Textile and Film Based Building Envelopes – Lightweight and Adaptive

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Summary. *This paper presents recent advances in the field of multilayer textile cladding systems with a focus on the latest findings. Primary topics are the special characteristics of textile materials in building envelopes in relation to thermal insulation, vapour issues and changing weather conditions as well as the acoustic evaluation of such ultralight systems and the ambitious demands of acoustic insulation and spatial acoustics.*

1 ADVANCED TEXTILE MATERIALS, AUTOMATED PRODUCTION PROCESSES AND MULTIDIMENSIONAL REQUIREMENTS

The development of production and manufacturing processes for textiles and a variety of established technical products have allowed the extension of the functionality of textile materials and the expansion of market shares over the past three decades, especially in the sectors of automotive technology, aeronautics and astronautics, sports and leisure, protection and security, as well as the medical field, communication and information technology.[1,2]

Fibres, their semi-finished and their final products are omnipresent in our durable goods and commodities. Breathability, non-combustibility, energy absorption and storage capacity are just a few of the possible characteristics of textiles. Such properties have been achieved in recent years through the development of combined materials, coatings, embeddings, and the advancement of process technologies for fabrication, joining and processing textile materials. *Gries and Klopp* summarised comprehensively the development of processes and catalogued the possibilities and applications from a textile technological perspective.[1,2] Industry and science work on textile materials and membranes using different methods, approaches and goals. Cell biologists, for example, try to promote fundamental investigations by exploring the behaviour of semipermeable membranes. The material sciences enhance the structural performance of carbon fibres or nanotubes. The fashion industry, on the other hand, works on a user-oriented implementation of comfortable, heat-regulating clothes.[2,3]

The knowledge gain associated with research in textiles usually takes place in different disciplines and can be separated into clusters such as materials, processes and applications. The findings diffuse very slowly between the disciplines and inspiration for product design is often limited to sketches and preliminary studies. A comprehensive transfer of knowledge and an exchange of expert opinions in an interdisciplinary design process is, however, essential for a successful system and product development.[4] *Maeda* focuses on complex interactions and simple-appearing solutions.[4] *Ropohl* describes this kind of process in his introduction to transdisciplinary thinking and discusses the benefits based on a general systems theory.[5] Such an interdisciplinary, iterative process seems to get more important if the setting of requirements and criteria gets complex and if subjective estimation influences the design process. Those ‘soft’ factors for the design process are e.g. aesthetics, haptics, or sensation.[4]

Promising technologies that will gain importance for new functional applications in architecture can be seen in material science, communication technology or mechanical engineering. The use of these new materials and manufacturing techniques offer the opportunity to revitalize or replace existing solutions that are exposed to increasing criticism due to resource and energy consumption. The level of difficulty increases for the development and implementation of those technologies if the respective demands and operating conditions extend. Geotextiles or fabrics for textile-reinforced concrete can be easily developed with simple focus on material parameters. They can be produced, characterized, and finally established more easily and faster. On the other, the building envelope is likely the one of the most ambitious and complex components in the construction industry. It combines numerous requirements as an essential separation, functional and design element.[6]

2 CLADDING CONCEPTS AND DESIGN PROCESS

For many years there have been several efforts in research and practice to develop the building envelope as an ultralight, adaptable system through the use of different textile materials. A summary of results of recent research projects at the Institute for Lightweight Structures and Conceptual Design (ILEK) and description of practical examples of multilayer textile building envelopes is given by *Haase et al.*.[1,7-9]

Building envelopes – the sum of the exterior walls and the roof – must achieve various functional qualities. Environmental protection, security, sound and thermal insulation, aesthetics as well as static properties and low maintenance requirements throughout the life of a building are essential demands to be fulfilled simultaneously.[6] The influence of façade construction on increasing interior comfort criteria and correspondingly the well-being, health, and performance of occupants extends the affected requirements. In addition, functions important during production, transport and the separation of the components at the end of the lifecycle are to be considered. Existing solutions in the construction industry typically respond to this diverse range of requirements with complex components and assemblies using a differentiated construction typology.[1,6]

The concept of an adaptive multilayer textile building envelope as a façade solution can consistently implement the reduction of resource consumption, the interchangeability of all components of the system, and the application-specific adaptation to changing environmental conditions and user requirements. So far, the basic principles related to construction, thermal conditions and vapour transmission behaviour have been investigated and are integrated in the design process. Corresponding prototypes focusing on air regulation, moisture transfer and heat balance as developed over the last 5 years were characterized and verified using conceptual prototypes, simulations and experimental measurements.[1]

The design of the conceptual prototypes mentioned above is based on the approach of modular façade systems well-known in the construction industry. Modular façade systems are one of the advanced solutions to fully meet the complex demands of modern buildings and cladding systems.[6,10] They can be designed with very little variability from element to element in semi-industrial processes, equipped with different technologies, and transported and installed on site in a routine procedures.[6] Within the design process, single components of the modular façade system, their functionality and their arrangement can be supplemented, reduced or altered according to the varying requirements. This characteristic applies to the design process of adaptive multilayer textile building envelopes as well. Different aspects, such as requirements for a structural support system, the implementation and conception of individual layers and the manufacturing processes, joints and connection capabilities are developed in parallel processes and merged at their points of interface. As a result, pultruded fibreglass reinforced profiles for multifunctional purposes were realized in addition to the prototypical textile layering. Figure 1 shows the geometry of the substructure and a fully equipped façade element.

Figure 1: Pultruded Profiles and Equipped Module of a Multilayer Textile Façade Element (ILEK / Photo: G. Metzger)

Within the work on structural-physical and material-specific principles, a significant result is that modularity is consistently complemented by the strategy to use multiple textile layers. The different requirements of a façade system can be fulfilled in multiple ways exploiting the material characteristics and the system design of the framing in combination with the textile surface elements. The main task of the design is ultimately to incorporate the potential materials in the necessary position within the system in order to achieve the maximum impact on relevant physical, structural and aesthetical demands as well as the requirements related to building science as they were identified in the design process. Thus, the central challenge in the development of textile building envelopes consists in resolving the conflict between many competing demands. These demands inevitably lead to opposing objectives and interactions between different system elements. Balancing these interactions and solving the conflicts is only possible in a continuous, iterative design process, which leads to an improved façade system.

3 THERMAL INSULATION, VAPOUR AND CHANGING WEATHER CONDITIONS

Thermal insulation and a controlled vapour transport concerning in changing weather conditions represent two of the important requirements of modern façade systems. Therefore, the relevant aspects were investigated in previous research projects at the ILEK.[1]

The reduction of transmissive heat loss during winter is one prime aspect of textile façade systems. During summer, heat generation is an issue of consideration as to avoid cooling loads and reduce incident solar radiation while maintaining adequate daylight lighting conditions.[1] The reduced mass of textile building envelopes leads to major challenges with respect to climate control. In conventional wall and roof construction, heat transmission occurs mainly through heat conduction and convection.

In contrast, heat transfer within textile layers is governed by radiation exchange. Furthermore, the low thermal mass of textile systems leads to a more dynamic behaviour when changes in environmental conditions occur. This dynamic behaviour influences the vapour balance as well. Condensation and moisture formation within insulating layers are often described as causes of damage in buildings that use multilayer textile building envelopes.[10] At night, exchange of radiation with the clear, cold firmament can reduce the surface temperature of membrane layers below the ambient air temperature. If the air directly at the membrane surface drops beneath the vapour saturation temperature, condensation will form (see Figure 2).[1]

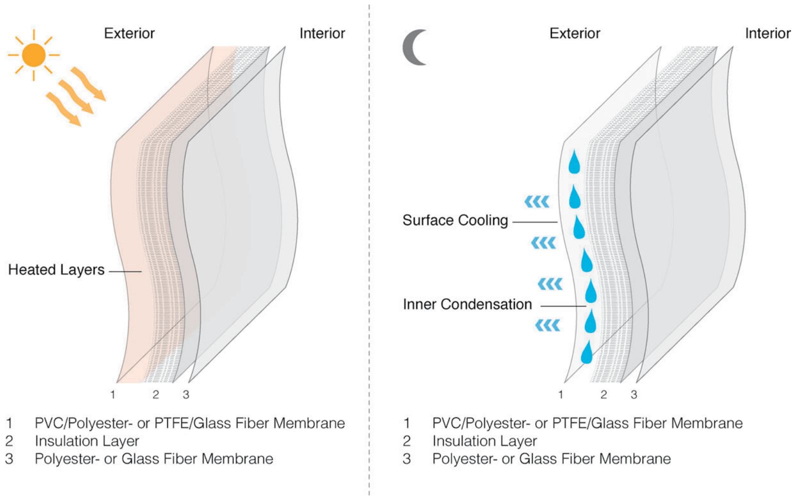

Figure 2: Principle of Night Cooling and Condensate Formation (ILEK)

The vapour diffusion resistance of the materials used must be considered in order to prevent the risk of moisture formation in the insulation. Three options to provide a reduction in the risk of condensation are available: the controlled ventilation of the insulation and interspaces to remove the vapour, the finishing of the outside layer with a low-e-coating to decrease heat losses, and the selective heating of single membrane layers to increase the surface temperature and avoid condensation.

As result of the investigations, the following criteria for the arrangement of the textile layers in a sensible system configuration are relevant: the material properties (thermal

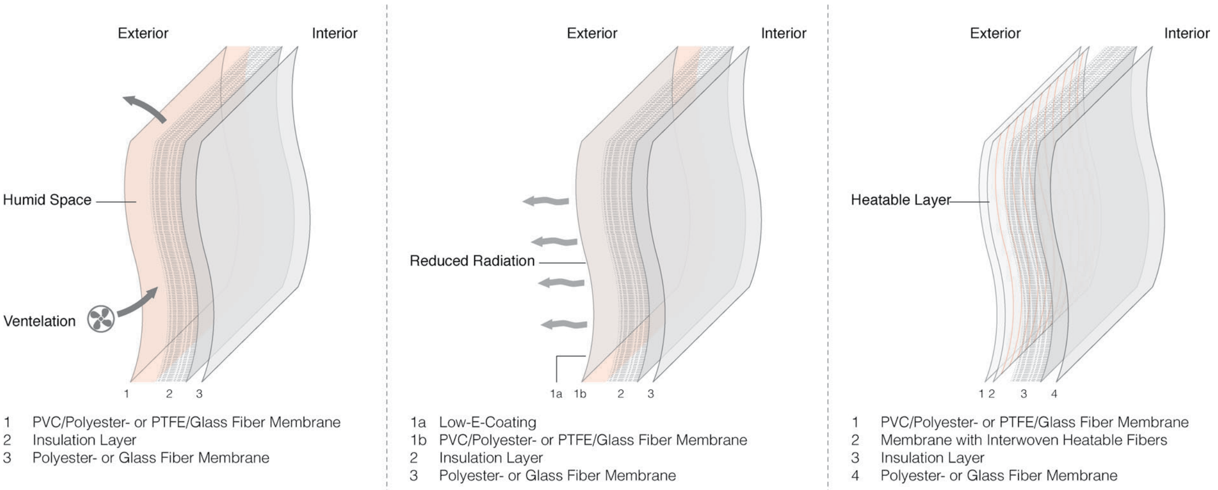

Figure 3: Principles of Avoiding Condensation in Multilayer Textile Façades (ILEK)

conductivity, radiation behaviour), the thickness of the insulation, the distance between the layers to provide ventilation and avoid condensation, and the reduction of the vapour diffusion resistance from the inner to the outer layers.[1]

As a proof of concept of the functional integration in a multilayer textile element, different materials and technologies were integrated in prototypical designs and were investigated conceptually. Figure 4 shows two of the various alternatives. Concept 1 provides a sufficient level of insulation using phase-change material (PCM) as a thermal buffer and aerogel granulate as translucent high-performance heat insulating layer. Adjustable vents are integrated to manage vapour transport and to equip the façade with a controllable ventilation system. Concept 2 uses common opaque, non-woven fabric insulation and compensates the resulting lower thermal insulation through a twin-collector. This collector combines a flexible photovoltaic layer with a solar thermal collector. The thermal radiation of the collector can be used to heat up the surfaces of the interior layers in order to avoid condensation.

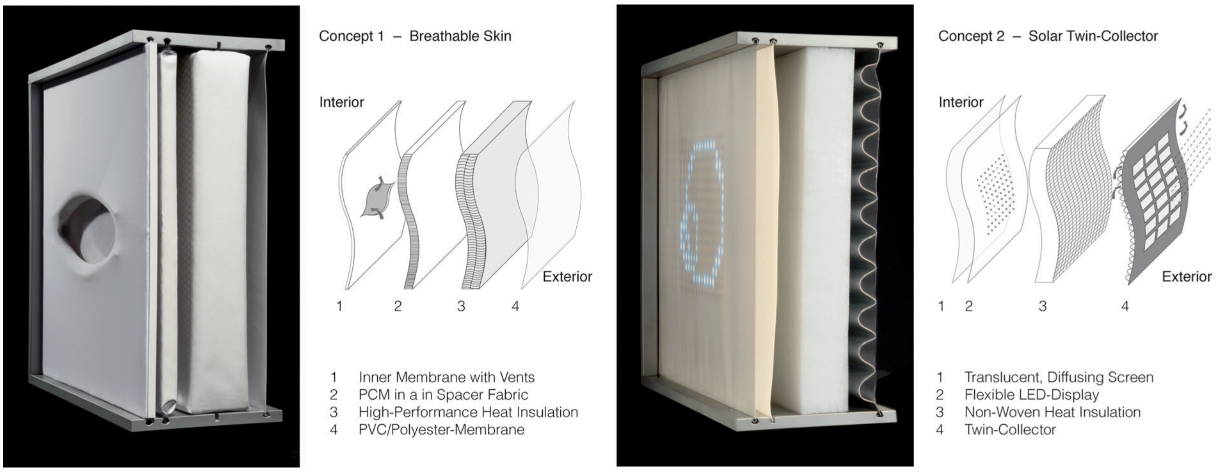

Figure 4: Concepts for Multilayer Textile Façade Solving Thermal Insulation, Vapour and Changing Weather Conditions (ILEK / Photo: G. Metzger)

4 NOISE INSULATION, SPATIAL AND URBAN ACOUSTICS

While the research described above focuses on structural profiles, thermal insulation and vapour management, the evaluation of the acoustic behaviour of materials and systems is an issue that has evolved as another important aspect of ultra-light textile façade systems. The aural perception of spaces increasingly affects the cognition through noise as one of the greatest environmental impact factors. Excessive background noise and acoustic deficiencies often underline a poor audibility and lead to significant loss of spatial quality.[7,8]

Designing spaces without considering spatial acoustics is as meaningless as focusing on noise insulation and spatial acoustics as an independent, physical topic. *Blésser and Salter* describe that the combination of design and acoustical performance needs to be discussed with an understanding of the underlying physics as well as the necessities of the application.[11] Being aware of visually non-perceptible influences will gain importance together with the increasing demand for sustainable, environmentally and health friendly buildings for the future. The relationships between material, construction, space and the resulting constructive and acoustic consequences will become of greater importance for designers and planning professionals in order to build high-quality spaces.[12]

Noise protection in an urban environment is achieved today mainly by reducing the noise of the cause, by establishing sound protection walls that shield the noise mainly due to reflection, and finally by integrating noise reducing glazing into existing buildings or by appropriate orientation of the rooms in new buildings. Usually, adequate quality for the occupants can be achieved only through the combination of schemes in all three categories. Even if the reduction of the actual sound source is the most effective method for reducing noise, it is not sufficient to significantly reduce the overall noise level especially in the urban environment with increasing sound-emitting infrastructure.[12,13] For an effective improvement of the urban quality in the context of increasing population density and noise-emitting infrastructure, reducing the sound level by means of noise-absorbing façade solutions is a potential addition. Emissions would thus no longer be redirected into the urban space through reflection and sound levels could be reduced by the surfaces. The comparison of absorbing and fully reflective sound-insulating walls in Figure 5 is described by *Möser*. It shows the effect in reduced noise levels and lower diffraction effects.[13]

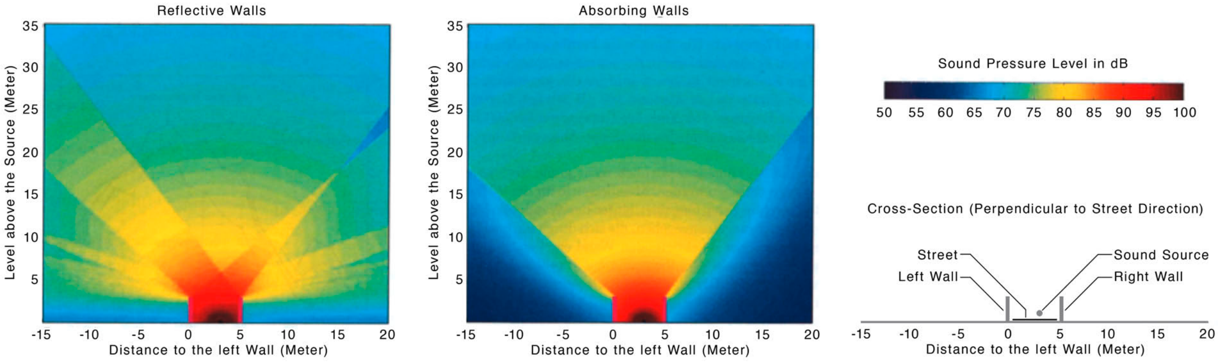

Figure 5: Sound Pressure Level Distribution in Reflective and Absorbing Walls (*Möser*: p. 357)[13]

In addition to new buildings, existing façades offer a great potential for improving the urban acoustics in connection with the pending modernisation of thermal insulations of buildings. However, façades must fulfil the functional, energetic, environmental, structural, aesthetic and social needs in comprehensive urban and architectural concepts.[13] The application of textile materials with their inherent aesthetic qualities promises a restrained, effective and aesthetically pleasing solution for retrofitting façades and reducing noise levels in streets and at noisy infrastructure.

Figure 6: Possible Application in a Translucent Sound Insulation Wall (ILEK LAB 2012, Eileen Dorer Li)

The optimisation of spatial acoustics is primarily determined by the adjustment of the reverberation time. This necessary adjustment becomes increasingly difficult in flexible used spaces and for short-term building conversions. As a result, those spaces increasingly use universal reference systems with electro-acoustic support. These methods, however, lack behind the distinctive acoustic potential of the utilized space.[12,13] Actively changing acoustically effective systems that can be adjusted specifically depending on the usage, are a different but expensive method. Such systems require a professional service and are used occasionally in high-quality multi-purpose halls.[12]

The functional and modular concept of adaptive multilayer textile building envelopes offers the possibility to use the façade system as an actively changing acoustic conditioning element for interiors.[7,8] The façade system must be developed further, focusing on cost effectiveness, material-saving, and independent controllability. Thus, spatial acoustics can be adapted automatically to different usage scenarios of rooms to provide an environment that allows, for example, concentrated working or clear conversation.[12,13]

From prototypical specimens for acoustically effective layering and the experimental examinations of potential textile materials, a solution according to the sheet, Helmholtz, and wideband resonators used commonly in spatial acoustics (see Figure 7) is identified. Core components are two or three vibrating sheets with higher area-specific mass, as well as porous, absorbing, and light interlayers. The basic design of a sheet or Helmholtz resonator allows the variation of the heavy layers by means of textile materials, additional ballast layers, inlays or of the material of the sound-absorbing layer. A perforated layer for the interior acoustics can be attached to expand the system to a wide-band resonator.

With regard to an active variable setup, the system offers the possibility of varying the amount of area-related mass, the distances and initial tension of the layers.

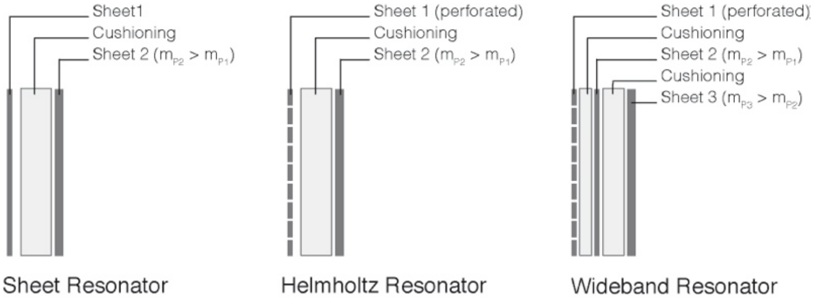

Figure 7: Closed, Perforated and Combined Shell Cavity Systems (ILEK)

5 SYSTEM SYNTHESIS

After studying the basic principles described above, the findings were combined into a prototypical system design, facilitated within an interdisciplinary process combining workshops and iterative development phases. The development of a passive system was focused on first in order to expand upon the configurations of existing membrane structures with minimal interventions. This enables a comparatively easy conversion of existing production and manufacturing processes. A dual-layer, non-woven system evolved from the conceptual phase, the study of different prototypes and an assessment of the feasibility. This system was developed to enhance the existing thermal insulation layer in order to increase the efficiency of the acoustic insulation.

A multilayered system was considered to be advantageous for the purpose of a sound-absorbing layer setup. One layer functions as heavy sheet with increased area-specific weight. From a manufacturing perspective, a weight of 1.5 to 2.0 kg / m² was considered feasible. The porous filling is used between the heavy sheets to reduce the dynamic stiffness and to prevent standing waves and interference. This porous filling is also produced as a non-woven fabric and combined into one element with the heavy fabric by needling. Figure 8 outlines the relevant elements of the compound material.

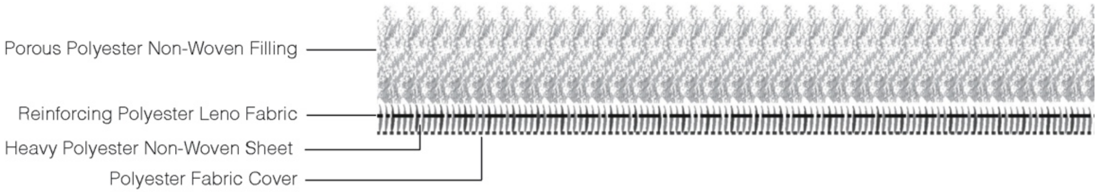

Figure 8: Systematic Elements of the Non-Woven Assembly (ILEK)

The compound material was then used for a first prototypical setup. It was integrated twice and positioned as mirrored layers to meet the configuration of a sheet absorber. The different layers and the acoustic behaviour is described in the diagram of Figure 9.

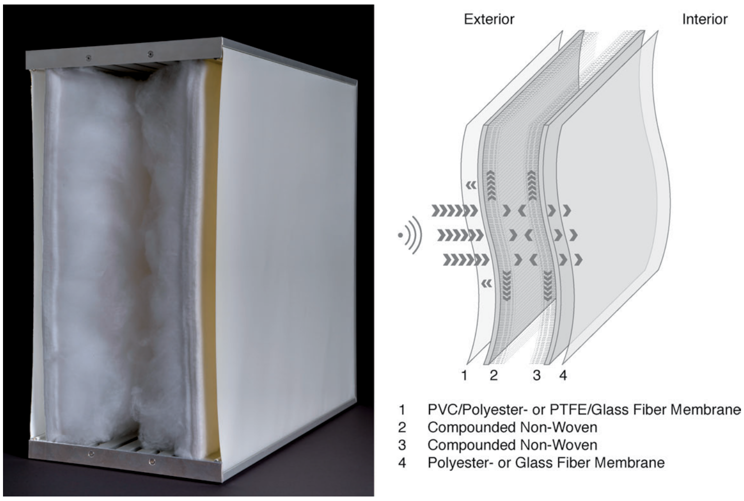

Figure 9: Acoustic Passive-Acting System Integrating a Non-Woven Insulation (ILEK / Photo: G. Metzger)

To demonstrate the adaptability of the reflective and absorptive characteristics of multilayer textile building envelopes, the design of the existing system was extended to an acoustically active system. A stitched tube system with a fluid filling was added to the system in front of the heavy fabric in order to vary the area-specific mass. The variability of the amount of the fluid and the filling pressure allows to influence the vibration behaviour of the layer and to increase the reflective characteristic in relation to the urban space or to the interior. Figure 10 shows the extension and the acoustic behaviour of the acoustic active-acting systems.

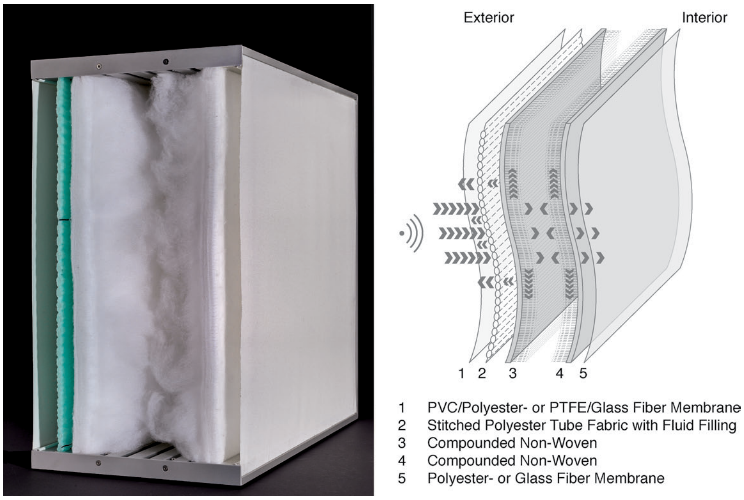

Figure 10: Acoustic Active-Acting System Integrating a Fluid Filled Tube System (ILEK / Photo: G. Metzger)

System designs developed with this adaptive principle can reduce the sound energy in an urban environment (layer positioned to the interior is filled and ballasted). (see Figure 11) It can also be configured inversely to mainly reflect the incoming sound field (layer positioned to the outside is filled and ballasted). In conjunction, the system includes the possibility to vary the spatial acoustics of the interior space through the reflection and vibration behaviour of the heavy layers.

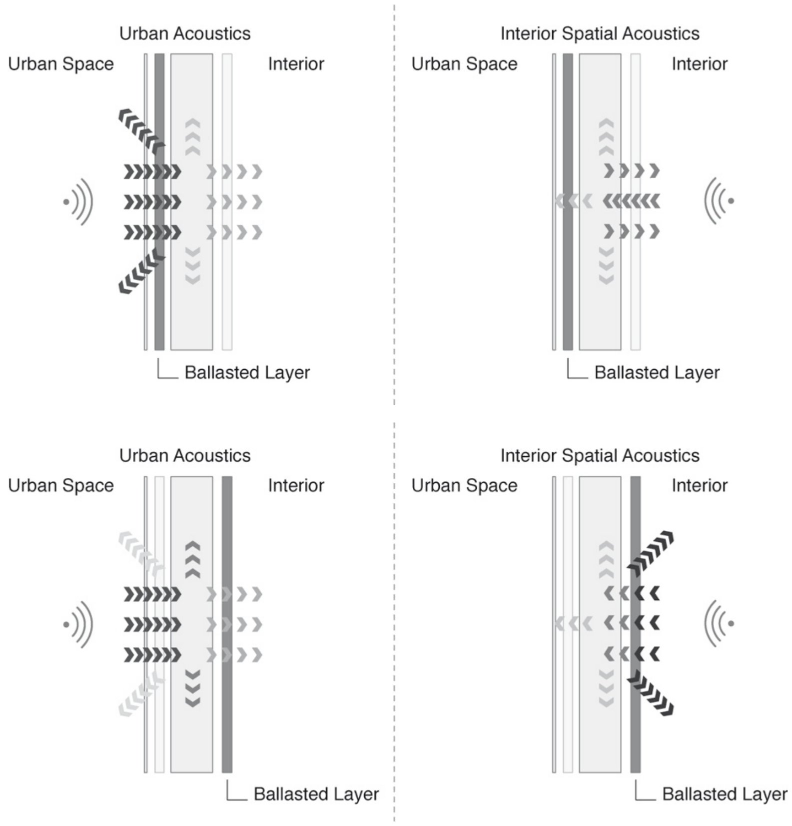

Figure 11: System Behaviour with Switchable, Ballastable Layers (ILEK)

As part of the system development, the concepts and prototypes are described above are currently being studied in more detail. The investigation of the thermal and vapour behaviour of the systems is being conducted using the simulation tool described by *Klaus et al.*.[14]

In the context of the ongoing research, the acoustic performance of the prototypes is quantified by the system specific sound reduction index. The determination of this index has been conducted at the Fraunhofer Institute for Building Physics in Stuttgart (see Figure 12). In Figure 13, the results are compared with commonly used textile systems and with a solid wall. The calculated weighted difference level of the passive-acting system (type A) is $D_W = 30$ dB, the active-acting system (type B) reaches $D_W = 34$ dB. In comparison to that, the dual layer PVC/Polyester Membrane described by *Maysenhölder* reaches a difference level of $D_W = 17$ dB. The acoustic performance of the system integrating a non-woven insulation is significantly better than the one of single or double layer membranes (type D and E). The addition of the fluid filled tube system with an area-specific mass of 17.75 kg/m^2 (type B) causes a further increase of the sound insulation performance, in particular in the frequency range above 500 Hz. This effect demonstrates the possibility to vary the acoustic behaviour of such systems on demand.

Figure 12: Equipped Door Test Bed (ILEK / Photo: F. Schmid)

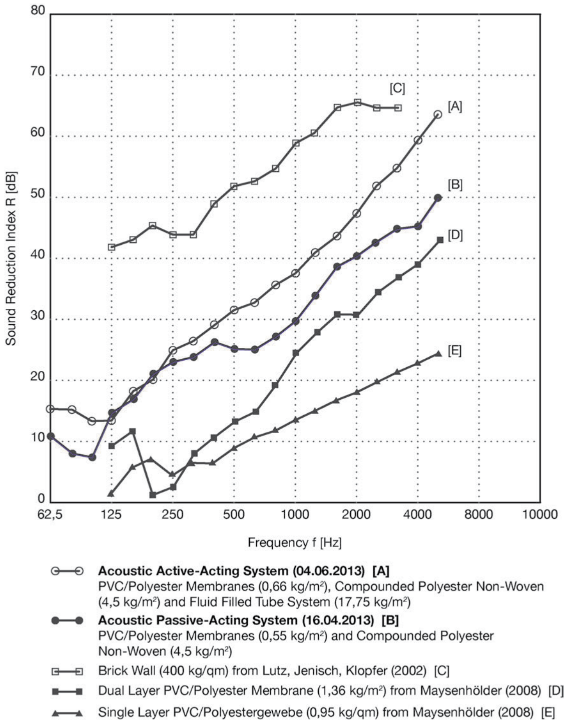

Figure 13: Comparision of Sound Reduction Indices (ILEK / LBP)[15,16]

6 CONCLUSION

The studies and experiments performed at the ILEK present the potential of multilayered textile building envelopes as an important high-quality solution for new façade constructions. The concurrent work on the relevant subject areas through systematic system development, the incorporation of a large number of textile layers or functional materials in appropriate structural frames and experimental investigations are part of a necessary discourse to develop the fundamentals for a meaningful choice of material and for an effective synthesis. The findings are used to improve the design of the textile façade solution in the manner of thermal and acoustic insulation, spatial acoustic and the interior quality.

The studies have shown that the thermal and vapour issues can be solved with rational material selection and integrated active elements. An effective solution to solve the acoustic requirements of ultra lightweight envelope systems is represented by the broadband absorber used in spatial acoustics.

Although the results are based on initial conceptual ideas, they nonetheless point in an important direction for a consistent development of multilayer textile building envelopes addressing changing requirements and conditions in a single system. The diverse requirements can feasibly be addressed only through a consistent system development of ultra-light systems. This must be driven by an interdisciplinary and iterative design process taking all potentials associated with the system synthesis into account. These potentials are exploited only through the appropriate use of material properties, relevant physical and functional features, structural efficiency, and by integrating consideration of production processes and facilities into the design process.[1,8,9]

The resulting conceptual designs and the findings with respect to construction principles and functionality represent a contribution to establish recyclable textile and film-based multilayer configurations as future ultra-light, highly efficient building envelopes. The importance to focus on such new kinds of façade solutions is obvious by the necessity to redevelop processes, technologies and products for the building sector in the current context of limited resources and urban development.[1]

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