International Symposium on "Novel Structural Skins: Improving sustainability and efficiency through new structural textile materials and designs"

Sustainability – the art of modern architecture

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Abstract

Over the last 10-15 of years the building industry has been faced with an increasing demand for sustainable solutions. According to Peter Bakker, president and CEO of the World Business Council for Sustainable Development (WBCSD), buildings are the largest energy consumers in the world economy, accounting for over one-third of final energy use and approximately 30% of global carbon emissions [1]. These figures do not take into account the energy and carbon emissions due to production of building materials or for logistics and building construction. The demand for both energy and resources is soaring as global construction booms, especially in countries such as China and India. This means that developments in building practice can significantly contribute to tackling climate change and energy use. The use of ETFE foils as a new transparent material substitute for glass provides the potential for not only vast savings in material quantities but simultaneously makes possible a new type of space for living and working. The environmental benefits are presented as results of a comparative study between glass and ETFE solutions on two projects in Germany, Domäquarée in Berlin and Kapuzinergraben in Aachen, based on a life cycle analysis. The social benefits will be presented using the example of Kingsdale School in London and Kuwait Avenues, Kuwait. It will be shown that the introduction of ETFE foil systems in modern architecture will significantly contribute not only to environmental sustainability, but also create economic and social advantages compared to more classic building materials.

Keywords: LCA; building cladding systems; membrane structures; ETFE; foils; sustainability; environmental; social; economic; comfort

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1. Introduction

The term “sustainability” has been applied extensively to many products and activities in recent years. It is generally considered that there are three distinct sectors in which sustainability can be effected and enhanced.

- environmental sustainability
- economic sustainability and
- social sustainability.

In the case of the building industry there is a strong demand for solutions that provide benefits for all of the three sectors. As global warming has increasingly become one of the main areas of social concern, reduction of energy consumption as well as significant prevention of pollution and damage to the natural environment is recognized as a task of highest priority [2]. As a consequence and in order to provide sufficient well protected living space for a still growing population worldwide the building industry is asked to provide more building space whilst simultaneously using less materials. Additionally a building’s energy consumption during the use phase should be minimized, which is not only a criterion for new buildings but for existing buildings and particularly heritage buildings. These parameters should be taken into account as well in the context of energy efficiency refurbishment.

Special attention has always to be payed to the costs involved in building structures. Environmentally sustainable buildings offend against fundamentals of economic sustainability if cost-efficiency is not taken into account. “Plus-energy-houses” that cannot be afforded by most of the building owners are by no means models for environmental sustainability.

Additionally new buildings as well as refurbishment of buildings have to allow for the altered social demands of multicultural societies. Light and spacious but well protected areas should come along with comfort, energy savings and aesthetics in order to create living spaces where people can meet.

The objective of this paper is to explore the potential of new building cladding systems, ETFE foil membrane systems in particular in comparison to more classic concepts, for instance glazed roof structures.

Special attention has been payed to environmental sustainability by means of a comparative life cycle assessment of two projects that were originally designed with glazed roofs but, due to loading problems, were subsequently realized with a Texlon® ETFE foil cladding system. All materials and their corresponding masses for the cladding system as well as for the primary supporting structure are well known for both the glazed and the ETFE foil solutions. The Life Cycle Assessment (LCA) framework was used to analyze the whole lifetime of the products and their components, from extraction of raw materials to disposal or recycling [3].

2. The projects

2.1. DE Berlin, Domaquarée – building D

In 2004 the architects nps Tchoban Voss GmbH & Co. KG, Hamburg, designed the Domaquarée complex on Alexanderplatz in Berlin which comprises four different buildings A, B, C and D (a four star hotel, an office and retail building, residential apartments, an open passage and the world’s largest indoor saltwater aquarium). The atrium of the office and retail building D is covered by a 1533 m² ETFE roof 33 meters above the floor. Initially the architects designed the roof in glass but because of load problems changed to a Texlon® ETFE system.

For the glass roof, panes of 2700 mm x 1330 mm were specified, supported by a steel structure and a secondary aluminum structure.

The Texlon® roof consists of 14 ETFE cushions with lengths between 36 m and 43 m, and widths between 2.66 m and 3.45 m.
2.2. DE Aachen, Kapuzinergraben

In the historic city of Aachen, a neglected and underused courtyard of 500sqm was in 2002 turned into a comfortable atrium in order to protect restaurant customers from the elements. The difficulty of this project was the historical façade which could not be modified.

In the first instance the architects KKK Ingenieure GmbH, Düsseldorf, planned the roof to be built in glass, with panes of 2020 mm x 1500 mm. But as the walls of the building could not support the weight of glass panes, the aluminum frames and the steel structure, several steel columns had to be added in order to split the loads and to reduce the stress on the façade, in particular horizontal loads. Since the passage was a heritage building additional steel columns were not allowed.

The alternative roof designed with a Texlon ETFE foil system was composed of 10 cushions supported by a sophisticated lightweight network of steel beams and cables. Due to the lightness of the materials and the load distribution the historical façade was not endangered.
3. Life Cycle Inventory LCI for Texlon® ETFE and glass cladding system

The quantity of material was estimated from the original plans provided by the architects nps tchoban voss (Domaquarée), KKK Ingenieure GmbH, Düsseldorf (Aachen Kapuzinergraben), and Vector Foiltec GmbH, Bremen, Germany.

Data concerning the production process for Texlon® and insulating glass units were collected in the framework of a cradle-to-gate life cycle assessment and provided by PE INTERNATIONAL AG.

Data concerning steel production and recycling were directly provided by the World Steel Association. Data concerning aluminum recycling were present in the GaBi professional database [4] and directly confirmed by the European Aluminum Association.

The absolute quantity of materials used for both projects Kapuzinergraben and Domaquarée [3] is shown in Table 1. The direct comparison of data for the ETFE and glass solutions provides good evidence of the environmental performance regarding material resources. For evaluation it is important to mention, that for Kapuzinergraben the primary supporting structure for glass had to be massively reinforced by installation of steel columns.

### Table 1. Absolute quantity of materials and percentage of total mass required for each roof type

<table>
<thead>
<tr>
<th>Project</th>
<th>Domaquarée</th>
<th>Kapuzinergraben</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>kg</td>
<td>kg</td>
</tr>
<tr>
<td>Steel</td>
<td>95466</td>
<td>103066</td>
</tr>
<tr>
<td>Aluminum</td>
<td>3719</td>
<td>22103</td>
</tr>
<tr>
<td>ETFE</td>
<td>1323</td>
<td>420</td>
</tr>
<tr>
<td>Glass</td>
<td>59311</td>
<td>17601</td>
</tr>
<tr>
<td>EPDM</td>
<td>216</td>
<td>420</td>
</tr>
<tr>
<td>PP</td>
<td>33</td>
<td>9.18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100756</td>
<td>184900</td>
</tr>
</tbody>
</table>

ETFE cushion systems require an inflation system to maintain the pressure inside the cushions (appr. 200 Pa). The mass of each component of the inflation system was estimated on the basis of technical data sheet provided by Vector Foiltec. The composition used in the model is given in Table 2:

### Table 2. Composition of the inflation system.

<table>
<thead>
<tr>
<th></th>
<th>Domaquarée</th>
<th>Kapuzinergraben</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation unit</td>
<td>2 x LTK3-1</td>
<td>LK-1500</td>
</tr>
<tr>
<td>Aluminum housing</td>
<td>54 kg</td>
<td>10.5 kg</td>
</tr>
<tr>
<td>Steel fan</td>
<td>20 kg</td>
<td>5 kg</td>
</tr>
<tr>
<td>Electronics</td>
<td>40 kg</td>
<td>10 kg</td>
</tr>
<tr>
<td><strong>Air dryer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel housing</td>
<td>39 kg</td>
</tr>
<tr>
<td></td>
<td>PTC heater</td>
<td>6 kg</td>
</tr>
<tr>
<td></td>
<td>Rotor</td>
<td>6 kg</td>
</tr>
<tr>
<td></td>
<td>Dryer motor</td>
<td>1 kg</td>
</tr>
</tbody>
</table>
Regarding overall amount of materials mass the contribution by the air system is minimal whereas energy consumption for whole lifetime has to be taken into account and will be discussed in paragraph 5.

Inflation units often comprise a small dryer system with a back-up fan to reduce the condensation within the cushions. The components of the inflation unit are expected to have the same lifetime as the roof, even if a regular inspection is necessary. As example, the inflation units of the Burgers’ Zoo in Arnhem, Netherlands, have never been replaced since installation in 1982.

For Domquarée the amount of steel required for the ETFE solution is approximately 90% of the glazed solution. The difference in total mass of ca. $84 \cdot 10^3$ kg is due to less mass of the cushion foils plus less aluminum used for secondary supporting structure. The total mass of aluminum for Texlon is approximately 17% of the glazed solution.

For Kapuzinergraben the supporting structure for ETFE did not require any additional steel columns. As a consequence the total mass required for the glazed solution is more than seven times the total mass of the Texlon® ETFE system. The significant advantage of the Texlon® foil roof is based on the low total mass of the cladding system allowing for vast savings at the primary structure (steel) since horizontal loads could be minimized and thus the classic facades were used for supporting the roof.

The consumption of the inflation system was estimated from average consumption measurements and technical datasheets of the materials. The cleaning operations data (quantity of water and frequency) were provided by Service Professionnel Nettoyage, St Germain en Laye, France.

Recycling of ETFE foils was documented by PETERS-plastic GmbH, Kelkheim, Germany. Not all elements were listed for this process. The main information was the energy consumption and the waste rate.

EU-15 power grid mix and diesel (from GaBi Professional database) were used for all transportations and productions in European countries. German power grid mix and diesel were used in all transportations and productions inside Germany.

4. Life cycle assessment LCA for Texlon® ETFE and glass cladding systems

The life cycle assessment for both solutions is carried out by means of the LCA software GaBi 4 [4], in compliance with ISO 14044 2006 [5]. The functional unit is one square meter of transparent roof. The study is a Cradle-to-Grave LCA, including the extraction of raw material, production of final products, use phase of the roof and end-of-life. All transports, including transport of raw materials and intermediate products, are taken into account. Use of the building as well as heating, cooling and lighting are not taken into account. The eventual service lifetime of Texlon® ETFE roof systems is not known but since the first project built with ETFE is 33 years old and still in perfect condition, a lifetime of 30 years is considered for both the foil and the glazed solutions. The lifetime of glazing in commercial buildings ranges between 25 and 40 years. Saint Gobain as well states a service lifetime for glass panes of 30 years [6].

4.1. LCA for Texlon® ETFE

The life cycle assessment for the Texlon® ETFE system has been calculated as part of the development of an Environmental Product Declaration for the Texlon® system of Vector Foiltec GmbH [7]. It is carried out in accordance with the boundary conditions specified in the PCR document “ETFE construction element” [8] and the general program rules of the Institut Bauen und Umwelt e.V. [9]. In order to cover the whole life cycle from cradle to grave the LCA information of the three companies involved in the production of the Texlon® system 3M Dynene (Burgkirchen, Germany, responsible for the production of the ETFE raw granulate), Nowofol (Siegendorf, Germany, responsible for the extrusion of the ETFE foils), and Vector Foiltec (Bremen, Germany, responsible for design, production and installation of the Texlon® system) has been evaluated by PE INTERNATIONAL AG in such a way that it can directly be used for the Environmental Product Declaration (Type III) [10].

The Texlon® system declaration [7] refers to the manufacturing of 1 m² of a standard foil cushion with a mass per unit area of 0.967 kg/m², and the average quantity of frame material required for the assembly of the roof construction. This mass refers to an average annual consumption of ETFE foils, Aluminum and Silicon gaskets in
2010. The main components are listed in table 3. The average value can change according to for instance different annual average cushion size or different numbers of ETFE layers. Table 4 shows the main components as results of the annual average quantities used in 2012 [11].

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass required [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETFE foil cushion</td>
<td>0.97</td>
</tr>
<tr>
<td>Aluminum profile</td>
<td>4.57</td>
</tr>
<tr>
<td>Gasket</td>
<td>0.016</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass required [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETFE foil cushion</td>
<td>0.896</td>
</tr>
<tr>
<td>Aluminum profile</td>
<td>4.02</td>
</tr>
<tr>
<td>Gasket</td>
<td>0.212</td>
</tr>
</tbody>
</table>

Due to a change of the gaskets towards a full width Silicone gasket the quantity of gasket was enhanced in 2012. Due to enhanced cushion sizes (the amount aluminum extrusions could be reduced) and less number of foil layers the total mass of ETFE foils and aluminum extrusions were reduced both by approximately 10%. Since EPD’s are setup in order to provide indicators for the optimization of the environmental performance of a building product the selection of 1 m² as reference unit provides good evidence.

The selected standard foil cushion consists of three layers of NOWOFLON® ET-foil (top layer 200µm, middle layer 100µm and bottom layer 200µm), keder and valve. After the cushions are installed, inner air pressure of approximately 200 Pa is provided by air units in order to inflate the cushion and to compensate for pressure fluctuations due to temperature variations.

4.2. LCA for Double Glazing

The first EPD for different types of glass has been published in November 2012 [6]. Data for the comparative study have been provided by PE INTERNATIONAL AG from their Gabi database since they were performing a life cycle assessment of glazing for windows and doors and therefore were able to provide the required information.

The glass considered is representative of the products used for roof constructions. It is a double glazing system with panes 6 and 8.8 mm thick enclosing an air gap of 16 mm. For safety reasons the thicker pane consists of two panes, laminated with a PVB (Polyvinyl butyral) film. The nominal thickness of the glass panes used for the laminate is 4 mm each. The thickness of the PVB film is 0.76 mm.

5. Life Cycle Impact Assessment LCIA for Texlon® ETFE and glass cladding systems

Based on the Life Cycle Assessment for both the glazed and the ETFE solution the environmental impacts have been assessed according to seven indicators of the CML method of Leiden University, updated in November 2009. Although only midpoint impacts are characterised, the environmental cause-effect chains [12] are:

- Abiotic Depletion Potential ADP elements
- Abiotic Depletion Potential ADP fossile
- Acidification Potential AP
- Eutrophication Potential EP
- Global Warming Potential GWP
- Ozone Layer Depletion Potential ODP
- Photochemical Ozone Creation Potential POCP

The results of the life cycle impact assessment of one square meter of roof for both cladding systems glass and Texlon® ETFE for the project Domquarée are presented in figure 1, for the project Kapuzinergraben in figure 3:
normalized on the Texlon® solution for Domaquarée figure 4 shows strength and weak points of the systems analyzed:

For all indicators, Texlon® has minor impacts, due to the minor quantity of materials used, except for ODP. Ozone layer depletion potential is much higher for Texlon® roofs than for glass roofs (2.4 to 2.7 times higher). Nuclear power plants represent a large contribution, because of the emissions of R11 and R114 (respectively trichlorofluoromethane and dichlorotetrafluoroethane) used as refrigerants for the reactors. Nuclear energy represents one third of the German power grid mix. However, with the decision of German government to phase out nuclear generation, ODPS of both cladding systems will be drastically reduced. This indicator is therefore closely related to the power consumption, explaining the importance of the use phase for Texlon® roof.

In Figure 5 the details of the production phase are presented. For Texlon® roofs, the contribution of ETFE cushions to the ODP is very important. Actually, although IGU production requires much more power than the production of Texlon® cushions, their ozone layer depletion potentials are almost equivalent (6.229 x10^-6 kg R11-eq/m² for Texlon® vs. 6.377 x10^-6 kg R11-eq/m² for IGUs). Indeed, ETFE is a halogenated polymer (it contains fluoride) and is polymerized from R22 (chlorodifluoromethane) which contains chloride atoms, which can dissociate the ozone and contribute to ozone layer depletion. As no measurement on the emissions was available of this chemical, a worst-case assumption was made. The R22 emissions represent 76% of the ODP during Texlon® cushions production and 62% of the production process for the whole roof.
6. Results and discussions

6.1. Environmental sustainability

Globally, the results of the environmental impact assessment are better for the Texlon® roof than for the glass roof, except the ODP. The results obtained for Kapuzinergraben are due to the massive additional steel structure required for the glazed solution which even if not representative for a typical Texlon® system, indicates the potential in certain building applications.

The use phase was proven to have a significant contribution to the environmental impacts of the Texlon® roof. There is at the present time no systematic measurement on-site of the consumption of the inflation units. The average consumption of Texlon® roofs is assumed to be comprised between the values of Kapuzinergraben and Domaquarée.

Concerning the ozone layer depletion potential, the emissions of chlorodifluoromethane during the synthesis of ETFE have to be measured to evaluate the real level of hazardous substances. The potential impacts during the use phase can be dramatically reduced by using renewable energies.

The environmental burden of the glass roof is mostly related to glass, steel and aluminum industries, which use large amount of fossil fuels to reach the high temperatures necessary in the furnace. Much improvement has been made in the past decades by changing oil to natural gas and by controlling the emissions during the transformation processes. Further significant reduction of the environmental impacts of these materials, and therefore of glass roofs, is unlikely to be possible.

The production of Texlon® cushions requires much less energy than glass production, and fewer structure materials are necessary to support the whole system, resulting in less impact during the production phase. As more solutions exist to reduce the environmental burden related to the use phase, the ETFE foil membranes can be considered as a more ecological solution than glass, and can still be further optimized.

6.2. Economic sustainability

The solution of using ETFE foil membranes as cladding systems for the projects Domaquarée and Kapuzinergraben allowed for significant saving of materials, steel and aluminum in particular. For Kapuzinergraben the amount of steel required for the Texlon® ETFE roof was only 15.65% of the steel required for the glazed solution. The feasible economic benefits very much depend on the complexity of the respective cladding system.

If it comes to energy efficient refurbishment, cladding of existing building facades with insulating cladding systems in combination with the exchange of windows and doors is currently the most common practice. This in
particular is a problem for refurbishment of heritage buildings. For the Kapuzinergraben project in Aachen for instance, the ETFE cladding system was the only solution which allows for transparency and the creation of a perfectly protected internal street, which allowed for energy savings due to reduction of the outside building surface as well as additional solar gain.

As an example for smart solar control Figure 6 shows the Kingsdale-School in London (drmm Architects & Designers, London) which has been built in the early 1960s. The atrium of the school has been covered by a Texlon® Vario system, a 3-layer ETFE cushion system with outer and middle layer printed with a positive-negative print pattern. The middle foil can be shifted towards the outer foil pneumatically and thereby provides control of solar light.

Fig. 6. GB – London – Kingsdale School: (a) building; (b) atrium

By protecting the atrium by an ETFE roof the outer surface of the building was reduced by more than 30 %. The solar heat gain was controlled by the Texlon® vario system as well as by allowing the warm air under the roof to excess to outside by means of a band of ventilation openings between roof and the building. No additional insulation on the inner walls had to be installed and existing windows could be used. The students as well as the teachers were allowed to enter and leave the class rooms by an additional colonnade on the first floor level. The ETFE cladding of the atrium thereby provided both, energy efficient refurbishment of the old building as well as new inner space for students and teachers, delivering economic and social benefits.

6.3. Social Sustainability

Refurbishment of the Kingsdale School in London is an example not only for alternatives offered by ETFE foil cladding systems regarding energy efficiency but also regarding creation of large well protected and comfortable areas for people to meet and work. Due to the lightweight of ETFE cladding structures, the transparency for nearly the whole of the solar spectrum and the high acoustic transparency [14] the inner space of the atrium provides a high comfort environment. Regarding acoustic comfort plane surfaces of modern architecture using concrete, steel and glass produce enhanced reverberation and enlarged reverberation time, responsible for a high level of acoustic background. Due to the high background noise levels there is a tendency to increase vocal intensity, the fundamental frequency, and the word duration this is recognized as the Lombard effect [15].

Acoustically, the effect of noise generated by heavy rain or hail under ETFE roofs is very well known and has been documented by C. Hopkins and M. Burdett in a BRE report in 2004 already [16]. In order to reduce the noise due to rainfall or hail impact a mesh was installed as an overlay on top of the outer foil [17]. A reduction of the A-weighted sound intensity level L_\text{IA} of 13 dB (100 to 3150 Hz) is documented. The low sound absorption properties of ETFE cushion systems are usually considered as a disadvantage in noisy environments, but because of the low reverberation time they do not require any additional installation of acoustic absorptive materials. These properties allow for new forms of living and education. Whereas acoustic performance very often is identified as a problem
after the building has been populated and acoustic discomfort can be managed by installation of additional sound absorption materials ETFE cladding structure will automatically provide the necessary acoustic comfort due to low reverberation time [14].

The overall properties of ETFE cushion system thus provide an environment analogous to outside conditions but well protected against the environment. This basic property of the ETFE systems creates a perfect atmosphere for people to meet, i.e. for any kind of building cladding structure that intends to provide space for many people. A good example is the project Kuwait Avenues (architects: Gensler, London) which actually undergoes the fourth enlargement (phase 4b). Approximately 35000 m² have been built during the last 4 years, and another 30000 m² is going to be built. The Texlon® ETFE cushion systems cover whole a region of the town attracting people from all over the country. In harsh environments like Kuwait with extremely high temperatures, high amount of dust and humidity no one really likes to be outside. A print pattern that covers 84% of the outer ETFE foil reduces the g-value to 0.26 thus providing sufficient shading for inner spaces. Due to thermal layering in hot climates warm air goes upwards and cold air provided by air conditioning inside the building (shops, restaurants, offices) stays at the floor level creating a high thermal comfort.

Figure 7 gives an impression of the level of acceptance. Cladding structures like Kuwait Avenues have been built in other areas of the near and middle east.

![Fig. 7. KW – Kuwait – The Avenues: (a) daylight; (b) sunset](image)

7. Conclusions

The comparative life cycle assessment between Texlon® ETFE and glazed systems [3] makes evident, that the basic imperative for reduced pollution of the environment addressed against the building industry can be obeyed by introduction of ETFE membrane systems replacing glazed roof structures. The most important impact of the Texlon® ETFE system compared to glazed systems is the ODP, for which potential of improvement has been identified on the production as well as the inflation units. The comparison of the structure for two projects, despite the lack of substantial information on economic data, allows to estimate the costs for the ETFE foil solution to be approximately 30% less than glazed solution. Due to both the environmental and economic performances, combined with the optical, thermal and acoustic properties of ETFE cladding systems this technology in terms of sustainability will create new possibilities for architects and engineers for new buildings as well as for refurbishments.

References

[3] F. Riesser, Comparative Life Cycle Assessment of Texlon and glass cladding systems for roof applications, European School of Materials Science and Engineering FEIGM, Nancy, France, August 2011


[8] PCR ETFE Bauelement, Institut Bauen und Umwelt e.V., Version 05/2011


[10] ISO 14025:2007-10, Environmental labels and declarations - Type III environmental declarations - Principles and procedures (ISO 14025:2006); Text in German and English


