Architectural membranes on building’s functional refurbishment

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Abstract. The aim of this study is to make an insight about architectural membrane applications for building’s functional refurbishment, analysing the characteristics that make architectural membranes suitable for this purpose. It is based on sixty interventions used as case studies that are classified chronologically and by countries and uses, pointing out also their applications. Several design strategies are identified and contrasted with the principles set for interventions in existing buildings. The results are illustrated with examples chosen from the case studies, highlighting how membrane building technologies can fulfil the most important principles of building refurbishment.

1. Introduction
Architectural membranes (composite textiles and foils/films) are used for space defining. Considering its lightness, resilience and flexibility, these are becoming inevitable solutions in specific buildings’ refurbishment contexts, when the needs of: weight reduction, enlarging useful floor space area or retrofitting the existing, arise as special requirements. A few millimetres membrane can be a self-supporting material (integrated in a tensile/pneumatic system) and a selective sunlight filter capable of absorbing or reflecting ultraviolet or infrared light whenever needed; they can also be used to support thermal or acoustic insulation materials [1].

While in the past architectural membranes have been used mainly as a covering system, nowadays a wider range of requirements is emerging and thus a multiplicity of diverse textile/foil architecture solutions can significantly fulfil many needs dealing with functional aspects to protect and valuing existing buildings. However, despite these benefits, many building practitioners are unfamiliar with the behaviour and the characteristics of membranes. The lack of information about their use and properties, by the design and construction community, limits their capability of achieving the highest possible standards in quality assurance and control on construction projects [1].

2. Interventioned projects sample
To determine how the characteristics of architectural membranes adapt (or fail to adapt) to the demanding requirements of building refurbishment, a detailed analysis of sixty interventions has been conducted. Some of these examples are particularly significant to show the way they achieve integration, or dialogue with the existing building. In order to obtain an overview about this, were prepared data sheets for each intervention project with information about the following aspects: contextual, programmatic, construction, economic and functional. The sixty case studies have been distinguished by the intervention on its building elements: roofs/courtyards/skylights (56%), ceilings (25%), facades (12%) and partition walls (7%). All intervention projects have been chronologically...
classified. According with the durability categories defined by Douglas [2], it is found that most of these refurbishment interventions with membranes occur at old buildings, older than 120 years (37%); considering the other case studies, 35% have a normal life (60-119 years old), 23% have a medium life (30-59 years old), 5% have a short life (under 30 years old) (Figure 1). Membrane’s envelope systems have experienced an important development in the last 30 years and an increase in the use of membranes over the last decade is clearly observed, led by applications in roofs/skylights/courtyards (Figure 2).

Referring to the 19 countries represented, two of them (Germany and UK) top the list with more than 10 interventions (17 – 22%) (Figure 3). Furthermore, Europe accounts with 81% case studies, Asia 10% and America 9%.

The refurbishment of buildings with non-residential use corresponds to 91% of the analysed case studies; cultural (20%), office (17%), sport/leisure (17%), transport (8%), or religious (11%) uses are those that present more interventions with membranes; buildings with these kind of uses often need to renew its image, or expand its capacity, and membrane materials easily respond to these requirements. Regarding constructive aspects, most of the interventioned buildings presents a mixed structure type (55%) and 90% of existing building elements do not need to be structurally reinforced to accommodate membrane’s building technologies. Concerning the building element type, the roof is the most interventioned element with membranes (55%), followed by ceilings (23%). Most intervention projects present tensioned (76%), or pneumatic (24%) building systems. However, most

Figure 1. Distribution of the case studies by their durability and interventioned building element.

Figure 2. Distribution of the case studies by its refurbishment/intervention year with membrane building technologies.

Figure 3. Countries where interventions are located.
of pneumatic solutions have a particularly domain in roofing intervention projects (where 75% are pneumatic). Most of surface membrane’s area of each analysed project range between 51-300 m² (30%) and 1000-5000 m² (30%); and mostly used metal profiles as substructure (61%), among other materials such as wood or polymer. In addition, 95% of the analysed intervention projects have fixed membrane installations, being the remaining movable.

2.1. Membrane materials
The use of building technologies that are environmentally more respectful is a growing concern in building design and construction. Textile membranes and films offer an efficient and aesthetic solution not only due to their lightness, mechanical and chemical properties, but also due to the possibility of being functionalized, altering membrane’s skin functional properties in a positive way - building’s envelope properties can be specifically adapted to changing environmental parameters. New developments in materials, such as low-e coatings, allow membranes to take on more tasks in the area of the building envelope, for example to influence the transmission properties of translucent building skins. Aerogels and phase change materials are in principle suitable to enhance membrane-sandwich structures to become polyvalent components, which can take over advanced tasks with regard to thermal control [3]. Active solar energy use is possible with bendable photovoltaic elements. In the future, other functions, such as electrical conductivity, electroluminescence, or integrated nanostructures will be also relevant [4]. In the field of architectural textile membranes, it is mostly composite textiles that are usually used, consisting of a fabric as carrier and supporting material and a suitable coating to protect and seal the fabric. In the following, basic properties of the most common and state-of-the-art membrane building materials are described on Table 1.

| Material | Polyvinyl chloride (PVC)-coated polyester membrane (16%) | Polytetrafluoroethylene (PTFE)-coated fiberglass membrane (16%) | Ethylene tetrafluoroethylene (ETFE) membrane (35%) |
|----------|---------------------------------------------------------|-------------------------------------------------------------|-----------------------------------------------|
| • less expensive material; | • increasing seen as an environmentally friendly and extremely durable - estimated to reach up to 35 years; | • used single or in pneumatic cushions; about 0.2 mm thick; | • compared to glass, this material offers high UV transmittance [5]; |
| • high strength and low weight; | • fluorine polymer coating acts as anti-adhesive to soiling; | • good coat ability, e.g. with screen printing can be used to limit the heat transmission, or to reflect the solar heat [5]; | • stress-strain behaviour and isotropic properties; |
| • suitable for convertible constructions; | • reduced stretch ability and resistance to buckling; | • stress-strain behaviour and isotropic properties; | • rated as not easily flammable. |
| • PVC coating emits pollutants when exposed to UV-radiation – limited durability - 15 to 20 years - material gets greyer during the years (due to unfavourable soiling) [5]; | • non-combustible. | | |
| • flame retardant. | | | |

2.2. Mapping of applications
In order to ensure a good representativeness of the intervention projects sample, it was also necessary to establish a mapping of membrane’s application on building’s rehabilitation - Table 2 classifies it into several large families (this list is not exhaustive). From the sample analysis were also identified five basic design options: (1) building inside a building: a membrane structure spans the entire building; (2) creation of facades, skylights and roofs; (3) roofed-over atrium: a courtyard retrofitted with a roof; (4) membrane envelope acting as a second skin; (5) suspended ceilings and stretched partitions.
Table 2. Overlook of main architectural membranes’ application on building refurbishment.

| Architectural Structures and Spatial definition elements | Floor coverings | Temporary/auxiliary structures | Structural reinforcement and monitoring | Protection elements | Installations Devices |
|----------------------------------------------------------|-----------------|-------------------------------|----------------------------------------|---------------------|-----------------------|
| • Tensile/pneumatic structure, cladding or under layering; | • Acoustic layer; | • Temporary facades/roof protection; | • Pneumatic beams; membrane device for “health structure monitoring” of buildings affected by an hazard; | • Shading and anti-UV protection devices; | • Air conducts; electric extensions (in membrane stripes); flexible PV integration. |
| • double skin facades; | • waterproofing layer; | • lost or provisory formwork; | • reinforcement bonding strips. | | |
| • covering of existing atriums; | • provide safety in the event of a fall. | • working wired platforms for open spaces; | | | |
| • horizontal, vertical extension structures; | | • acoustic and soiling barriers. | | | |
| • stretch ceilings and interior partitions (printed, back lighted, micro perforated); | | | | | |
| • covering for restyling; paint support or as finishing layer. | | | | | |

3. Principles of intervention

Most refurbishment interventions in existing buildings are motivated by the fact that functional aspects do not fulfil the necessary requirements, or because the building deterioration endangers their use. These motivations determine the depth of refurbishment interventions, which may lead to significant changes in the buildings. However, it is necessary to prevent those changes to damage the characteristics of the building in an irreversible way.

According to the principles of International Council on Monuments and Sites (ICOMOS) [6], interventions on historic buildings and sites should: (1) preserve their historic character and particular significance; (2) be non-invasive and compatible with the existing size, scale and architectural values; (3) be differentiated from the historic parts and be reversible.

The first principle refers primarily to the replacement’s approach - seeking to re-create a missing section or component of the building. This approach requires a high level of accuracy, throughout the design phase. The second principle has to be taken into account mostly in the integration’s approach. Adding functions to an ancient building requires additional space, and this leads to a review of the entire structure and to find a dialogue between new and old building components. The last principle has been led by the juxtaposition’s approach between old and new elements, where the membrane becomes a light medium between the environments of the past and the present. Thanks to the few following examples, the authors emphasise that the juxtaposition approach seem to be compatible with the outstanding aesthetics of membrane structures, and that the replacement and integration approaches are most often preferred and technically feasible. From the following case studies, some guidance should be concluded for a broader textile application in the future building refurbishment approaches.

In rehabilitation interventions, when new technologies and materials are used to preserve, extend or form some construction, there is always a problem regarding the intrusion’s level of new solutions. In any intervention, choosing a solution involves subjective decisions and, therefore, subject to criticism. However intervening and respecting built heritage can be compatible actions; each structure is unique and only a careful study enables to select the intervention that best suits each situation [7].

3.1. Replacement – compatibility

Seeking to re-create a missing section or component of a building, this approach requires the highest level of accuracy throughout the design phase, in order to: (a) preserve the character of the existing building; (b) avoid any future problems, guaranteeing the compatibility of new elements with the existing building. Regarding compatibility aspect, this approach considers that the intervention should be compatible with the existing size, scale and architectural values.

Diagnosis is a very important design tool, because it allows selecting the best rehabilitation design options [7]. For example, in the intervention project on Dresden’s train station [8] (Figure 4a) the option to replace the existing roof by a membrane was taken considering the structure’s condition. Due
to membrane’s lightness it was possible to maximize the preservation of existing structural elements, improving, at the same time, the indoor natural lighting. Another example is the intervention project Camellia house [9] (Figure 4b) – one of the Europe’s oldest cast iron structure. An inspection to the existing building revealed that the cast iron structure was debilitated to withstand a variety of overloads, such as snow or wind, and that there were many broken windows due to vandalism acts. It was also found that the existing glass roof, which did not withstand snow and wind loads, had a reduced slope. Thus, to protect the structure, it was designed a second roof with ETFE membrane (with slope correction) that fits over the existing glass/iron roof. The ETFE membrane, applied with aluminium profiles, is sufficiently resistant to withstand snow loads and don’t break - making it safer than glass. Therefore the building can maintain its function, as the transparent ETFE membrane ensures: necessary light transmission; reduced overload to existing structure and opening panel’s incorporation to allow the roof’s maintenance. One of the difficulties of this project was the ETFE membrane’s roof modelling due to geometric complexity of existing roof. Figure 5 shows other intervention projects where functional rehabilitation was made through a replacement approach / recreation of missing parts with systems that integrate membrane materials.

![Figure 4](image1.png)

**Figure 4.** (a) Dresden’s train station (before and after) [8]; (b) Camellia house (before and after) [9].

![Figure 5](image2.png)

**Figure 5.** (a) Kostel Povšení sv. Kříže [10] – reconstitution of vaulted ceiling to achieve higher acoustic performance; (b) Corbera d’Ebre church [11]; (c) Ténnis club bourg-la-reine [12] – roof replacement to increment natural lighting performance; (d) Bologna museum [13].

### 3.2. Integration – adaptability

Adding functions to an ancient building requires additional space, and this leads to a review of the entire structure to find a dialogue between new and old materials and techniques. It becomes a meticulous work with the objective of finding: (a) linguistic coherence; (b) structural compatibility and (c) feasible connexion.
When intervening in existing buildings, usually composed by orthogonal planes, membrane materials have to put aside their morphological freedom. This requires the design of transition components that ensure the correct connection between membranes and existing building. This integration is enabled by the lightness and other physical properties of the membranes (i.e. which do not overload the existing building, while providing protection and functional performance improvements).

In the recovery and reuse of urban fabric, membranes can "repair" dismembered parts, giving new identity and functions to secondary spaces. This is the case of “Imagination Headquarters” (UK, 1990) [14] (figure 6a) – a rearrangement of an existing space between two buildings, eliminating a number of service facilities between them, to create a large internal covered gallery with a PES/ PVC membrane (surface area of approx. 590m²) - that ensures necessary light conditions to host a new use/function. Another example is the Wismar Nursery [15] (figure 6b), where the enclosing space between two existing volumes created a buffer zone that increase the thermal regulation and ventilation of adjacent spaces. The atrium can be shaded through the air pressure adjustment of the pneumatic roof with triple ETFE membrane. Thus, it was not necessary to refurbish the facades that face the created atrium, so its thermal inertia remained unchanged.

Fukiya parish council [16] presents a room extension, aiming to build a large meeting room space without intermediate supports. The connection between new and old was inevitable; the new roof had to be compatible with the structural configuration and architectural characteristics of the surrounding buildings. Naturally, the first option was a tiled roof; however the users desired a copper roof, which was an expensive option. Nearby, as alternative, it was chosen a glass fibre/ PTFE membrane dyed in a similar colour of the surrounding ceramic roofing tiles (figure 6c), not only due to economic factors, but also to the possibility to achieve a bigger span without intermediate supports.

Originally built in 1900, the interventioned project Logan Offices [17] (figure 6d) resulted in the conversion of an industrial warehouse into offices. To adapt/ convert this space it was necessary to create new compartments and adapt it to acoustic and luminous requirements for the new use. Thus, it was decided to add a second interior skin, in a translucent membrane, to the existent vertical and horizontal surfaces. The suspended ceilings, with translucent and back-lit membrane, enable artificial light diffusion without shadows’ creation. The vertical lining, with a stretched PES/PVC open mesh membrane, acts as an unifying element of intervention, hides any aesthetic imperfections, keeps the passage of natural light, improves acoustic performance (absorption) and keeps the viewing of original/ existing building elements (such as frames, pipes and iron structure).

![Figure 6](image)

**Figure 6.** (a) Imagination headquarters - exterior and interior views [14]; (b) Wismar nursery - before and after [15]; (c) Fukiya parish council [16]; (d) Logan office – interior view.

### 3.3. Juxtaposition – durability, repeatability and reversibility

Little guidance can be generally assumed from the juxtaposition approach, which requires a different strategy every time, finding the right balance between two opposite requirements: (a) how to differ the new elements from the old ones and (b) how to minimize the visual impact of new buildings in order to guarantee the perception of pre-existing elements. With this approach the intervention aims to be
differentiated and reversible from the existing parts - reversibility of the new intervention is the most important aspect that designers have to take into account. The durability requirement of refurbishment solutions for old buildings with historic and cultural value is more severe than in the case of current modern buildings, because its useful lifetime is significantly bigger. In consequence, regarding a repeatability approach, it is possible to consider that, depending on interventions’ specifications, the use of membranes, even with a durability of 10-35 years, may be viable solutions. Attending to constant functional changes that a building is called to support nowadays, whether for social and economic, among other reasons, it requires flexibility of use, and membrane building technologies can meet these needs, extending building’s useful life. The use of membranes can also be include into the group of Reversible design, due to the fact of being lightweight solutions, easily mounted/dismounted and with a reuse/recycling process relatively simple – characteristics that were presented in all intervention projects analysed.

Above all, it may be considered that refurbishment solutions with membrane are repeatable, i.e. when they reach the end of their useful life, they can be re-implanted. In the intervention project on a 19th century house “Evidencia light hotel” [18] (Figure 7a), a membrane lining solution was chosen due to the reduced room dimensions and the possibility of renew/reuse it in future scenarios. In addition, it allowed to: achieve useful area gains (due to its reduced thickness), include acoustic insulation, hide existent surfaces’ imperfections and constitute a substrate that could be printed.

3.4. Roof-over

Membranes are increasingly replacing glass in roofing structures on the retrofit of buildings with courtyards. Here, the advantages of membranes are: lightness; the possibility of having large surfaces with a single membrane (5mx20m) (which requires fewer structural supporting elements) and its satisfactory durability. In addition, in most of the interventioned projects, the connections to the existing buildings is reversible, causing no significant damage to it.

In the case of the intervention project Irgatza palace [19] (Figure 7b), classified as cultural built heritage, a pneumatic ETFE membrane roof was applied over the existing atrium to preserve the building (with wood structure) from the effects of climatic changes, mainly from rain (very frequent in this local), improving its hygrothermal performance and expanding its usefull floor area at the same time. At Fuchun Kosa Zou Ma Lou [20] (Figure 7c) - a vernacular courtyard house - the existing courtyard was covered with a single transparent PVC membrane, supported by a bamboo structure, to increase the useful floor area. The membrane can be partially open to promote space ventilation and thermal regulation and its configuration promote rainwater collection for later reuse.

The intervention project “Shishiodoshi house” [21] (Figure 7d) resulted in a vertical extension of a building built in 1980. With a height of eleven meters, this vertical extension was made with a wooden structure totally covered with a stretched white colour PES/PVC membrane. The membrane was chosen due to its lightness and reduced cost.

Figure 7. (a) Evidencia light hotel [18]; (b) Irgatza palace [19]; (c) Fuchun Kosa Zou Ma Lou [20]; (d) Shishiodoshi house [21].
4. Conclusion
Results analysis highlights an accurate walk-through architectural membrane performance, in accordance with design refurbishment principles.
The case studies’ sample shows the wide range of possible uses for architectural membranes in refurbishment projects - highlighting good practices in their current application and defining guidelines to support decision-making in future.
Textile/foil materials present inherent qualities and performances that motivate the use of membranes in building refurbishment, such as: resistance; structural reinforcement and flexibility; adaptability; lightweight; ease of implementation; durability and weather change resistance; electromagnetic/ electrostatic/ anti corrosion; passive of being functionalized; reduced economic and environmental impact and architectural aesthetic - allowing design of reversible and repeatable solutions. Nevertheless, the performance of these materials in refurbishment interventions, as well as the design methodologies need to be further investigated in order to assure the better response to each specific context – in a close relation with the peculiarity of existing buildings.

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Acknowledgments
First author thanks to FCT (Fundação para a Ciência e Tecnologia – Portugal), MCE (Ministério da Educação e Ciência – Portugal) and ESF (European Social Fund) for supporting the research fellowship with the reference SFRH/BD/104891/2014; and with other authors thanks the financial support from the Project UID/AUR/04509/2013 by FCTMEC by national funding and, when applicable, FEDER co-financing under the new PT2020 partnership agreement - Lab2PT, School of Architecture/ University of Minho, Portugal and Project POCI-01-0145-FEDER-007457 - CONSTRUCT - Institute of R&D In Structures and Construction of Faculty of Engineering/ University of Porto, Portugal, funded by FEDER funds through COMPETE2020.