Smart Textile Sun Shading

Development of Functional ADAPTEX Prototypes

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Abstract

The research project ADAPTEX pursues the goal of developing adaptive, energy-efficient textile sun shading systems using the smart material Shape Memory Alloy (SMA). Within this approach lies a high potential for novel sun protection systems demanding little energy or even self-sufficiently adapting to external stimuli while reducing operation and maintenance costs and at the same time offering solutions to tackle growing demand for sun and glare protection. A Design Categories Matrix is presented that brings together various involved fields from textile design and façade construction to smart material development. Based on this, two concepts have been further elaborated: ADAPTEX Wave and Mesh. Both incorporate SMA into textile structures but express different design and performance potential by changing the geometry and openness factor of the surface area. For further evaluation, various functional prototypes that scale up from 0.2 x 0.2 m to 1.35 x 2.80 m are developed and reviewed. The buildability and functionality of SMA-driven textile sun shading systems that incorporate requirements from the various involved fields are verified. The feasibility of parallel ADAPTEX Wave and Mesh were assessed in comparison to the performance of state-of-the-art sun shading systems. The technological ideas are subsequently optimised and scaled up in various cycles for follow-up testing in both indoor and outdoor environments.

Keywords

Adaptive sun shading, textile building envelope, smart materials, autarkic operation and control mechanism, Shape Memory Alloy (SMA)

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1 INTRODUCTION

The United Nations' "Transforming our world: the 2030 Agenda for Sustainable Development" (United Nations General Assembly, 2015) proclaims that there has been a highly increased demand in energy- and resource-efficient building construction. This calls for a new alliance of simplicity and performance in the technology and operation of future building systems.

The building envelope plays a major role in such needed improvements by enabling the use of efficient or even autarkic systems that minimise energy demand by, for example, reducing cooling requirements through efficient sun shading.

ADAPTEX aims to develop such a novel sun shading system. By combining the potentials of lightweight textile construction and the smart material Shape Memory Alloy (SMA), significant reductions in production and material consumption, in transportation and installation, and in operation and dismantling (Barozzi, Lienhard, Zanelli, & Monticelli, 2016) could be achieved.

Shape Memory Alloys (SMA) are metal alloy materials that in the last twenty years have caught the interest of designers and researchers working in the field of adaptive surfaces, due to their shape-changing properties. These materials show solid-state phase transformation through temperature change between martensite and austenite. When heated up, the material is in the high strength austenite state e.g. as shrinkage of a wire, and on cooling, the material changes to the low strength martensite state, moving back into its original state (Josephine, Ruth, & Rebekah, 2020). SMA elements are generally very suitable for construction applications due to their performance, free from wear and maintenance. Moreover SMAs are activated by changes in temperature, allowing an autarkic and adaptive reaction to external stimuli like ambient heat or solar radiation - complemented by decentralised control through electric voltage (smart^3 e.V., 2017). The small size actuator induces force and movement and therefore is able to supersede complex motors and driving mechanisms. However, SMAs are designed for the accuracy and standards of mechanical engineering rather than for architectural façade applications. ADAPTEX closes this gap by integrating SMA into large-scale architectural surfaces using textile technologies (see Fig. 1). Implemented into soft surfaces, SMA initiates changes in geometry thus adjusting parameters like transmission and reflection for shading and enhancing building performance (Denz, 2015).

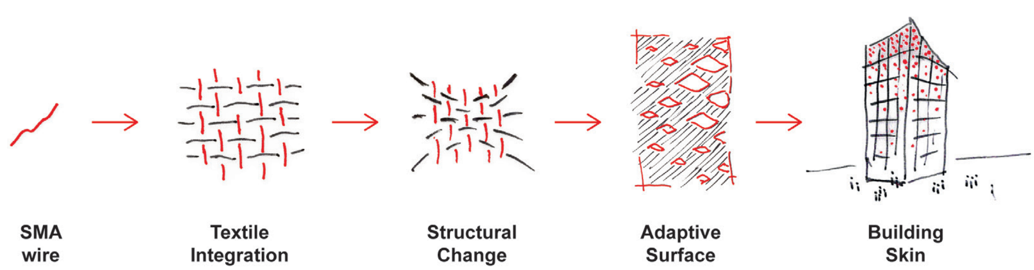


FIG. 1 Conceptual approach ADAPTEX

Although smart materials have been discussed in architectural discourse for many years (Addington & Schodek, 2005; Ritter, 2007; Braun, 2008), so far Smart Textile solutions as envisaged by ADAPTEX have not reached built reality. Smart Materials in combination with textile or membrane structures are often dealt with in the context of responsive / adaptive architecture (Khoo, Salim, & Burry, 2011;

Dewider, Mohamed, & Ashour, 2013), directly influenced by external stimuli or user interaction. Several design studies were developed in which the textile surface is deformed through actuator systems such as SMA. At TU Delft, an adaptive building component using shape memory alloy and shape memory polymer as a composite material to create an exterior layer of fins to reduce wind-loads by changing the façade surface accordingly was investigated (Lieleveld, 2013). More concrete, although still in conceptual/experimental stage, are the Smart Textile Skins using SMA that have been developed. For example, self-sufficient driven courtyard textile shadings such as those used in Seville, Spain, use a shape memory alloy spring as actuator (Callejas Ortega, 2015). In addition, at IAAC in Barcelona, shape memory alloys are used to deform textile surfaces by the external actuator controlling light coming in through stacked textile layers creating a responsive façade solution (Begle, 2013). The most advanced research on Smart Textiles in building construction can be seen in Cherif (2017), but only as a component i.e., as shape memory alloy fibre within concrete reinforcement. Further examples can be found within the smart^3 research network, such as Solar Curtain, flower-like shading units run by SMA (Sigmund, 2016), or Smart Skin, where the usage of SMA as a substitute for a motor in state-of-the-art venetian blinds has been investigated (smart^3 e.V., 2017). However, following the review by Fiorito et al. (2016) it is apparent that SMA is one of the most favourable actuators in research for shape morphing solar shading systems.

This proves that the potential of SMA driven façade systems has not yet been exploited to any great extent. The research by Wærsted (2014) further illustrates how Smart Textiles in general do not yet play any role in the material practise of architects when designing new projects and façades. Simultaneously, complexity in façade design is increasing due to higher expectations and regulations towards environmental, societal, and economic performance requirements (Loonen, Trčka, Cóstola, & Hensen, 2013). ADAPTEX aims at tackling these challenges and developing a Smart Textile Sun Shading feasible for actual façade implementation that can contribute to novel solutions enabling highly efficient building envelopes as defined by Böke, Knaack, and Hemmerling (2018).

2 DEVELOPMENT APPROACH

Due to the interdisciplinary team within the ADAPTEX project, the aim from the beginning was to bring together all relevant requirements to align the knowledge on the topic and develop novel and feasible solutions. In an initial stage, a Design Categories Matrix collecting all necessary data was used to allow for an early design phase – free from major constraints but having the overall requirements in view. These concepts have been reviewed, narrowed down, and grouped into the main typologies. The feasibility of the designs has been continuously checked throughout prototyping, and underlined with a comparison to state-of-the-art systems. During the development, digital tools were used to stay agile and adjust to necessary changes of the concepts during development and for later application, concluding in a high leap of Technology Readiness Level (European Comission, 2014) from TRL 2, formulated technology concept, to TRL 5/6, technology validated/demonstrated in relevant environment, within ADAPTEX. With the help of this research by design approach within ADAPTEX, an interdisciplinary team is able to develop a theoretical research idea (TRL 2) up to relevant size and environment prototypes for performance testing (TRL 5/6), thus aiming at exceeding TRL of former research in the field of Smart Material enhanced adaptive façades as reviewed, for example, by Aelenei et al. (2018).

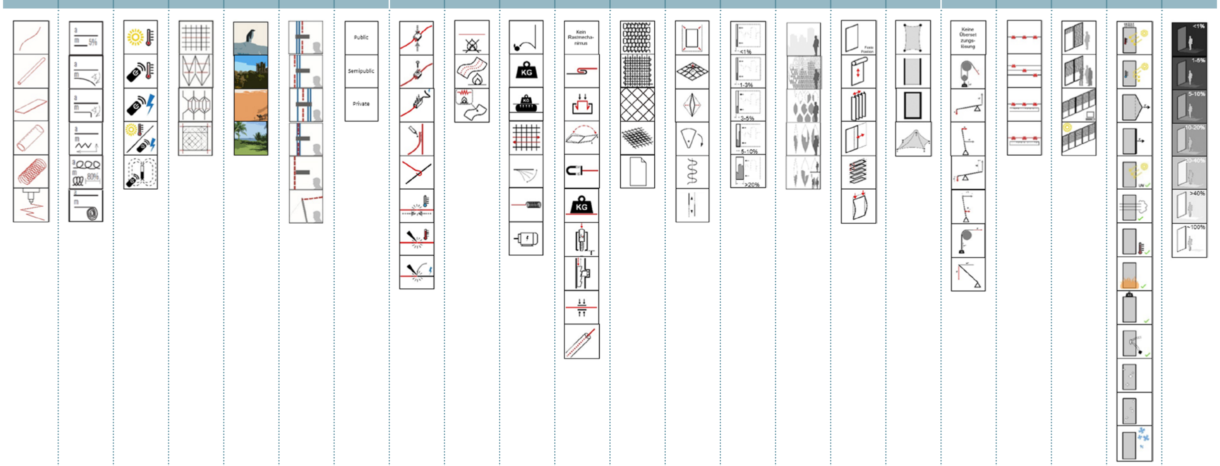
3 ADAPTEX CONCEPTS

3.1 DESIGN MATRIX

As the basis for the cross-disciplinary development of the intended textile sun shading device, a visual and conceptual *Design Categories Matrix* was developed. As shown in TABLE 1, this comprises the main features and requirements of Shape Memory Alloy technology, building envelope construction, architectural application, and textile design. Among other things, these 22 categories span from *SMA components* such as wire, rod, sheet, spring, or even 3D-printed components, to *Textile Principles* like woven or knitted fabric, mesh, or foil, to general *Façade / Material Requirements* defined as optical properties, fire protection class, or UV resistance. With the help of the Matrix, the partners from various fields could first design conceptual scenarios for SMA-driven textile sun shading solutions, choosing a criterion per category and linking these to each other.

TABLE 1 Design Categories Matrix

FIXED CATEGORIES							FLEXIBLE CATEGORIES										OPTIONAL CATEGORIES				
1. SMA components	2. SMA deformation	3. SMA activation	4. Textile connection/integration	5. Climate regions	6. Façade integration/typology	7. Building/usage type	8. SMA fixing	9. SMA training/programming	10. Reset force	11. Snapping mechanism	12. Textile principle	13. Textile closing mechanism	14. Precision in execution	15. Opening size/movement	16. Sun shading movement	17. Façade construction	18. Gearing	19. SMA circuiting	20. Sun shading control	21. Material requirements	22. Light transmission



The categories of the Matrix are divided in three main groups: *Fixed Categories*, which have to be chosen first, and solely one chosen per category because of its high influence on the following categories, as well as a high dependency within this group. This is followed by *Flexible Categories* that lead to a more detailed concept, and which first enable visual and physical model-making.

Within this concretisation phase, the *Flexible Categories* might adjust, changing the selected option due to an iterative design process. Lastly, *Optional Categories* have to be reviewed, however, these have only a small impact on the early stage research by design process due to the very precise correlation with execution or even specific real-life project requirements. Within this group, various selections per category, or even none, could be made. These categories become more relevant in the further development, when designs are narrowed down, leading to a more concrete building envelope scope.

Based on these Design Categories, 13 Scenarios for SMA-driven, textile sun shading devices were elaborated, following decision processes in each category incorporating the relationship between the different categories and fields (Denz, Sauer, Waldhör, Schneider, & Vongsingha, 2020). As an example, shown in Figure 2 on Scenario No. 03, the design process is based on the selection of Category values leading to a Scenario plot, for comparison between Scenarios, a Code as well visual representation of the selected Categories is documented. Based on this theoretical concept development, operation and construction sketches, small-scale prototypes, as well as visualisations, were first created. All 13 Scenarios have been developed and formulated according to this scheme for further discussion within the interdisciplinary consortium setting basis for the following development steps (see 3.2 and 3.3).

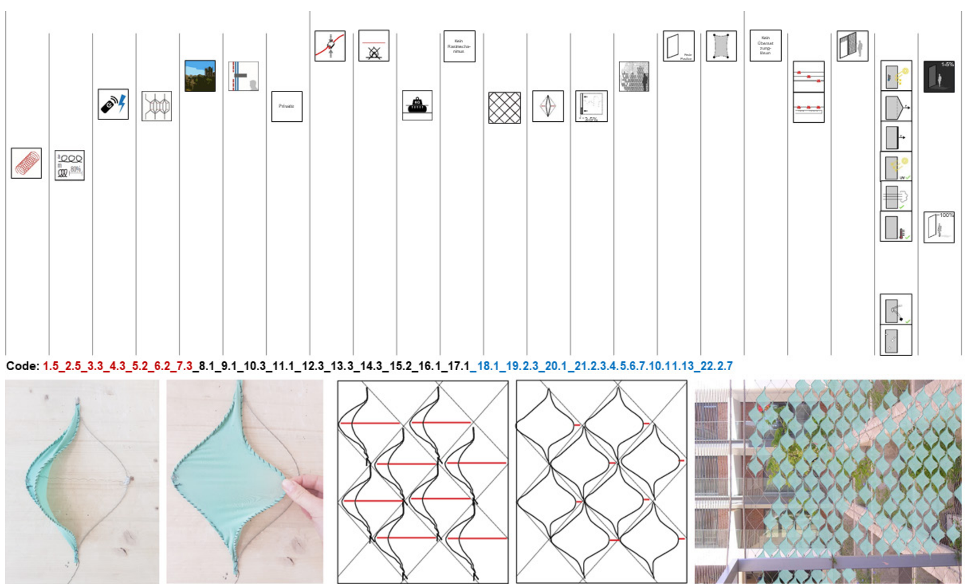


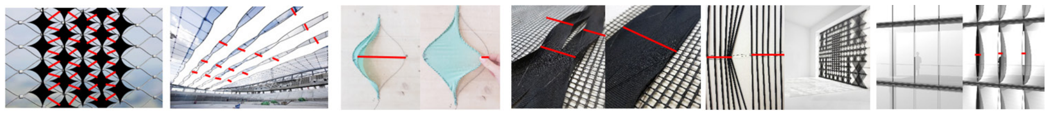
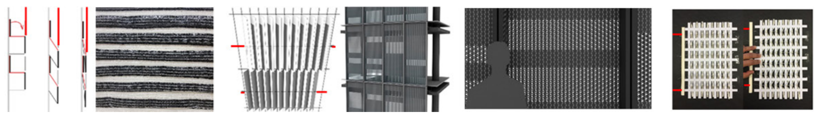
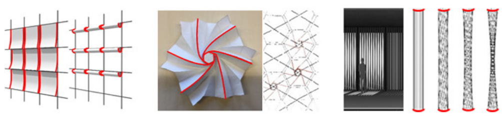
FIG. 2 Scenario No. 03; visual selection of Categories to develop concept (top); Scenario Code according to Categories selection (middle); physical small-scale prototype, sketches of the operation scheme and visualisation (bottom, left to right).

These Scenarios were summarised into three main Typologies (see TABLE 2) based on its application of SMA to focus on the main system properties for further development, thus also leading to a combination of previous scenarios, narrowing down the scope:

- *Pulling:* With this method, SMA is only shortened in a linear direction. The movement can take place along the plane (tangential direction) or perpendicular to the plane (normal direction) of the textile. (Summarising 6 of 13 scenarios).

— *Pushing:* With this method, the surfaces consist of at least 2 layers that move against each other. The overlap of these two layers defines the transparency of the sun protection. (Summarising 4 of 13 scenarios).
— *Rotating:* With this method SMA are moved / deformed by bending force, which causes a rotary movement in the surface. 3-dimensional deformations can be included in this typology. (Summarising 3 of 13 scenarios).

TABLE 2 Scenarios sorted by Typologies

PULLING	
PUSHING	
ROTATING	

After evaluating these main approaches due to the main feasibility of SMA usage as wire that shrinks/extends in a longitudinal direction, the Rotating category was discarded. This is also directly linked to a higher force, as well as a higher number of cycles that could be undertaken if SMA is not geometrically deformed when activated.

These concepts and design categories and the subsequent decisions within the development process have also been applied and put to the test in various student courses, such as an interdisciplinary workshop on Smart Textile Building Skins at the University of Antwerp (Denz, 2017), or a seminar on textile sun shading at the Weißensee School of Art and Design in Berlin (Sauer et al., 2018).

3.2 ADAPTEX WAVE

Continuing the *Pulling* typology (see 3.1), the system ADAPTEX Wave as a three-dimensional shading device was developed. This concept consists of the following main components (Fig. 3):

— *Textile Band*: A continuous wave-shaped textile band is interwoven with a SMA running through defined points of the textile. Under controlled tension from the shortening of the SMA actuator, the band is deformed by introduced pulling forces at the defined intersection of textile and SMA, resulting in a buckling process, thus moving the edges of two textile bands towards each other, enabling a closing mechanism. This also occurs vice versa, going back into its original shape and stretching the SMA once the SMA is deactivated.

- The textile is specifically designed following three main aspects:
  - Optical properties: High reflection facing outward for optimised sun-protection, currently silver-coloured glass fibre. Low reflection and dark colour for high contrast to enhance the view out and reduce glare in the interior, currently dark blue-coloured glass fibre.
  - Internal stress/stiffness: For a two-way operation, enabling the change from closed to open state, the textile must hold enough internal stress to move back into its original shape and extend the SMA in its deactivated state. Therefore, an exact balance between SMA force and textile stiffness has to be achieved. At the same time, the textile band has to be flexible enough to realise the necessary buckling and induced radius for full closure. In the current prototype, a two-layered glass-fibre laminate is used.
  - Cutting pattern: The wave-like cut of the textile band is optimised to enable a maximum closure/shading once the system is activated and at the same time minimises the necessary length reduction of SMA, which is directly linked to the distance between the fixing point of the textile band and the point at which the SMA passes through the textile. The current design leads to an openness factor of 70 % in its open state versus 0-5 % in its closed state.

- *Shape Memory Alloy*: The SMA, a nickel titanium alloy, is an active component that reacts to temperature change and operates the whole system. Once activated, either by electricity or ambient heat, the SMA shrinks, and once cooled down it is extended again. In the current design, the SMA is activated around a base temperature of 60 - 65 °C while performing a length alteration of up to 5 % and a pulling force of 0.7 N.

- *Sub-Structure*: A main structure to which the textile band is attached as a fixed point to perform geometrical deformation. In the current design, this is performed by a steel-rope net. This not only enables a stiff but at the same time flexible construction but also reduces the material effort as well as thickness to a minimum. This emphasises its overall textile character and reduces the system's impact on the view while in open state.

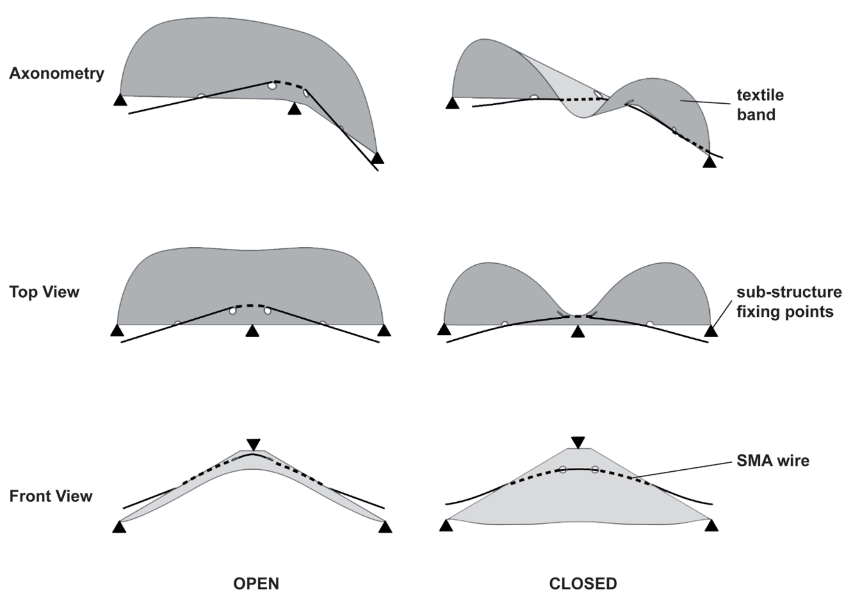
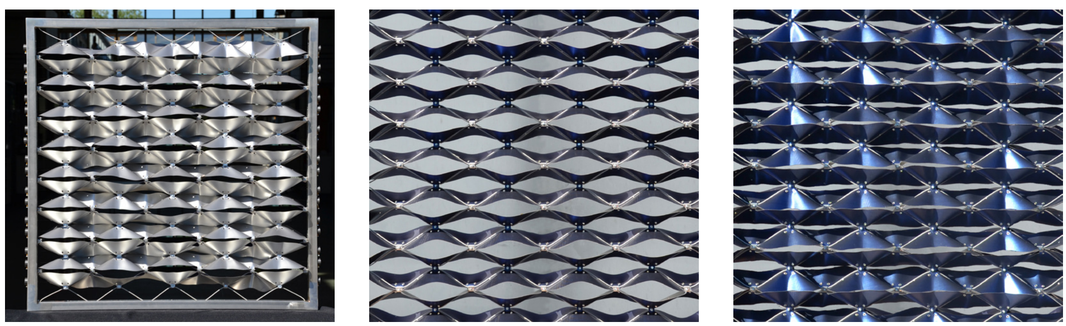


FIG. 3 ADAPTEX Wave Design Principle

Further components to execute the functional Wave system for current prototypes are, among others, a steel frame that holds both the steel-rope net and the SMA, and various small components like screws, eyelets etc. to fix the separate components or enable the threading of the SMA through the textile band. All these components underly a continuous optimisation process aiming for a reduction in material and costs using market available parts.

To develop, optimise, and adjust all these parameters in accordance with input from various partners/components, as well as results from test samples, various tools like Rhino, Grasshopper, Kangaroo, Sofistik, etc. were used (Schneider et al., 2020). An iso-geometric analysis incorporating the textile material values of flexibility, elongation limit, elasticity, etc., was integrated into these computational models. A two-dimensional cutting pattern was generated out of the virtually deformed 3D-model, while calibrating opening angles and fixing parts, thus enabling an iterative design process that led to optimal and feasible solutions as shown in latest Large Scale Demonstrator (Fig. 4.).



1 *2* *3*

FIG. 4 Demonstrator of ADAPTEX Wave within a constructional frame facing the outer surface (1); close-up of the open state (2), and of the closed state (3) facing the inside surface

3.3 ADAPTEX MESH

As a result of the *Pushing* typology (see 3.1), the system ADAPTEX Mesh as a double (or multiple) layered shading device was developed. This concept consists of the following main components (see Fig. 5):

- *Textile Layers*: Two perforated textile layers move against each other, changing the overall density of the structure in different overlapping states. These textiles are optimised according to the following criteria:
  - Optical/Material Properties: The external, fixed layer aims for high reflectivity to ensure high sun-protection, currently glass fibre mesh, and thus white in colour. The internal, moving layer has a low reflectivity and dark colour for high contrast to enhance the view out and reduce glare in the interior; it is currently dark brown/black in colour, as given by basalt fibre mesh. For the selection of currently used non-woven mesh, the possibility of easy transport, e.g. rolling, as well its stiffness within the final system layout, was taken into consideration.
  - Pattern: A customised pattern of diagonal and vertical fibres to maximise the difference between open and closed state while at the same time minimising the Moiré Effect (Amidror, 2009) has been developed. Currently, the system ranges from an openness factor of

roughly 30 % in its open state to 7 % in its closed state. The pattern can easily be adjusted, e.g. by reducing fibre thickness, or scaled to change these values accordingly.

- Integration of SMA: The SMA is directly integrated into the non-woven mesh during its fabrication process. The design of the pattern specifically gives guidance for the SMA while specific pre-treatment of the SMA prevents a firm connection with the textile fibres, enabling a constant shrinkage of the SMA along the whole distance when activated. The SMA is either fixed at the bottom of the textile layer, or within, depending on the dimensions of the system as well as the necessary length adjustment of the SMA. The weight of the moving textile layer and the moving distance, as well as the force of the SMA, have to be fine-tuned to ensure a full shift from open to closed and back.

- *Shape Memory Alloy*: The SMA, a similar nickel titanium alloy as for Wave, is an active component that reacts to temperature change operates the moving layer. Once activated either by electricity or ambient heat, the SMA shrinks, pulling up the moving textile layer and raising the system density; once it cools down it is extended again, releasing the textile back into the original position imposed by the textile's self-weight. In the current design, the SMA is activated around a base temperature of 60 - 65 °C, while only performing a length alteration of 3 %, lifting a textile of roughly 3.0 kg.

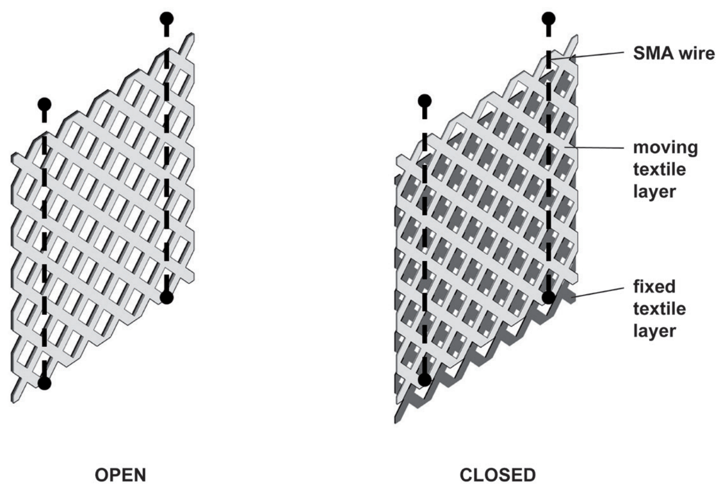


FIG. 5 ADAPTEX Mesh Design Principle

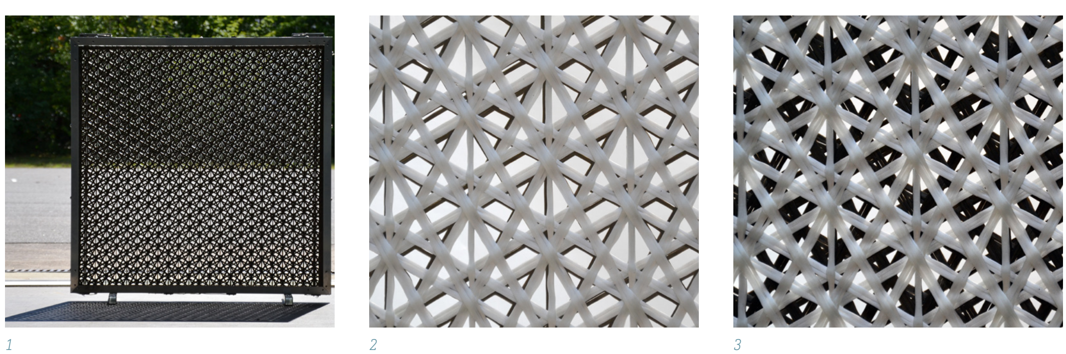


FIG. 6 Demonstrator of ADAPTEX Mesh within the constructional frame (1) facing the inner surface; close-up of open state (2) and close-up of closed state (3) facing the outer surface

To conclude, in the Mesh system a frame structure is used to fix the non-moving outward-facing layer and at the same time to attach the SMA and the inward-facing layer with loose fixings. These fixed and loose points simultaneously ensure the correct positioning of the two layers towards each other: exact overlapping of the same pattern in the open position, defined distance between the layers to prevent or make use of the parallax effect (Waldon & Dyer, 1993) and maximum offset of the pattern towards each other to gain the highest shading values (Fig. 6). To customise the system to project a specific design, performance, and scaling requirements, a parametric script incorporating both textile and architectural demands was developed (Schneider et al., 2020).

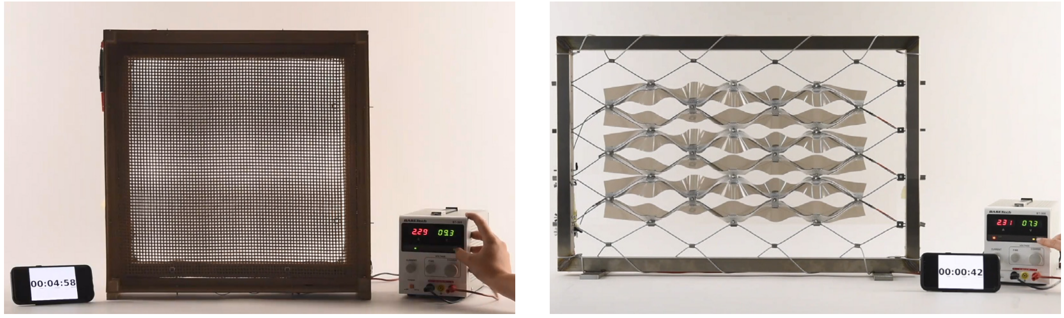
4 RESULTS

4.1 FUNCTIONAL PROTOTYPES

Following the development approach (see 2.0) from the first conceptual stage and compiling the Scenarios (see 3.1), moving forward with physical models and prototypes was a crucial part of the research to understand the interplay of textile, SMA, system layout, and geometry. All of these models were created at 1:1 scale, reflecting material and constructional requirements and restrictions. From early-stage geometrical models, *Small Scale Test Samples,* and *Large-Scale Demonstrators* to *Full Scale Prototype,* the main function and operation principles continue. Within ADAPTEX, this is a very feasible approach due to the system design as a textile construction. Consisting of various small-scale components, as shown in 3.2 and 3.3, the scaling up by roughly 100 times from first concept (in average measuring 0.04 sqm) to *Full Scale Prototype* (measuring 3.78 sqm) does not change the core system design. The textile layout uses additional further components, bands, and filaments to enlarge the covered surface – thus also easily integrating the SMA as wire. SMA specifically is very feasible for this scaling up approach due to its customisation potential and strength as well as durability (Habu, 2011). Within ADAPTEX, SMA is adjusted to the various designs and scales solely by choosing appropriate alloys and different wire diameters from market-available products. Working with diameters from 0.1 to 0.4 mm in ADAPTEX, has little to no impact on the design, nor on the construction of Wave and Mesh.

4.1.1 Small Scale Test Samples

Following the two most promising scenarios (see 3.1, 3.2, 3.3), small-scale functional test samples were created to review its feasibility. Both Mesh and Wave test samples, measuring roughly 25 x 25 and 25 x 40 cm, have been run for more than 50 cycles while the SMA was activated by an electrical voltage, as seen in Figure 7.



1 2

FIG. 7 Small-scale functional test samples of ADAPTEX Mesh (1) and ADAPTEX Wave (2).

4.1.2 Large Scale Demonstrator

As already presented in 3.2 (see Fig. 4) and 3.3 (see Fig. 6), functional demonstrators of 1.0 x 1.0 m, including a constructional frame for integration into façade construction, were manufactured. These incorporate a first optimisation loop and have resulted in geometry, material, as well as performance improvement. These demonstrators are already designed following actual façade requirements and can be seen as a clipping of a *Full-Scale Prototype* for further finetuning. The exact sizing was also dependent on the size limitations of the testing setup (see also the following paragraph). This leap from small scale to large scale already shows the potential of further scaling to reach actual façade dimensions and integration. At the same time, these functional demonstrators both run on electricity as well as self-sufficiently on external heat input. However, the current layout of the SMA needs rather high temperatures that are not very common in façade operation.

Apart from providing proof of the viability of further developing both concepts into façade/ architectural usage, these demonstrators are also used to verify its actual sun-protection properties. Both Mesh and Wave are currently undergoing verified indoor testing at the Fraunhofer ISE to measure optical as well as calorimetric performance values under various circumstances, e.g. within a double-skin façade or as an external sun-protection device. The first visual test runs have already verified its architectural design potential, as well as the basic operations of opening and closing the structures as sun-protection (see Fig. 4, Fig 6).

4.1.3 Full Scale Prototype

To prove in-situ feasibility, and review fabrication and operation processes, approaching TRL 6 (technology in relevant environment), two double-skin façade units of 1.35 x 2.80 m are being planned to incorporate both Mesh and Wave. These real-size prototypes will then undergo long term outdoor field tests outside of Berlin and will be presented to relevant stakeholders during fairs and project-related lead-user workshops. These prototypes are based on the construction and design of the *Large Scale Demonstrators*.

For Wave, due to its additive Textile Band design, only a small scaling from 1.0 to 1.35 m in width is necessary. To increase height, this requires solely adding more bands, which doesn't affect the basic design or construction. Only a slight adjustment in the layout of the SMA has to be made to provide sufficient pulling force to operate a longer textile band, and therefore more openings. Fixing and frame construction will be optimised focusing on market-availability of components and meeting higher forces within the system and sub-structure.

For Mesh, an even scaling of the pattern will be undertaken still ensuring the same openness factor for open and closed states. This is driven by an optical and design review, rather than by constructional or functional reasons. Within the *Large Scale Demonstrator,* the pattern of the two layers merged into each other with increasing distance of the viewpoint from the surface. To ensure a visual differentiation between the two states and a clear change in view, the pattern is scaled by a factor of 2. Concerning the fixing and frame construction only small changes for assembly and operation are carried out, without affecting the overall Mesh concept. With the larger size of the unit, and therefore textile layers, higher loads have to be carried by the SMA, thus a stronger SMA is used. However, the positioning and amount of SMA stays the same, as in the previous prototyping stages. For the *Full Scale Prototype,* the SMA can even be run shorter in proportion to the full layer height compared to previous layouts. This is a consequence of the direct relation between percentage shrinkage of the SMA (3 %) to the SMA length to the favourable movement of the two mesh layers towards each other. In this case, the SMA is fixed within the mesh layer using a terminal at the end of the SMA.

4.2 COMPARISON TO STATE-OF-THE-ART

Parallel to the previously described design processes and prototype manufacturing, the first comparisons to state-of-the-art systems (Kuhn, 2017) have been conducted to evaluate basic reasonableness of the ADAPTEX approach to incorporate in next step optimisation processes (Denz et al., 2018) . Simulations on the shading potential of the developed systems compared to standard venetian blinds verified against non-existing shading shows similar results to those shown in Table 3. Although these simulations need to be updated with the outcomes from, for example, Fraunhofer ISE testing (see 4.1), their functionality as sun shading, even in the early design stages, has already been shown, verifying the feasibility of the followed concepts.

Furthermore, quantitative assessment of the scenarios and later developed concepts in comparison with not only standard but also customized and adaptive sun-protection solutions has been conducted. Therefore, properties like *Design Flexibility, Solar Heat Gain, Durability,* or *Costs* have been qualitatively rated from 1 to 5 – 1 for lowest performance, 5 for highest performance, in relation to all reviewed case studies, as well as ADAPTEX Wave and Mesh. The comparison in form of radar charts (Table 4) of ADAPTEX Wave and Mesh to the adaptive sun shading solutions such as those on Al Bahr Towers (Cilento, 2012) or X-LED steel-rope net for second skin façades (Carl Stahl ARC GmbH, 2019) shows similar to better coverage and therefore overall performance.

TABLE 3 Shading/Illuminance simulation with no shading, venetian blind, ADAPTEX Mesh and Wave.

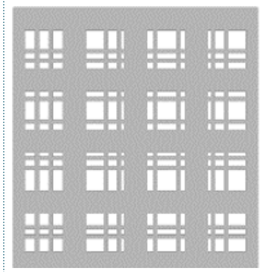
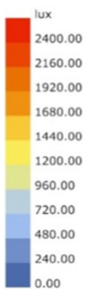
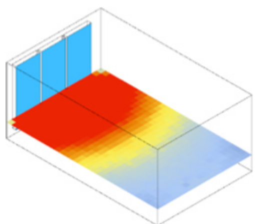
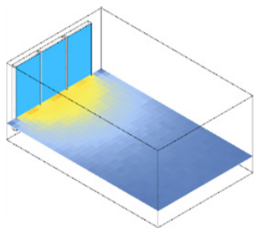
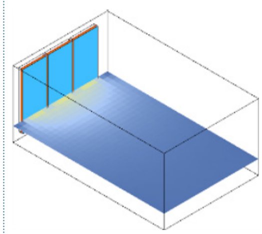
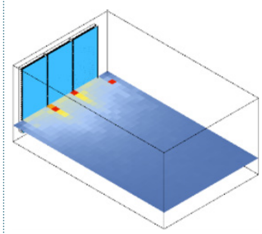
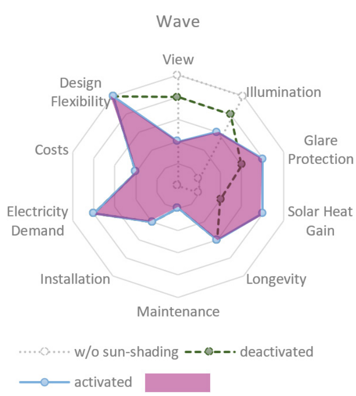
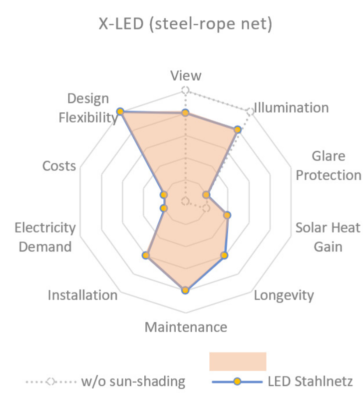
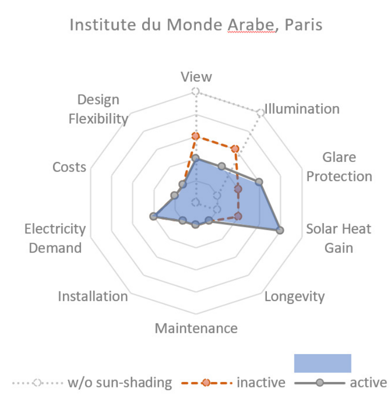
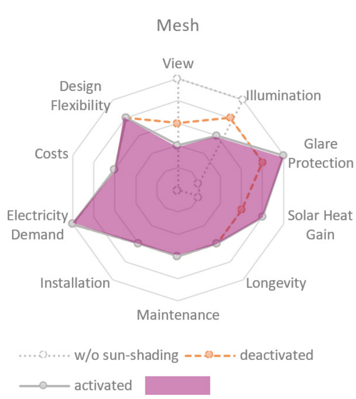
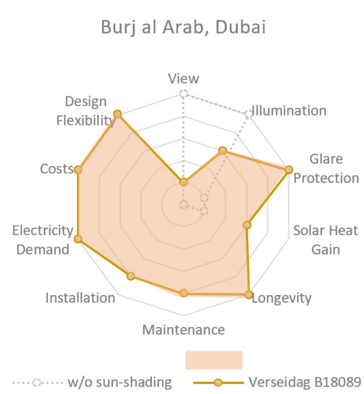
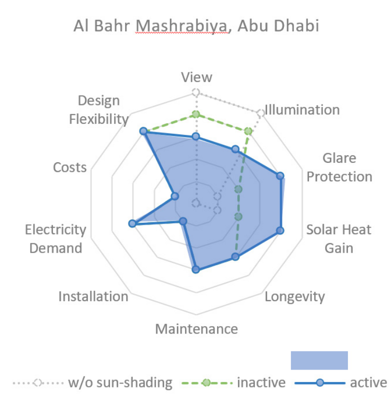
	Without sun-protection	Venetian Blind 45° slats	ADAPTEX Mesh	ADAPTEX Wave
FRANKFURT ORIENTATION: South 21. June (Summer) 12:00 h ROOM SIZE: 5 x 8 x 3.5 m				
				

TABLE 4 Radar chart comparison of ADAPTEX Wave and Mesh to specialized and adaptive facade systems.

ADAPTEX	SPECIALIZED FACADES	ADAPTIVE FACADES
		
		

It is worth mentioning that for this comparison both ADAPTEX concepts have been evaluated as electrically driven, which is the worst-case scenario, since with customised SMA these systems can run fully autarkic from any building induced energy source. However, for specific usage cases or building locations, a self-sufficient operation might not be realisable. In that case, the fall-back option would be an electrically-driven ADAPTEX shading system. Within the development, this option has always been investigated in parallel. Therefore, prototypes and testing also made use of electrically induced heat to the SMA, since, within various laboratory or research environments, the naturally appearing solar radiation, and therefore heat, cannot be induced or controlled for reliable evaluation. Still, in general an electrically driven ADAPTEX solution would pursue the initial intent to reduce material input, extend longevity, and reduce energy demand as, for instance, SMAs perform more energy efficiently than state-of-the-art motors (Neugebauer, Drossel, Pagel, Bucht, & Zernecke, 2011). Nevertheless, the overall goal of ADAPTEX is to run SMA self-sufficiently and the various design and development steps always consider this requirement.

5 CONCLUSION

5.1 POTENTIAL

The presented development process within ADAPTEX concluded in two feasible concepts, Mesh and Wave, for Shape Memory Alloy driven textile sun shading solutions. Not only was the basic operation, meaning activation and de-activation of SMA within these textile systems, proven, but various prototypes of different size and detailing, run for several cycles, showed major changes in openness factor (70 to 0 % and 30 to 7 %). Newly developed tools for development, optimisation, and customisation of both concepts enable the following steps for actual façade applications, not only as prototype but as real use cases. Academic exchange undertaken in parallel on the ADAPTEX approach, as well as alignment of Mesh and Wave concepts with realised façade solutions, ensure a high potential for implementation of the concepts into façade construction at a later stage, thus confirming its feasibility.

5.2 FURTHER STEPS

Although these findings already underline the functionality and potential of the ADAPTEX approach, major steps still lie ahead. As mentioned before, the developed prototypes will be used for further testing at indoor and outdoor test facilities, thus providing new insights on the system performances that need to be fed back into the set-up iterative development process as well as assessment tools. Based on this, further optimisation of Mesh and Wave will be undertaken. In addition, the aim to create solely self-sufficient Smart Textile sun shading systems will be focused on. Therefore, a follow-up project, ADAPTEX KLIMA+, is already projected to further investigate the correlation of local climate, ADAPTEX layout, and building skin integration.

FIG. 8 Possible application of ADAPTEX Mesh (top) and Wave (bottom) in open (left) and closed state (right).

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References

Addington, D. M., & Schodek, D. L. (2005). *Smart materials and new technologies : for the architecture and design professions.* Oxford, USA: Architectural Press.

Aelenei, L., Aelenei, D., Romano, R., Mazzucchelli, E. S., Brzezicki, M., & Rico-Martinez, J. M. (2018). *Case Studies - Adaptive Facade Network*. TU Delft Open.

Amidror, I. (2009). *The Theory of the Moiré Phenomenon*. London: Springer-Verlag. doi:10.1007/978-1-84882-181-1

Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The Sustainability of Adaptive Envelopes: Developments of Kinetic Architecture. *Procedia Engineering* (155), 275-284. doi:10.1016/j.proeng.2016.08.029

Begle, M. (2013, June 9). *Advanced Materials – Shape Memory Alloy – Nitinol*. Retrieved from http://www.iaacblog.com/programs/advanced-materials-shape-memory-alloy/

Böke, J., Knaack, U., & Hemmerling, M. (2018, March 26). State-of-the-art of intelligent building envelopes in the context of intelligent technical systems. *Intelligent Buildings International*. doi:10.1080/17508975.2018.1447437

Braun, D. H. (2008). *Bionisch inspirierte Gebäudehüllen. Konzeption einer bionisch inspirierten Gebäudehülle nach dem Vorbild natürlicher Hüllen und Häute (Bionically inspired building envelopes. Conception of a bionically inspired building envelope based on the model of natural envelopes and skins)*. Stuttgart: Universität Stuttgart.

Callejas Ortega, M. A. (2015). *Análisis y estudio metodológico de las aplicaciones de los materiales con memoria de forma y superelasticidad en arquitectura y urbanismo (Analysis and methodological study of the applications of materials with shape memory and superelasticity in architecture and urbanism)*. Seville: Escuela Técnica Superior de Arquitectura, Universidad de Sevilla.

Carl Stahl ARC GmbH. (2019). *X-LED*. Retrieved from https://x-led.de/en/

Cherif, C. (2017). E*ntwicklung von Textilstrukturen mit textiltechnisch integrierten Formgedächtnislegierdrähten zur Umsetzung komplexer Verformungen in Faserkunststoffverbundanwendungen (Development of textile structures with textile-technically integrated shape memory alloy wires for the implementation of complex deformations in fiber plastic composite applications)*. Retrieved from https://forschungsinfo.tu-dresden.de/detail/forschungsprojekt/16051

Cilento, K. (2012). *Al Bahar Towers Responsive Facade / Aedas*. Retrieved from archdaily: https://www.archdaily.com/270592/al-bahar-towers-responsive-facade-aedas

Denz, P. R. (2015, September 22). *Intelligente Gebäudehüllen und Smart Textiles - eine ideale Kombination (Intelligent building envelopes and smart textiles - an ideal combination)*. Retrieved from https://smarttex-netzwerk.de/en/events/199-workshop-on-22-09-2015

Denz, P. R. (2017). Textile Building Skin. New Functionality due to Smart Textiles. In U. Knaack, & U. Pottgiesser (Eds.)., *efnMOBILE 2.0 : Efficient Envelopes* (pp. 94-109). Delft: TU Delft Open. Retrieved from https://facades.ning.com/profiles/blogs/efnmobile-workshop-textile-building-skin

Denz, P.-R., Sauer, C., Boxberger, L., Waldhör, E. F., Schneider, M., & Vongsingha, P. (2018). ADAPTEX. *smart^3 Tage*. Berlin.

Denz, P.-R., Sauer, C., Waldhör, E. F., Schneider, M., & Vongsingha, P. (2020). Smart Textile Sun Shading. *15th Conference on Advanced Building Skins*. Bern.

Dewider, K., Mohamed, N., & Ashour, Y. (2013). Living Skins: A New Concept of Self Active Building Envelope Regulating Systems. *SB13 Conference*. Dubai.

European Comission. (2014). *Technology readiness levels*. Retrieved from https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape Morphing Solar Shadings: a Review. *Renewable and Sustainable Energy Reviews*(55), pp. 863-884. doi:10.1016/j.rser.2015.10.086

Habu, T. (2011). Applications of shape memory alloys (SMAs) in electrical appliances. *In Shape Memory and Superelastic Alloys* (pp. 87-99). Cambridge: Woodhead Publishing.

Josephine, S., Ruth, D., & Rebekah, S. D. (2020). Shape Memory Alloys. In Inamuddin, R. Boddula, M. I. Ahamed, & A. M. Asiri (Eds.). *Alloy Materials and Their Allied Applications,* pp. 213-223. Beverly, MA: Scrivener Publishing LLC. doi:10.1002/9781119654919.ch11

Khoo, C. K., Salim, F., & Burry, J. (2011). Designing Architectural Morphing Skins with Elastic Modular Systems. *International Journal of Architectural Computing*, 4(9).

Kuhn, T. E. (2017). State of the art of advanced solar control devices for buildings. *Solar Energy*. Advance online publication. https://doi.org/10.1016/j.solener.2016.12.044

Lieleveld, C. (2013). *Smart Materials for the Realization of an Adaptive Building Component.* Delft: TU Delft.

Loonen, R. C., Trčka, M., Cóstola, D., & Hensen, J. L. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews,* 25, 483-493. doi:10.106/j.rser.2013.04.16

Neugebauer, R., Drossel, W.-G., Pagel, K., Bucht, A., & Zernecke, A. (2011). Design of a controllable shape-memory-actuator with mechanical lock function. *Active and Passive Smart Structures and Integrated Systems*, 11.

Ritter, A. (2007). *Smart materials in architecture, interior architecture and design*. Basel; Berlin et al.: Birkhäuser.

Sauer, C., Waldhör, E. F., Schneider, M., Denz, P.-R., Vongsingha, P., Miodragovic, N., & Brucks, M. (2018). *Shaping Shades.* Retrieved from weißensee kunsthochschule berlin: https://kh-berlin.de/projekt-detail/Project/detail/shaping-shades-2830.html

Schneider, M., Waldhör, E. F., Denz, P.-R., Vongsingha, P., Suwannapruk, N., & Sauer, C. (2020). Adaptive textile façades through the integration of Shape Memory Alloy. *ACADIA 2020 Conference Proceedings*.

Sigmund, B. (2016). Solar Curtain – Sonnenschutz durch Formgedächtniseffekt (Solar Curtain - sun shading through shape memory effect). *DETAIL Research*. Retrieved from https://www.detail.de/artikel/solar-curtain-sonnenschutz-durch-formgedaechtniseffekt-28272/

smart^3 e.V. (2017). *Smart Skin : Selbstregulierende Sonnenschutzkomponenten für die Gebäudehülle (Smart Skin: Self-regulating sun protection components for the building envelope)*. Retrieved from http://www.smarthoch3.de/projekte/

United Nations General Assembly. (2015). *Transforming our World: The 2030 Agenda for Sustainable Development. United Nations*.

Wærsted, E. H. (2014). *Textiles in the Material Practice of Architects - Opportunities, Challenges and Ways of Simulating Use*. Lyngby: Technical University of Denmark.

Waldon, S., & Dyer, C. R. (1993). Dynamic Shading, Motion Parallax and Qualitative Shape. *Proceedings IEEE Workshop on Qualitative Vision*, pp. 61-70. doi:10.1109/WQV.1993.262949