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Textile Membrane for Façade Retrofitting: Exploring Fabric Potentialities for the Development of Innovative Strategies

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Abstract: The European building stock demands urgent renovation due to the age of the buildings, their expected lifetime, and their excessive energy consumption, which accounts for more than a third of the EU's total emissions. However, the complexities involved, such as time, costs, and structural modifications, often discourage clients, tenants, and occupants from undergoing a building renovation process. Textile membranes, despite their long history in various architectural applications, have only been employed in façades in the last decades. Their intrinsic properties, such as lightness and flexibility, together with rapid assembly and low maintenance make these materials particularly suitable for façade retrofitting. Therefore, they are worth exploring as a way to promote the development of lightweight and easy-to-assemble façade products that could help overcome the current limitations of building retrofitting efforts. This paper aims to establish relationships between textile membranes and potential building retrofit applications. To this end, this study builds on the categorization of traditional façade retrofit strategies and proposes a new classification for textile façade retrofit products. The methodology includes a comprehensive literature review of textile properties and characteristics, along with a thorough assessment through case studies, of membrane use in façade applications. A sequential investigation leads to the main outcome of identifying three clear pathways for the development of new textile-based façade products for building retrofit.

Keywords: façade retrofit; textile façade; membrane; innovative strategies; resilient constructions; sustainability; lightweight structures

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1. Introduction

Buildings are responsible for almost 40% of the EU's energy consumption, resulting in them being the greatest energy consumer and one of the most significant sources of CO_2 emissions in Europe [1]. Approximately 35% of the European building stock is over 50 years old, with nearly 70% of it being energy-inefficient. The annual renovation rate for these buildings is just approximately 1% [2,3]. Furthermore, considering that around 85–90% of current buildings will still be in operation by 2050, it is imperative to take decisive measures in order to achieve neutrality in Europe by that deadline.

While renovating a building is the most desirable approach to reduce time investment and waste production and extend the lifespan of building components, it is a lengthy process that is often disregarded by developers, tenants, and occupants due to the substantial expenses, time commitment, and disruptive impact on occupants.

According to Giebeler [4], building retrofitting involves the replacement and/or repair of the defective and/or outdated components of a building, and it is considered a medium-scale intervention. The three terms 'renovation', 'refurbishment', and 'retrofitting', which are often used interchangeably, denote distinct yet interconnected techniques that are not mutually exclusive and can be concurrent. According to the information provided by designing buildings, the construction wiki [5]:

- 'Renovation' refers to the process of returning something to a good state of repair;
- 'Refurbishment' implies a process of improvement by cleaning, decorating, and re-equipping;
- 'Retrofitting' means 'to provide something with a component or feature that was not fitted at the time of manufacture, or to add something that it did not have when it was first built' [6]; it is often used to enhance building performance by integrating new systems or components.

All the three practices are usually employed when the building components exhibit signs of aging or deterioration, and when the performance of the building has decreased over time and no longer satisfies the required current standards. Considering that building retrofitting "finds its foundation in the urgency of reducing the harmful effects of buildings in the environment and improving them as healthier places for occupants" [7], it is essential to establish the timeframe and extent of an intervention prior to designing it, taking into account the three different approaches and their respective effects on the buildings.

The central role of façades in the energy efficiency of buildings is driving current interest in widespread façade retrofitting to improve the energy performance of the building sector, thereby reducing energy consumption and associated carbon emissions.

Historically, façades evolved from being the main visual and thermal barrier between the interior and the exterior to become primarily important in terms of their aesthetic qualities over other aspects, thus replacing the attention to their performance. Consequently, they have undergone modifications for several reasons [7]. In their role as mediating elements, the scope of façades is not limited to the actual space they occupy within the building, nor to their understanding as a physical barrier. Conversely, its design exerts a significant impact on the spatial configuration within and surrounding the building [8].

A wide range of new technologies and technical solutions are being explored to increase retrofitting practice. A particular field of interest is the advancement of standardized dry assembly processes. These methods aim to reduce construction times and enable the consistent dismantling and reuse of components. Within this range of innovative solutions, the use of architectural textiles and membrane products represents a clear opportunity. By harnessing the inherent qualities of these materials, which have contributed to their growing use in recent years, it is conceivable to foresee their use for less intrusive applications. While recent research studies promote the use of membranes in façades primarily to achieve either material savings [9] or complex shapes [10], their potential for aesthetic and energetic retrofit remains thoroughly unexplored, except for a few instances of passive or active shading devices through the addition of smart integrations [11,12]. However, their application is worthy of investigation as it can result in the development of novel retrofit strategies and façade products that may benefit exclusively from their intrinsic properties. Indeed, these features can ensure that the intervention has the same life expectancy as traditional practices, while also enabling the implementation of temporary and reusable façade retrofit practices.

Hence, the aim of this paper is to conduct a systematic investigation of potential textile applications for façade retrofitting. The goal is to identify new development lines for lightweight façade products that can address the existing constraints of building retrofitting practices and enhance the resilience of buildings.

2. Materials and Methods

The article delves into the analysis of textile membrane applications in façades and their potential connections to building façade retrofitting practices. The primary objective is to determine which textile-based product development lines could offer compelling, yet complementary, alternatives to conventional façade retrofitting strategies.

Building upon the comprehensive overview of current façade refurbishment strategies proposed by Konstantinou T. [13], this study aims to refine the understanding of façade retrofitting in the specific context of textile materials. Konstantinou's classification serves as a crucial foundation, guiding the categorization of Textile Façade Retrofit Strategies.

The research methodology consisted of two parallel textile review analyses, conducted in order to gather the required information. These analyses were followed by the creation of a schematic overview depicting potential development lines for Textile Façade Retrofit Strategies. Finally, a sequential investigation was employed to match the acquired data related to textiles with conventional retrofit solutions, identifying suitable and promising textile-based retrofit strategies (Figure 1).

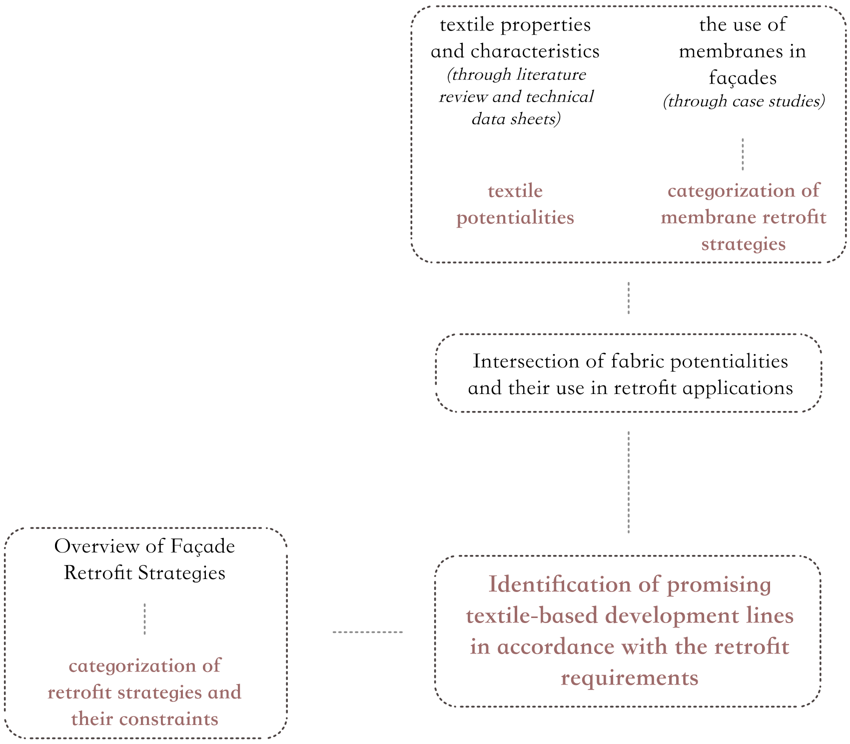


Figure 1. Methodological map.

These parallel analyses, based on the materials and data acquired through the literature review and relevant case studies, encompassed the following: (1) the review of properties and characteristics of textile products available on the market, and (2) a comprehensive review of the use of membranes in façade applications, specifically exploring their potential in retrofit façade applications. The analysis of textile properties and characteristics involved combining information from the literature review and technical data sheets provided by major membrane producers. The review of membrane applications in façades primarily relied on the analysis of 55 case studies completed in the past three decades. These case represent a diverse pool of current applications of textiles in façades. The primary factor for the selection of the case studies was the use of textiles as an envelope component, regardless of the function of the building. The selection and categorization were based on various criteria, including building function, year of construction, location, climate zone, degree of enclosure, material used (silicon fiberglass, PES—PVC, PTFE, ETFE, vinyl), and type of application of the membrane. To fulfill this objective, a database has been developed to gather these instances, which are schematically reported in the following table (Table 1).

Table 1. Database of collection of the case studies.

	Name of the Project	Year	Location/Climatic Zone	Membrane Function	Degree of Enclosure	Number of Layers
Silicon Fiberglass						
1	Zenith	2016	Strasbourg, France *Temperate climate*	Cladding	Fully enclosed	Mono layer
2	Ubpa b3-2 pavilion world expo	2010	Shanghai, China *Temperate climate*	Finishing	Fully enclosed	Mono layer
PES-PVC						
3	Mobile Spaces Textile Pavilions	2014	India *Various climates*	Cladding	Fully enclosed	Mono layer
4	Tavaru Tower	2014	Velaa, Maldives *Tropical climate*	Sun-shading	Open structure	Mono layer
5	Arthouse	2015	Düsseldorf, Germany *Temperate climate*	Sun-shading	Open structure	Mono layer
6	Kita Metro	2012	Düsseldorf, Germany *Temperate climate*	Sun-shading	Open structure	Mono layer
7	Vafibank Sports Palace	2015	Instanbul, Turkey *Temperate climate*	Sun-shading	Open structure	Mono layer
8	Finmeccanica	2016	Farnborough, UK *Oceanic climate*	Cladding	Fully enclosed	Double layers
9	Revealing cover for the EU Presidency	2015	Amsterdam, Netherlands *Temperate climate*	Finishing	Fully enclosed	Mono layer
10	Olympic Shooting Venues	2012	London, UK *Oceanic climate*	Wrapping	Fully enclosed	Mono layer
11	Curtain Wall House	1995	Tokyo, Japan *Temperate climate*	Sun-shading	Open structure	Mono layer
12	Haus Mit Atelier	2008	Wissgoldingen, Germany *Temperate climate*	Sun-shading	Open structure	Mono layer
13	Lindt Chocolate Shop	2009	Legnano, Italy *Mediterranean climate*	Cladding	Open structure	Mono layer
14	United Bamboo Store	2003	Tokyo, Japan *Temperate climate*	Cladding	Fully enclosed	Double layers
15	Garage Screen Cinema	2020	Moscow, Russia *Continental climate*	Wrapping	Fully enclosed	Mono layer
16	Merkez Ankara Showroom	2018	Ankara, Turkey *Temperate climate*	Cladding	Open structure	Mono layer

Table 1. *Cont.*

	Name of the Project	Year	Location/Climatic Zone	Membrane Function	Degree of Enclosure	Number of Layers
17	AntiRoom Pavilion	2015	Valletta, Malta *Mediterranean climate*	Dividing	Open structure	Mono layer
18	Gotha Cosmetics Headquarter	2018	Lallio, Italy *Mediterranean climate*	Double skin	Fully enclosed	Mono layer
19	Cincinnati Medical Center UC Neuroscience institute	2018	Cincinnati, OH, USA *Mild oceanic climate*	Sun-shading	Fully enclosed	Mono layer
20	The Bubble	2017	Denmark *Temperate climate*	Wrapping	Fully enclosed	Mono layer
21	Bragado building	2018	Bragado, Argentina *Temperate climate*	Sun-shading	Open structure	Mono layer
22	London Basketball Arena	2011	London, UK *Oceanic climate*	Wrapping	Fully enclosed	Mono layer
23	pPod Mobile Theatre	2005	Manchester, UK *Oceanic climate*	Cladding	Fully enclosed	Double layers
PTFE Fiberglass						
24	Hazza Bin Zayed Stadium	2012–2014	Al Ain (Abu Dhabi), UAE *Desert subtropical climate*	Sun-shading	Open structure	Mono layer
25	Green Point Stadium	2007–2009	Cape Town, South Africa *Mediterranean climate*	Cladding	Open structure	Mono layer
26	Arena da Amazonia	2014	Manaus, Brasile *Tropical climate*	Cladding	Open structure	Mono layer
27	Burj Al Arab Jumeirah	1999	Dubai, UAE *Desert subtropical climate*	Double skin	Fully enclosed	Double layers
28	Forschung Sedus Stoll AG	2010	Dogern, Germany *Temperate climate*	Cladding	Fully enclosed	Double layers
29	Westraven Office Complex	2008	Utrecht, Netherlands *Oceanic climate*	Double skin	Fully enclosed	Mono layer
30	iGuzzini Ibérica S.A. Headquarters	2011	S. Cugat del Valles, Spain *Mediterranean climate*	Wrapping	Fully enclosed	Mono layer
31	King Fahad National Library	2013	Riyadh, Saudi Arabia *Desert subtropical climate*	Sun-shading	Fully enclosed	Mono layer
32	"Magical" Science and Technology Park	2011	Tàrrega, Spain *Light continental climate*	Wrapping	Fully enclosed	Mono layer

Table 1. *Cont.*

	Name of the Project	Year	Location/Climatic Zone	Membrane Function	Degree of Enclosure	Number of Layers
33	Meme Experimental House	2011	Taiki, Japan *Semi contintental climate*	Cladding	Fully enclosed	Double layers
34	Esseker Centar	2007	Osijek, Croatia *Semi contintental climate*	Cladding	Fully enclosed	Mono layer
35	Public Service Hall	2012	Marneuli, Georgia *Continental climate*	Sun-shading	Fully enclosed	Mono layer
36	Free University Philological Library	2005	Berlin, Germany *Temperate climate*	Cladding	Fully enclosed	Double layers
37	Textile Academy NRW	2018	Mönchengladbach, Germany *Temperate climate*	Cladding	Fully enclosed	Double layers
38	Thyssenkrupp Test Tower	2017	Rottweil, Germany *Temperate climate*	Cladding	Fully enclosed	Various layers
ETFE						
39	BC Place Stadium	2010–2012	Vancouver, Canada *Moderate oceanic climate*	Cladding	Partially enclosed	Double layers
40	German-Chinese House	2007–2010	Shanghai, China *Humid subtropical climate*	Cladding	Fully enclosed	Mono layer
41	11 March memorial	2007	Madrid, Spain *Mediterranean climate*	Wrapping	Fully enclosed	Mono layer
42	Traveling Exhibition Pavilion	1998	Cologne, Germany *Tropical climate*	Cladding	Fully enclosed	Mono layer
43	Mountain Stations of the Gaislachkogl Cable Car	2011	Sölden, Austria *Temperate climate*	Cladding	Fully enclosed	Mono layer
44	Allianz Arena	2005	München, Germany *Temperate climate*	Wrapping	Partially enclosed	Double layers
45	ETFE Façade Unilever Building	2009	Hamburg, Germany *Temperate climate*	Double skin	Fully enclosed	Mono layer
46	Cycle Bowl Pavilion	2000	Hanover, Germany *Temperate climate*	Wrapping	Fully enclosed	Mono layer
47	Allianz-Riviera Stadium	2013	Nice, France *Temperate climate*	Cladding	Fully enclosed	Mono layer
48	San Mames Stadium	2013	Bilbao, Spain *Mild oceanic climate*	Sun-shading	Open structure	Mono layer

Table 1. *Cont.*

	Name of the Project	Year	Location/Climatic Zone	Membrane Function	Degree of Enclosure	Number of Layers
49	Aichinger House	2010	Kronstorf, Austria *Contintental climate*	Sun-shading	Fully enclosed	Double layers
50	Sacmi Auditorium	2007	Imola, Italy *Mediterranean climate*	Double skin	Fully enclosed	Triple layers
51	The Shed	2019	New York City, NY, USA *Humid subtropical climate*	Wrapping	Fully enclosed	Four layers
52	Malaysia Tunnel	2016	Kuala Lumpur, Malaysia *Equatorial climate*	Wrapping	Open structure	
53	National Acquatic Centre	2008	Beijing, China *Contintental climate*	Wrapping	Fully enclosed	
Nylon						
54	Ashui Pavilion	2020	Hang Trong, Vietnam *Temperate climate*	Sun-shading	Open structure	Mono layer
55	Juniper House	2007	Katthammarsvik, Sweden *Temperate climate*	Sun-shading	Open structure	Mono layer

As a result, possible scenarios for the development of Textile Façade Retrofit Strategies were identified and evaluated. The pivotal phase of the study involved a systematic intersection of detected retrofit requirements and fabric potentialities in order to outline future textile-based development lines for façade retrofit products. This investigation was based on data gathered from the aforementioned analyses and employed a comparison approach to intersect the findings.

3. Strategies of Interventions for Building Façade Retrofit: A Framework for Further Classification

The building retrofit practice is expanding increasingly due to the urgent need to improve the energy performances of the building stock, thereby promoting environmental, social, and economic development [14].

The current building stock is a consequence of the high demand for housing in Europe throughout the middle of the 20th century, which led to a lack of any standard of comfort and poor energy performance. Buildings built in the post-World War II period are notably lacking in insulation layers or thermal mass, resulting in very low energy efficiency, especially when compared to the current standards for Nearly Zero Energy Buildings (NZEB) and even for Zero Emission Buildings (ZEB) [15]. If in the last three decades the focus on energy-oriented innovations in building technology has emerged regarding new buildings, lately it has shifted towards the renovation of existing dwellings, acknowledging it as the most significant opportunity to reduce global energy consumptions and greenhouse emissions [16].

Considering that buildings are the primary energy consumers in Europe, accounting for around 40% of EU energy consumptions and 36% of greenhouse gas emissions [2], it is necessary to improve the building stock in order to significantly contribute to the European Commission's goal to diminish greenhouse gas emissions by 85–90% compared to 1990 levels by 2050. Thereby, to seek a sharp increase in energy retrofit rates of the building stock, new strategies and solutions need to be pursued.

To outline future textile-based development lines for façade retrofitting products, which is the aim of the article, it is necessary to start by analyzing the current façade retrofit strategies and the building envelope components they target. The analysis will allow us to subsequently identify potential applications for textiles in this context.

With the increasing recognition of the topic, the scientific literature contains numerous papers that tackle the issue of façade refurbishment strategies and attempt to categorize them. Some articles provide methods for advocating guidelines for the retrofitting of building façades [17]. Others attempt to categorize them according to the typology of measures [18], the type of design [14], or the demand and supply aspects [19]. However, a unique classification is missing. Based on Konstantinou's classification [13], façade refurbishment strategies could be grouped into five different categories based on how building components are replaced, upgraded, or added, and the resulting impact on the performance of the building envelope. Although the five categories do not encompass all the possibilities of intervention, as they could be limitless, they represent an exhaustive overview of the refurbishment strategies with relation to the type of intervention required and the specific façade component they address.

In understanding façade refurbishment strategies, Konstantinou T. [13] provides valuable insights into the benefits and limitations of each approach, as highlighted below:

- Replace: the replacement of a façade consists of the removal of the old façade elements (part or all of them) and their replacement with new ones. This strategy is commonly used to replace old elements with new components that are more effective and may even have a longer lifespan. However, the cost of the intervention may be higher when compared to alternative solutions as well as the disturbance for the occupants. Furthermore, it is necessary to take into account critical connections and thermal bridges.

- Add-in: the upgrade of the façade from inside is a common practice and it is especially applied to avoid a change in the appearance of the building (for instance, when a building is listed under monument protection). The process involves adding an insulation layer to the interior of the façade in order to improve its thermal performance. Regrettably, this strategy fails to address thermal bridges, while simultaneously causing significant discomfort for the occupants.
- Wrap-it: this approach consists in enveloping the building with an additional layer of exterior insulation or a supplementary façade. The main benefits lie in the enhancement of the thermal resistance of the building envelope, along with the removal of the thermal bridging. Additionally, while it is possible to gain extra living space, this strategy requires the possibility to enlarge the building footprint. If a second façade is achieved, it can either fully envelop the original façade or only partially cover it, thus creating a buffer-zone for the building.
- Add-on: the add-on strategy implies the addition of a new structure or volume into an existing building, with the purpose of acquiring additional space or integrating supplementary functions. In this way, the old façade would no longer be part of the building envelope, while a new façade is built in accordance with the new requirements. The disturbance for the occupants and the need to expand the building's size are significant drawbacks in this scenario. A viable alternative to this strategy involves the addition of an extra story, which enables the enhancement of the roof's performances.
- Cover it: the last strategy analyzed allows one to upgrade the performance of an existing building by enclosing the courtyards. This enclosure increases heat gains by the application of transparent elements which, additionally, allow for visual connection. This strategy adds functional space to the building and alter the relation between inside and outside. Additionally, the insufficient thermal performance of the existing façade is in this way solved as it turns to face a new interior space. In any case, it is essential to take into account adequate shading and ventilation.

By leveraging this existing classification, the research aims to refine the understanding of façade retrofitting, focusing specifically on the interplay between textile materials and the identified refurbishment strategies. The objective is to uncover new avenues for the development of textile-based retrofitting solutions for façades.

4. Outcomes and Discussion

4.1. Review of Textile Properties and Characteristics

Membranes are increasingly employed in the construction field with different applications. The main characteristics that make these materials attractive for use are their lightweight and flexible nature, as well as their aesthetic features, visual properties, translucency, and the possibility of sun and light control [20]. In parallel, if membranes are used as the only layer between the interior and the exterior of a building, they should comply with mechanical and thermal requirements, facing daily and seasonally temperature differences [21].

Membranes must possess a range of characteristics tailored to their specific applications. These features include weight reduction, mechanical strength, thermal insulation, energy efficiency, waterproofing, and durability. Additionally, membranes can exhibit various aesthetic qualities, being either transparent, translucent, or opaque. They can also be designed to be fixed, retractable, or movable.

Different types of membranes can be employed according to specific parameters, such as the function of the building and/or that of the membrane, the duration of the building construction, and the climatic conditions of the location. The aforementioned case studies were analyzed to provide a comprehensive overview of the current use of textiles in building façades. It compared the current applications of textile materials in façades in light of (i) the location of the building and its climate, (ii) the function of the building and (iii) that of the membrane, (iv) the degree of enclosure of the envelope, and (v) the number of layers of the membrane employed in its application. The investigation determined that the environmental properties of textile materials are consistent across different typologies, indicating that the choice of material for a structure is not influenced by its location. On the contrary, it is highly affected by the function of the building and its context of application. For example, when membranes are used as roof closures (fixed or openable) or in greenhouse envelopes (e.g., the famous case of the Eden Project by Grimshaw Architects), ETFE solutions are preferred due to their ability to provide high transparency and allow for adequate daylight. In the case of arenas or stadiums, both PTFE and ETFE are commonly used because they offer high levels of translucency and transparency. On the other hand, for pavilions, temporary structures, tents, and emergency shelters, PES-PVC is the favored material due to its high tensile strength and resistance, as well as its affordability, despite its shorter lifespan of up to 20 years. Their applications in façades are mainly recorded as façade cladding systems for commercial buildings or occasionally as the second skin layer for an existing façade.

At the same time, since textiles can be employed in architecture for many reasons, a diversified range of products have entered the construction market for application in retrofitting practices of existing buildings, either as sunscreens, acoustic panels systems, interior partitions, tensioned ceilings, or backlit surfaces [20].

Due to the increased interest towards this material, the current trend aims at researching and improving its inherent properties. Additionally, given that textile structures have the advantage of being dismantlable, it is feasible to foresee a second (and even a third) life for these types of structures [9,22]. The efficient use of materials and the reduced environmental impact contribute to the diffusion of textiles and to their spread in temporary structures, while also benefiting from the shortened installation and maintenance time.

Two different types of products can be adopted in façade applications: membranes and foils. They offer immeasurable opportunities for architectural expression, and their employment in façades can even be foreseen for free-form and complex geometries which are structurally feasible and economically attractive [10]. The primary distinction between the two lies in their manufacturing method. Textile membranes are composite materials consisting of a woven base cloth that is typically coated on both sides. On the other hand, foils are extremely thin extrusion with a thickness of approximately 0.4 mm, resulting in a high transparency up to 96%. These materials have a relatively low U-value, especially when single-layer membranes are adopted. This configuration is therefore preferred for outdoor sun-screens, wind and rain protection, the skin of semi-air-conditioned areas, and visual barriers. On the other hand, multi-layer membrane systems are majorly employed for thermal envelopes as inflated membrane cushions, typically consisting of two or three layers (although additional layers can be incorporated). Two-layer systems with intermediate insulation can also be applied.

The employment of membranes in architectural façades can be classified in three main categories according to the tensioning system [23]: pneumatic façades, double-curved membrane façades, and flat tensioned façades, as shown in Figures 2–4. Although both membranes and foils could be adopted with the above-mentioned tensioning systems, ETFE foils are usually preferred for pneumatic façades, while PVC membranes are primarily used for flat tensioned façades. It must be pointed out that the tensioning systems have an impact on the performance of the membrane application. Specifically:

- Pneumatic façades take advantage of the air under pressure for achieving the required bearing capacity. In addition, the pressurized air chamber increases the insulating capabilities of the material, although the thermal efficiency may be affected by the size of the air chamber;
- Double-curved membrane façades achieve the required load-bearing capacity through the double curvature of the surface and the pretension of the membrane;
- Flat tensioned façades, despite having a limited load-bearing capacity due to the absence of double curvature, are extremely attractive to the market thanks to their reduced thickness and the similarities of the systems with traditional external cladding systems. Their structural performances rely on the pre-existing tension applied to

the membrane and its ability to recover from temporary deflections caused by external loads.

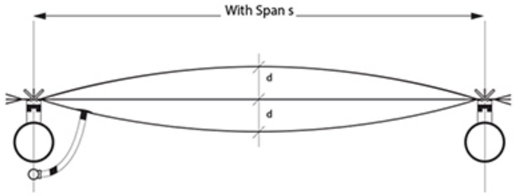


Figure 2. Pneumatic system.

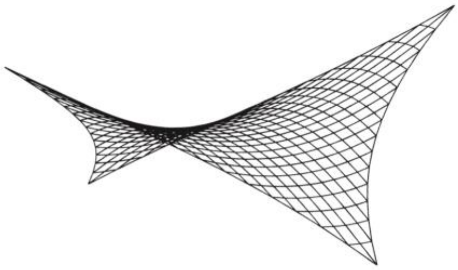


Figure 3. Double-curved membrane.

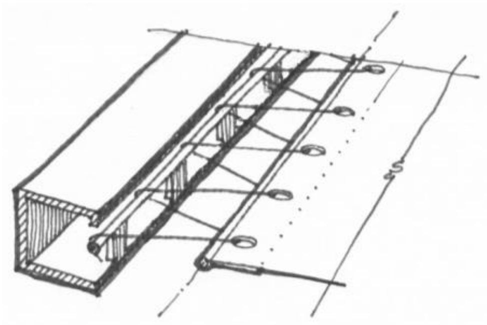


Figure 4. Flat tensioned system.

According to Paech C. [10], the most significant potential demands as the main requirements for the application of the cladding material can be grouped into five main categories:

- Architectural characteristics: this refers to the ability to create complex architectural geometries, aesthetic qualities, and surface appearance, such as translucency and color. It also includes the creation of private interiors;
- Context-related performance: this refers to the ability of the material to protect from external environmental conditions, such as wind, rain, temperature, and sun. It also includes the ability to provide thermal, solar, light, and acoustic performance;
- Mechanical properties: This corresponds to the material's weight for substructural design, its ability to withstand external loads like wind, temperature, and maintenance loads, as well as its fire resistance and durability;
- Assemblage requirements: this denotes the methods used for maintenance and replacement, the modularity of the material, and the reduction of installation costs and time;
- Sustainability: this relates to the economic sustainability of the material costs and the environmental sustainability related to the recycling of the materials.

In accordance with the classification established by Paech C. [10], the properties of both membranes and foils have been systematically categorized in Table 2. This classification aligns with the material properties identified by Hu J. [24] and is further informed by a comprehensive analysis of data sheet documentation. Notably, the table encompasses insights into the properties of the 11 most widely used coated membranes and foils, providing a valuable comparative reference.

Table 2. Comparison of textile properties.

Category	Light Performances			Material Properties		Structural Properties		Environmental Properties					Economic Values
Coated Fabric	**Translucency %**	**Transparency %**	**UV Resistance**	**Mesh Type**	**Colour**	**Tensile Strength**	**Fire Resistance**	**Waterproof**	**Self-Cleaning**	**Frequency of Maintenance**	**Sustainability**	**Expected Lifetime**	**Cost**
Polyvinylchloride-coated polyester fabric (PVC-PES)	8–15%	no	Medium–high	Closed mesh with full faced coating	Various	Good	B1–B3	Waterproof	Dirt-repellent surfaces	High	Recyclable	~20 years	Economic
Polyvinylchloride-coated glass fiber (PVC-glass)	up to 30%	no	high–excellent	Closed mesh with full faced coating	Limited	Good	A2	Waterproof	Dirt-repellent surfaces	High	Not recyclable	>35 years	Economic
Polytetrafluorethylene-coated glass fabric (PTFE glass)	8–22%	no	high–excellent	Closed mesh with full faced coating	Various	High	A2–B1	Waterproof	Dirt-repellent surfaces	Medium	Not recyclable	>35 years	Expensive
Silicone-coated glass fabric (silicone glass)	up to 20%	no	high–excellent	Closed mesh with full faced coating	Various	Good	A2–B1	Waterproof	Dirt-repellent surfaces	Medium	Not recyclable	>35 years	Economic
Polytetrafluorethylene-coated polytetrafluorethylene fabric (PTFE fabric)	12–40%	no	high–excellent	Closed mesh with full faced coating	Limited	Good	B1	Waterproof	Dirt-repellent surfaces	Medium	Not recyclable	>35 years	Expensive
Expanded polytetrafluorethylene (ePTFE)		slightly	excellent	Closed or open mesh with coating	Various	High	A2–B1	Hydrophobic	Dirt-repellent surfaces	Medium	Not recyclable	>35 years	Expensive
Polytetrafluorethylene fabric (PTFE fabric)	up to 40%	slightly	high–excellent	Closed mesh without coating	Limited	high	B1	Hydrophobic	Dirt-repellent surfaces	Medium	Not recyclable	>30 years	Expensive
Polyvinylchloride-coated polyester mesh (PVC-PE)	up to 90%	no	medium–high	Open mesh, coated yarns	Various	High	B1–B3	Can be waterproof	Dirt-repellent surfaces	High	Not recyclable	~20 years	Economic
Polytetrafluorethylene-coated glass mesh (PTFE glass)	40–85%	no	high–excellent	Open mesh, coated yarns	Limited	Medium–high	A2–B1	Waterproof	Dirt-repellent surfaces	Medium	Not recyclable	>30 years	Expensive
ETFE film	up to 98%	yes	high	Film	Transparent, white, colored, printed	Medium	B1	Waterproof	Self-cleaning	Low	Recyclable	>30 years	Expensive
Fluoropolymer fabrics (ETFE-PTFE)	up to 70%	no	high–excellent	Laminated open mesh	Limited	Medium	B1	Waterproof	Self-cleaning	Medium	Not recyclable	~20 years	Expensive

4.2. A Comprehensive Review of Textile Membranes for Façade Applications

Textile membranes possess unique characteristics that make them versatile for various applications in architectural façades, offering solutions through diverse combinations of materials, coatings, and tensioning systems. To explore the potential use of textile membranes in retrofitting façades, the study delved into analyzing their practical implementation in façades. Hence, as stated earlier, a total of 55 case studies have been collected and categorized according to the textile material used and the typology of application of the membrane as a component of the building's façade.

The collected and analyzed case studies encompass a diverse range of instances of the current applications of textiles in façades across various architectural building typologies. It is worth emphasizing that the function of the building does not dictate the type of membrane application. The collected information pertained to the building's function and degree of enclosure, its location and climatic zone, the year of construction, and the application of the membrane in terms of numbers of layers, type, function, and cover material.

Figure 5 provides a summary of the state of the art in the field of textile membrane use in façades. It identifies two main categories of applications: structural membranes, which serve a dual purpose of providing both structural support and enclosure, and enclosures, which are solely used for enclosing spaces. The parameters analyzed and compared among the six identified application typologies include the following: (i) the relationship with the enclosure, assessing whether the membrane was used as an additional distinct layer in relation to the main façade or integrated within its design; (ii) the function and application of the membrane; and (iii) the hermeticity of the layer.

	Structural Membranes			Enclosures		
	Defining	Wrapping	Nesting	Dividing	Finishing	Covering
Description	The membrane defines the whole space. It works both as a structure and as façade.	The membrane embraces the building structure. It creates an exterior buffer zone.	The membrane is enclosed within the building structure. It creates an exterior buffer zone.	Separation between the interior and the exterior through one single layer.	The membrane is used as finishing layer of the façade system.	The membrane is used as a covering layer of the façade.
Relation with the enclosure	Main façade - In line	Main appearance - Additional layer	Interior façade - Additional layer	Main façade - In line	Main façade - In line	Main appearance - Additional layer
Function and Application	Structuring layer: Configuration and Separation between the building interior and the exterior	Second layer: Protection of the building façades components; buffer zone	Second layer: Creation of an interior spacer interior buffer zone	Separation layer: Separation between the building interior and the exterior.	Finishing layer: Improvement of the thermal performances	Second layer: Protection of the building façades components; Sun-shading
Hermeticity of the layer	Fully enclosed	Fully enclosed	Fully enclosed	Fully enclosed	Closed layer	Open layer

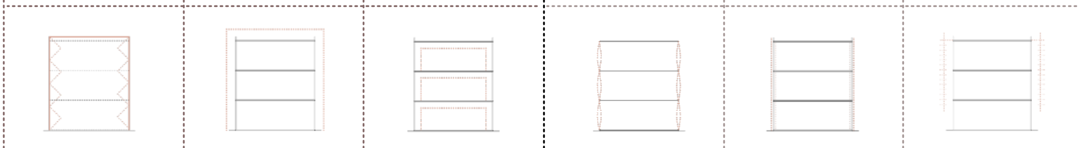


Figure 5. Textile façade applications.

Within the category of structural membranes, three distinct applications can be recognized:

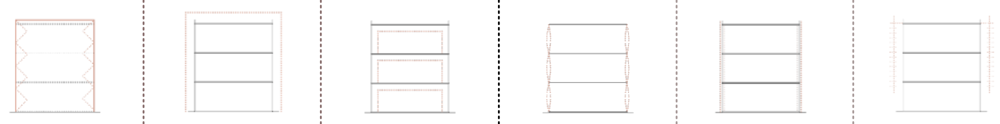
- Defining membranes serve as the sole layer of the façade, separating the interior and exterior of the building. They not only act as the primary separation element but also contribute to the overall structure and the design of the building;
- Wrapping membranes are applied as a second skin to the façade, enveloping the building structure. They are upheld by their own framework and establish the primary visual aspect of the building. When used a second layer, these membranes act to preserve the building's façade components while also defining an exterior buffer zone that enhances the energetic performance of the façade;
- Nesting membranes, on the other hand, are applied inside the building rather than on the outside, although the application process is similar to that of wrapping membranes. Their self-supporting structure allows for the creation of a building within a building, providing the benefits of an inner buffer zone and the ability to define the interior space.

Three categories of application can be detected within the enclosure group:

- Membranes used as Dividing elements are the only layer of the façade that divides the interior and exterior of a building. The difference between Dividing and Defining elements is that Dividing elements lack structural capabilities and rely on the main structure of the building for support. Dividing membranes, along with Defining, Wrapping, and Nesting membranes, establish a fully enclosed structure;
- Finishing membranes serve as the final layer of the façade system, whether on the interior or exterior of the building;
- Covering membranes are employed to cover either the entire façade or specific components or sections of the façade (e.g., to cover or protect windows). They serve as an extra layer added to the existing façade to protect the building façade components and function as sun-shading devices. They are applied as an open layer.

Starting from the textile façade application categories (Figure 5), the investigation examined the use of textiles in façade applications, specifically focusing on retrofit scenarios. The analysis took into account the aforementioned refurbishment strategies proposed by Konstantinou T. [13]. If the categorization of textile façade applications can be found in Figure 5, Figure 6 demonstrates that textile membranes can be used in retrofit strategies in three ways: (i) replacing the existing façade, (ii) totally or partially wrapping the existing building, or (iii) adding a new layer to the existing ones. The six categories of textile façade retrofit applications reiterate those of textile façade applications. However, they are specifically analyzed in the context of a façade retrofit, with a focus on the primary benefits and limits of the retrofit solutions. The application of textile membranes over existing façades offers several benefits, including the reduction of additional weights, the definition of a buffer zone, the preservation of existing elements, the minimization of connections between the existing façade and the additional element, and the integration of a sun-shading device. It is important to note that their employment could totally or a partially alter the appearance of the existing building, which may result in various challenges, particularly when dealing with preserved and historical buildings. In such a case, the Nesting or Interior Finishing strategies may be the most favored options.

On the contrary, the limits of applying Textile Façade Retrofit Strategies are quite similar to those of other conventional façade retrofit strategies. The main distinction lies in the positivity that using a textile solution could limit the increased thickness of the façade and therefore confine the reduction of the interior space or the enlargement of the dimensions of the building.



	Structural Membranes			Enclosures		
	Defining	Wrapping	Nesting	Dividing	Finishing	Covering
Refurbishment strategy	Replace	Wrap it	Add in	Replace	Add on Add in	Wrap it Add on
Benefit	+ Limited additional weights; ± Total change of the appearance of the existing building.	+ Embracing of the whole building; + Creation of a new intermediate space / buffer zone + Self-supported (new) façade; ± Total change of the appearance of the existing building.	+ A new structure into the structure; + Preservation of the existing façade; + Self-supported (new) structure; ± Relevant trasformation of the interiors.	+ Limited additional weights; ± Total change of the appearance of the existing building.	+ Exterior and Interior application; ± Total change of the appearance of the existing building	+ Partial attachment to the structure; + Embracing of the existing façade; + Sun-shade; ± Partial change of the appearance of the existing building.
Limits	− Replacement of the existing façade.	− Increase in the thickness of the existing façade.	− Reduction of the interior space.	− Replacement of the existing façade.	− Application onto the existing façade; ± A little increase in the thickness of the existing façade.	− No buffer zone; no additional space; ± A little increase in the thickness of the existing façade.
Key component	Walls	Walls; Balconies; Windows	Walls	Walls	Walls; Balconies	Walls; Balconies; Windows

Figure 6. Textile façade retrofit applications.

4.3. The Identification of Development Lines for Textile-Based Façade Retrofitting Products

The following section outlines the results achieved through the systematic intersection of the aforementioned reviews with regard to (i) the textile properties and characteristics and (ii) the use of textile membranes in façade applications. The objective of this section is to outline potential avenues for the development of textile-based strategies applicable to façade retrofitting. The investigation has been based on the data acquired from the above-mentioned analyses and has been carried out using a comparative approach for intersecting the findings.

According to the analysis of the state of art presented by Ma et al. [19], three different orientations of building retrofit measures can be recognized. Their applications are focused either on the (i) supply side, that differently imply the use of renewable energy sources, (ii) the demand side, that intend to reduce the energy demand through advanced technologies, and (iii) the energy consumption patterns, by changing human factors such as the environmental lifestyle and their interaction with building comfort. Ruggeri et al. [14] pointed out that the most common type of building energy retrofit measure is aimed at reducing energy demand. This can be achieved either actively, by implementing new technologies, thermal storage, or heat recovery systems, or passively, through the use of shading systems, natural ventilation, and site planning.

Among the several building retrofit strategies mentioned earlier, the improvement of the façade performance can often be accomplished without extensive interventions, while still offering numerous benefits. The façade retrofit has the potential to enhance the visual, energetic, and acoustic qualities of the building. This can be achieved by addressing both the opaque and transparent components of the façade. Sarihi et al. [18] classified the energetic Façade Retrofit Measures (FRMs) into three categories: Energy Generation Measures (EGMs), Energy Conservation Measures (ECMs), and Energy Modulation Measures (EMMs). The primary distinction between ECMs and EMMs consists of the extension of the measure over time: ECMs are permanently applied to building façades, while EMMs modulate energy consumption only in specific periods. Therefore, ECMs are prohibiting measures that aim at preventing significant heat/gain losses through the façade in order to minimize energy consumption, whereas EMMs are responsible for temporarily modulating the building's energy efficiency. Given that the thermal transmittance of the building envelope is the primary reason for high energy consumption, ECMs are being extensively applied to stabilize the internal temperature during both summer and winter. This helps reduce the need for technological appliances to improve interior thermal conditions. The EMMs focus on controlling solar features through the application of solar thermal-driven heating and cooling technologies. Thus, the analysis identified insulation and shading strategies as the most common measures, representing the most effective solution in heating-dominated and cooling-dominated climates.

Textile Façade Retrofit (TFR) applications can yield strategies that could either belong to the groups of ECMs or EMMs. The aim of the present study has been to uncover potential TFR solutions which could open up new development lines for textile-based façade products. The identified lines presented in Figure 7 have been grouped in three main categories which refer to three of the five refurbishment strategies previously mentioned: replacement, addition (which encompass both the add-in and the add-on strategy), and wrapping. Every solution has been categorized based on its strategy, application plane, application of the membrane, retrofitting measure, material, operation, limitations, and variations. Additionally, each of them includes a reference project of a textile façade (from one of the 55 case studies). It is important to note that the reference project may not necessarily be a retrofitted façade, but it serves as an example of the textile application and the final effect.

Within the Replace retrofit strategy, two main products can be identified: tensioned membranes and cushions. Both alternatives require a replacement of the entire façade with the new product. It would be applied in line with the original plane of the façade. Considering that two different technology solutions are tackled, it follows that different materials are applied and, as a result, different operation methods are attained. One important difference to highlight is that tensioned membranes can only be used for the wall components, whilst cushions can also address window elements.

Concerning the Addition retrofit strategy, a broader range of possibilities might be identified. The three products—Finishing, Adding, and Covering—differ at first due to the strategy and the application method. Specifically, whereas Finishing requires the replacement of the existing finish, Adding and Covering involve adding a new layer from the interior and the exterior, respectively. The main difference between these latter two is that the Covering is not applied in line with the original plane of the façade (as in the case of the Adding method), but rather it is juxtaposed as an additional layer on a more outward plane. Therefore, in order to achieve both effectiveness and energy efficiency, the Finishing requires the coupling of the textile with an insulation layer. On the other hand, the Adding method is applied onto the existing façade taking advantage of an air gap. In contrast, the Covering works as a screen or a sun-shading device and does not require the addition or the coupling with any additional material or component.

There are four TFR products that fall under the group of the Wrap it retrofit strategy: Wrapping, Double Skin, Enclosing, and Nesting. The main difference among the four products lies in the extent of the intervention. The Wrapping product encompasses the entire building, while the Double Skin focuses solely on the single façade. The Enclosing products target specific elements of the façade, and the Nesting products involve adding a structure within the original one, resulting in an interior wrapping.

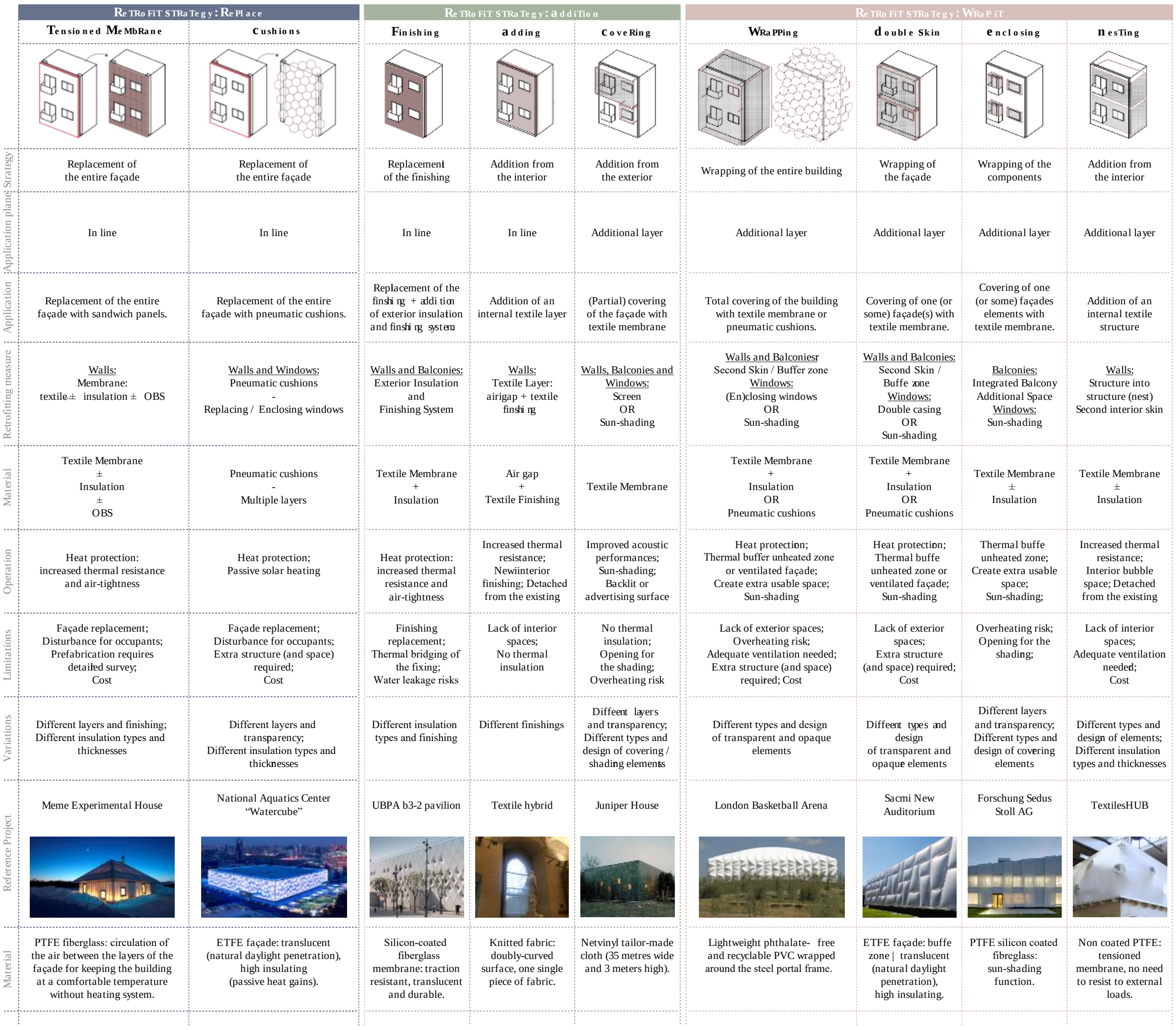


Figure 7. Textile façade retrofit products.

The main advantage related to the application of these products is the definition of a thermal buffer, which can be exploited as an unheated zone, a ventilated façade, or an inside bubble space. However, the primary constraint associated with it is the requirement for additional space, as each product is applied on an additional layer compared to the original plane of the façade.

An additional aspect that must be taken in consideration before comparing the above-presented products deals with their construction methods. Indeed, together with the type of strategy which could be less or more advantageous, the choice of the construction method can determine the level of invasiveness of the intervention. With regard to this parameter, it is feasible to group the types of intervention into six categories (Figure 8), each of which can address various retrofit strategies in different ways. The distinguishing factor between the methods lies in the supporting structure, which can take one of two forms:

1. The original façade structure, either connected to the finishing layer or attached to it through some elements, along with the final membrane;
2. An additional supporting structure, combined with either cushions, a tensioned membrane, or tensioning elements along with the tensioned membrane or the cushions.

	Finishing	Supporting cushions	Supporting membrane	Structuring	Tensioning membrane	Attaching membrane
Construction method	Façade structure + Finishing layer	Primary Supporting Structure + Cushions	Primary Supporting Structure + Tensioned membrane	Supporting structure + Tensioning elements + Tensioned membrane OR cushions	Supporting structure + Tensioned membrane OR cushions	Façade + Attaching elements + Membrane
Material	Façade layering + Tensioned membrane panels	Steel supporting structure + Cushions	Steel or Wood Supporting Structure + Tensioned membrane	Steel structure and tensioning elements + Tensioned membrane OR cushions	Steel elements + Tensioned membrane OR cushions	Attaching elements + Membrane
Retrofit strategy w/ TFR product	**Addition:** finishing	**Replace:** Cushions	**Replace:** tensioned membrane	**Replace:** tensioned membrane; **Wrap it:** wrapping, double skin; nesting	**Replace:** tensioned membrane; **Addition:** adding, covering **Wrap it:** double skin	**Wrap it:** enclosing
Photo						

Figure 8. Textile façade retrofit products—construction methods.

Each construction detail corresponds to a specific tensioning systems, as identified by Beccarelli and Chilton [23]. A flat tensioned façade is achieved by a Finishing or Supporting Membrane strategy, a double-curved solution is applied with a Structuring or Tensioning Membrane, while a pneumatic solution is accomplished through Supporting Cushions. The attached membrane is the sole approach that does not imply any tensioning of the systems, therefore not aligning with any of the classifications highlighted by the authors.

4.4. The Selection of Possible Development Lines for Textile-Based Façade Retrofitting Products

Based on the aforementioned analyses, this research aims to combine the obtained results in order to identify innovative approaches for retrofitting building façades using architectural textiles.

It is important to note that the identified strategies do not encompass all possibilities, but rather categorize them based on basic principles. This classification emphasizes the benefits and limitations of each approach and helps in defining potential development lines for textile-based retrofit products. Each typology of façade retrofit allows for variation according to three factors: (i) the original geometry complexity of the building, (ii) the construction method, and (iii) the objective of the façade retrofit.

Each of these strategies implies not only advantages but also various disadvantages [25] which may discourage tenants and builders from pursuing a building façade retrofit. However, certain solutions exhibit better potential for overcoming these constraints compared to others. As discussed by Corrêa et al. [25], some primary constraints limit the extensive application of the façade retrofit practice, such as execution difficulties, mechanical and structural problems, physical issues, cost, disturbance for occupants, and final effect. These constraints have been associated with the identified strategies for TFR applications in Table 3, taking into account the varying degrees of influence of each strategy. The dots refer to the minimum and maximum level of influence of the constraint to the strategy. While certain constraints can be related to all TFR strategies due to their reliance on similar finishing materials, some other constraints vary according to the type of intervention. For instance, addressing durability concerns associated with the system coating may involve a replacement solution. However, this alternative comes with constrains such as significant disruption for occupants and substantial cost investment. These factors may make this approach less practical when compared to current retrofit strategies. Additionally, disturbance for occupants arises when interventions are applied from the inside or when considering the entire façade. Despite TFR strategies normally limit the additional weights on the existing structure, some strategies may be heavier than others.

Table 3. Textile Façade Retrofit Strategies and their constraints.

	Tensioned Membrane	Cushions	Finishing	Adding	Covering	Wrapping	Double Skin	Enclosing	Nesting
Durability issues related to system coating	••	••	••		••	••	••	••	
Finishing execution complexity due to architectural constraints	••	•••	••	•	•	••	••	••	•
Vulnerability to mechanical stresses	••	••	•	•	•	••	••	•	••
Addition of weights to the structure	•	••	•	•	••		•	•	•
Exposed execution to weather conditions	•••	•••	••		••	•••	•••	••	
Lack of protection of the façade from outside actions									
Poor reduction of thermal inertia	•	•	••	••	•••	•	•	••	•
Increase in moisture-related problems				••					
Presence of thermal bridges				•					
Fire spreading risk									
High skilled labor requirements	••	•••	•	•	•	•••	•••	••	••
Aesthetical modification of the building appearance	••	••	••		•	•••	••	•	
High cost investment	•	••	•	•	•	••	••	••	••
Disturbance for the occupants during the execution	•••	•••	•	••	•	••	••	••	••

In addition to analyzing each practice in detail, it is important to consider certain aspects that limit the widespread adoption of FRMs. These factors include the disturbance experienced by occupants during the execution of the process, the high-cost investment requested for the retrofit practice, and the limited durability of the strategy in terms of life-cycle assessment. Overcoming these barriers is crucial for increasing the number and potential applications of FRMs.

Architectural textiles offer a potential solution to the limitations of façade retrofitting, hence promoting its widespread adoption. These materials can be effortlessly put over existing structures without causing undue weight due to their lightweight nature. Additionally, thanks to their ease of construction, these materials may be easily and quickly applied, reducing the disturbance for the occupants in terms of time extension. Thanks to their replaceability, they have the potential to enhance the longevity of the solution. At the same time, they are effective for temporary solutions.

However, additional factors must be taken into account when comparing the TFR applications and their resulting products:

- The products that focus on retrofitting by replacing existing components are not a viable alternative to current retrofit strategies. This is because they still cause significant disruption to occupants, require a high investment cost, expose the execution to weather conditions, and may result in aesthetic changes to the building's appearance;
- On the other hand, "addition" products are a suitable alternative in cases in where the goal is to minimize intervention on the existing façade. In these situations, it is

preferable to interact with the façade by adding a further layer. Nevertheless, this solution involves decreasing the available space either inside or outside the building, as the intervention requires increasing the thickness of the façade;
- The “wrap it” products offer significant benefits by allowing the creation of a thermal buffer zone, thereby enhancing the thermal performance of the façade. Like the addition items, these products require additional space, either inside or externally, to expand the limits of the façade. The distinction lies in the fact that, while the addition products solely increase the thickness of the façade itself, the wrap products create an intermediate space. This space, although formally relates to the façade, practically serves as an additional area that can be used for architectural purposes.

Thus, considering that the three aforementioned products, namely tensioned membrane, cushions, and finishing, do not serve as viable alternatives for partially or completely replacing existing façades, it is imperative to shift the attention towards other products that clearly demonstrate significant potentials.

The intervention accomplished at Sala delle Asse in Castello Sforzesco [26] demonstrates that textile solutions can effectively control the amount of daylight gains without completely preventing them. Moreover, thanks to their self-supporting ability, these solutions can reduce the need for additional anchoring supports, while still guaranteeing the same structural performance. This is particularly advantageous when working with historic buildings or buildings with weak structural systems. In the instance of a covering solution (i.e., the ArtHouse in Düsseldorf, Germany, in 2015 [27]), which allows for the shading of the façade, the main advantage of using a tensioned membrane is the possibility of the membrane to cover high spans with limited supports. The main advantage of this solution, in comparison to current ones, is in its minimal use of supporting elements. This leads to a decrease in both environmental impact [28] and structural weights. Regarding both Wrapping and Nesting products, the original façade structure is not a significant factor since both products require the addition of a further structure. The Wrapping solution minimize disturbance for the occupant; however, the Nesting solution, similar to the Addition from the interior, causes high disturbance as it requires intervention from inside the building, so interfering with ongoing activities. Additionally, these solutions also have a high impact in terms of the initial cost investment.

The Double Skin and Enclosure solutions focus on a specific portion of the building, thereby somewhat mitigating the associated constraints. Consequently, both the initial cost investment and the disturbance for the occupants are restricted due to the limited extension of the intervention. Additionally, these solutions allow for a relevant improvement of the façade’s performance through the addition of a layer that can contribute to the definition of a ventilated façade or a second skin façade.

The achievement of a prosperous façade retrofit necessitates the utilization of a blend of technical methodologies and strategic approaches in order to effectively tackle predetermined objectives. The selection of particular technological solutions for a façade retrofit endeavor will be contingent upon various elements, including financial resources, architectural characteristics, climatic conditions, and objectives related to environmental sustainability.

Considering the above-mentioned, only selected TFR strategies possess the capability to rival certain well-established approaches. The adoption of these strategies may be particularly relevant in situations when shading devices are necessary to improve the energy efficiency of current building façades.

Additionally, Textile Façade Retrofit Strategies exhibit a competitive advantage in relation to the enhancement of the building’s aesthetic appeal owing to their ability to be easily installed on top of an existing façade in place of the most common approach of replacement. This is primarily attributed to their lightweight nature, which eliminates the need for structural modifications that are frequently required. Additionally, membranes possess dimensions that enable them to span considerable distances, making them well-suited for the retrofitting of expansive façades on a wide scale.

Regarding the previously identified and analyzed TFR strategies, and taking into account the given considerations, three primary strategies deserve further considerations: Covering, Wrapping, and Double Skin. Indeed, all of these strategies involve the addition of a textile layer onto the existing façade as an extra layer, distanced from the primary one. This results in the creation of an air gap in between the two façades both in the Wrapping and Double Skin scenarios. Alternatively, the covering has the potential to enhance the thermal resistance and function as a sun-shading device.

These strategies exploit the reduced weight of the material and can be either self-supporting or dependent on the existing façade for support. In the latter case, careful design is crucial to minimize the weight, not only of the finishing material but also of its sub-structure.

As a result, these three selected approaches can fulfill both aesthetic and energy retrofit purposes, with their main distinction lying in the degree of coverage on the building's façade. The Covering strategy only addresses a portion of the façade, Double Skin covers one or more distinct façades, and Wrapping envelops the entire building.

Specifically:

- Covering can function as a screen over the existing façade, sheltering both opaque and transparent components. Although it does not enhance thermal resistance of opaque components, it can nevertheless have a beneficial impact on the transparent components by working as a sunshade and limiting the amount of sunlight radiation on the façade surface. It primarily employs a tensioned membrane, which can enhance both acoustic and energetic properties depending on its shape. It requires a supporting structure that maintains the tension of the membrane. The supporting structure can be either attached to the main façade or exist as a self-standing structure. This strategy is primarily effective in summer conditions and hot contexts.
- Wrapping involves constructing an additional structure above the existing one, potentially avoiding additional weight on the façade while improving its energy efficiency by creating a designated buffer zone. This approach provides the building with a new appearance, differently encompassing both opaque and transparent components. The buffer zone, defined as an area with an air gap and ventilation, can improve thermal performance. It can be effective both in summer, due to the ventilation layer, as well as in winter, thanks to air gap insulation. This happens even more when double or triple layers of ETFE cushions are employed as cladding. Structurally, it can be attached to the façade through a supporting structure, or it can stand on its own, sometimes requiring both a primary and a secondary sub-structure.
- Double Skin operates similarly to the Wrapping system, except it specifically targets a single façade rather than the entire building. It allows for a new aesthetic definition of the building and enhances energy performance by leveraging the air gap during winter and ventilation during summer. Similarly to Wrapping, structural support can either be ground-based or rely on the existing structure, often necessitating both a primary and secondary substructure.

Textile properties remain consistent across various typologies, as they all fall under the category of textiles. However, their specific properties differ based on the chosen material. Structural properties, for instance, play a role in strategy selection. On the contrary, the material influences the final appearance of the façade. While the energetic performance of a façade can be enhanced through strategies that involve air gaps or ventilation layers, the sunlight gains can be limited through the use of strategies that imply shading devices. It follows that the objective of the intervention affects the choice of the strategy and consequently the one of the material. In parallel, architects have diverse options for enhancing aesthetic qualities using textiles. The flexibility of textiles allows for an array of solutions, ranging from flat to 3D configurations, and the choice of material influences translucency preferences. During retrofit interventions, certain properties, such as aesthetic qualities, structural performance, durability, and economic aspects, may carry more weight in the decision-making process. It is essential to note that the identified TFR strategies are adaptable to various textile materials. Understanding the properties of each material guides the selection of construction methods and solutions, maximizing their unique characteristics.

While methodologies and strategies for façade retrofit projects may differ based on factors like building age, condition, location, and rehabilitation objectives, the identified strategies show promise for achieving both aesthetic and energy-related goals in façade retrofit projects.

5. Conclusions

This study examined the applications of textile membranes in façades and their potential connections with the practice of building retrofitting. The objective was to point out compelling but complementary alternatives to conventional façade retrofit products through the identification of textile-based products. The methodology comprised two main parts: an initial review of textile properties and characteristics and membrane applications in façades and façade retrofitting, followed by a subsequent intersection of these insights to unearth novel possibilities. The study collected data by doing a literature review, analyzing technical data sheets, and employing a pool of 55 representative case studies.

The necessity to expand retrofit practices drove the development of standardized techniques for dry assembly, streamlining construction processes and preparing for potential component reuse. This imperative guided the analysis. Architectural textiles and membrane products offer a promising opportunity to use their unique properties for less-invasive applications. These solutions can ensure the same life expectancy as conventional methods, while also paving the way for temporary and re-usable façade retrofit practices.

The outcomes identified various potential development lines for textile-based façade retrofit products, comparing their application against current retrofit limitations. The research revealed three prospective lines of development among the textile façade retrofit products that deserve further consideration due to their potential to improve both the aesthetic and energetic performances of existing building façades.

Overall, the research demonstrated the potential of textile-based retrofit products in advancing alternative technologies for building façade retrofit, aiming to diversify possibilities in the field and provide alternatives to conventional technologies to address their limitations.

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