee a sustainable and LCA effective result. This optimization design process can be properly achieved by both an effective envelope surfaces (*principle 01*) and a well-balanced weight ratio between the supporting structure in relation to the whole envelope surface (*principle 02*).

From the comparison of results some critical issues can be taken into account.

1. Firstly, some designs seem to push forward the ETFE technology, using a lighter sub-structure of steel ropes and cable, instead of wider aluminium profiles; as a result, the eco-profile of those design solutions are awarded, as it is emerging from the case study C1 and also confirmed by the author simulation of case study A3.

Table 1: Principles' results for the case study 1 (P= Perimeter, A= Area, We= Weight envelope finishing layer, Ws= Structural weight of the fixing system)

case study A: KAPUZINERCARREE, Aachen (Germany) - Architects: Ingenhoven Overdiek + Partner (2002)				***Principle 1*** **[P/A]**	***Principle 2*** **[We/Ws]**
A1 - ETFE			**FIXING SYSTEM**		
				**0,45**	**0,097**
P (m)	195,07	A (m^2)	390,82		
We (kg)	410,36	Ws (kg)	4.247,00		
We/m^2 (Kg/m^2)	1,05	Ws/m^2 (kg/m^2)	10,87		
Wtot (Kg)	4.657,36	Wtot/m^2 (kg/m^2)	11,92		
A2 - GLASS			**FIXING SYSTEM**		
				**0,65**	**9,852**
P (m)	252,76	A (m^2)	390,82		
We (kg)	17.820,00	Ws (kg)	1.809,00		
We/m^2 (Kg/m^2)	45,60	Ws/m^2 (kg/m^2)	4,63		
Wtot (Kg)	19.629,00	Wtot/m^2 (kg/m^2)	50,23		
A3 - ETFE			**FIXING SYSTEM**		
				**0,25**	**0,188**
P (m)	97,22	A (m^2)	390,82		
We (kg)	410,36	Ws (kg)	2.180,65		
We/m^2 (Kg/m^2)	1,05	Ws/m^2 (kg/m^2)	5,58		
Wtot (Kg)	2.591,01	Wtot/m^2 (kg/m^2)	6,63		

2. The ETFE technology shows some unquestionable advantage, which is emerging by every internal comparison of the single case study (A1 and A2; B1 and B2; and so on), as many LCA studies has been already shown [2, 4, 8]. Nevertheless, the designer has to aware that a non-optimal application of

the ETFE technology, again linked to the disregarding of the two "doing more with less" design principles, leads to the rising of environmental impacts very close to those ones which are typical of other common and heavier transparent building technologies. This is the case of the simulation design approach of D2 for glass in comparison to the real design strategy of D1 for ETFE, where we can notice a very disadvantaged result of the LC design principle 01.

3. Furthermore a well-optimized use of the typical ETFE supporting system in aluminium frame can be appreciated in some case studies, as i.e. A1 and B1, where further design simulations, as i.e. B2, E3 show us that the better ratio between P/A (as in B1 instead of B2) is confirming that the structural and manufacturing criteria of 3.5 m span cushion can be good and sustainable choice for the designers every time the snow loads have to be taken into account.

Table 2: Principles' results for the case study 2 (P= Perimeter, A= Area, We= Weight envelope finishing layer, Ws= Structural weight of the fixing system)

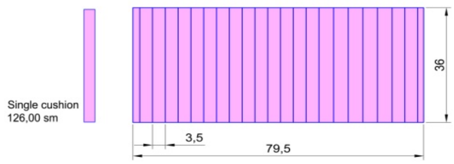
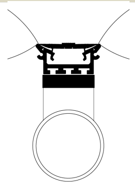
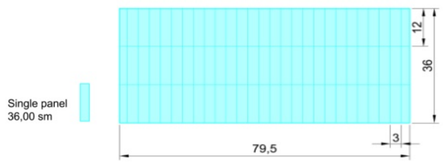
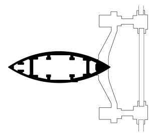
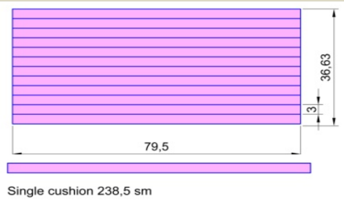
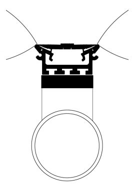
case study B: KINGSDALE SCHOOL, Dulwich, UK - Architects: de Rijke Marsh Morgan (2004)				***Principle 1*** **[P/A]**	***Principle 2*** **[We/Ws]**
B1 - ETFE			**FIXING SYSTEM**		
				**0,36**	**0,090**
P (m)	1.023,00	A (m^2)	2.862,00		
We (kg)	2.003,40	Ws (kg)	22.314,50		
We/m^2 (Kg/m^2)	0,70	Ws/m^2 (kg/m^2)	7,80		
Wtot (Kg)	24.317,90	Wtot/m^2 (kg/m^2)	8,50		
B2 - GLASS			**FIXING SYSTEM**		
				**0,46**	**13,811**
P (m)	1.326,00	A (m^2)	2.862,00		
We (kg)	130.512,00	Ws (kg)	9.450,00		
We/m^2 (Kg/m^2)	45,60	Ws/m^2 (kg/m^2)	3,30		
Wtot (Kg)	139.962,00	Wtot/m^2 (kg/m^2)	48,90		
B3 - ETFE			**FIXING SYSTEM**		
				**0,39**	**0,083**
P (m)	1.105,50	A (m^2)	2.862,00		
We (kg)	2.003,40	Ws (kg)	24.100,00		
We/m^2 (Kg/m^2)	0,70	Ws/m^2 (kg/m^2)	8,42		
Wtot (Kg)	26.103,40	Wtot/m^2 (kg/m^2)	9,12		

Table 3: Results for the case study 3 (P= Perimeter, A= Area, We= Weight envelope, Ws= Structural weight)

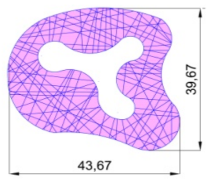
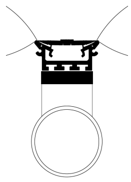
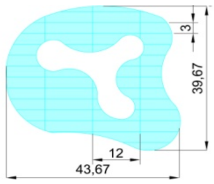
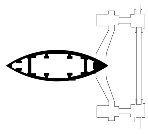
case study C: BUSBAHNOHF, Aarau (Switzerland) - Architects: Vehovar & Jauslin Architektur				***Principle 1* [P/A]**	***Principle 2* [We/Ws]**
C1 - ETFE			**FIXING SYSTEM**		
Unique cushion				**0,21**	**0,135**
P (m)	233,42	A (m^2)	1.084,81		
We (kg)	759,37	Ws (kg)	5.640,50		
We/m^2 (Kg/m^2)	0,70	Ws/m^2 (kg/m^2)	5,20		
Wtot (Kg)	6.399,87	Wtot/m^2 (kg/m^2)	5,90		
C2 - GLASS			**FIXING SYSTEM**		
Different panels				**0,63**	**22,900**
P (m)	684,12	A (m^2)	1084,81		
We (kg)	49.464,00	Ws (kg)	2.160,00		
We/m^2 (Kg/m^2)	45,60	Ws/m^2 (kg/m^2)	1,99		
Wtot (Kg)	51.624,00	Wtot/m^2 (kg/m^2)	47,59		

Table 4: Results for the case study 4 (P= Perimeter, A= Area, We= Weight envelope, Ws= Structural weight)

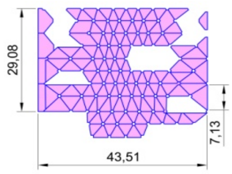
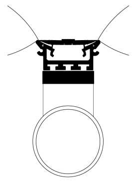
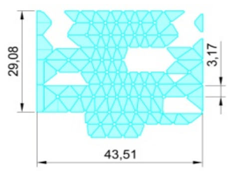
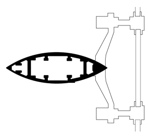
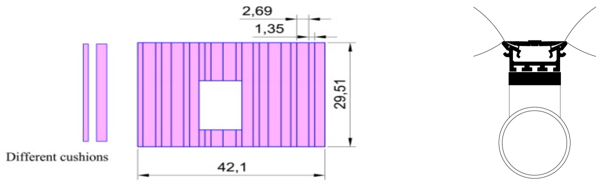
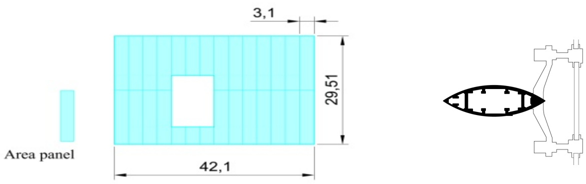
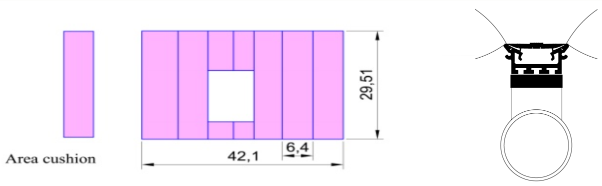
case study D: MEDIA TIC - facade 2, Barcelona (Spain) - Architects: Cloud9 (2007-2010)				***Principle 1* [P/A]**	***Principle 2* [We/Ws]**
D1 - ETFE			**FIXING SYSTEM**		
 Different cushions				**0,93**	**0,034**
P (m)	1.071,45	A (m^2)	1.146,02		
We (kg)	802,21	Ws (kg)	23.369,50		
We/m^2 (Kg/m^2)	0,70	Ws/sqm (kg/m^2)	20,39		
Wtot (Kg)	24.171,71	Wtot/sqm (kg/m^2)	21,09		
D2 - GLASS			**FIXING SYSTEM**		
Different panels				**0,95**	**5,290**
P (m)	1.087,15	A (m^2)	1.146,02		
We (kg)	52.248,00	Ws (kg)	9.882,00		
We/m^2 (Kg/m^2)	45,59	Ws/m^2 (kg/m^2)	8,62		
Wtot (Kg)	62.130,00	Wtot/m^2 (kg/m^2)	54,21		

Table 5: Principles' results for the case study 5 (P= Perimeter, A= Area, We= Weight envelope finishing layer, Ws= Structural weight of the fixing system)

case study E: MEDIA TIC - facade 2, Barcelona (Spain) - Architects: Cloud9 (2007-2010)				*Principle 1* [P/A]	*Principle 2* [We/Ws]
E1 - ETFE			**FIXING SYSTEM**		
				**0,63**	**0,051**
P (m)	696,44	A (m^2)	1.107,92		
We (kg)	775,55	Ws (kg)	15.219,00		
We/m^2 (Kg/m^2)	0,70	Ws/m^2 (kg/m^2)	13,74		
Wtot (Kg)	15.994,55	Wtot/m^2 (kg/m^2)	14,44		
E2 - GLASS			**FIXING SYSTEM**		
				**0,47**	**7,860**
P (m)	518,11	A (m^2)	1.107,92		
We (kg)	50.520,00	Ws (kg)	6.426,00		
We/m^2 (Kg/m^2)	45,60	Ws/m^2 (kg/m^2)	5,80		
Wtot (Kg)	56.946,00	Wtot/m^2 (kg/m^2)	51,40		
E3 - ETFE			**FIXING SYSTEM**		
				**0,37**	**0,086**
P (m)	412,75	A (m^2)	1.107,92		
We (kg)	775,55	Ws (kg)	8.967,00		
We/m^2 (Kg/m^2)	0,70	Ws/m^2 (kg/m^2)	8,09		
Wtot (Kg)	9.742,55	Wtot/m^2 (kg/m^2)	8,79		

4. Conclusion

The paper has shown the validation of the mentioned LCA design procedure through five different case studies of ETFE built structures, both compared with a) other conventional transparent technology, b) other designs and geometries of ETFE cushions. 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. The improvement and application of these eco-efficiency analyses will be meaningful for the optimization of the design of foil building skins, from the technically, economically and environmentally point of view.

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WG2 on Sustainability and LCA of structural skins. The authors would like to thank the COST initiative to support all the scientific exchanges between the involved partners.

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