FUNCTIONAL REHABILITATION OF BUILT INDUSTRIAL HERITAGE WITH
ARCHITECTURAL MEMBRANES: PROGRAMMATIC, CONSTRUCTIVE AND
ECONOMIC ASPECTS

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Resumo: No âmbito da utilização de membranas arquitetónicas na reabilitação
funcional de edifícios, destacam-se as intervenções sobre o património industrial.
No presente estudo são analisados 9 projetos representativos deste tipo de
intervenções, de acordo com parâmetros programáticos, construtivos e
económicos. Verificou-se que a maioria deste património localiza-se na Europa e foi
convertido para atividades culturais ou escritórios. Os resultados desta análise
realizam o desempenho adequado das membranas arquitetónicas, como o elevado
grau de adaptabilidade/reversibilidade em relação ao edifício pre-existente,
permitindo, intervenções ligeiras.

Palavras-chave: membranas; reabilitação funcional, edifícios industriais.

Abstract: In the research framework of the use of architectural membranes on
functional buildings rehabilitation, stands out interventions on industrial heritage. In
this study 9 representative projects of this intervention’s type are analyzed,
according with programmatic, constructive and economic parameters. It was found
that most of these buildings are located in Europe and were converted into cultural
or office activities. The results of this analysis highlight the adequate performance
of architectural membranes, as a high degree of adaptability/reversibility with
respect to the pre-existences, allowing, in general, light interventions.

Keywords: membranes, functional rehabilitation, industrial buildings.

1. Introduction

1.1. Assumptions for building rehabilitation

According to Appleton (2003), building rehabilitation should
attempt to meet three basic criteria: reversibility; compatibility and
durability. The reversibility intendes to safeguard pre-existances from
possible ineffectiveness of adopted solutions, although total
reversibility is in most cases impractical. Nevertheless, the
intervention proposals must guarantee, at least, the compatibility
between what exists and what is proposed, as well as the durability of
the adopted solutions.

To the notion of technical and material compatibility, Douglas
(2006) adds the importance of use compatibility. It is essential that
use choice does not be a threat to the constructive and architectural
character of the building, but, on the contrary, this same choice
should be based on the identified building capabilities to guarantee an
optimal appropriation of the space, with minimal intervention and
disorder. About use compatibility, industrial building appears to be an
example of interest because of their spaces features. It would seems
unsustainable the effort, for example, to transform a large and
daylight plenty industrial building in a markedly compartmented use,
or the reverse. Durability criteria aspires to restrain maintenance
needs, and consequent impacts and costs, extending the period for
the future next intervention. Equally important as basic premises are
the principles of adaptability, repairability/examination acess and
sustainability. Where possible, it is necessary to ensure visual access
to essential points of the building to early detect any anomalies or
pathologies (related with the importance of diagnosis mentioned by
Guedes et al, 2003). On the other hand, it should be given preference
to solutions that address the possibility of partial repair instead of
their complete replacement.

Assuming that the base structure doesn’t present significant
damages, intervention’s degree is more associated with architectural
decisions (space, function, comfort, etc.) that could impose
significative changes/transformations. In these transformations,
building technologies and material choice (with respect to its
expression, feasibility, etc.) must consider the above mentioned.

2. Adopted methodology
The research has been focused on possibilities that architectural
membrane technologies could improve in relation with functional
retrofitting of industrial heritage buildings. This study started from
the analysis of 60 representative examples, from which 9 were
focused on retrofitting of industrial buildings (representing 15%);
they were analysed according to parameters shown on Table 1. Thus,
selected projects have been grouped and compared.

Table 1. Main parameters in study.

<table>
<thead>
<tr>
<th>Programmatic</th>
<th>Constructive</th>
<th>Economics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use/function; Building typology; Type of rehabilitation intervention; Type of use</td>
<td>Type of membrane; Type of anchoring; Auxiliary reinforcements; Self weight; Fire resistance; Type of pre-existing building’s structure; Type of load transmission from membrane to existing structure; Membrane’s span.</td>
<td>Global cost (material+ installation) Total cost of intervention Financing Source</td>
</tr>
</tbody>
</table>

3. Analysis of main parameters in study
3.1. Programmatic Parameters
The third analysis criteria regards building program, type of use
(permanent or temporary) and type of rehabilitation intervention;
important data to evaluate the trend application of these solutions. In
It was found that membrane materials have had a significant
application in buildings with non-residential category. It was found
that 67% of all 60 membrane interventions correspond to use
conversions of non-residential buildings. These use conversions occur
mainly in buildings with industrial original use (31%) (Figure 1).
Most part of buildings with industrial use that were intervened with membranes suffer use conversions (67%) (Figure 2). Among these, 33% were converted into cultural use and offices (Figure 3). One possible interpretation is that frequent amplitude and flexibility spatial features of industrial interior space, combined with a generous natural lighting, make these buildings strong candidates to accommodate special programs or for collective use; which otherwise would be more dependent on new constructions.

As any other building, it isn’t possible to understand industrial buildings without knowing the program to which it responds. Regarding industrial program, generally, perhaps the main requirement is its fast and constant redefinition requirements. Independently of symbolic and representative character that industrial building can take, from a certain point, it is first of all a functional shelter. Its appearance, shape and implantation depends on functional and economic factors that derive from evolution stage of a particular industry in a given place and time. In this sense, the resultant architectural features may or may not be a direct consequence, in stylistic and aesthetic sense of the function that it hosts. It is first of all the result of different functional type’s relationship that the building can establish with their industrial occupants. In this line of thought, Cartier (2002) proposes a comparative approach, rather than trying to establish a chronological categorization, aesthetics, or by industry type. Then are identified
some typologies industrial buildings: minimum shelter, neutral envelope, envelope, tailored envelope and building machine.

It was found that most rehabilitation projects under study focus on neutral envelope typology (45%) (Table 2). Neutral envelope is defined a building typology whose relationship with its host function it’s relatively indifferent. This doesn’t mean that industrial use does not impose certain conditions to the space, but these are guaranteed by excess in the form of a neutral box, capable of host the said industry as adapt later to another. These buildings have high ceilings, where comes out its large vertical windows and/or roof with skylights to ensure uniform natural lighting. Appear associated with emerge and development of new industrial materials - such as iron, glass and later reinforced concrete - whose features allow to perform larger spans without structural walls.

<table>
<thead>
<tr>
<th>Industrial buildings typology*</th>
<th>Rehabilitation projects with membranes [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral envelope</td>
<td>45%</td>
</tr>
<tr>
<td>Minimum shelter</td>
<td>33%</td>
</tr>
<tr>
<td>Tailored envelope</td>
<td>11%</td>
</tr>
<tr>
<td>Building machine</td>
<td>11%</td>
</tr>
</tbody>
</table>

* Defined by Cartier (2002).

The membrane’s average durability contrasts with the high durability of the physical structure of industrial buildings, but it keeps up with the relative short/medium use period of the new programmes/requirements that determine the functional rehabilitation of these areas. It’s found that the interventions with membranes have increasingly for permanent use (89%). Regarding the degree of interventions it’s found that they are mostly Light (45%) (Table 3).

<table>
<thead>
<tr>
<th>Intervention degree</th>
<th>Example</th>
<th>Percentage of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>P.04. Logan offices</td>
<td>45 %</td>
</tr>
<tr>
<td>Medium</td>
<td>P.08. Frasilo</td>
<td>33 %</td>
</tr>
<tr>
<td>Deep</td>
<td>P.03. Dresden Train Station</td>
<td>22 %</td>
</tr>
<tr>
<td>Exceptional</td>
<td>-</td>
<td>0 %</td>
</tr>
</tbody>
</table>

3.2. Constructive Parameters

Another analysis criteria of selected projects is related with constructive parameters. Depending on improvements to be achieved, it resorts to different solutions that can be characterized by the combination with other materials, components or structures, as follows: second membrane skin system (Mendonça, 2005), by the interior or building exterior, placed in tension and executed on a pre-existing support; membrane panel’s system, mounted on another panel (made by other material or substructure); multi-layer system, composed by different materials and technologies, which external layers are membranes with protection and non-structural function (whose intermediate layers aren’t tensioned); double membrane system under pressure (with positive or negative air insufflation).
According to the studied proposals, most of them are built with metallic substructures, mainly steel (89%) (Table 4).

Table 4. Constructive data of projects in analysis.

<table>
<thead>
<tr>
<th>Functional Rehabilitation projects of industrial heritage buildings with architectural membranes</th>
<th>Constructive parameters</th>
<th>Pre-existing</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.01. Salzburg Train Station</td>
<td>T 1 PE ME 1,08 1 PTFE</td>
<td>1700 38 ME no</td>
</tr>
<tr>
<td>P.02. Sakuragicho Train Station</td>
<td>T 1 L ME 0,9 1 GF + PTFE</td>
<td>3573 13 ME yes</td>
</tr>
<tr>
<td>P.03. Dresden Train Station</td>
<td>T 1 L ME 1,2 3 GF + PTFE</td>
<td>30000 13 ME yes</td>
</tr>
<tr>
<td>P.04. Logan offices</td>
<td>T 1 PE PO 0,2 0,8 PVC</td>
<td>1200 50 MI no</td>
</tr>
<tr>
<td>P.05. Casting house, Landschaftspark</td>
<td>P 2 PE ME 1 4 ETFE</td>
<td>580 81 ME no</td>
</tr>
<tr>
<td>P.06. Eco Membrane</td>
<td>T 1 PO ME 0,5 0,5 PVC</td>
<td>1400 85 ME no</td>
</tr>
<tr>
<td>P.07. Frac Art Centre</td>
<td>P 2 PE ME 1 4 ETFE</td>
<td>1362 81 MI no</td>
</tr>
<tr>
<td>P.08. Freslo</td>
<td>P 2 PE ME 1 4 ETFE</td>
<td>9800 90 CO no</td>
</tr>
<tr>
<td>P.09. Mino</td>
<td>T 1 PE ME 0,5 0,8 Polyester</td>
<td>80 20 MI no</td>
</tr>
<tr>
<td>Average</td>
<td>T 1 PE ME</td>
<td>1 2 ETFE</td>
</tr>
</tbody>
</table>

* Tensioned (T), Pneumatic (P); ** Ponctual (PO), Perimetral (PE), Lineal (L); *** Wood (WO), Metallic (ME), Polymer (PO); **** Concrete (CO), Metallic (ME), Mixed (MI).

With respect to the materials adopted, since its birth ETFE foil has been used in most of the studied proposals (34 %) (Table 5), mainly in the last decade. The self-cleaning, durability and high light transmission have favoured the use in many permanent envelopes, breaking the traditional relation between membrane systems and temporary buildings. Most of the building uses where the pneumatic system has been designed are still focused on cultural programs. But in the last decade, the range of uses has been extended to permanent typologies, like covering of courtyards. The lightness of inflated systems, compared with glass, and the improvement of the membrane resistance materials have favoured the international promotion of this technology; in the last decade they have been used in substitution of glass technologies (Gonzales et al, 2012). Other membranes, like PES or fiberglass coated with PTFE, are also used in large surface envelopes, where higher membrane resistance is needed (Table 6).

Table 5. Membrane materials adopted in the analysed projects.

<table>
<thead>
<tr>
<th>Membrane material</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene tetrafluoroethylene (ETFE) membrane</td>
<td>34 %</td>
</tr>
<tr>
<td>Glass fabric coated with polytetrafluoroethylene (PTFE)</td>
<td>22 %</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>22 %</td>
</tr>
<tr>
<td>PTFE membrane</td>
<td>11 %</td>
</tr>
<tr>
<td>Polyester (open wave) membrane</td>
<td>11 %</td>
</tr>
</tbody>
</table>

Tensile structures, as that term refers, reach structural capacity through tensile forces for most components, such as cables or membranes (with the exception of rigid limits and structural
components subject to compression and bending). According to Lewis (2003) this structure’s type are usually subdivided into: perimetrically tensioned, pneumatic and with prestressing elements (such cable networks and beams). It’s found that most projects under analysis presents perimetrically tensioned structure (67%) and pneumatic (33%) (Table 5).

Planning a rehabilitation intervention begins with the analysis of pre-existing; it’s found that type of pre-existing structure isn’t concrete or mixed, but mostly metallic (78%) (Table 7). Also verifies that 78% of pre-existences didn’t need to be structurally reinforced to receiving interventions with architectural membranes.

It’s found that constructive membrane systems in analysis transmit loads to the pre-existing structure by following substructure’s types: perimetral (67%), lineal (22%) and punctual (11%). Most perimetral substructures are frameworks, frames and rings; while the linear substructures are beams, arches, trusses and vertical elements; regarding punctual substructures, it only regist masts and hooks.

A particular aspect of interventions with membrane building technologies is their high adaptability/reversibility to existing constructions. It turns out that membranes (due to its features) presents a solution to functional rehabilitation of industrial spaces because they efficiently adapts to large spans typical of these buildings; registering membrane’s span execution with 26m (in average) ranging between 15 and 50m. In addiction applied membranes presents large surface areas, between 1001-5000 m² (45%) (Table 8).

### 3.2.1. Membranes for metallic elements protection

Many industrial buildings presents metallic building components, such as roofs - and there are many reasons to choose membrane materials over other roofing materials. Membrane cladding will never rust, in wet climates, or when storing corrosives. For
example, an ETFE membrane, due to its properties, can acts as protectors against metals corrosion from sodium c (FRAC art center (ref. P.07) and Dresden Train Station (ref. P.03) are examples of this). In addition to being unsightly, a corroded roof is unsafe and expensive to repair. Even a small amount of corrosion in the roof is enough to let moisture drip into the building, causing more rust and possibly ruining the interior of the building. Any type of metal, even when treated with an anti-corrosion treatment, is susceptible to rust. A current rehabilitation solution consists in adding a membrane liner on the inside or outside of a roof, to keep corrosive agents out of contact with the steel, making it impossible rust starts.

3.2.2. Auxiliary protection uses

There are some interesting proposals related with auxiliary uses which have a great potential in the retrofitting projects. They take advantage of the flexibility and lightness of the new structure, in order to create large covered spaces where the retrofitted building is protected during the work. Recently research has been developed by the Airlight Ltd. (Tensairity® systems). These structures can cover large dimensions with the optimization of compression and tension efforts in the inflated beams, helped by auxiliary elements. Also, the easy assembly and removal, have great potential use in future projects.

3.3. Economic Parameters

A common recorded aspect of the analysed projects is that they aims to achieve a low construction cost and low energy consumption during the use phase. The last parameter in analysis is the economic. Imports to retain that the global cost of membrane solutions depends on design complexity, location and skilled labor cost (Armijos, 2008); average global cost (Table 9) it’s around 199 €/m² (range from 30 to 400€/m²). Pneumatic membrane building systems have, in average, higher costs (333€/m²) than other membrane systems (133€/m²) possibly due to membranes layers multiplication and air keep pressure devices; despite its spent less substructure. Among the industrial buildings interventions analysis, expansions are those that have, on average, the highest global cost. (400€/m²) and the modifications have the lower global cost (138€/m²); interventions made in old buildings (built before 1960) have, on average, higher global costs (209€/m²). At project ref. P.03. all membrane’s components for attachment were selected regarding cost reduction and ease of installation (Foster, 2016).

Table 9. Main parameters for economic analysis of projects in study.

<table>
<thead>
<tr>
<th>Projetos em análise</th>
<th>Type of Intervention</th>
<th>Membrane area [m²]</th>
<th>Global cost of membrane [%]</th>
<th>Financing source</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

Table 9. Main parameters for economic analysis of projects in study.
### 4. Conclusions

The paper summarizes the most relevant trends, according to the study of international proposals, mainly in the last decade, which have been analysed through a broad range of qualitative parameters. In the last decade, architectural membrane proposals associated with retrofitting projects has increased considerably. The improvement of membrane materials and the influence of some mediatic projects have also helped to this development. The higher durability helps to promote the application on permanent buildings; their integration in retrofitting processes can takes also advantage of its lightness and easy maintenance requirements. Because of that, functional retrofitting represents one of the most interesting areas of improvement.

### References


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