Eco-design principles for a preliminary eco-efficiency assessment in the design phase: application on membrane envelopes

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Abstract

Stating the necessity of increasing the designers’ awareness of both lightweight and flexible materials and their performances, in a life cycle thinking perspective, this contribute is based on the updated identified needs of the membrane sector (Cost Action TU1303, 2017): Life Cycle Assessment, durability aspects, recyclability, social acceptability, thermal, optical, acoustic comforts. Into the frame of the Tensinet association activity, the Textile Architecture Network of Politecnico di Milano is continuing the search of Eco-design strategies and enlarging the mapping of case studies, by the application ex-post of two eco-efficiency principles in order to verify their validness and their efficacy for the designer’s need, during the design process of a membrane system. The main advancement of this work is here presented adding new membranes case studies to the initial analysis. The aim is to verify the applicability of the principles to a wider and different uses of membranes and the identification of reference rates. The results demostrate relations between the rate of the eco-efficiency, the year of construction and the evolution of the technology and the impostance to take into account in the design phases the environmental impact of membrane structures.

Keywords: Sustainability and comfort, membrane architecture, eco-efficiency principles, ETFE envelope, case studies.

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1. Introduction

Currently the construction industry has a considerable impact on the sustainability of the society, and consumes a substantial amount of raw materials (Vivian, Khoa, 2019; EU, 2018). The environmental effects of the construction of a building are dependent on the choice, of materials and construction techniques, made in the design process. It is therefore necessary to opt for solutions suited to the expected performances, with the lowest environmental impact. The material search in architecture is going toward the lightness, with the optimization of the thickness, the section and the quantity of materials in a construction. When evaluating the energy performance of a membrane closure, more often employed in permanent buildings, immediate reference is to the requirements of thermal insulation, thermal inertia, solar control, ventilation: the higher the performance, the lower the use of mechanical systems to ensure an optimal microclimate and, consequently, greater energy savings. In addition to these aspects, it is essential to demonstrate also how the design and shape affect the performance of the envelope, in order to improve its eco-efficiency. Light in the shape configuration or lightweight and, therefore, a reduced impact? Some interesting solutions seem to be considered innovative and eco-efficient because of their lightness like the membrane structure: but this alleged correlation does not mean that lighter is more sustainable, even when compared to heavier and more massive solutions. The quality and eco-efficiency of a membrane building are not linearly dependent on the environmental profile of the individual material. Consideration must be given to other factors such as the amount of needed material for one technical solution over another (which is not proportional to the surface of the building, but to the density and thickness of the material involved), the design of the envelope and its parts and structural fixing system.

2. Aim of the study - Eco-design principles for membrane buildings

Due to the current gap between studies and real practice in membrane architectural design, the research takes care of harmonizing the available eco-data for the membranes and proposing a first set of eco-design principles. A strong effort to overcome fragmentation and encourage the sharing of information and experiences between companies is underway thanks to TensiNet, a multidisciplinary association for those interested in building structures of members in tension. Into this activity, the Textile Architecture Network of Politecnico di Milano is continuing the search of Eco-design strategies for the membrane architecture (Monticelli et alii, 2017). The aim of this research is to validate the eco-efficiency principles and to insert them in the design guidelines for membranes to be used during the design process: a. the current stage is focusing on enlarging the mapping of case studies, by the application ex-post of two eco-efficiency principles, to verify their validness and their efficacy; b. the expected next step is their introduction in the best practices for membrane
design and their verification on the specific project during the design process of a membrane system. These eco-efficiency principles aim to be considered as a verification stage in the design process, quite similar as 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, in relation to 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 and eventual specific Life Cycle Assessment.

Their verification helps to point out the advantages and disadvantages of membrane materials and the correct exploitation of their characteristics. The evaluation criteria mostly concern three relationships: 1st principle - the comparison between the sum of the Perimeters of the membrane modules with respect to the Surface covered by the envelope solution; 2nd principle - the comparison between the weight of the membrane and the weight of the fixing systems; 3rd principle - the comparison between the supporting structure of the membrane and the mechanical load of the structure itself. These principles are applied on membrane structures, roofs and facades.

First principle \([P / A]\) - this principle aims at evaluating the eco-efficiency of a surface, be it a roof or a facade, which has the task of covering or closing a space by highlighting the use of panels and sheets of which a membrane can be formed. When the value resulting from the ratio is very low and approaches zero, it means that the surface taken into consideration is composed of a single cushion or is composed of the fewest possible panels and therefore the frame perimeter that supports the fabric is the minimum essential. This corresponds to a reduction in the structural material used for the fastening system and consequently, a reduction in environmental impacts (the concept of doing more with less).

Second principle \([We / Ws]\) - the second principle aims at analyzing the Life Cycle impact of the membranes and the effectiveness of their choice and to do this it is necessary to verify the quantity and weight of the total elements that make up the casing, or the fastening system, and their real need in terms of structural loads and rigidity, and of the membrane system used as a real dividing element between inside and outside. The higher the value of the ratio is 1 and the closer it is to 1, the more it means that the weight of the fixing systems, which is usually very important with respect to the weight of the fabric, is reduced and optimized.

Third principle - verification of the structure relationship of the membrane / mechanical load of the structure: this principle considers steel and wood as materials mainly involved in membrane structures. Starting from this base, it optimizes the mechanical aspects and the structural behaviors and their form with a relation with respect to the quantity of used material.
3. Application on membrane case studies for the principles’ validation

The core advancement of this work is here presented adding new membranes case studies to the collection started in 2017 (Monticelli et alii), in order to enlarge the application of the principles to a wider and different uses of membranes, and to comprehend possible relations between the rate of the eco-efficiency, the year of construction and the evolution of the technology. The previous study (2017) was focused on the application of the two first principles and on the comparison of the built envelope solutions with hypothetical comparisons made by glass or optimized membrane solution. In this study the application was conducted on different case studies, starting with the ex-post application of facades or roofs existing in ETFE. In this case specifically the objective is to evaluate the results obtained for the two principles among the different configurations and to understand which is the objective reference parameter, to compare the project eco-efficiency. This comparison allow to identify which configuration and technological solutions best optimize the use of light technologies and, consequently, reduce environmental impacts. The cases were chosen based on the different aesthetic configurations that were obtained during the design phase, to investigate how the shape can affect technology and then the impact on the environment. The choice was also determined by the level and quality of the information obtained from the project engineering and installation companies.

3.1. Case studies

The first two principles were verified and compared by selecting 13 buildings with ETFE casing, analyzing their formal and material characteristics. Buildings with an ETFE envelope were selected thanks to the necessary information, obtained sometimes more easily or for such cases desumed from the drawings. In some cases the ETFE systems are composed with roof, in others only for the facade and in some others both. Thus a total of 8 cases of coverings and 10 of facades were analyzed (fig. 1).

The Kapuziner carree in Aachen, Germany (2002) (an atrium roof on an existing building), the atrium of the Kingsdale School in Dulwich, London, United Kingdom (2004) (part of a new school), the Busbahnof in Aarau, Swiss (2013) (an enormous cantilever roof, for the bus station with an organic curved shape), the two facades with the ETFE cushions of the Media Tic building in Barcelona, Spain (2009) are part of the calculation developed in the previous studies [4].

Eight additional buildings were added to the previous analysis.

The Sport Hall in Korce, Albania (2018), has a curved roof with three layers ETFE pneumatic cushions and two vertical facades.

The Auditorium 1919 – Sacmi, Imola, Italy (2017), is a tertiary building, of which two sides are built with three layers ETFE pneumatic facades.

The City Life shopping center in Milan, Italy (2015), has a big multicushion roof with three layers ETFE for covering the shopping mall.
The Actor Galaxy Apartments Complex in Sochi, Russia (2014), is a residential multi-storey and multi-owners building with a big multicushion roof with three layers ETFE for covering the internal common courtyard.

The Equipement Polyvalent Lille, France (2013), is a multipurpose cultural center with facades in large regular cushions with two backlit ETFE layers.

The Chemnitz Station, Germany (2012), is the main trains and buses station, renovated by a wrapped double layers ETFE facades.

The Schloßhof in the Dresden Schloss, Dresden, Germany (2008), during the reconstruction of the castle, has the roof of the small courtyard made with two layers romboidal ETFE cushions for covering the foyer of the castle museum.

The Unilever Headquarter in Hamburg, Germany (2009), has the second skin of the building built with a single layer ETFE tensioned facade system.

3.2. Methodology and calculation

The necessary details, namely the design drawings and the dimensions of the components, for the calculation of the first and the second principle, were provided by the designers and by the producers and installation companies of the membrane systems.

To calculate the first principle, the dimensions of the components of the considered roof or façade were taken into consideration: the perimeter of the cushions or panels, therefore the sum of the lengths of the profiles (both perimeter and intermediate between a cushion / panel and the other) and the surface area covered by the same layer of the cushions, which usually have slightly higher areas being inflated and curved.

For the second principle, the quantity of materials used is introduced: the weight, expressed in kilograms, of the ETFE membrane and the profiles of the fixing system is taken into consideration. These elements have been calculated for each case study.

The quantification of the dimensions (area and perimeter) is based on precise information provided by the designers and producers of the company taken into consideration. Some companies have provided us with drawings directly and in those cases the data have been calculated based on these drawings, adding the lengths of the profiles and calculating the areas in m². In building systems made up of many panels, the profiles were considered only once in the calculations, being shared between two panels. Also with regard to the data referring to weight, both of the membrane and of the fixing system (not supplied in most cases) an average density of the materials in question was considered, successively multiplied by the total volume. The density considered for ETFE films is 1700 Kg/m³, for aluminum profiles 2700 Kg/m³ and 7800 Kg/m³ for steel profiles. Generally, the results have, understandably, some margins of uncertainty, given some approximate estimate of the dimensions.

To obtain the values referring to the first principle, the perimeter has been divided by the overall area of the roofing material. For the second principle the ratio is obtained by dividing the weight of the roofing material with the weight of the fixing material.
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Figure 1: The compared building envelope solutions and their dimensions.
4. Results

A tendency of the evolution of the membrane technology, but at the same time a contrast between the best practice focused to the eco-efficiency and the independent design choices of the designers is gathered. The results obtained allow us to understand how the different configurations of the covers or facades presented start from design will linked to the shape, structural optimization and also to the experimentation of advanced solutions with ETFE pneumatic technology.

The quantification offers indications to understand how the geometry of a façade or have a roof, on which the quantity of material to be used depends, is decisive in influencing the environmental impacts. Moreover it allows understanding if the technology has also evolved over the years or if it is only the result of curious applications without a deep knowledge of the intrinsic possibilities of the membrane systems by the designers.

The graph in figure 3 shows the results divided by type of layer or cushion used and, in each group, listed in chronological order. In order to specify and explain the value derived from the principles, it seemed effective to analyse the case studies by categories:

a. category 1 Regular facades: Equipment Polyvalent Lille (7) and the Chemnitz Station (8);

b. category 2 Covers: which includes the coverage of the Korce Sports Center (1A), the Lilientalhaus (3), that of the City Life Shopping Center (4), the Actor Galaxy Complex Sochi (5), the coverage of the Busbahnhof in Aarau (6), the Schlosshof (9), the Kingsdale School (11) and the Kapuzinercarree (12);

c. category 3 Irregular facades: including the Sacmi Auditorium (2) and the facades of the Korce sports center (1B -1C), the Media Tic (10) and Unilever (13).

Additionally the representation of the results follows a chronological order, to understand if research and development in the textile sector have evident improvements, notable during the last years.

As far as the first principle is concerned, it is preferable that the result is very low, closer to zero, or, with respect to the area covered, the perimeter of the cushion profiles is limited: therefore the wrapping solution has been optimized from the point of view maximum surfaces that can be covered with this technology. From an interpolation of data from these case studies and from the parametric analysis of Chilton (2013), it emerges that the value close to 0.7 is a limit above which the first principle is not positively satisfied.

Regarding the second principle, it is preferable that the value is greater, closer to one, since it means that the ratio of the weight between the membrane and fixing profiles is balanced and therefore that the weight of the profiles is not much higher than that one of the membrane.

The nature of textile cladding layers suggests their application for a curtain wall, made of big panels instead of many small panels, exploiting all their potentials and especially enhancing the ratio “frame/covered area”, by avoiding the use of lightweight material with a high weight of the structure, which penalizes the environmental performance.
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It can be highlighted how, with regard to category 1 of the regular facades, the results are slightly different from each other, both for the first and for the second principle, with a
maximum value of $P/A = 0.73$ of the South facade of Chemnitz Station (8A) for the first principle, which means that, with respect to the West facade with a value of 0.60 and to the façade of the Polyvalent Lille Equipment equal to 0.64, the total profiles’ length for the fixing system is greater in relation to the area covered.

For the second principle the obtained results are $W_e/W_s = 0.08$, 0.09 and 0.07 respectively, values very similar to each other but still far from a balanced relationship between the weights of the materials used.

If the results of category 3 - irregular façades - with those of category 1 are compared, it emerges on average, that the values are higher for the first principle, meaning that the ratio of the surfaces to the area is less optimized. This could be due to the fact that the use of regularized geometries means less use of fixing profiles compared to the use of a more sophisticated design. In fact, a peak is of 0.94 for the façade A of Media Tic and 0.92 for Unilever, then 0.84 and 0.83 for the façades of the Sacmi Auditorium.

For the second principle the results are clearly different than in category 1 with a peak that reaches 0.39 for the Sacmi Auditorium, a higher value than the category 2 - coverings, which reached a maximum of 0.23 with the Schlosshof castle roof in Dresden. Also the facades of the Korce Sports Center show considerable results equal to 0.20 for the main North-West façade and 0.18 for the South-West façade. This means that, for category 3, the material used for the fixing profiles is closer to the weight of the membrane. The reason is due to the choice of the materials: the profiles for the Auditorium and for the Sports Center are made entirely of aluminium while those used for the Chemnitz Station have been used both aluminium and steel, which has a clearly higher density equal to 7800 Kg/m$^3$ compared to 2700 Kg/m$^3$ of aluminium. This is demonstrating how the impacts of the design choices has relapses on the eco-profile of the building.

Regarding category 3 - the roofs, the data obtained are quite different from each other. For the first principle the best result is for the case of Lilientalhaus and the Aarau Busbahnhof, equal to 0.21, a value that is even better compared to categories 1 and 2. This intervention strategy leads to better results having only a huge cushion, the perimeter of the profile is much lower than another technology being present only in the perimeter part. It must be said, however, that this type of structure has disadvantages in terms of maintenance: if a cushion were to break in such a fragmented covering, it would be sufficient to replace only the one in question, whereas in the Lilientalhaus and Busbahnhof the only solution would be to change the entire membrane. All this to the detriment of the coverage of the Korce Sports Center, which presents a poor result satisfactory equal to 0.83. This means that the area that is covered in Korce is almost the same as the perimeter of the fixing system and this is inconvenient as they could have used less material for the profiles and therefore not only had economic advantages, but also more precautions regarding the environmental impact.

The result for the covering of Schlosshof are higher overall and, for the first principle, they demonstrate, looking the geometry of the panels, the inefficacy thinking to a comparative
solution made by glass: the lightness of the covering material is not exploited to be optimal. But enlarging the evaluation to the second principle the ratio $W_e/W_s$ has a valid result, and that is a good balance between the weight of the double layer envelope and the supporting structure. It has to be noticed here that the last one has the role also of the primary structure, without additional components.

For the second principle, City Life Shopping Center is the most optimized project in category 3 with a value of 0,28. Instead, the Actor Galaxy Complex Sochi has a fairly low result of 0,07. For the sports coverage in Korce the second principle is on average equal to 0,16, this means that it is more optimized in the weight ratio (principle 2) rather than in that of surfaces (principle 1).

As it is notable from the previous work which analysed the cases chosen not only as planned but assuming to replace the ETFE with glass to see the differences, the use of glass would have led to a greater imbalance for the second principle in that the weight of the glass would have been of great length greater than the weight of the fixing structure, bringing the values up to 9, 13 or even 22 (Monticelli et alii, 2017). The reading of the results indicates that lightweight technologies allow designers a high degree of freedom in shaping geometries and shapes, while 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 in relation to the envelope (principle 2).

5. Conclusions and further developments

The improvement and application of this eco-efficiency analysis will be significant for optimizing the design of lightweight structures, from a technological, economic and environmental point of view, providing ideas and clear references available to designers and manufacturing companies. The three principles, developed from the interconnection between research and design and production and realization areas, require a deepening of the experts, to avoid a purely theoretical vision and analyse the validity of these three principles and their convenience, also in the practicality of installation and maintenance. Looking at the principles, in terms of eco-efficiency, these solutions are optimal but in the design phase it is necessary to consider different approaches to balance. The designer, for example, might prefer a single cushion for an aesthetic factor or for a visual matter, to allow the greatest amount of light to enter. However, the other phases of a building’s life cycle have to be considered in the whole assessment. In fact, this solution could lead to risks during installation of a single cushion/panel, which should then be replaced entirely in case of damage. It is understandably more handily and safe to install a structure divided into many cushions, therefore with a global longer profile length, despite to the environmental impact. It is, therefore, appropriate to find the right balance between many factors, with respect to the context of the project.
Further steps of the research are oriented to investigate the third principle, which needs a more sophisticated tool to correlate the design of the structure, its optimization and the minimizing of the involved materials. The trend is going towards the elaboration of a parametric procedure to be easily interfaced with the changing choices during the design process, in order to immediately observe the results of the three principles, adding the possibility of a real time variations of materials and quantities for the optimization of the environmental impacts. In the construction sector one the recent trends is the integration of building information modelling with the life cycle assessment (LCA) and life cycle costing (LCC) (Santos et alii, 2019).

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