Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2025) 583-594

ECCOMAS Proceedia

XI ECCOMAS Thematic Conference on Smart Structures and Materials - SMART 2025
M. Krommer, M. Nader and M. Schagerl (Eds)

Received: 25 June 2025 / Revised: 19 August 2025 / Accepted: 14 October 2025

Design of a Thermoresponsive Shading System with shape memory material

Weifeng He, Aniket Pal, Thomas Wortmann, Maria Matheou

Abstract. This paper presents a comparative experimental study of an Adaptive Shading System (ASS) integrating smart material-based actuators to enhance building energy efficiency and visual comfort. 3D-Printed rhomboid façade modules of size 75 cm x 75 cm incorporate Shape Memory Polymers (SMPs) and Shape Memory Alloys (SMAs) in their horizontal axis, allowing folding configurations. This study adopts an integrated design methodology driven by a performance-based approach, employing a closed-loop process that includes material study, SMP geometry design, performance evaluation and prototype fabrication. Feedback from the performance evaluation informs the geometry design and material selection, optimising the shading's overall functionality. Experimental prototypes in scale 1:3 focus on three material-based actuation methods for the Two-Way Shape Memory Effect (TWSME), including a single SMA with a compliant mechanism, dual SMAs and integration of SMA into SMP. The aim is to assess these three methods in terms of responsiveness, such as responsive time and maximal folding angles (based on visual comfort criteria) and energy efficiency. Results indicate that dual SMA-driven solutions are particularly effective for adaptive shading, requiring only 183 J compared to the integration of SMA into SMP which requires 549 J. Additionally, daylight analysis was conducted in the summer and winter solstices at 9:00 am, 12:00 pm and 3:00 pm to evaluate the performance of the proposed adaptive shading installed on an office building with a floor area of 113 m^2 in Stuttgart, Germany. The proposed ASS with dual SMAs offers a TWSME for shape-changing mechanisms aligned with performance-driven architectural goals for sustainable façade design.

Key words: Adaptive Shading System, Daylighting Analysis, Shape Memory Alloy, Shape Memory Polymer, Two-way Shape Memory

Weifeng He & Maria Matheou
Institute for Lightweight Structures and Conceptual Design, University of Stuttgart, Pfaffenwaldring 14, 70569 Stuttgart, Germany
e-mail: weifeng.he@ilek.uni-stuttgart.de,maria.matheou@ilek.uni-stuttgart.de

Aniket Pal
Institute of Applied Mechanics, University of Stuttgart, Pfaffenwaldring 7, 70569 Stuttgart, Germany
e-mail: aniket.pal@mib.uni-stuttgart.de

Thomas Wortmann
Institute for Computational Design and Construction, University of Stuttgart, Keplerstraße 11, 70174 Stuttgart, Germany,
e-mail: thomas.wortmann@icd.uni-stuttgart.de

ISSN:3078-543X. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of SMART 2025.
doi: 10.7712/150125.13661.205002

1 INTRODUCTION

The operations of buildings account for 30% of global final energy consumption and 26% of global energy-related emissions. While energy codes and renewable technologies are advancing, the sector must accelerate its transformation to align with the Net Zero Emissions by 2050 (NZE) scenario, ensuring all new buildings and 20% of the existing stock are zero-carbon-ready by 2030 [1]. Façades are the physical barrier and interface between external environmental conditions and internal comfort requirements. Given their dynamic nature, traditional static façades respond inadequately to climatic changes, failing to address the optimisation issues under dynamic constraints [2]. Hence, dynamic façade systems, capable of altering their properties in response to climatic conditions or seasonal variations, have been developed to meet evolving environmental conditions and occupant needs, thereby enhancing building efficiency continually [3]. These adaptations can be achieved through various actuation methods, broadly categorised into mechanical actuation (i.e. pneumatic and hydraulic) and material-based actuation [4].

Several researchers are looking into the “organic” or biological paradigm of kinetic adaptation, which relies on the material instead of mechanical actuation [4]. For example, a biobased 4D printed humidity-responsive smart structure, which could produce an actuated response (bending) when exposed to changing levels of humidity was developed in [5].

This paper presents a comparative experimental study of an Adaptive Shading System (ASS) integrating smart material-based actuators to enhance building energy efficiency and visual comfort. In this study, three different actuation methods, including a single Shape Memory Alloy (SMA) with a compliant mechanism, dual SMAs and integration of SMA into Shape Memory Polymer (SMP), have been proposed for the Two-Way Shape Memory Effect (TWSME) of the ASS and evaluated their performance in experimental prototypes.

2 INTEGRATED DESIGN METHODOLOGY

The aim of this paper is to design an ASS that can adjust its configurations according to the changing seasons, as shown in Figure 1. The proposed design methodology follows a performance-based approach and is divided into four key phases: Material Study, Geometry Design, Performance Evaluation, and Prototype Fabrication, as illustrated in Figure 2. In the Material Study phase, we explore flexible and shape memory materials through 3D-Printed (3DP) compliant hinges at a scale of 1:7. This phase also integrates SMA actuation with various parameters (Section 3.5). The Geometry Design phase is divided into macro and meso levels. At the macro level, we focus on shape, dimensions and curvature of the hinge.

In contrast, the meso level optimises the 3DP direction, material selection and combinations for actuation. We tested three actuation methods using 1:3 scale prototypes (Section 4.3). The Performance Evaluation phase assesses energy consumption and daylighting, analysing power requirements and illuminance levels at specific times to ensure visual comfort. A prototype built at a scale of 1:5 demonstrates the chosen actuation method.

Figure 1: Outdoor views of the ASS during the summer (left) and the winter solstice (right)

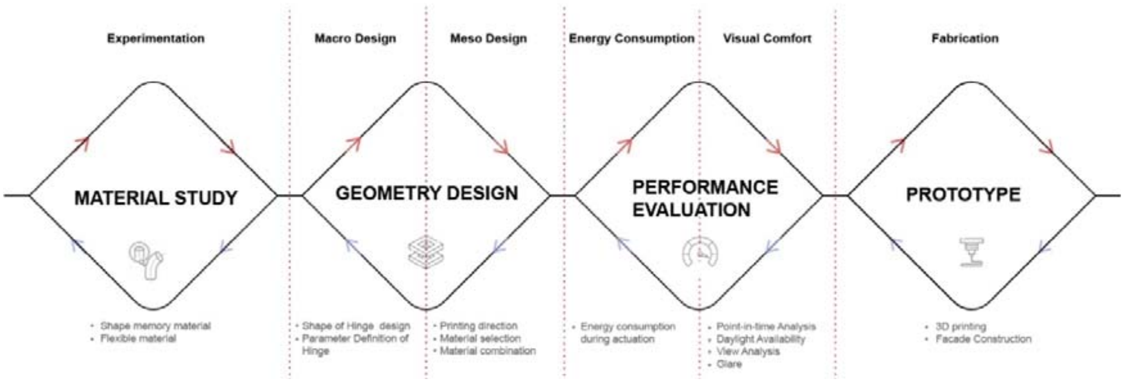


Figure 2: Design methodology of the proposed ASS

2.1 Experimental studies

Three different scales of prototypes were developed in this study. Initially, preliminary 3DP prototypes were created at a 1:7 scale, consisting of a single 10.5 cm x 6 mm strip. These served to explore printing direction, materials and reconfiguration within a simplified framework. Subsequently, façade module prototypes were built at 1:3 and 1:5 scales to investigate material behaviour and system performance further. In the next phase, panels were incorporated to refine the adaptive functionality.

2.2 Simulation study for the daylighting analysis

The daylight analysis was conducted in the summer and winter solstices at 9:00 am, 12:00 pm and 3:00 pm in Stuttgart, Germany, to evaluate the performance of the ASS installed on an office building with a floor area of 113 m^2. The office model is south-oriented, with the south and west elevations fully glazed. The width of the south and west elevations measures 13.64 m and 10.9 m, respectively, while the office height is 3.0 m. All material properties were assigned accordingly using Climatestudio for Rhino3D [6]. The walls, floor and ceiling have default values for lighting simulations as per the Illuminating Engineering Society Lighting Metrics 83 [7]. The glazing has a visible transmission of 0.546 and a U-Value of 1.05 W/m^2K. A white opaque material with a reflectance of 79 % has been assigned to the façade panel.

3 SHAPE MEMORY MATERIALS AND INTEGRATION

3.1 Thermally induced shape-memory effect in polymers

Figure 3 illustrates the shape-memory effect in polymers. At room temperature, the SMP remains in its original shape. When an external force is applied, it deforms, reaching its maximum folding angle while still at room temperature, thereby maintaining a temporary shape. Upon heating to the target temperature (Tg), the polymer chains regain mobility, allowing the material to recover its original shape. Figure 4 shows the transformation process, where the polymer is heated through the current provided by two batteries with 1.5 volts respectively.

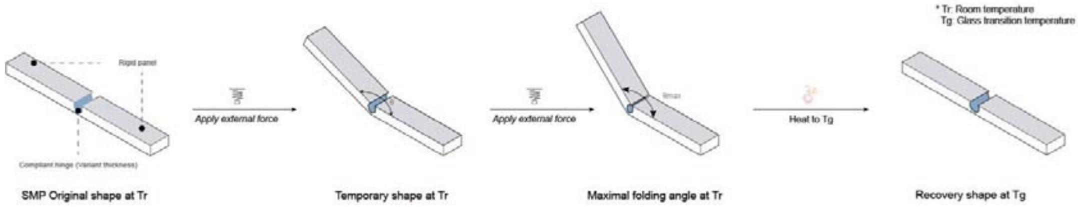


Figure 3: Thermally induced shape-memory effect in polymers

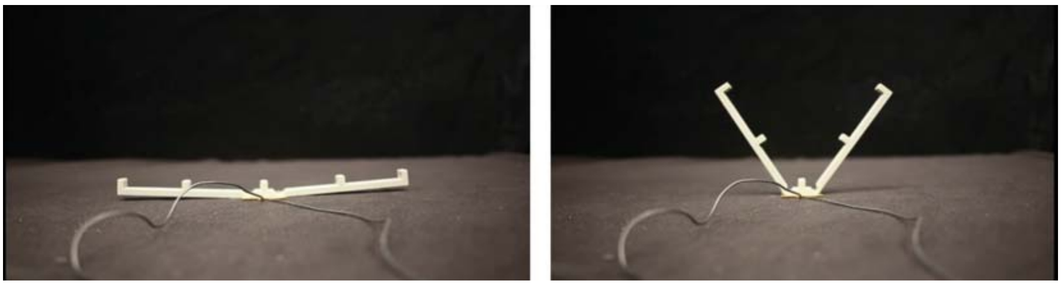


Figure 4: Experiment of shape memory effect with the original shape (left) and deformation after external force (right)

3.2 Shape-memory effect in SMAs

Figure 5 illustrates the shape-memory effect in SMAs. At low temperatures, the SMA remains in its original shape. When an external force is applied, it deforms into a temporary shape, but its internal crystalline structure retains a "memory" of the original form. Upon heating to the target temperature (Tg), the alloy undergoes a phase transformation, allowing it to return to its original shape.

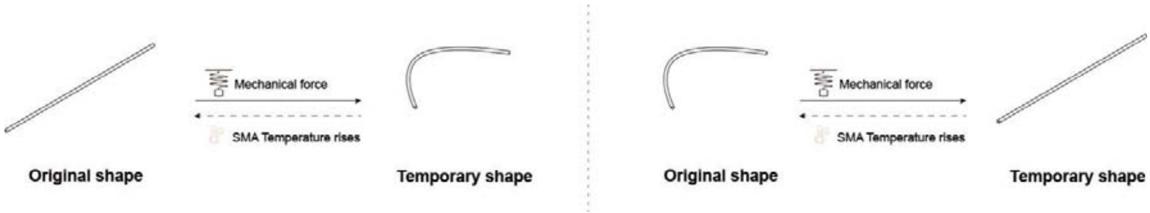


Figure 5: Shape memory effect in SMAs

3.3 Three actuation methods

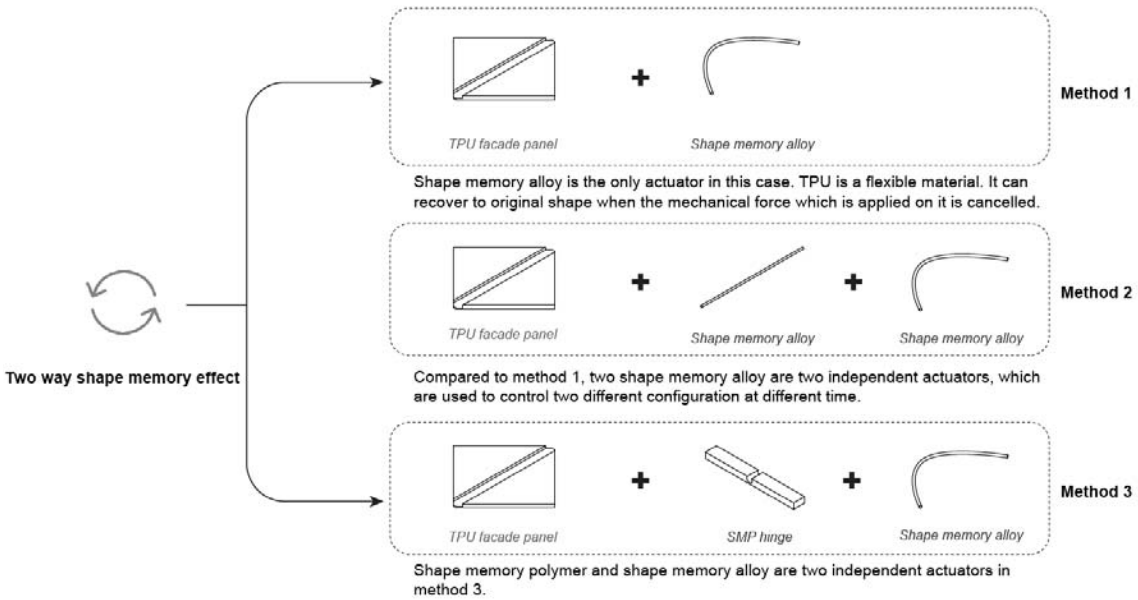
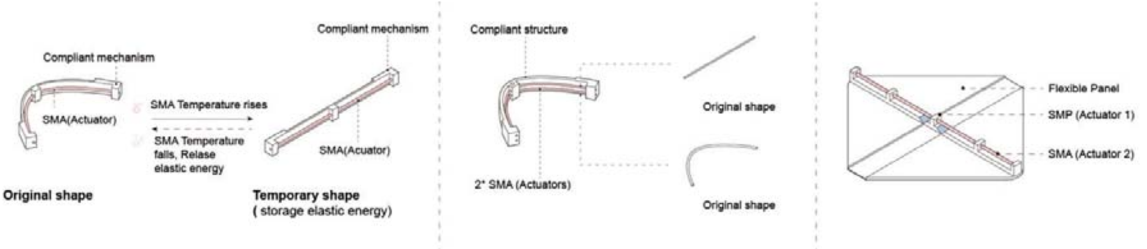


Figure 6: Three actuation methods for two-way shape memory effect

Achieving a TWSME can be realised through innovative material combinations and integration strategies, enabling reversible shape transformations without manual intervention. Figure 6 shows the three actuation methods proposed in this paper, which were evaluated through experimental studies. All experiments utilised a SMA specifically Nitinol alloyed with copper (NiTiCu), with a diameter of 1 mm and a phase change temperature of 60° (+-5). Method 1 integrates a single SMA wire into a Thermoplastic Polyurethane (TPU) façade panel. The SMA is known for its ability to return to a pre-programmed shape, while the TPU offers flexibility, enabling the panel to recover its original shape once the external force is removed. Method 2 integrates two SMAs with distinct original shapes into the flexible façade panel. This dual-SMA system allows for more complex and programmable movements, as each SMA responds differently to temperature changes, thus enhancing adaptability. Method 3 takes a different approach by integrating an SMA into SMP hinges, which are then combined with the façade panel. This method leverages the simple programmability of SMP.

A comparison of the three different actuation methods will be discussed in Section 4.3. Figure 7 illustrates the principle of the three actuation methods in detail: a) the principle of Compliant Structure (CS) and SMA in Method 1; b) two different pre-programmed (original) shapes of SMA in the dual SMA system; c) the connection between the flexible panel and SMP with SMA in Method 3.



a) b) c)

Figure 7: a) Method 1; b) Method 2; c) Method 3

3.4 Stiffness matrix of three actuation methods

The stiffness relationship among different components is essential for ensuring proper actuation and recovery in an integrated system. In accordance with Hooke's law [8], the stiffness relationship among different components for the three actuation methods is outlined below.

Method 1:		
Temporary shape ($_{SMA}{}^{h}$:*High temperature, CS:Compliant structure*):	$K_{SMA}^{h} > K_{CS}$	(1)
Original shape ($_{SMA}{}^{l}$: *Low temperature*):	$K_{SMA}^{l} < K_{CS}$	(2)
Combine (1) and (2):	$K_{SMA}^{l} < K_{CS} < K_{SMA}^{h}$	(3)
Method 2:		
Temporary shape (SMA as actuator):	$K_{SMA1}^{h} > K_{CS} + K_{SMA2}^{l}$	(4)
Original shape:	$K_{SMA2}^{h} > K_{CS} + K_{SMA1}^{l}$	(5)
Both SMAs have the same stiffness:	$K_{SMA1} = K_{SMA2} = K_{SMA}$	(6)
Combine (5) and (6):	$K_{CS} < K_{SMA}^{h} - K_{SMA}^{l}$	(7)
Method 3:		
Open configuration (SMA as an actuator, *PA:Panel*):	$K_{SMA}^{h} > K_{PA} + K_{SMP}^{l}$	(8)
Closed configuration (SMP as an actuator):	$K_{SMP}^{h} + K_{PA} > K_{SMA}^{l}$	(9)
Combine (8) and (9):	$K_{SMA}^{h} - K_{SMA1}^{l} < K_{PA} < K_{SMA}^{h} - K_{SMA}^{l}$	(10)

After we get the stiffness relationship among different components, it is necessary to analyse what parameters have an influence on the stiffness of them. The stiffness matrix (K)can simply deconstruct into two parts: Coefficient Matrix(α) and Parameter Matrix(P), as shown below:

$$K = \alpha * P$$

For different components, the stiffness matrices are slightly different:

Method 1 and Method 2:
$K_{SMA} = [a] * [D]$ *(a:coefficient; D: Diameter)*
$K_{CS} = [b \quad c] * [T_{cs} \quad H]^T$ *(b and c: coefficients, T_{cs}: Thickness of the compliant structure, H: Height of the compliant structure)*
Method 3:
$K_{PA} = [d \quad e] * [T_{panel} \quad T_{hinge}]^T$ *(T_{panel} : Thickness of the panel, $T_{hinge:}$ Thickness of the hinge on the panel.*
$K_{SMP} = [f \quad g \quad h] * [T_{SMP\_Hinge} \quad T_{joint} \quad H_{SMP}]$ *($T_{SMP\_Hinge:}$ Thickness of SMP hinge, $T_{joint:}$ Thickness of joint part of the SMP hinge, H_{SMP} : Height of SMP hinge)*

3.5 Experimental studies

3.5.1 3DP Compliant hinge

Preliminary experimental studies in scale 1:7 were conducted on a single 3DP strip with different flexure thicknesses to evaluate the stiffness of the compliant hinge made of TPU (Figure 8). By systematically varying these parameters and actuating the integrated SMA with current, the experiments demonstrated how the geometry design of the compliant mechanism influences its folding behaviour and recovery angle.

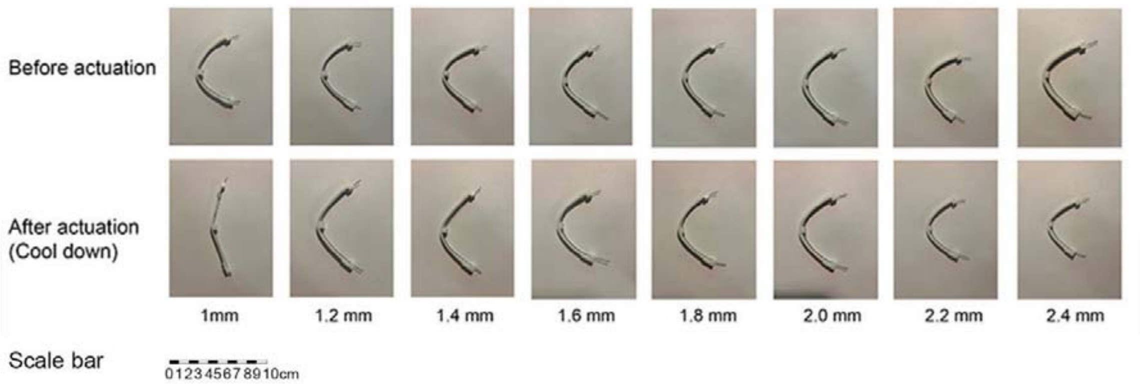


Figure 8: 3DP strips before and after actuation

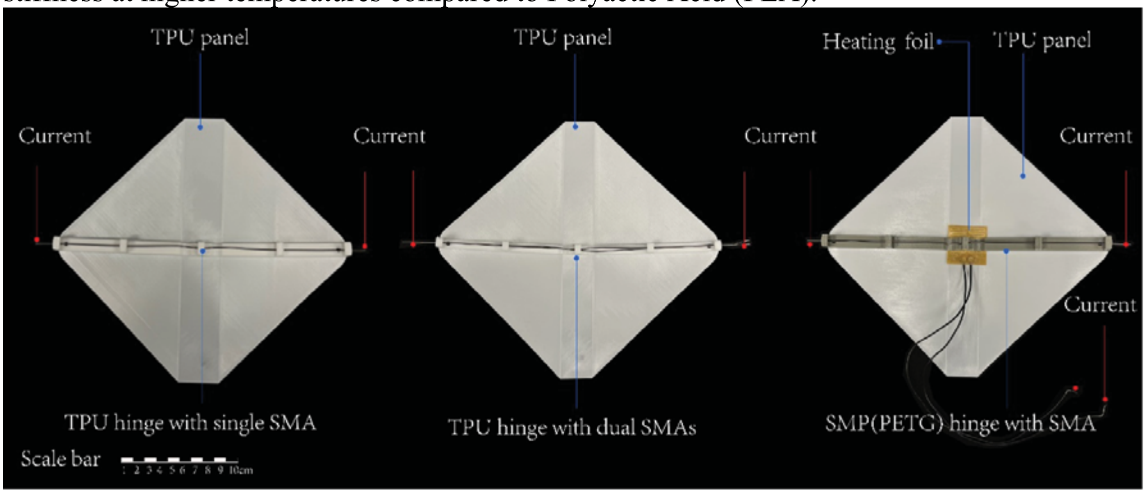
Table 1 presents the flexure thickness and folding angles of the 3DP strips, which affect the stiffness of the CS during actuation by an integrated actuator, such as an SMA. Thinner flexures enhance actuation but may compromise durability. Flexure properties are also vital during recovery, as they store and release elastic energy to restore the original shape. For instance, a compliant hinge with a flexure thickness of 1.8 mm has the largest transformation angle range, achieving a maximum folding angle of 60° when actuated and a corresponding recovery angle. Experimental results emphasise the importance of balancing flexibility and stiffness for precise and efficient shape reconfiguration.

Table 1: Flexure thicknesses and folding angles

Flexure Thickness (mm)	1	1.2	1.4	1.6	1.8	2.0	2.2	2.4
Maximum folding angle when actuated (°)	175	150	150	145	145	125	120	110
Recover angle without actuation (°)	140	100	95	90	85	80	80	80
Transformable angle range	30	50	45	55	60	45	40	30

3.5.2 3DP façade module

To evaluate the three actuation methods, three 1:3 scale 3DP rhomboid façade prototypes (25 x 25 cm) were fabricated (Figure 9). Each integrates SMPs and SMAs along the horizontal axis, depending on the method. The panel is made of TPU with a different in the compliance hinge material. For single SMA and dual SMA actuation, the hinges are TPU, whereas Polyethylene Terephthalate Glycol (PETG) is used for SMA-SMP integration. PETG, heated by a foil to enhance thermal distribution and reduce actuation time, was selected for its higher stiffness at higher temperatures compared to Polyactic Acid (PLA).



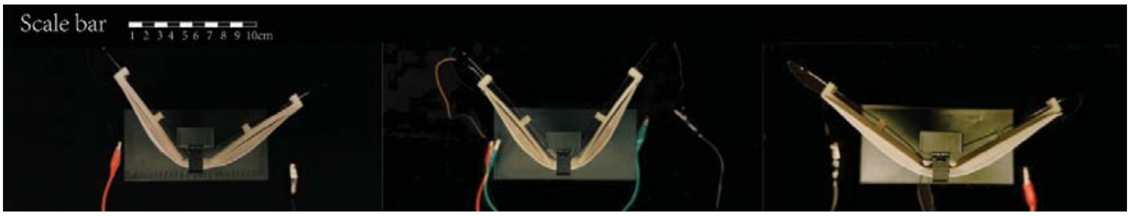
a) b) c)

Figure 9: Prototypes in scale 1:3: a) (1) SMA; b) (2) SMAs; c) SMP + (1) SMA

4 RESULTS AND DISCUSSION

4.1 Performance Evaluation

Figure 10 presents the maximal transformation angles for each façade module across the three actuation methods. Both SMA and SMP are activated by electric current to reach their phase change temperatures. Method 2, using a dual SMA system, shows the fastest reconfiguration at 50s for folding and 48s for recovery, with the largest transformation angle of 60°. Method 3, which integrates SMP and SMA, demonstrates the slowest reconfiguration at 80s for folding and 105s for recovery, with the smallest transformation angle of 45°. Method 1 requires a continuous activation to maintain its deformed state.



a) b) c)

Figure 10: Folded configuration of the three actuation methods a) Method 1; b) Method 2; c) Method 3

4.2 Daylight Analysis

Figure 11 compares the illuminance levels of a static façade with the proposed ASS. The red dashed lines indicate optimal office lighting levels based on EN 12464 [9]. Results show that the static façade modules admit excessive or insufficient daylight during the seasons. On the other hand, the proposed ASS dynamically adjusts panel angles to improve daylight control. Further analysis on glare and light uniformity shows a need for geometry and material optimisation. Figure 12 illustrates indoor and outdoor visualisations of the ASS for an office room in Stuttgart during the summer and winter solstices.

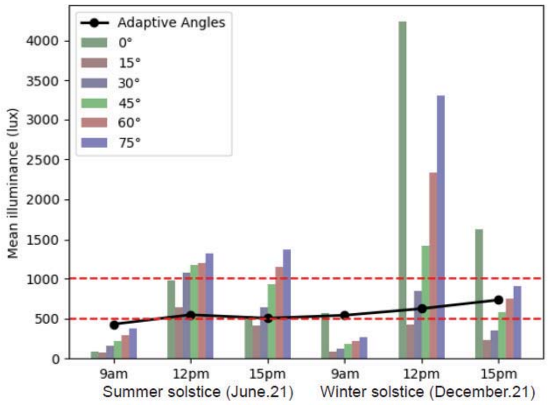


Figure 11: Mean illuminance simulation study of static and adaptive façade

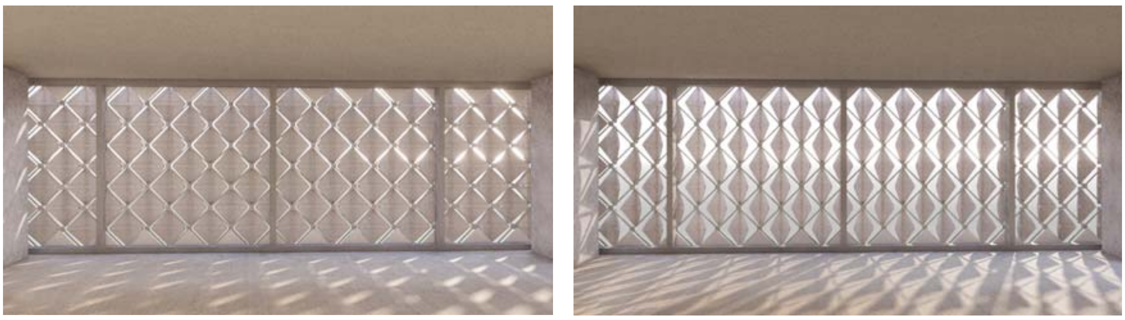


Figure 12: Indoor views of the ASS during summer (left) and the winter solstice (right)

A prototype in scale 1:5 of Method 2 was built with 15 cm x 15 cm panels. The 3DP panels, made of TPU, incorporate two SMAs per panel, as shown in Figure 13.

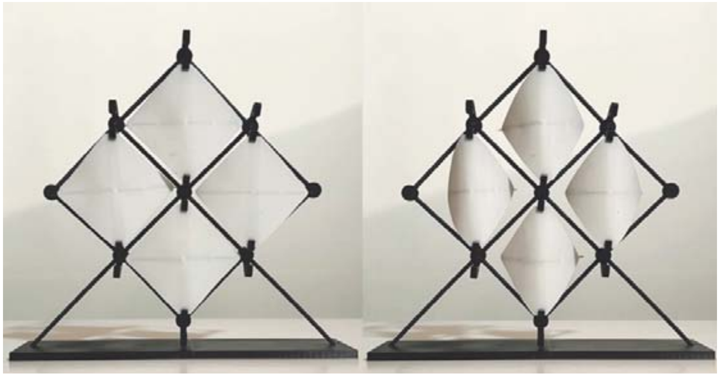


Figure 13: Prototype in scale 1:5 with open (left) and folded configuration (right)

4.3 Discussion

As shown in Table 2, the dual SMA-driven method is the most energy-efficient, requiring only 183 J for folding and recovery, about one-third of the 549 J needed for the SMA-SMP approach. While a single SMA uses only 121 J for folding, its requirement for continuous actuation to maintain fixed positions increases daily energy use. Overall, SMA/SMP-based systems achieve comparable motion to conventional mechanical solutions [10] with substantially lower energy demand, highlighting their potential for energy-efficient adaptive shading.

The comparative assessment of the three actuation methods for achieving the TWSME reveals distinct strengths and limitations, underscoring the adaptability of shape memory materials in reconfigurable systems. Method 1 prioritises simplicity but lacks high holding-energy requirements, Method 2 combines adaptability with low energy consumption, and Method 3 facilitates easier programmability for complex configurations. These differences make each approach suitable for specific functional and design objectives in adaptive façade applications.

This study demonstrates feasibility at prototype scales (1:3, 1:5), but requires further work to refine manufacturing, improve structural durability, and assess long-term performance under real environmental conditions. At the façade scale, optimising SMP-based panel geometry and material properties can improve mechanical strength, lower activation energy, reduce glare, and enhance indoor light uniformity.

Although we used 3DP to prototype different designs of our adaptive shading systems, more effective manufacturing methods can be used for mass production on a real scale. For example, large TPU panels can be produced efficiently using extrusion of injection molding. SMA wires can be used as purchased, similar to those used in this manuscript. The SMP PETG is highly adaptable to various traditional manufacturing processes like die-cut, machining, thermoforming etc., although 3DP can remain a viable option at larger scales due to the relatively smaller footprint of the SMP part.

Table 2: Evaluation criteria for the three actuation methods

Dimensions for a single façade module	Actuation Method	Actuator [no.]	Actuation	Progra-mmed angle [°]	Transfo-rmation angle [°]	Actua-tion Time [s]	Power [W]	Energy Consumption (W=P*t) [J]
25 x 25 cm	Method 1	(1) SMA	Folding (1 SMA)	80	55	65	1.875	121
	Method 2	(2) SMA	Folding (1 SMA)	80	60	50	1.875	93
			Recovery (2 SMA)	0	5	48	1.875	90
	Method 3	SMP + (1) SMA	Folding (SMA)	80	45	80	1.875	150
			Recovery (SMP)	0	15	105	3.8 (Heating foil)	399

Beyond architectural applications, the thermo-responsiveness of this system can scale down to create wearable applications such as clothes with adaptive ventilation. For such small-scale application, multimaterial 3DP will become the preferred fabrication method, allowing simultaneous printing with two polymers (passively flexible TPU and thermo-responsive PETG) to create monolithic parts for easy integration into fabric. Alternative shape memory polymers, with lower glass transition temperatures such as Poly (vinyl acetate) or PVAc can also be considered as a way of using body temperature to regulate the actuation of the panels, and in turn, the ventilation of the clothes.

5 CONCLUSIONS

This study highlights the effectiveness of dual SMA-driven solutions in enhancing the energy efficiency and adaptability of thermo-responsive shading systems. Compared to single SMA and SMP-SMA integrated designs, the dual SMA approach offers a balanced trade-off between energy consumption and dynamic shape transformation, making it an efficient solution for sustainable architecture. By leveraging the inherent properties of shape memory materials, these systems contribute to responsive façade technologies that optimize daylighting, thermal comfort, and energy consumption in buildings. The findings emphasize the potential of such shading systems to play a crucial role in sustainable building methodologies, aligning with the broader goal of reducing reliance on active energy-intensive climate control solutions. Future work could focus on the scalability and seamless integration of these systems into full-scale architectural projects.

REFERENCES

[1] International Energy Agency, *Buildings,* 2025. [Online]. Available: https://www.iea.org/energy-system/buildings.

[2] D.-K. Bui, T.N. Nguyen, A. Ghazlan, N.-T. Ngo, and T.D. Ngo, "Enhancing building energy efficiency by adaptive façade: a computational optimization approach," *Appl. Energy*, vol. 265, 2020 114797, https://doi.org/10.1016/j.apenergy.2020.114797.

[3] J. Böke, U. Knaack, M. Hemmerling, "Automated adaptive façade functions in practice - case studies on office buildings," *Automation in Construction*. vol. 113, 2020, Art. no. 103113, https://doi.org/10.1016/j.autcon.2020.103113.

[4] B. Kolarevic, V. Parlac, *Building Dynamics: Exploring Architecture of Change*. Routledge, 2016.

[5] Y. Tahouni, T. Cheng, S. Lajewski, J. Benz, C. Bonten, D. Wood, and A. Menges, (2022). "Codesign of biobased Cellulose-Filled filaments and mesostructures for 4D printing humidity responsive smart structures." *3D Printing and Additive Manufacturing*, vol. 10, no. 1, pp. 1–14, 2022 https://doi.org/10.1089/3dp.2022.0061

[6] Solemma, *ClimateStudio*, 2025. [Online]. Available: https://www.solemma.com/climatestudio. [Accessed: 10-Mar-2025].

[7] Illuminating Engineering Society (IES), *Lighting Handbook*, 10th ed. New York, NY, USA: IES, 2011.

[8] R. Hooke, De Potentia Restitutiva, or of Spring. Explaining the Power of Springing Bodies. London, U.K.: John Martyn, Printer to the Royal Society, 1678

[9] European Committee for Standardization, *EN 12464-1: Light and Lighting – Lighting of Workplaces – Indoor Workplaces*, Brussels, Belgium, 2021.

[10] Jeong, M., Rössle, R., Böhm, M., Matheou, M., & Sawodny, O. (2024). Bridging exterior and interior climate: interdisciplinary design of a dual-functional adaptive kinetic façade prototype. Proceedings of the International Conference on Computer-Aided Architectural Design Research in Asia, 1, 435–444. https://doi.org/10.52842/conf.caadria.2024.1.435

Acknowledgments

The project was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Project-ID 279064222—SFB 1244 and Germany's Excellence Strategy – EXC 2120/1 390831618.