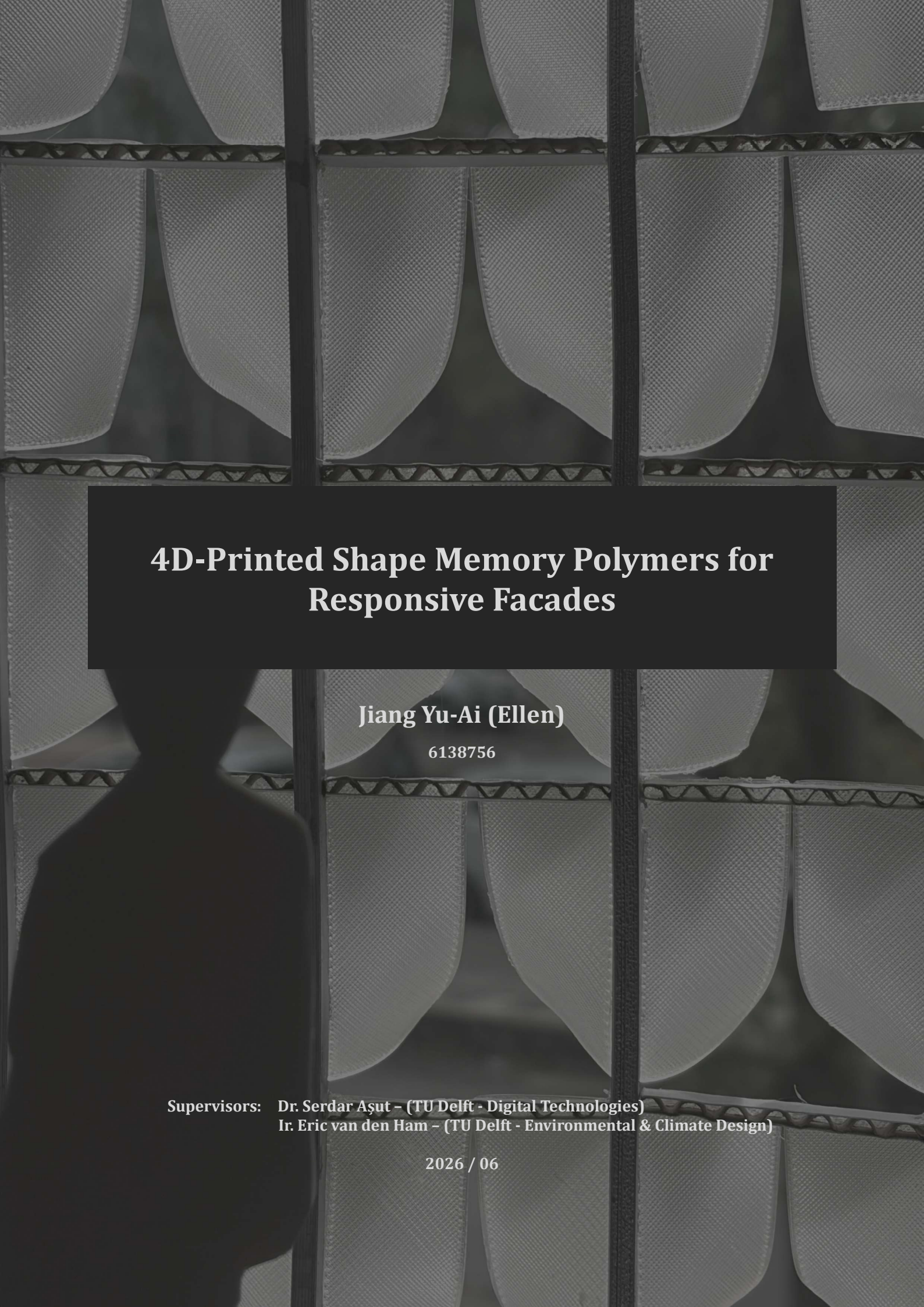




4D-Printed Shape Memory Polymers for Responsive Facades

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Abstract

This thesis presents the preliminary findings of ongoing research that investigates how 4D Printing (4DP) parameters influence the deformation behavior of Shape Memory Polymer (SMP)-based façade elements, and how such parameter guidelines can be applied to improve indoor environmental performance. Additive manufacturing (AM) refers to the process of fabricating three-dimensional objects directly from digital models by joining materials layer by layer. 4DP expands upon AM by introducing time-dependent transformation, allowing printed elements to reconfigure their geometry or material properties when triggered by environmental stimuli such as temperature, moisture, or light (Tibbits, 2014; Momeni et al., 2017). SMPs are smart polymeric materials that can be programmed into a temporary shape and subsequently recover their original configuration upon environmental stimulation, most commonly thermal activation (Behl & Lendlein, 2007).

As the interface separating indoor and outdoor environments, building façades are pivotal in moderating energy exchange and environmental quality, making them one of the most effective building elements for enhancing human comfort and reducing energy consumption (Wigginton & Harris, 2013; Zhang et al., 2022). While adaptive façades can respond to dynamic environmental conditions, most existing systems depend on mechanical actuators, sensors, and control units, leading to increased complexity and maintenance (Loonen et al., 2013a; Heidari Matin & Eydgahi, 2022).

In contrast, material-based adaptation offers an alternative paradigm in which responsiveness to the environment is embedded directly within the material itself (Mansoori et al., 2023). Among various smart materials, SMPs show strong potential for thermo-responsive applications due to their large recoverable strain, tunable activation temperatures, and low cost (Ahmed et al., 2021; Mahmood et al., 2023; Ding et al., 2025). The integration of SMPs with 4DP facilitates the fabrication of passive, self-actuating façade components, where deformation behavior is directly programmed via geometric and fabrication parameters (Yoon, 2019; Yi & Kim, 2021a).

This thesis investigates how three key 4DP parameters, thickness, infill ratio, and infill pattern, influence the deformation behavior of SMP-based façade elements, and how that understanding can be translated into a passive, climate-responsive façade. Flat SMP specimens (40 × 100 mm) were tested to quantify deformation and establish relationships between fabrication parameters and shape transformation behavior. The results demonstrate that infill pattern governs deformation directionality, thickness modulates bending rigidity, and infill ratio adjusts deformation magnitude, together forming a programmable deformation vocabulary that can be spatially distributed across a single printed element

to encode controlled curvature directly into the fabrication process.

Based on these findings, two primary façade concepts were developed. The SMP Panel organizes a slitted element into active and passive zones through spatially varied parameters, where upon thermal activation the active zones deform outward, expanding closed slits into open apertures with diverse geometries controllable through print parameters and slit orientation. The SMP Louver translates uniform printed curvature into controlled shading angles through spatially defined anchor positions. A parametric CAD tool was then developed, integrating material behavior mapping, geometry generation, fabrication-ready G-code output, and environmental performance evaluation within a single workflow.

A case study on environmental simulations across two climate contexts, Delft and Taipei, shows that in subtropical conditions the curved SMP Panel effectively reduces solar exposure and promoting natural ventilation, while in temperate conditions the horizontal SMP Louver provides balanced daylighting and passive heating through adjustable tilt states. Together, these contributions establish an empirical parameter-to-deformation map, climate-specific design strategies, and an integrated computational framework linking material behavior, façade geometry, and environmental performance, serving as a preliminary guideline toward energy-efficient and autonomous building envelopes.

1 Introduction

1.1 Emergence of Material-Driven Responsive Facades

The building sector accounts for a major proportion of global energy demands and greenhouse gas emissions, where building envelope functions as the main role regulating energy transfer between interior and exterior environments. Among envelope components, façades are particularly influential due to their direct exposure to solar radiation, ambient temperature fluctuations, and daylight availability. Conventional architectural façades are built for static, worst-case, or average climatic scenarios; however, this constrains their capacity to adapt to highly dynamic environmental fluctuations across diurnal and seasonal cycles. (Loonen et al., 2013b; Wigginton & Harris, 2013).

In recent decades, adaptive façade concepts have emerged as a promising strategy to enhance building performance by enabling envelopes to respond to climatic stimuli. Climate Adaptive Façades (CAFs) are advanced building enclosures that dynamically adjust their behavior to ambient fluctuations, optimizing both energy efficiency and occupant comfort. (Loonen et al., 2013b). Existing adaptive façade solutions often rely on mechanical actuation, sensors, and control systems, which can introduce complexity, maintenance demands, energy consumption, and failure risks (Heidari Matin & Eydgahi, 2022).

To address these limitations, material-based responsiveness has gained increasing attention. Smart materials, such as Shape Memory Alloys (SMA), Phase Change Materials (PCM), hydrogels, and Shape Memory Polymers (SMP), are able to reconfigure their material properties or geometric topologies upon exposure to external environmental triggers, including temperature, moisture, and heat, etc. (Zhang et al., 2022). Among these, SMPs show strong potential for architectural applications because of their cost-effectiveness, substantial recoverable strain limits, low density, and tailorable activation thresholds (Ahmed et al., 2021; Mahmood et al., 2023; Ding et al., 2025).

Parallel to material innovation, additive manufacturing has broadened the possibility of architectural components. 4D Printing (4DP), an extension of 3D printing, introduces time-dependent transformation, allowing printed elements to change their initial as-printed shape when triggered by environmental stimuli such as temperature, moisture, or light (Mahmood et al., 2023). When combined with SMPs, 4DP allows for the fabrication of programmable, self-actuating elements whose deformation behavior can be embedded directly into their geometry, material composition, and printing parameters.

Despite growing interest in 4DP SMP systems (Ding et al., 2025), their application in architectural-scale façade elements, particularly as passive adaptive shading devices, remains limited. Most existing

studies focus on small-scale prototypes, biomedical or aerospace applications, or mechanically assisted systems (Yoon, 2019; Yi & Kim, 2021a). There is a lack of systematic investigation into how 4DP SMPs components can be designed, parameterized, and evaluated as climate-responsive façade systems.

Consequently, the objective of this thesis is therefore to develop and evaluate a passive, climate-responsive façade system based on 4DP SMP, covering the full chain from material characterization to façade design and environmental performance evaluation. The research focuses on thermally activated SMPs, considers two representative climate contexts, and addresses façade components at the module scale rather than full-building structural integration.

1.2 Research Questions

The development of an effective 4DP SMP-based façade involves challenges at multiple interconnected scales. At the material and fabrication level, the deformation behavior of SMP elements is strongly influenced by printing parameters and layer configurations. At the component level, geometric design determines how material-level deformation can be translated into functional adaptive façade motion. At the building envelope level, the effectiveness of these responsive components must be evaluated in terms of environmental performance. The research questions are structured to address these three scales: material programming through 4DP, geometric translation into adaptive façade mechanisms, and façade-scale performance evaluation. (Figure 1)

Main research question

How can 4D-printed Shape Memory Polymers be used to create a passive, climate-responsive façade?

Sub-research questions

- (1) How do 4DP parameters (infill pattern, thickness, and infill ratio) affect the deformation behavior of SMP elements?
- (2) How can these programmed deformations be translated into effective passive adaptive façade mechanisms?
- (3) What performance improvements in Indoor Environmental Quality (IEQ) can be achieved through such systems?

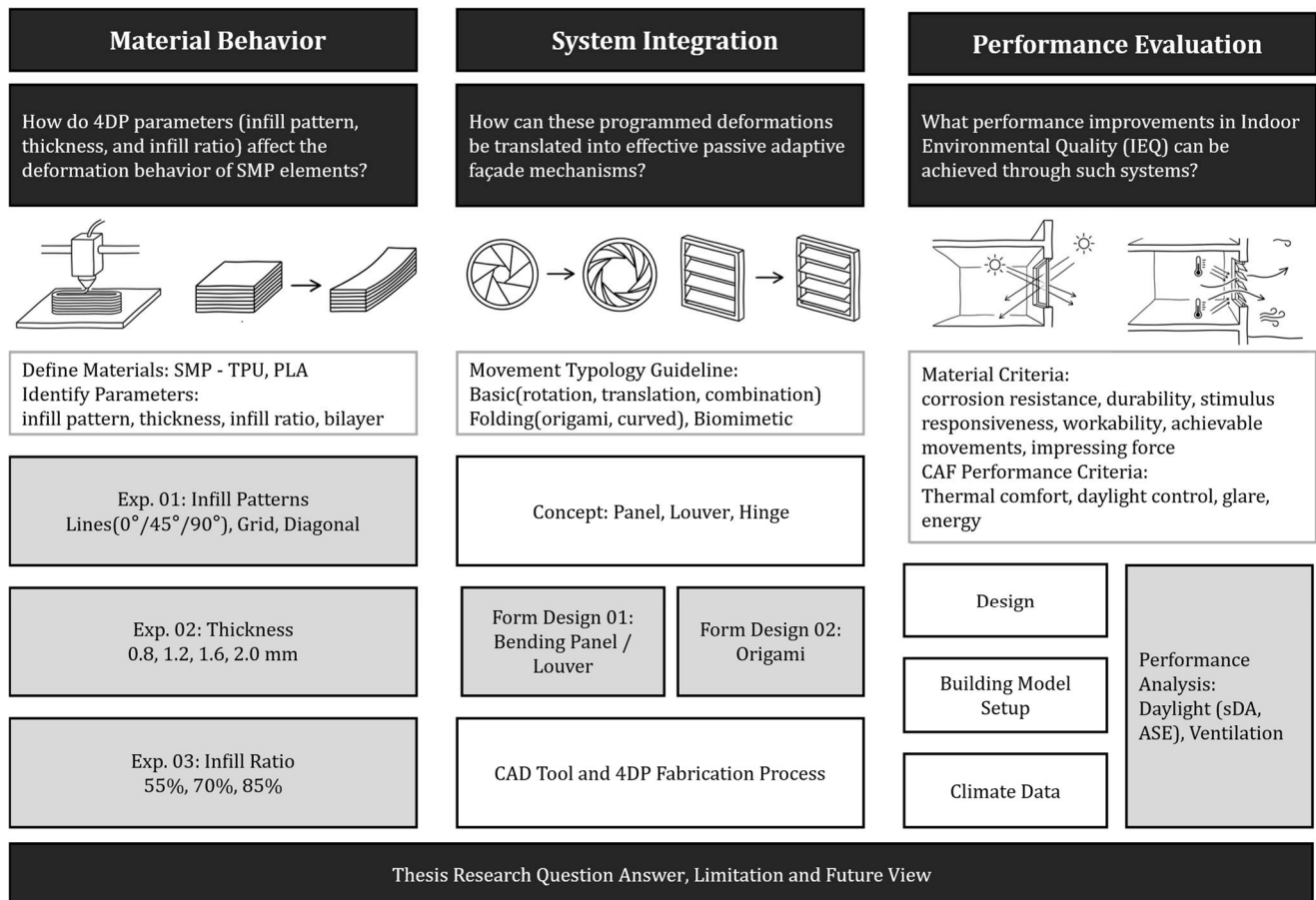


Figure 1 Three interconnected scales, sub-questions and main structure of this thesis. (Image Generated with Gemini AI)

1.3 Thesis Structure

In Chapter 2, this thesis starts with a state-of-the-art review of CAF, 4DP technologies, and SMP applications in architecture, identifying the research gaps that motivate this work. Chapter 3 then addresses the first research sub-question through a systematic experimental study, varying thickness, infill ratio, and infill pattern across TPU-SMP and PLA specimens to establish a quantitative mapping between fabrication parameters and deformation behavior. Building on these findings, Chapter 4 translates the experimental results into architectural design, exploring three façade concepts and developing an interactive CAD tool that links material behavior, parametric geometry, and environmental performance within a single workflow. Chapter 5 evaluates the IEQ through CFD-based ventilation simulation and Radiance-based daylighting analysis across two climate contexts, Delft and Taipei. Chapter 6 and 7 emphasizes the findings, reflects on limitations, outlines directions for future research, and personal reflections.

2 State-of-the-Art

2.1 Passive Responsive Façade

2.1.1 Climate Adaptive Façade

Loonen et al. (2013b) define Climate Adaptive Façade (CAF) as a building envelope composed of materials, components and control systems capable of altering their functional behavior when triggered by climate stimuli, such as sunlight, temperature, humidity and airflow, in order to improve indoor comfort or energy performance (Figure 2). As the interface of a building's indoor and outdoor environment, façades are critical in moderating energy exchange and environmental quality, making them one of the most effective building element for enhancing human comfort and reducing energy consumption (Wigginton & Harris, 2013; Zhang et al., 2022). In contrast, conventional façades are static and unable to adapt to diurnal or seasonal variations, often causing glare, overheating, and reduced occupant comfort or energy performance (Loonen et al., 2013b). The development of façade therefore marks a paradigm shift toward locally adaptive, performance-driven building skins, emphasizing user comfort and long-term energy efficiency.

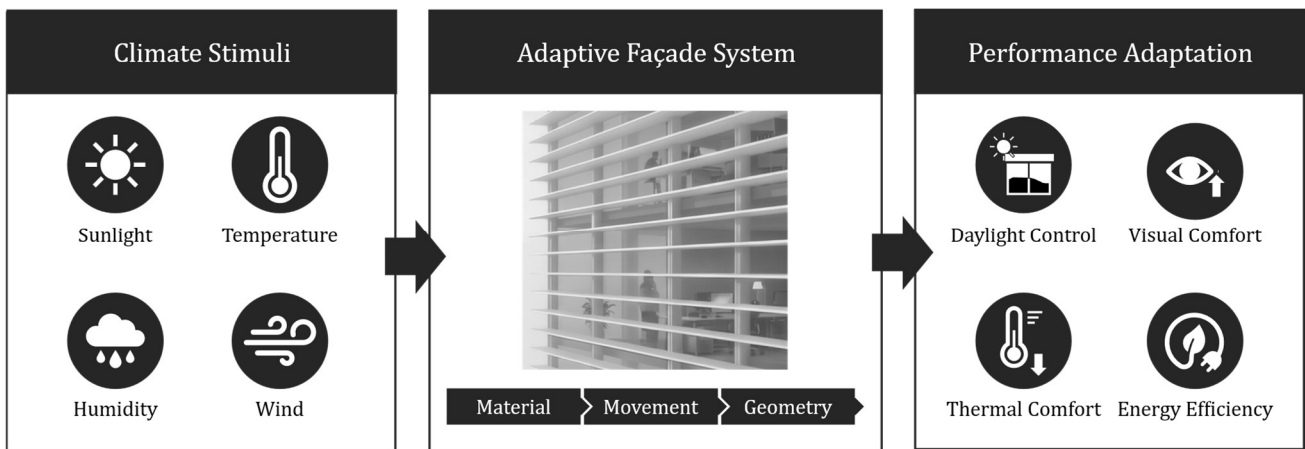


Figure 2 Climate Adaptive Façade (CAF) definition concept diagram.

2.1.2 Passive Material-Based Responsive Façade (PMRF)

According to Heidari Matin & Eydgahi (2022), technologies used in CAF can be broadly classified as active or passive. Several limitations of active adaptive façades have shifted research interest toward intrinsic PMRF. Active systems rely on sensors, controllers and actuators to adapt façade geometry or material states, offering precise control but introducing higher energy demands, mechanical complexity, and

maintenance requirements. A well-known example is the Arab World Institute in Paris, which is no longer fully operational (Ateliers Jean Nouvel, 1987).

In contrast, passive systems overcome these limitations by embedding responsiveness directly into material or structural properties, enabling autonomous adaptation to environmental stimuli without external power (Mansoori et al., 2023). Particularly, material-driven technologies offer alternatives to traditional active CAF by embedding all sensor, controller, and actuator directly into material properties, thereby reducing dependency on external power or moving parts.

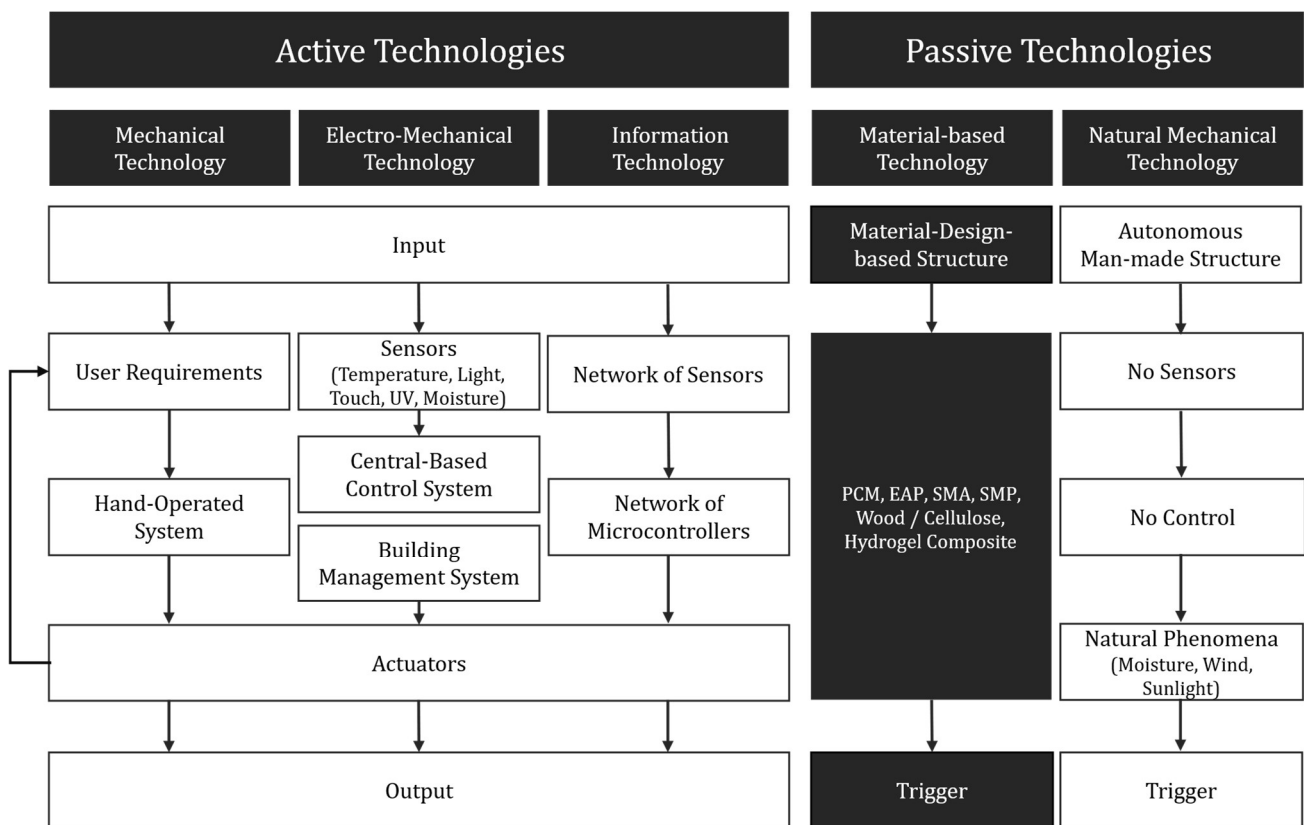


Figure 3 Sensing, actuating and control technologies used in CAF. Adapted from (Heidari Matin & Eydgahi, 2022).

2.1.3 Stimulus-responsive Materials

Stimulus-responsive materials are key elements that enable façades to passively or with minimal energy respond to environmental inputs such as heat, moisture, light, or wind (Fiorito et al., 2016). Common categories include:

- (1) *Thermal-responsive materials:* e.g., phase change materials for heat storage (Weinläder et al., 2005; M. Turrin et al., 2015; Martin Tamke et al., 2017), shape memory materials that recover

pre-set forms with temperature changes (Sun et al., 2012; Schneider et al., 2021), bilayer metals that bend due to differential thermal expansion (Minner, 2011; Furuto, 2012).

- (2) *Hygro-responsive materials*: e.g., wood composites (A. Menges et al., 2013) or hydrogels (Irene Ayala Castro et al., 2017) that expand or contract with humidity.
- (3) *Photo-responsive materials*: e.g., photochromic windows (Meng et al., 2024) that alter color or transmittance under light.
- (4) *Wind-responsive materials*: e.g., flexible membranes that deform under airflow.

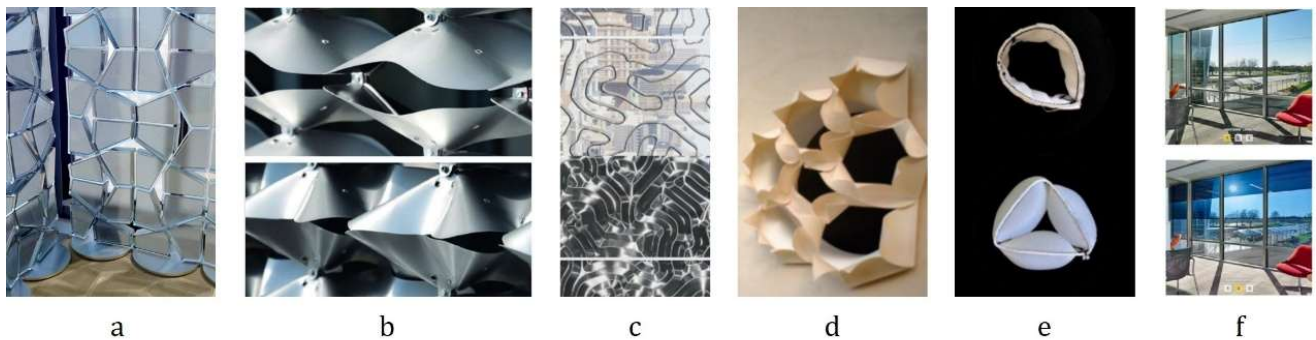


Figure 4 Examples of PMRF. a) Double Face (M. Turrin et al., 2015). b) ADAPTEX Wave (Schneider et al., 2021). c) Homeostatic Façade (Minner, 2011). d) HygroSkin (A. Menges et al., 2013). e) Water driven-breathing skin (Irene Ayala Castro et al., 2017). f) Thermo-chromic Glazing (Tulubas Gokuc & Şahin, 2020).

In short, these developments position PMRF as a promising alternative to conventional and mechanically-driven adaptive systems, demonstrating how material-intrinsic responsiveness can enable autonomous, low-energy adaptation to climate variations. Yet, despite their potential, research shows that current PMRF strategies often remain limited in controllability, geometrical complexity, and programmability of deformation, suggesting a need for fabrication approaches that allow material behavior to be designed rather than merely observed (Heidari Matin & Eydgahi, 2022). This research therefore turns toward 4DP as a means to intentionally program and enhance such material-driven transformations (Yi & Kim, 2021a), aiming to explore how digitally fabricated responsive elements may advance the next generation of CAF.

2.2 PMRF Design Guideline

2.2.1 Movement Typologies

Apart from material behavior, another key design element that affects the performance of the PMRF is movement typologies (Tabadkani et al., 2021). systematically categorize adaptive façade movement strategies into three dominant families: basic movements, folding structures, and biomimetic skins. Each is defined by its deformation logic (Figure 5).

- (1) **Basic Movement Systems:** Operate through single-degree motions such as rotation, translation, expansion/contraction, and remain the most commonly implemented due to their mechanical simplicity and controllability (Svetozarevic et al., 2019).
- (2) **Folding Structure Systems:** Bending and folding mechanisms allow façades to achieve complex morphing geometries, making them suitable for dynamic shading. Generally, there are two main approaches: (a) rigid origami, using planar facets (AHR Architects, 2013), and (b) curved-line folding, guiding with smoother deformation paths (ERNST GISELBRECHT + PARTNER, 2007; Henning, 2014; Yazdani Studio, 2016). Folding strategies are particularly relevant for material-driven facade, as hinge-like deformation may be encoded by material gradients or programmed parameters.
- (3) **Biomimetic Skins:** Translate principles observed in biological systems into two strategies for environmental responsiveness: (a) material, intrinsic material properties without mechanical actuation or (b) structural, physical shape transformation. Many of these mechanisms draw inspiration from plant morphologies, where movement is achieved through differential swelling, hygroscopic layers, or fiber orientations (e.g., Air Flower, 2013; Prof. A. Menges, O. Krieg, S. Reichert, 2013).

In short, basic and folding systems are the most common in architectural applications, while biomimetic skins illustrate how material properties can be harnessed to mimic natural processes. Reviewing these movement strategies provides a framework to understand the design space and possibilities for PMRF.

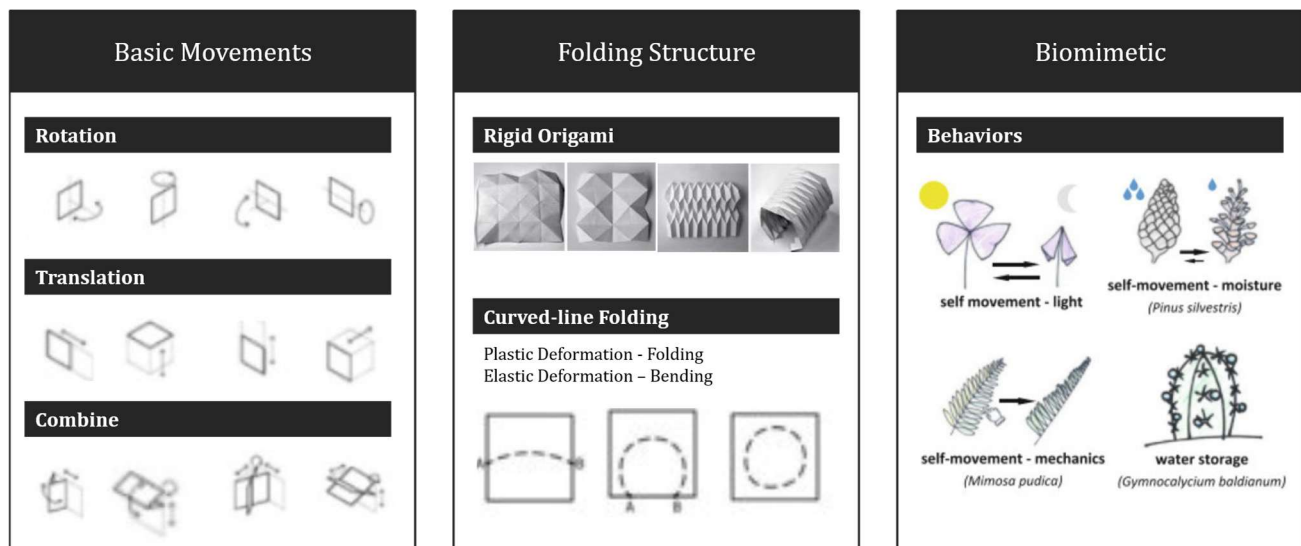


Figure 5 Summarized table of three movement strategies in adaptive façade. Adapted from (Vergauwen et al., 2014; Sandak et al., 2019; Tabadkani et al., 2021).

2.2.2 Material Criteria

Since material behavior is the core driver of transformation in PMRF, the selection of suitable smart materials requires careful consideration. The following criteria are commonly used to identify and evaluate suitable smart materials for the façade design (Fiorito et al., 2016): (1) *corrosion resistance*: materials must withstand exposure to weather conditions; (2) *durability*: the life cycle of the smart movement should ensure long-term functionality; (3) *stimulus responsiveness*: materials should respond reliably to environmental stimuli; (4) *workability*: materials must be feasible to shape, process, and adapt during fabrication; (5) *achievable movements*: the material should enable the desired deformation modes; (6) *impressing force*: for materials used as actuators, the generated force must meet functional requirements. Thus, materials selected for adaptive façade systems must simultaneously ensure durability under outdoor exposure, manufacturability at architectural scale, and sufficient stimulus-driven actuation performance, forming the foundation for feasible and resilient passive responsive façade solutions.

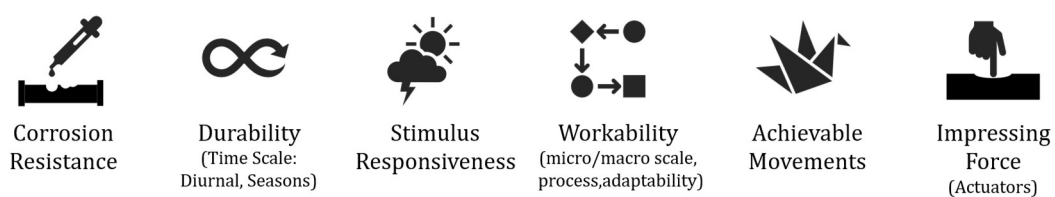


Figure 6 6 criteria to identify and analyze smart material.

2.2.3 Climate Performance Criteria

What makes a “good” PMRF? PMRF design should be evaluated through multiple performance criteria to ensure both environmental and occupant-oriented effectiveness. According to Tabadkani et al. (2020), there are five key criteria for façade performance assessment: (1) *thermal comfort*, determining the system's ability to maintain acceptable indoor temperature conditions; (2) *daylight level*, ensuring sufficient natural illumination without excessive artificial lighting demand; (3) *glare control*, preventing visual discomfort caused by uncontrolled luminance contrast; and (4) *view-out quality*, maintaining visual connection to the external environment for psychological well-being. These human-centric comfort dimensions directly influence occupant experience and are increasingly incorporated alongside (5) *energy-oriented metrics*, such as lighting and cooling load reduction. (ANSI/ASHRAE, 2023; NEN-EN 17037, 2019) These performance criteria serve not only as indicators, but also as further decision parameters guiding material selection, responsiveness logic, and movement mechanisms in subsequent façade development.



Figure 7 Diagrams of five performance criteria of CAF.

2.3 4D Printing

2.3.1 Definition and Architectural Significance in Façade

4D Printing (4DP) introduces time as the fourth dimension to additive manufacturing, allowing fabricated structures to autonomously transform in response to external stimuli (Mahmood et al., 2023). Unlike conventional additive manufactured components, whose behavior is predetermined and remains static once produced, 4DP elements alter their geometry or mechanical states upon exposure to environmental triggers such as heat, moisture, or light, activating material-encoded deformation pathways. As summarized by existing definitions, “4DP is the creation of objects which alter their shape when removed from the printer, self-assembling when exposed to water, heat, or air due to material reactions.” (Ahmed et al., 2021).

While traditional fabrication methods for PMRF offer limited post-production adaptability, restricted geometric variation, and rely on discrete components whose behavior is difficult to customize, 4DP enables programmable behavior directly through material distribution, orientation, and structural configuration (Niazy et al., 2024). Such digitally controlled manufacturing supports non-standard, multi-scale geometries, locally differentiated responses, and material-geometry integration. (Figure 8)

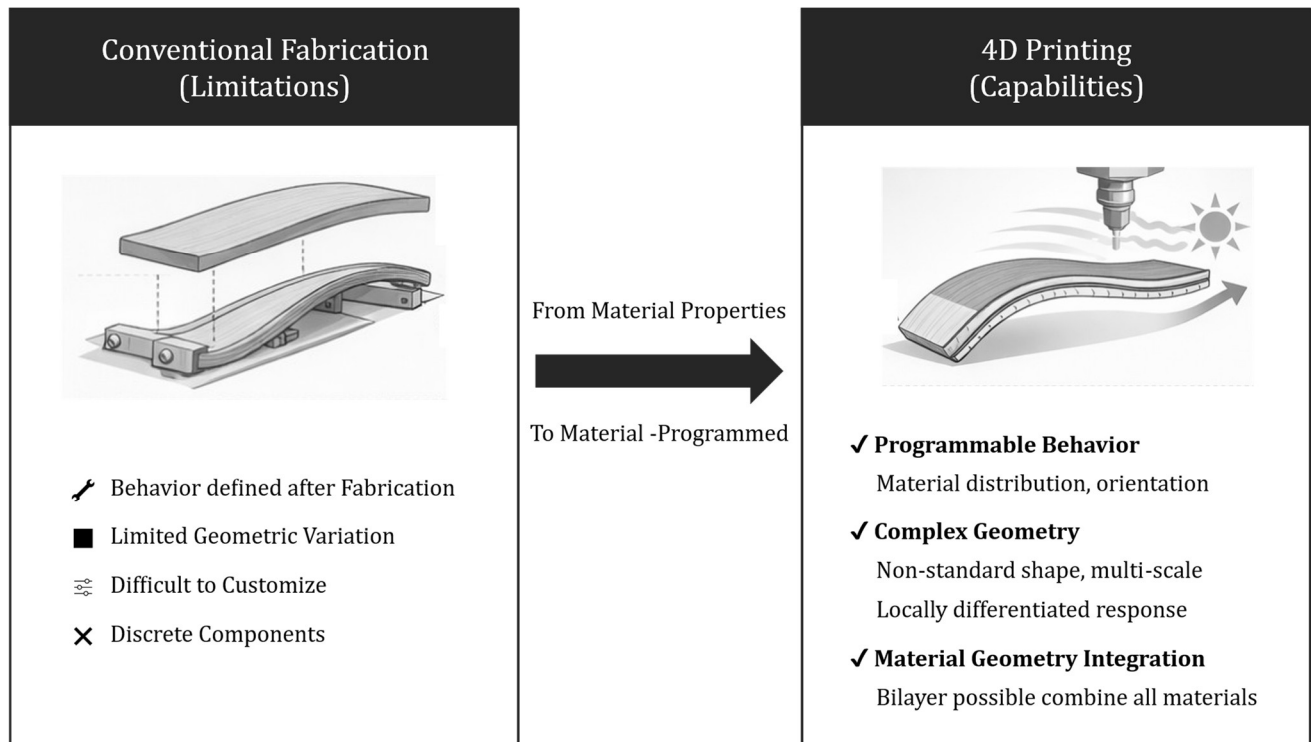


Figure 8 Transformation from traditional fabrication to 4DP. (Images generated from Gemini AI)

In the context of façade sustainability, Niazy et al. (2024) summarize that 4DP responsive systems can enhance material utilization efficiency, optimize environmental performance through strategic material placement, and reduce energy demand by harnessing natural stimuli as renewable actuation sources. Although comprehensive life cycle assessments of 4DP façades are still ongoing, early evidence suggests that programmable passive responses may support more resource-efficient and lower-energy building skins when appropriately designed and deployed (Figure 9).

This positions 4DP as a compelling approach for programmable passive façades, transitioning material responsiveness from inherent behavior to intentionally encoded actuation, and offering a sustainable direction in which façade performance, energy demand, and material usage can be optimized through programmable morphing strategies.

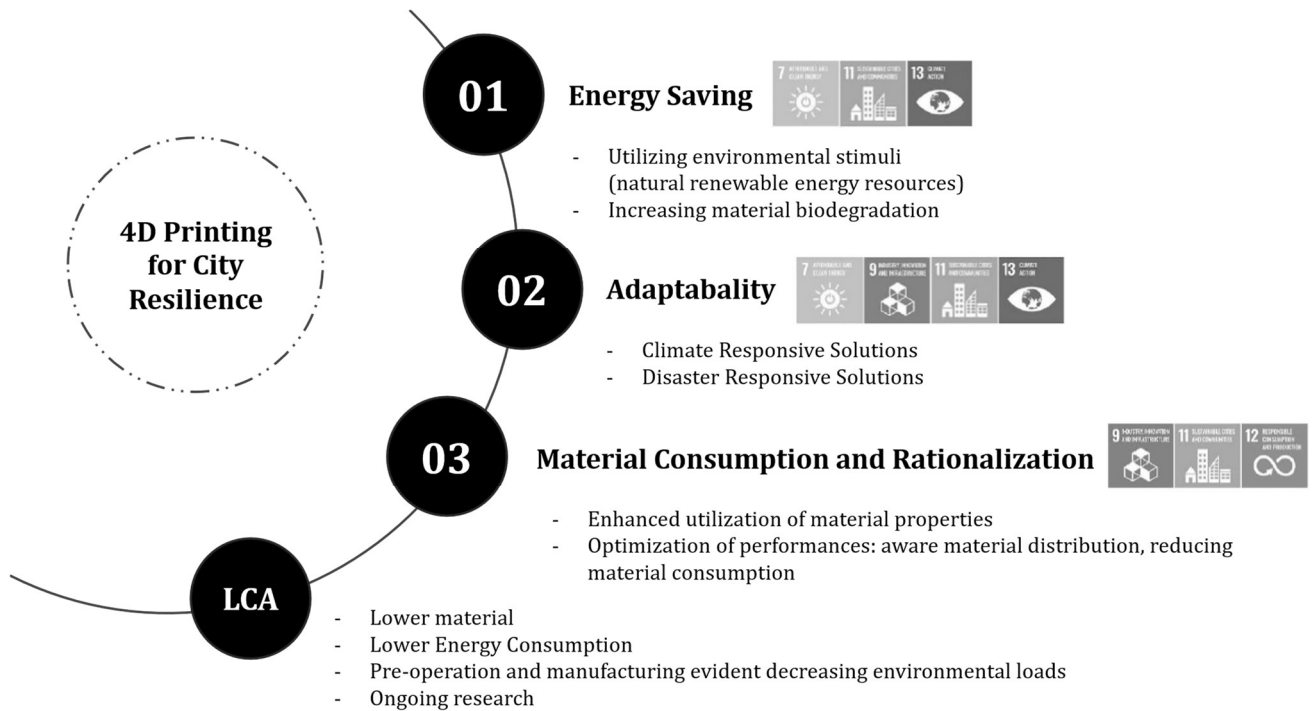


Figure 9 SDGs Achieving Goals and LCA for 4DP in Art, Architecture and Constructions. Adapted from (Niazy et al., 2024).

2.3.2 Key Factors Enabling 4DP PMRF

According to Ahmed et al. (2021), the transformation behavior of a 4DP system is not determined by material composition alone, but emerges from the interaction between material, stimulus, geometry, fabrication parameters, and programming strategy. As stated, “the stimulus is applied on the smart material using a suitable interaction mechanism and mathematical modeling during an additive manufacturing process which results into a 4DP structure”, highlighting that actuation is designed rather than incidental (Ahmed et al., 2021). 4DP is mostly governed by these five factors: stimuli, smart materials, additive manufacturing (AM) process, interaction mechanism and mathematical modeling (Figure 10) (Momeni et al., 2017), and are therefore essential variables when tailoring façade-responsive performance.

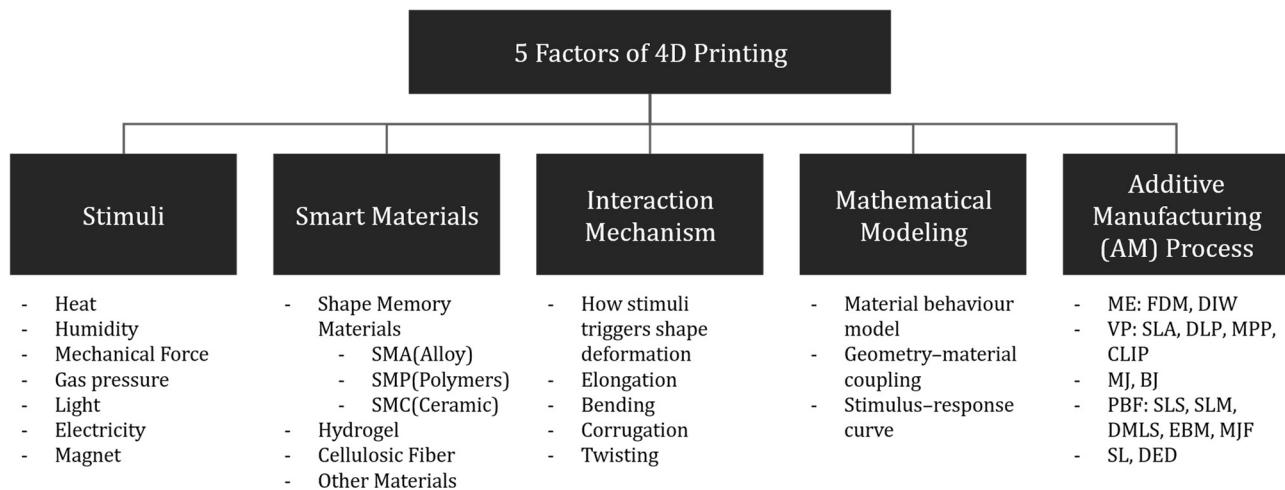


Figure 10 5 main factors when designing a 4DP façade.

2.3.3 Stimuli & Smart Materials

As illustrated in Figure 11, 4DP transformation relies on the interaction between five primary stimuli, namely light, heat, electricity, magnetism, environmental physical quantities (humidity or pressure) and the smart materials capable of responding to them (Liu et al., 2021). Material responsiveness is encoded during additive manufacturing, where material composition, distribution, and geometry collectively determine how a printed component will morph when stimulated (Mahmood et al., 2023).

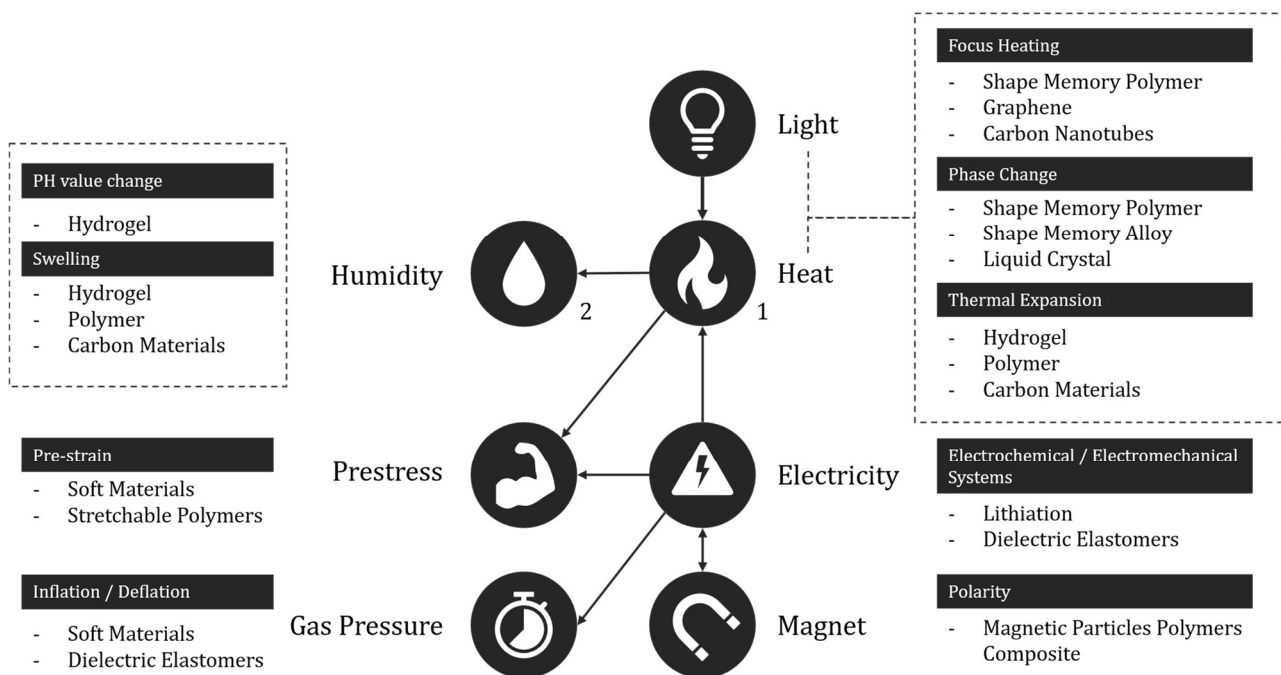


Figure 11 Relationships between Stimuli and Smart Materials. Adapted from (Liu et al., 2021).

When translated into the context of the built environment, this stimulus–response logic directly corresponds with the environmental drivers already present in PMRF (Section 2.1.3), such as temperature fluctuation and humidity variation. Whereas conventional PMRF relies on the material’s inherent reaction, 4DP enables these reactions to be intentionally programmed, amplified, or spatially localized. As a result, PMRF materials selected for 4DP must extend beyond mere stimulus responsiveness, satisfying the requirements of printability and programmability.

The following sections therefore examine key 4D-printable material families, assessing their stimulus mechanisms, printing compatibility, and potential for programmable passive adaptive systems within PMRF-based façade design.

Thermal-responsive Materials

Shape Memory Materials (SMM): SMM constitute shape memory alloys, shape memory polymers, and shape memory hybrids, represent a category of smart matter distinguished by their ability to revert to a predefined configuration from a deformed state upon exposure to an external trigger. Driven by reversible structural or phase alterations within the material matrix, this phenomenon is widely recognized as the shape memory effect (Figure 12) (Sun et al., 2012).

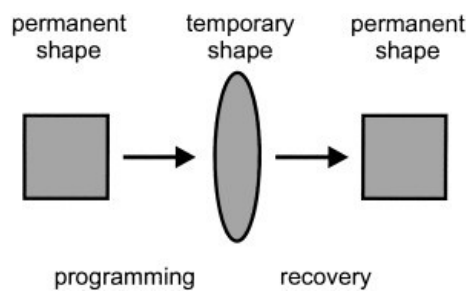


Figure 12 Schematic diagram of one-way SME (Lendlein & Kelch, 2002).

- (1) *Shape Memory Alloy (SMA)*: Exhibit thermally activated reversible phase transition between martensite and austenite, enabling controlled geometric recovery when heated above a transformation temperature (Figure 13). Their high actuation stress and fatigue resistance in engineering applications have historically made them attractive for smart structures (Sun et al., 2012).

SMA has been implemented extensively in biomedical, aerospace, and micro-actuation systems due to its strong solid-state actuation (Ding et al., 2025). However, its applicability in architectural 4DP remains limited. SMA requires high processing temperatures, and carries high material cost; moreover, current additive manufacturing routes for SMA are still constrained by printability, thermal control requirements, and scalability (Ismail Hossain et al.,

2025). As a result, façade-related studies predominantly employ SMA wires or sheets embedded in mechanisms rather than AM components (Schneider et al., 2021; Lanfranco et al., 2023).

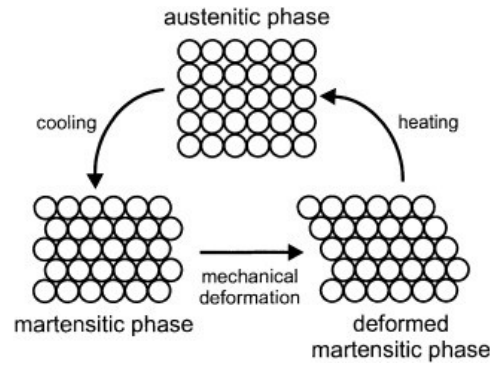


Figure 13 Schematic diagram for mechanism of SMA (Lendlein & Kelch, 2002).

(2) **Shape Memory Polymer (SMP):** Derive their actuation from molecular mobility changes near the glass transition or melting temperature, allowing large reversible deformation (Section 2.4) (Wu et al., 2013). SMPs are highly compatible with additive manufacturing, enabling direct integration of programming into the printing process through anisotropic toolpaths, layer orientation, and composite reinforcement strategies. Although SMPs exhibit lower actuation force compared to SMA, they offer far greater geometric freedom, tunability, and responsiveness optimization (Ge et al., 2016). Consequently, SMPs currently represent the most promising candidate for 4DP façade systems, particularly in thermally driven louvers, adaptive shading panels, and lightweight self-deployable skins (Niazy et al., 2024).

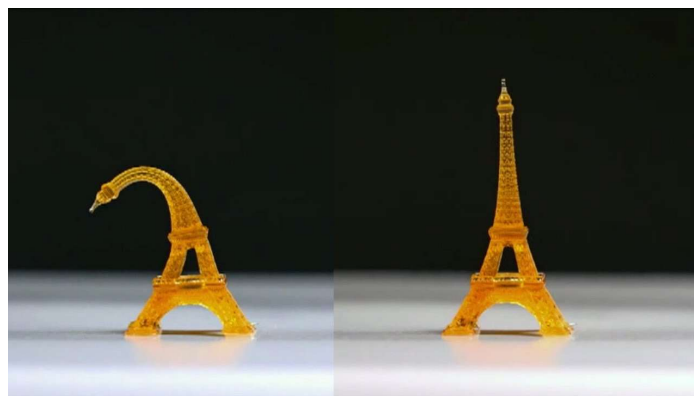


Figure 14 SMP temporary and permanent shape example. (Ge et al., 2016)

Figure 15 demonstrate the stiffness of SMA and SMP after heating. According to Sun et al. (2012), unlike SMA, where deformation is recovered through a thermally driven martensite–austenite phase shift,

SMPs are typically stiff at low temperature and soften upon heating, enabling deformation and fixing upon cooling. However, this conventional one-way transition means that SMPs alone do not inherently support cyclic actuation, as shape recovery usually requires automatic reprogramming. This indicates that future SMP in façade system will likely depend on two-way SMP or 4DP bilayer strategies rather than monolithic polymers to achieve cyclic, climate-driven motion.

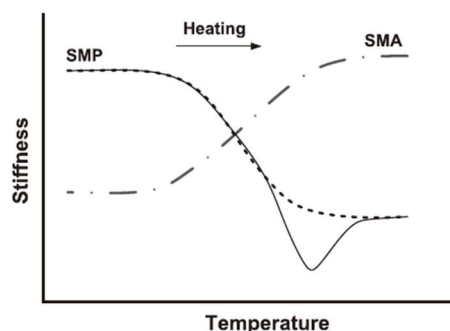


Figure 15 Stiffness variation after heating in SMP and SMA (Sun et al., 2012).

Hygro-responsive Materials

Similar to solar radiation, relative humidity (RH) exhibits significant diurnal fluctuations within the building microclimate. During the night and early morning, high humidity levels can trigger material expansion, while the lower RH during midday promotes desiccation and contraction. By harnessing this "natural intelligence," 4DP hygromorphs can facilitate passive ventilation and moisture control without any external energy input (Holstov et al., 2015).

- (1) *Wood/Cellulose-based Composite*: Wood serves as the quintessential biological model for hygro-responsiveness due to the hygroscopic nature of cellulose fibers. In the realm of 4DP, researchers have successfully moved from inherent material behavior to encoded actuation.

By using wood composite filament, it is possible to program the deformation through grain orientation, layer thickness, combining multi-material, layer configuration, and infill patterns to create wooden actuators that warp predictably in response to RH changes (Correa et al., 2015; El-Dabaa & Salem, 2021; Correa, 2022; Bianconi et al., 2023). Furthermore, Tahouni et al. (2021) demonstrate that the timescale and magnitude of motion can also be programmed through multilayer design by controlling parameters, such as active layer thickness, different filling density of active and passive layers.

Tahouni et al. (2020) proposed a self-shaping curved folding framework, encoding target 3D folded shapes directly through material layup and curved crease geometry to achieve

complex self-folding behavior. Further research tailored both biobased filament composition and mesoscale structuring to achieve reversible and rapid humidity response (Tahouni et al., 2023).

Cheng et al. (2024) developed biobased hygromorphic bilayer systems using cellulose composites and scale to real building facades prototype, validating material performance, cyclic robustness, and architectural applicability in outdoor deployment.

Although wood and cellulose-based composites have become a prominent direction in 4D-printing façade research, existing studies largely remain at the prototype or demonstrator scale. Current systems, while capable of visually compelling shape-change, continue to face challenges, such as long-term durability, fatigue resistance, and environmental stability to achieve a robust façade (Tahouni et al., 2023).

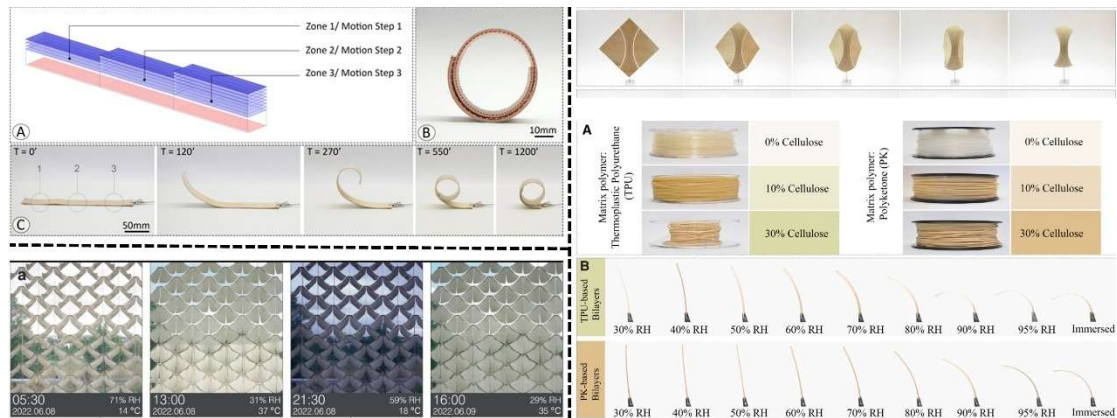


Figure 16 Examples of wood or cellulose-based composite. Top left: (Tahouni et al., 2021), Bottom Left: (Cheng et al., 2024), Right: (Tahouni et al., 2023).

(2) *Hydrogel*: Hydrogels are polymer capable of swelling and deswelling in response to environmental stimuli, such as humidity or pH, due to water diffusion within their structure (Mahmood et al., 2023). Though there are widely investigated in biomedical, applications in real façade systems remain limited, and 4DP hydrogel facades are rarely reported. Current studies mainly focus on composite systems to improve strength and durability (Irene Ayala Castro et al., 2017). Although hydrogels offer a unique ability to generate reversible, moisture-driven shape change, their slow response, low mechanical output, and outdoor stability challenges mean that most façade-related explorations remain at prototype or conceptual research scale (Al-Marzouqi et al., 2025).

2.3.4 Additive Manufacturing Process

According to Ding et al. (2025), the main 4DP techniques for responsive materials are Fused Deposition Modeling (FDM), Direct Ink Writing (DIW), and Stereolithography (SLA). FDM melts and extrudes thermoplastic filaments layer by layer, making it suitable for SMPs and wood-filled filaments, and allows programming of anisotropy through toolpath and layer orientation (Solomon et al., 2021). DIW extrudes viscous inks that solidify after deposition, ideal for soft materials like hydrogels or pastes and for multi-material structures. SLA uses light to cure liquid resins with high resolution, making them well-suited for photopolymer-based SMPs (Shahzad & Lazoglu, 2021).

In general, SMPs, wood composite and thermoplastics are best printed via FDM or SLA, while hydrogels require DIW or other extrusion-based methods (Ding et al., 2025). Choosing the right printing technique is crucial to match the material's properties with the desired actuation performance in 4DP façade systems.

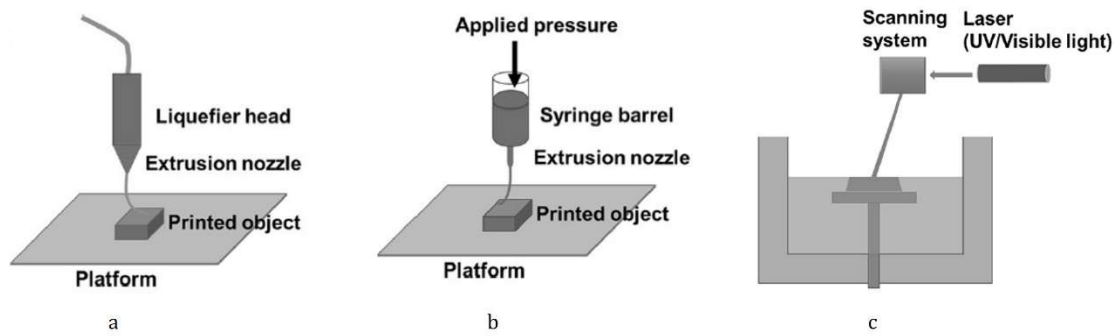


Figure 17 Schematic illustration of a) FDM, b) DIW, and c) SLA (Ding et al., 2025).

2.3.5 Interaction Mechanism & Mathematical Modeling

3 Laws of Interaction Mechanism

The shape-changing physics of 4DP structures are governed by three fundamental laws formulated by Momeni & Ni (2018). The First Law attributes all morphological transformations (e.g., bending or twisting) to the relative expansion between active and passive phases. The Second Law identifies the drivers of this expansion, which, in the context of SMP façades, are dominated by thermal expansion and molecular state shifts. Finally, The Third Law introduces the temporal dimension via time constants of stimulus absorption and material reaction. Together, these laws provide the physical framework to program the speed and magnitude of a façade's kinetic response (Momeni & Ni, 2018).

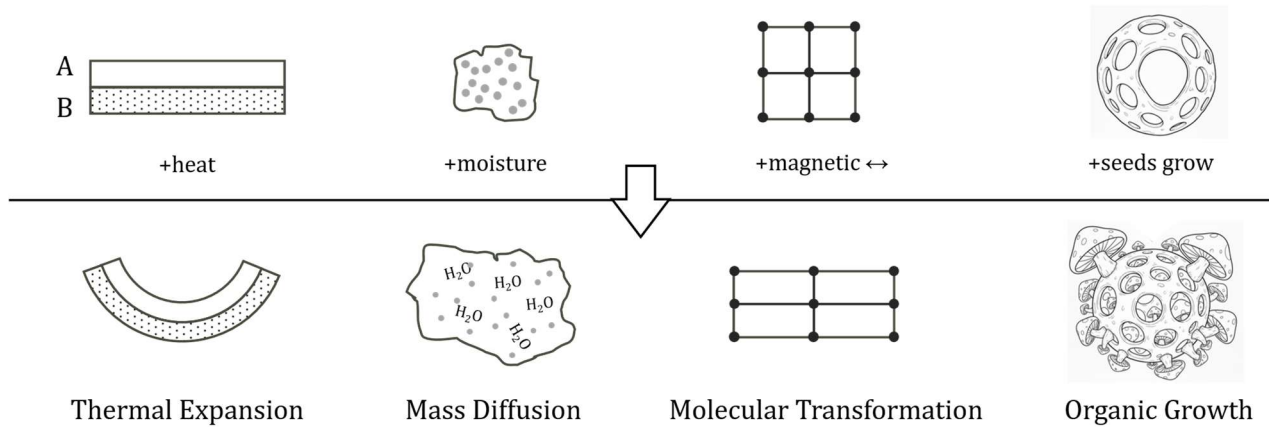


Figure 18 Four physical factors of shape changing ability.

Timoshenko Beam Theory of Mathematical Modeling

While 4DP relies on material-driven physics, Timoshenko's Beam Theory establishes that the resulting curvature is directly driven by the strain mismatch between the active and passive layers (Timoshenko, 1925). In FDM-based fabrication, this means bending behavior can be precisely tuned without altering the material composition. Instead, designers can strategically control the deformation by adjusting **filling density, printing pathways (toolpaths), and layer height** (Timoshenko, 1925). Modifying these toolpath parameters directly alters internal toolpath constraints and layer-by-layer residual stresses, functioning as the foundational "geometric logic" needed to program specific aperture angles or folding curvatures in passive shading facades.

2.3.6 Short Summary

In conclusion, the selection of a smart material for 4DP PMRF is a strategic trade-off between actuation force, environmental durability, and ease of fabrication. While wood composites offer a sustainable, bio-based solution with high aesthetic value, their reliance on humidity results in slower response times and sensitivity to fluctuating weather conditions. SMA provide the highest mechanical output but are constrained by high costs and the lack of a monolithic 4DP workflow suitable for architectural scales.

SMP, particularly when processed through FDM, emerge as the most versatile candidate in 4DP of PMRF. They offer a unique balance of high geometric programmability, low material cost, and a rapid thermal response that aligns with solar radiation cycles. The following table (Table 1) synthesizes the comparative analysis of these materials, highlighting the research gap in SMP-based cyclic actuation that this thesis aims to address.

Table 1 Comparison Summary for Smart Materials in Façade Potential.

Smart Material	Stimulus	Actuation Force	4DP Method (Ease, Price)	Architectural Research Maturity & Core References
SMA	Heat	High	Hybrid / Powder Bed (Hard, \$\$\$\$)	High (but not 4DP)
SMP	Heat / Light	Medium	FDM (Filament)/SLA (Easy, \$\$)	Emerging (few prototypes) (Yi, 2021; Yi & Kim, 2021a)
Hydrogel	Moisture / pH	Low	DIW (Paste) (Medium, \$)	Low (structural stability gap)
Wood Fiber / Cellulose-based composites	Moisture	Medium	DIW (Paste) / FDM (Medium, \$)	High (many prototypes) (Tahouni et al., 2023; Cheng et al., 2024)

2.4 Shape Memory Polymers (SMP)

While SMPs respond to diverse stimuli, including pH, UV light, and moisture, this research focuses exclusively on thermally-activated SMPs due to their direct correlation with solar thermal gains in building envelopes.

2.4.1 Mechanism

The framework governing the thermo-responsive SME in polymers (Figure 19) relies on a dual-component architecture. According to Sun et al. (2012), this configuration consists of an elastic domain and a transition domain. The former retains its structural integrity throughout the stimulation cycle, whereas the latter exhibits the capacity for reversible stiffness modulation.

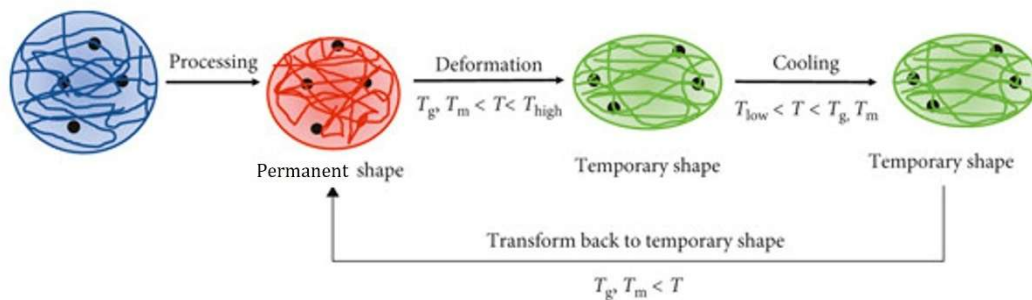


Figure 19 Schematic typical SME of SMP. (Li et al., 2018)

In thermo-responsive SMPs, this transition is typically achieved through the glass transition (T_g) of the polymer chains. This molecular behavior can be described through the following four-stage configuration cycle (Figure 20). When heated above T_g , the segments soften, enabling deformation while

the elastic domains store strain energy. Cooling below T_g fixes the temporary shape as the transition segments harden and restrict chain mobility. Upon reheating, these softened domains release the stored energy, driving it recover to the original configuration.

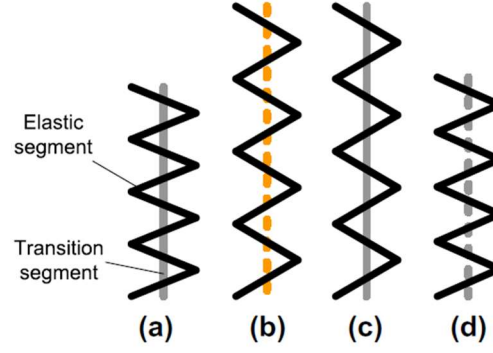


Figure 20 Schematic diagram for mechanism of SMP (Sun et al., 2012)

In Figure 21, SME in polymers is a thermomechanical process consisting of two primary phases: programming and recovery. As defined by Wu et al. (2013), the cycle begins with programming “a”, where the SMP is deformed under a specific load at an elevated temperature (above T_g) to a maximum strain (ϵ_m). This temporary shape is then “locked” by cooling the material while maintaining the load. Upon unloading “b”, the material retains a residual strain (ϵ_u). The subsequent recovery phase is triggered by reheating the material “c”, allowing it to return toward its original permanent shape, leaving a final permanent strain (ϵ_h).

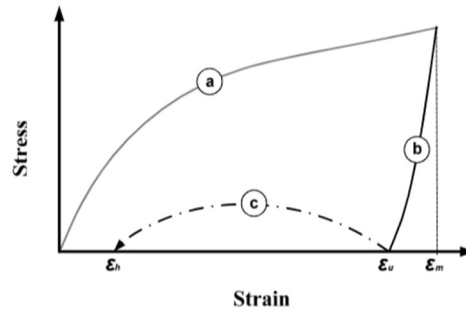


Figure 21 Relation between stress and strain of SME cycle in SMP, a. loading, b. unloading, c. heating (Wu et al., 2013).

2.4.2 Applications in Architecture

Selection of SMP T_g

The integration of SMPs into responsive façades requires a precise alignment between the material's T_g and the building's thermal microclimate. While the SME cycle defines the logic of movement, the T_g acts as the operational threshold. In architectural applications, the façade surface temperature, driven by solar absorption, can significantly exceed the ambient air temperature.

Many research shows different façade orientations and material colors result in varying surface temperatures (Hens, 2017). Dark-colored building envelopes can reach temperatures exceeding 60°C even when ambient temperatures are moderate 25-30°C (Table 2). Empirical studies on adaptive facades, Yi & Kim (2021a) confirm that this thermal gradient provides sufficient energy to trigger the SME in SMPs with a T_g between 45 °C and 65 °C, eliminating the need for active heaters. Therefore, T_g is not just a chemical property but a design parameter. If the T_g is too low, the façade may lose its "shape fixity" on a warm day without direct sun; if too high, the environmental energy may never be sufficient to trigger recovery.

Table 2 Typical façade surface temperatures and target SMP T_g selection.

Façade Material/Color	Ambient Temp (°C)	Surface Temp (°C)	SMP T_g
Dark-colored Metal/Polymer	25°C - 30°C	50°C - 70°C	55°C - 65°C
Light-colored Polymer	25°C - 30°C	35°C - 45°C	40°C - 50°C

Inherent Material Limitations in Architectural Contexts

While SMPs offer a promising path toward passive, responsive building skins, several inherent material limitations must be addressed to transition from laboratory prototypes to industrial-scale PMRF. These constraints define the current research landscape and motivate the experimental methodologies in the following studies. There are two primary challenges:

- (1) **Low Actuation Force:** SMPs exhibit a significant drop in elastic modulus when heated above their glass transition temperature T_g (Behl & Lendlein, 2007; Balogun & Mo, 2014) (Figure 22a). This structural softening limits their ability to overcome external loads such as high wind pressure or the self-weight of large-scale facade components.
- (2) **One-Way Actuation and Fatigue:** Most FDM-printed SMPs are intrinsically one-way, requiring manual resetting or complex hybrid systems (e.g., SMA integration) to achieve the diurnal reversibility necessary for building skins (Yi & Kim, 2021a) (Figure 22b). Furthermore, repeated thermal cycling often leads to interface degradation and gravity sagging.

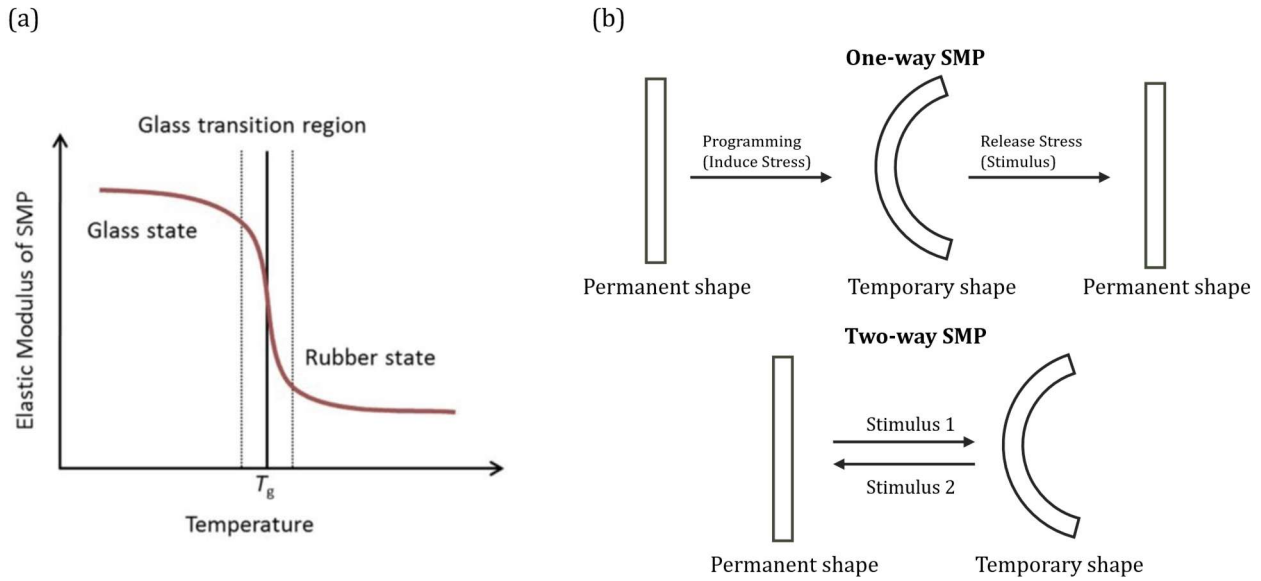


Figure 22 (a) Relation between temperature and Young's Modulus of SMP. (Zhong et al., 2020);

(b) Schematic diagram of one-way SMP and two-way SMP. Adapted from (Eryildiz, 2021).

Current Research

To overcome the aforementioned limitations, recent research has evolved from basic material testing toward Integrated Design. The following cases illustrate how researchers utilize geometric programming, 4DP parameters, and hybrid materials to transform these constraints into functional architectural assets.

(1) Geometric Programming: Structure Reinforcement

Both Beites (2013) and Tolley et al. (2014) proposed a strategy utilizing SMPs as localized active hinges embedded within rigid panels, enabling the self-folding structures through uniform heating. Yoon (2019) utilized this concept and develop multiple prototypes, then focus on the design and performance validation of thermo-responsive SMP shading louvers for passive climate adaptation (Yoon, 2019; Yoon et al., 2020; Yoon, 2020). SMP acts as a self-sensing passive actuator, eliminating the need for external power and complex mechanical sensors. The innovation lies in the material-level programming of response thresholds and the use of folded plate geometries to overcome the structural softening challenge at macro-scales (Figure 23).

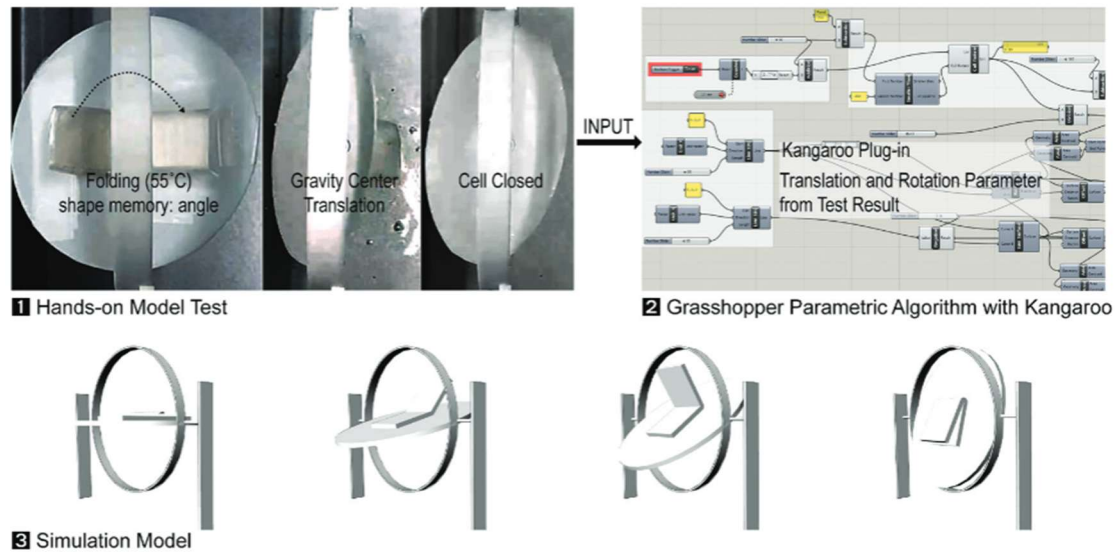


Figure 23 Designed cell unit and simulation model. (Yoon, 2019)

Kuboki (2019) introduce the concept of breathing façades, combining auxetic-inspired SMP patterns. Their work demonstrates that 4DP SMP elements can passively respond to temperature and wind, providing ventilation and cooling while remaining rigid under load. This approach highlights how material behavior and geometric design can enable functional, climate-responsive façades (Figure 24).

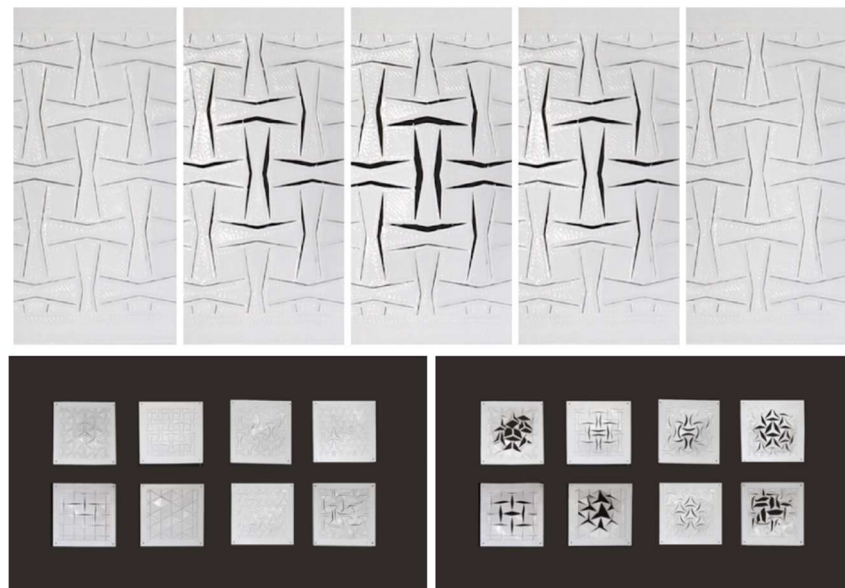


Figure 24 Prototypes of auxetic patterns of SMPs. (Kuboki, 2019)

Zameem et al. (2023) explored the implementation of SMP actuators within adaptive architectural envelopes to optimize thermal regulation. Their proposed framework utilizes SMP components as passive, temperature-responsive deployment mechanisms that dynamically reconfigure the façade topology. Validated through performance simulations, this adaptive system yields a decrease in cooling loads while

enhancing indoor thermal comfort via the autonomous modulation of solar heat gain (Figure 25).

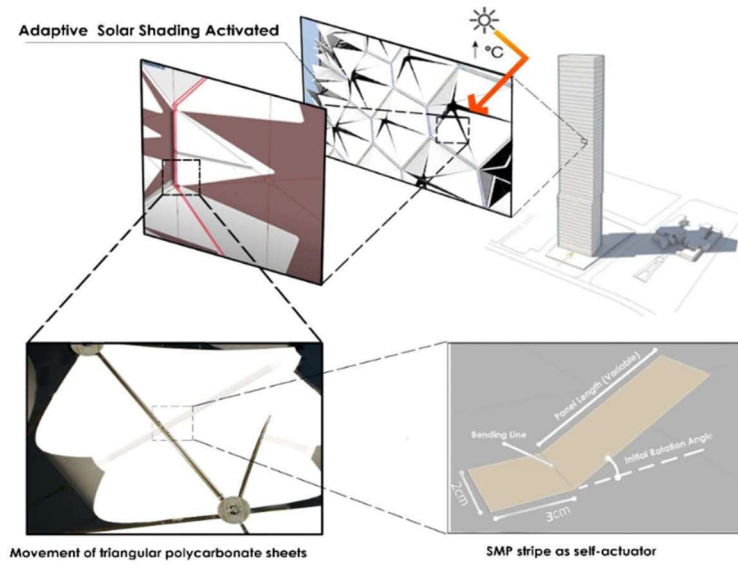


Figure 25 SMP actuator in façade shading elements. (Zameem et al., 2023)

(2) 4DP Parameters: Precise Control

Niazy et al. (2021) demonstrated that mono-material SMP elements fabricated via FDM can be programmed to achieve predictable and controllable thermally induced deformation through printing parameter design. By systematically varying infill ratios and multilayer configurations, the study showed that differential internal density distributions generate strain gradients within the material, resulting in curvature toward regions with lower infill upon thermal activation. To ensure reliable fabrication and reproducibility, the authors adopted a heuristic process-parameter optimization framework originally proposed by Bakradze et al. (2020) for material-extrusion additive manufacturing (Figure 26).

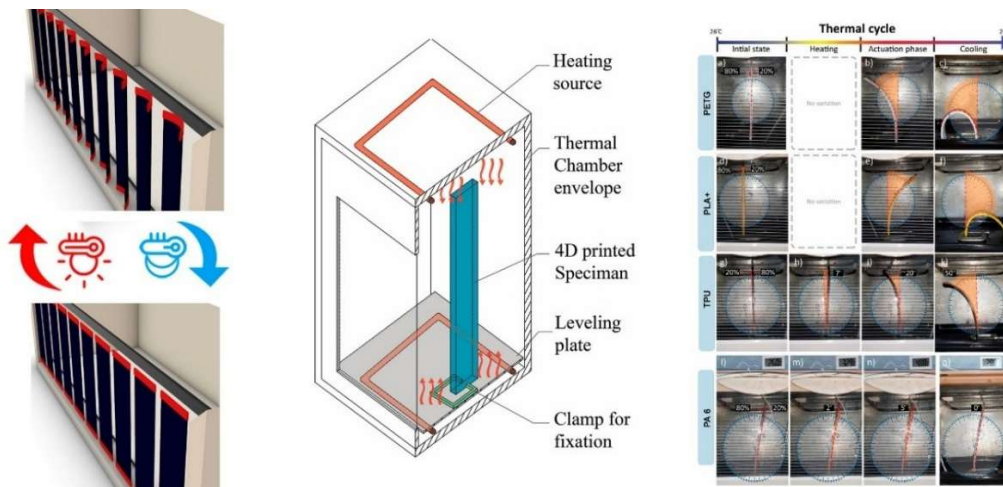


Figure 26 Illustration of shading system using SMP, testing experiment setup and results. (Niazy et al., 2021)

(3) Hybrid Materials: Two-way Actuation or Structure Reinforcement

Most SMPs naturally exhibit one-way shape memory behavior, and reversible deformation is crucial in façade diurnal cycle. This sometime limit more research into applications in façade. Fortunately, recent studies show that although reversible (two-way) actuation can be achieved through material design or laminate strategies (Lee et al., 2017). Yi (2021) and Yi & Kim (2021) pioneered a Two-way Shape Memory Composite (TWSMC) system that integrates SMA wires within a additive manufactured SMP matrix. Unlike monolithic systems, this hybrid approach utilizes an antagonistic mechanical logic (Figure 15): the SMA wires act as active actuators that contract upon heating to trigger bending, while the SMP matrix provides structural resistance and guides the return to the initial state during cooling. (Figure 27)

While the author successfully demonstrates a bidirectional 4DP facade using an SMA-SMP hybrid system, the research highlights critical macro-scale limitations, structural fatigue and interface degradation over repeated thermal cycles, significant response hysteresis due to passive heat conduction, and gravity sagging caused by the loss of material stiffness near T_g . These challenges, along with the difficulty of integrating SMA in additive manufacturing, currently hinder the transition from laboratory prototypes to durable, industrial-scale architectural applications.

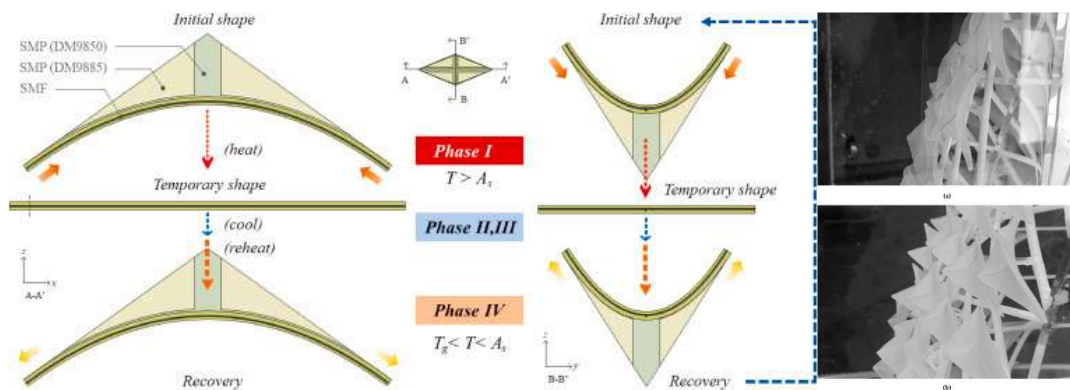


Figure 27 Diagrams and scale model of TWSMC, (a) High environmental temperature; (b) Low temperature. (Yi & Kim, 2021b)

Hassan et al. (2025) explore the development of bio-based SMP composites for sustainable architectural applications. The study focuses on combining SMP behavior with natural fiber reinforcements to produce environmentally responsible materials capable of thermally induced shape transformation. Compared with traditional petroleum-based plastics, the formulated biocomposites deliver comparable SME, alongside a substantially lower environmental burden, as confirmed by experimental characterization. The authors further discuss potential applications in self-configuring architectural components, such as shading devices and adaptive skins (Figure 28).



Figure 28 Thermo-fold self-adaptive biocomposite SMP façade. (Hassan et al., 2025)

2.4.3 Research Gaps

Despite increasing interest of SMP in PMRF and the growing body of research on 4DP, several knowledge gaps remain (Ahmed et al., 2021; Ding et al., 2025). While existing research acknowledges the low actuation force and structural softening of SMPs as primary hindrances, few studies systematically investigate how FDM process parameters, specifically the interplay between **infill patterns, thickness ratios, and thickness** can be utilized as a strategic design tool to compensate for these mechanical weaknesses. This focus is directly inspired by established 4DP frameworks (Correa et al., 2015; El-Dabaa & Salem, 2021; Correa, 2022; Mansoori et al., 2023; Cheng et al., 2024), where parameters such as density gradients and layer thicknesses have been proven essential for encoding predictable, self-shaping behavior in hygromorphic composites.

Consequently, this research shifts the focus from merely achieving movement to establishing a quantifiable mapping between digital printing inputs and physical geometric outputs. By systematically exploring how variations in infill and thickness dictate curvature, this study aims to develop a controllable geometric framework for adaptive facades. Rather than attempting to overcome the chemical limitations of the material, the objective is to leverage geometric development as a means to transform unpredictable experimental samples into predictable, self-supporting architectural prototypes that can be precisely tailored for climate-responsive applications.

3 Material Behavior and Deformation Principles

3.1 Experiment Framework

This chapter investigates how different 4DP fabrication parameters influence the deformation behavior of SMP-based elements. The findings from this parameter study is intended to establish design guidelines for applying such elements in CAF systems. As illustrated in Figure 29(a), the experimental framework is structured around the SME cycle. This chapter focuses on the transition from the as-printed state to a deformed configuration, driven by the release of internal stresses induced during fabrication. The next chapter assumes the use of an optimized two-way SMP material and focuses on connecting material behavior with façade unit design, particularly the reversible deformation between low and high temperatures.

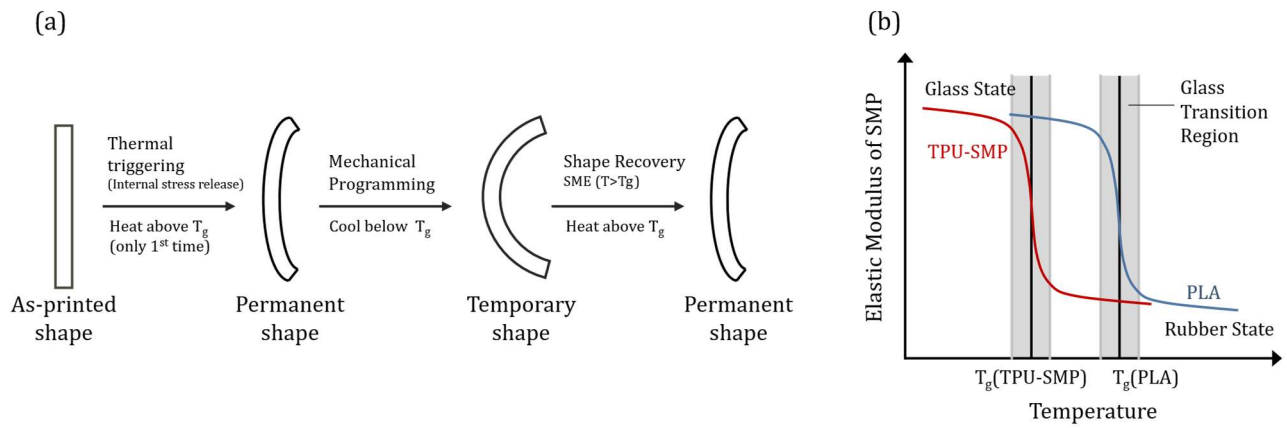


Figure 29 (a) Deformation cycle of SMP-based 4DP elements. (b) Relationship between elastic modulus and temperature for TPU-SMP and PLA. Modified from (Zhong et al., 2020; Eryildiz, 2021).

3.1.1 Materials and Fabrication

All specimens were fabricated using FDM. During FDM processing, filaments are heated, extruded, stretched, and rapidly cooled upon deposition, introducing directional internal strain within the printed structure. A Bambu Lab X1-Carbon FDM printer was used, enabling precise control of fabrication parameters and supporting the potential for multi-material printing in later design stages.

Two SMP materials were investigated: Polylactic Acid (PLA) and Thermoplastic Polyurethane-based Shape Memory Polymer (TPU-SMP). PLA is widely used in additive manufacturing, while TPU-SMP exhibits stronger shape memory performance with higher recovery forces. Both materials can be

programmed into temporary shapes and recover their original configurations upon exposure to elevated temperatures (Convena, 2025; Mehrpouya et al., 2021). The key processing parameters for both materials are summarized in Table 3. TPU-based SMP was printed with a nozzle temperature ranging from 210 to 230 °C, while PLA was printed at the standard setting of 220 °C. The bed temperature for TPU-SMP varied between 0 and 45 °C, whereas PLA used a bed temperature of 35 °C. The cooling fan speed was set between 80% and 100% for TPU-SMP and 100% for PLA. Print speed for TPU-SMP ranged from 30 to 60 mm/s, while PLA was printed at the speed of 50 mm/s. Both materials have a density of 1.24 g/cm³.

During FDM printing, anisotropic pre-strain is embedded within the printed structure by designing specific filament deposition strategies. When heated to temperatures approaching the glass transition temperature (T_g), the material transitions from a rigid glassy state to a flexible rubbery state (Figure 29b) (Behl & Lendlein, 2007; Balogun & Mo, 2014). During this transition, stored internal strain energy is released, producing thermally induced deformation. Based on preliminary experiments, activation temperatures were set at 70 °C for TPU-SMP and 85 °C for PLA (Figure 29b), exceeding the nominal T_g values of both materials (Convena, 2025; Slavković et al., 2024). These two temperatures were selected from a tested range of 55–85°C for TPU-SMP and 70–100°C for PLA because at which each material produced consistent and measurable deformation without compromising structural integrity. Temperatures below this range yielded insufficient activation, while PLA specimens tested at 100°C exhibited thermal softening and loss of rigidity.

Table 3 Fabrication parameters for TPU-SMP and PLA specimens (Convena, 2025).

Parameter	TPU-SMP	PLA
Nozzle temperature	210–230 °C	220 °C (standard)
Bed temperature	0–45 °C	35 °C (standard)
Cooling fan	80–100%	100%
Print speed	30–60 mm/s	50 mm/s (standard)
Density	1.24 g/cm ³	1.24 g/cm ³
Activation temperature	70 °C	85 °C

3.1.2 Experimental Design Overview and Workflow

To evaluate the influence of fabrication parameters on deformation behavior, we established a structured experimental workflow (Figure 30), consisting of four main stages: (1) specimen design and printing parameterization, (2) thermal activation and cooling, (3) physical measurement and documentation, and (4) geometric reconstruction and analysis.

In Phase 01, rectangular plates specimens were designed, then sliced and parameterized in Bambu Studio prior to fabrication. In Phase 02, all specimens were simultaneously immersed in hot water to ensure consistent thermal exposure and minimize environmental variation. After 180 seconds, the specimens were removed and immediately transferred to cold water to fix the deformed geometry. In Phase 03, the deformed geometry was documented through manual tracing measurements and rectified photographic images, including the outlines from four elevations and the top view. In Phase 04, the curves were rebuild in grasshopper and rhino, and the final deformed geometries were then generated through spatial alignment and surface reconstruction, enabling quantitative comparison across different parameter configurations. More technical details are described in the following sections.

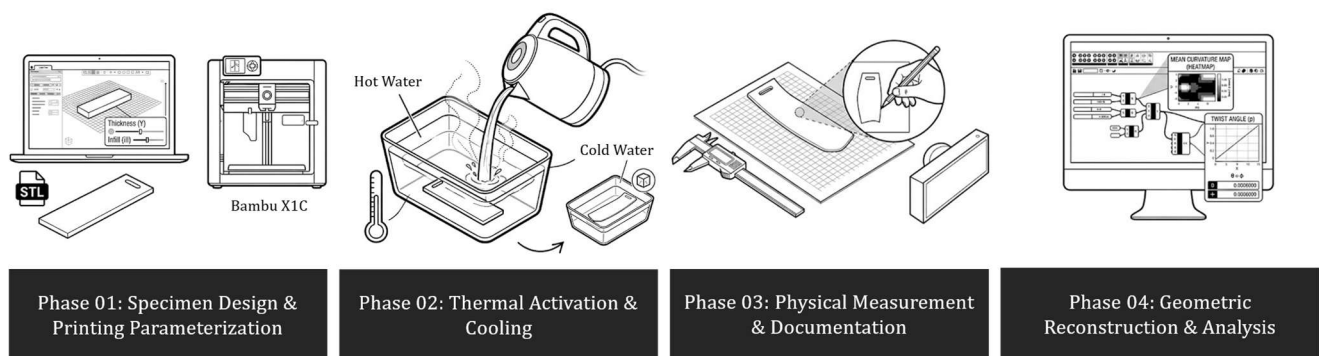


Figure 30 Experimental workflow comprising four phases.

3.1.3 Specimen Configuration

All specimens were designed as rectangular plates measuring 40 mm × 100 mm, with a baseline thickness of 1.2 mm. This geometry provides sufficient surface area for visible deformation. Baseline printing parameters included a layer height of 0.2 mm, a 45° cross-diagonal infill pattern, an infill ratio of 70%, and a wall thickness of 0.84 mm. These parameters were selected to achieve a balance between structural stiffness and internal strain storage capacity, establishing a reproducible reference condition for comparative analysis.

3.1.4 Parameter Study

To systematically evaluate the influence of fabrication parameters, three parameter groups were investigated while maintaining all other conditions at baseline values (Figure 31 a). This single-variable approach isolates the individual contribution of each parameter to the resulting deformation behavior.

- Thickness (A-series): 0.8 mm to 2.0 mm (0.2 increment). Since bending rigidity scales with the

cube of thickness ($EI \propto t^3$), this parameter is expected to have an influence on deformation magnitude. The formula follows from Euler–Bernoulli beam theory for rectangular cross-sections.

- Infill ratio (B-series): 55%, 70%, 85%. The density affects the structural stiffness and the volume of pre-strained material within the specimen.
- Infill pattern (C-series): linear orientations (0° , 45° , 90°), cross-diagonal, and grid patterns. These configurations introduce varying degrees of anisotropic stiffness and directional pre-strain, thereby influencing deformation pathways.

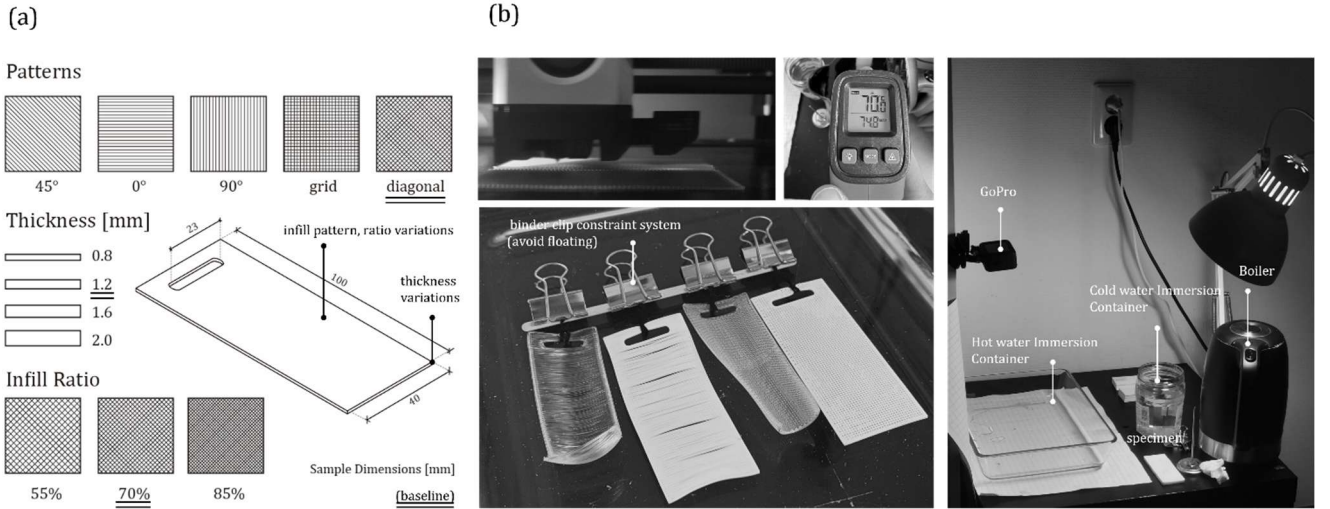


Figure 31 (a) Specimen configurations with baseline parameters indicated. (b) Experiment setup: (bottom) specimens during hot water immersion with binder clip constraint system.

3.1.5 Deformation Measurement and Analysis

Thermal activation was performed through hot water immersion to ensure uniform temperature exposure across all specimens. To prevent floating caused by internal porosity, specimens were secured with a simple clip constraint system that ensured full submersion while allowing unrestricted deformation (Figure 31b).

Following activation, deformed shapes were captured through high-resolution imaging and manually traced. The extracted curves were subsequently reconstructed, spatially aligned, and used to generate surface models for quantitative comparison. To enable systematic measurement of local deformation variation, each reconstructed surface was discretized into a 5×10 UV grid (50 cells per specimen), allowing curvature and displacement values to be sampled consistently across all configurations (Figure 32).

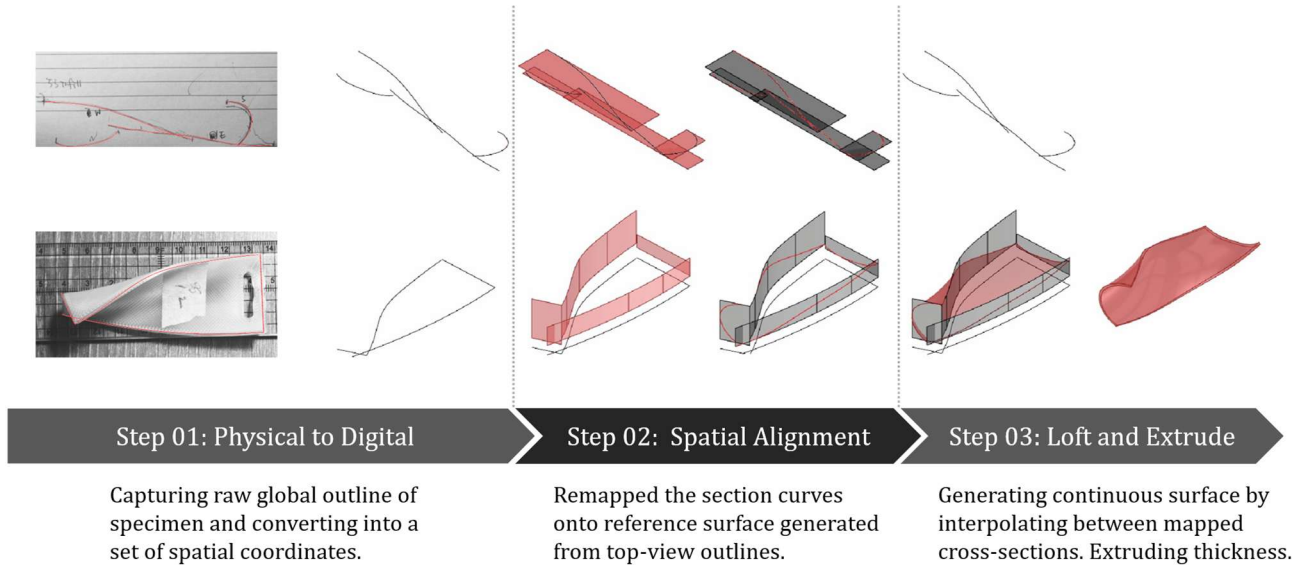


Figure 32 Digital reconstruction workflow.

The following deformation indicators were extracted from each reconstructed geometry (Table 4). Curvature values (κ) are defined as the inverse of the local radius of curvature ($\kappa = 1/r$), and principal curvatures κ_u and κ_v are computed at each UV cell from the reconstructed surface. Maximum tip deflection (δ_{max}) is defined as the greatest displacement of any point on the deformed surface relative to the original flat plane. Coverage area ratio (A_r) is computed as the ratio of the top-view projected area of the deformed specimen to that of the original flat geometry, providing a direct measure of overall shape change relevant to façade opening performance. Shrinkage area ratio (S_r) is defined as the ratio of the actual 3D surface area of the reconstructed geometry to that of the original flat plate ($A_0 = 40 \times 100 = 4000 \text{ mm}^2$), distinguishing geometric deformation from material-level thermal shrinkage.

Table 4 Deformation indicators extracted from reconstructed specimen geometries.

Indicator	Symbol	Description
Max surface curvature	κ_{max}	Maximum principal curvature across all surface cells (5×10 UV grid), identifies the most concentrated bending region.
Mean surface curvature	κ_{mean}	Area-weighted average of principal curvatures over the full surface; reflects overall deformation intensity. Computed as $\kappa_n = (\kappa_u + \kappa_v) / 2$ per cell. $\kappa_{mean} = (\kappa_0 + \kappa_1 + \dots + \kappa_n) / n$
Max tip deflection	δ_{max}	Displacement of the free end relative to the fixed base.
Coverage area ratio	A_r	Ratio of top-view projected area of deformed specimen to original flat surface area $A_r = A_{projected} / A_0$
Shrinkage area ratio	S_r	Ratio of 3D surface area of deformed geometry to original flat surface area. Values below 1 indicate material shrinkage. $S_r = A_{deformed} / A_0$

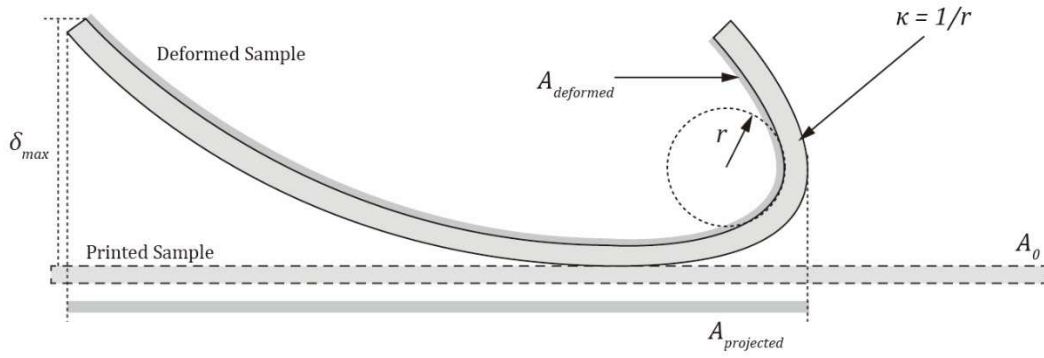


Figure 33 Deformation indicators diagram.

3.2 Material Experiment Results

Figure 34 presents the deformation outcomes of fabricated specimens after thermal activation across all tested parameter configurations. Figure 35 illustrates the manual tracing measurement procedure applied to each specimen. Reconstruction is visualized in Figure 36 and detail analyses are presented by parameter group and summarized in Table 5. It should be noted that curvature heatmaps indicate the spatial distribution of local bending intensity and do not directly represent overall deformation magnitude.

Activation Temperature Study

Prior to the main parametric study, preliminary temperature tests were conducted to identify appropriate activation ranges for each material (Figure 36a and Table 5Tp). Given that TPU-SMP has a glass transition temperature (T_g) of approximately 55°C (Convena, 2025) and PLA approximately 65°C (Slavković et al., 2024), a range of activation temperatures was evaluated: 55°C, 70°C, and 85°C for TPU-SMP, and 65°C, 80°C, and 100°C for PLA. At 55°C and 65°C respectively, TPU-SMP and PLA showed only minimal deformation, suggesting insufficient thermal activation. At 70-85°C for TPU-SMP and 80°C for PLA, specimens demonstrated clear and measurable deformation while maintaining structural integrity. At 100°C, PLA specimens underwent thermal softening rather than programmed shape recovery, resulting in loss of rigidity and non-recoverable deformation. Based on these observations, 70°C was selected as the primary activation temperature for TPU-SMP and 85°C for PLA for subsequent parametric experiments, as it produced consistent and substantial deformation in both materials without compromising specimen stability.

SMP-TPU Before

After
SMP-TPU@70 °C

PLA Before

After
PLA@85°C



Figure 34 Results photos of TPU-SMP and PLA.

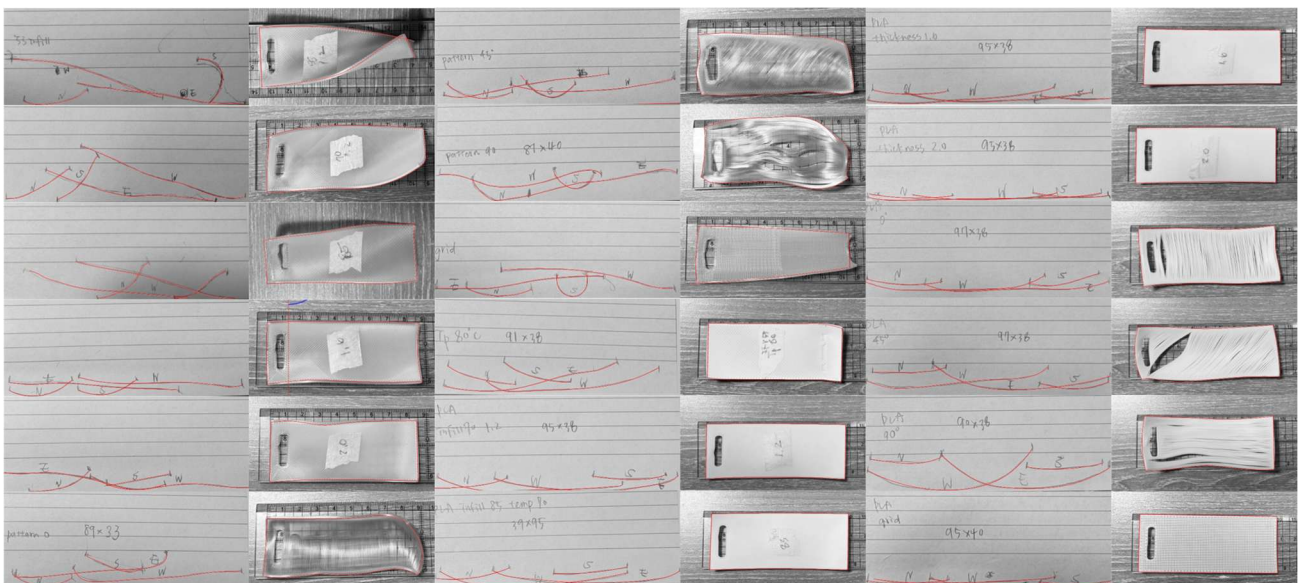


Figure 35 Physical measurement to digital curves feature extraction.



Figure 36 (a) Temperature series. (b) Infill ratio series. (c) Thickness series. (d) Infill pattern series. Top row: post-activation. Bottom rows: curvature heatmap, orthographic reconstructions (top, right, left, bottom).

Table 5 Deformation indicators for all specimens across three parameter groups.

Parameter	Specimen ID	Parameter Value	$\kappa_{\max}$ (mm ⁻¹)	κ_{mean} (mm ⁻¹)	$\delta_{\max}$ (mm)	A _r (%)	S _r (%)	Deformation trend
Temperature [°C]	Tp-TPU-1	55	0.020	0.009	8.966	87.20	11.00	Minimal
	Tp-TPU-2	70	0.041	0.014	23.894	69.93	21.41	Moderate
	Tp-TPU-3	85	0.048	0.019	21.876	32.41	54.81	High
	Tp-PLA-1	65	0.019	0.009	10.06	94.27	3.88	Minimal
	Tp-PLA-2	80	0.032	0.012	15.05	87.37	8.28	High
	Tp-PLA-3	100	0.415	0.023	8.95	83.67	15.31	loss of rigidity
Thickness [mm]	A-TPU-1	0.8	-	-	17.50	-	-	Over curl (excluded from analysis)
	A-TPU-2	1.2 (baseline)	0.041	0.014	23.89	69.93	21.40	High
	A-TPU-3	1.6	0.030	0.017	8.86	69.22	26.79	Moderate
	A-TPU-4	2.0	0.027	0.010	9.24	65.12	32.23	Less than Moderate
	A-PLA-1	0.8	0.031	0.012	17.496	79.73	15.03	Lack of stiffness
	A-PLA-2	1.2 (baseline)	0.047	0.013	10.02	87.56	9.96	Slight
	A-PLA-3	1.6	0.010	0.007	7.73	86.79	12.07	Minimal
	A-PLA-4	2.0	0.018	0.008	4.82	89.07	10.16	Near flat
Infill Ratio [%]	B-TPU-1	55	0.110	0.027	22.20	53.70	33.69	High but low coverage
	B-TPU-2	70 (baseline)	0.041	0.014	23.89	69.93	21.40	High
	B-TPU-3	85	0.048	0.012	17.93	60.71	33.65	Moderate
	B-PLA-1	55	0.032	0.012	15.05	87.37	8.28	Slight
	B-PLA-2	70 (baseline)	0.047	0.013	10.02	87.56	9.96	Slight
	B-PLA-3	85	0.020	0.010	9.37	89.64	8.19	Near flat
Pattern	C-TPU-1	0°	0.078	0.025	14.96	64.56	28.54	Moderate
	C-TPU-2	45°	0.058	0.022	13.80	68.45	22.57	Moderate
	C-TPU-3	90°	0.848	0.033	15.32	67.85	21.69	High
	C-TPU-4	Grid	0.073	0.034	13.32	56.32	30.17	Multi-axis deformation
	C-TPU-5	Cross-Diagonal (baseline)	0.041	0.014	23.89	69.93	21.40	High
	C-PLA-1	0°	0.021	0.011	8.79	88.72	8.96	Slight
	C-PLA-2	45°	0.024	0.013	13.85	85.08	11.30	Moderate
	C-PLA-3	90°	0.025	0.015	19.78	77.16	15.72	High
	C-PLA-4	Grid	0.029	0.009	5.38	92.33	6.59	Near flat
	C-PLA-5	Cross-Diagonal (baseline)	0.047	0.013	10.02	87.56	9.96	Slight

As a general trend across all parameter groups, TPU-SMP consistently exhibited substantially greater deformation than PLA, confirming TPU-SMP as the more responsive material for thermally activated façade applications. The results are documented and discussed in detail in this section, while the design principles derived from the discussion are summarized in the next section.

Effect of Thickness

Thickness exerted a strong and consistent influence on deformation magnitude across both materials. The 0.8 mm TPU-SMP specimen (A-TPU-1) exhibited uncontrolled over-curl upon thermal activation. This behavior suggests that below a critical thickness threshold, TPU-SMP loses structural stability during shape recovery, making 1.2 mm the practical minimum for controlled deformation. For the remaining TPU-SMP specimens, maximum tip deflection decreased from 23.89 mm at 1.2 mm thickness to 8.86 mm and 9.24 mm at 1.6 mm and 2.0 mm respectively, reflecting the cubic relationship between thickness and bending rigidity ($EI \propto t^3$). Maximum surface curvature similarly declined from $\kappa_{max} = 0.041 \text{ mm}^{-1}$ at 1.2 mm to 0.027 mm^{-1} at 2.0 mm, indicating a reduction in localized bending intensity with increasing thickness. Coverage area ratio (A_r) remained relatively stable across TPU-SMP thickness variants (65–70%), suggesting that the overall projected footprint of deformation is less sensitive to thickness.

In contrast, the 0.8 mm PLA specimen (A-PLA-1) remained measurable but exhibited notably different behavior from its TPU-SMP counterpart. Despite producing a tip deflection of 17.50 mm comparable to the over-curved TPU-SMP specimen, it displayed lower κ_{max} (0.031 mm^{-1}). This suggests that at 0.8 mm, PLA lacks sufficient stiffness to maintain a stable deformed geometry, resulting in irregular, poorly controlled bending rather than structural failure. For thicker PLA specimens, maximum tip deflection ranged from 10.02 mm at 1.2 mm to 4.82 mm at 2.0 mm, with κ_{max} values consistently below 0.05 mm^{-1} . PLA specimens exhibited moderate bending with limited lateral displacement, as reflected by the consistently high coverage area ratios (87–89%). S_r for PLA was also markedly lower (approximately 10%), confirming that PLA undergoes less internal strain release during thermal activation compared to TPU-SMP.

Effect of Infill Ratio

Infill ratio produced a more complex and non-linear effect on deformation behavior than thickness. For TPU-SMP, the lowest infill ratio (55%) yielded the highest κ_{max} (0.110 mm^{-1}) and the lowest A_r (53.70%), indicating concentrated local bending and significant area reduction. Despite this extreme curvature, δ_{max} at 55% infill (22.20 mm) was smaller than at 70% infill, suggesting that the specimen underwent self-folding behavior in which the deformed geometry partially twisted back toward the base

plane. At 85% infill (B-TPU-3), κ_{mean} recorded a value of 0.012 mm^{-1} , the lowest among TPU-SMP infill ratio specimens, while κ_{max} remained elevated at 0.048 mm^{-1} . This divergence between local and mean curvature suggests that deformation at higher infill densities is more spatially concentrated rather than distributed evenly across the surface.

On the other hand, PLA specimens showed a mild negative trend in deformation with increasing infill ratio, consistent with greater structural stiffness at higher densities suppressing internal strain release. All PLA infill ratio specimens maintained A_r above 87%, confirming limited deformation compared to TPU-SMP counterparts.

Effect of Infill Pattern

For infill pattern, a consistent governing principle was observed across both materials: deformation directionality is determined by filament orientation, with the bending axis perpendicular to the principal filament direction. Specimens with 0° oriented filaments bent along the short axis, while 90° oriented filaments induced bending along the long axis. Diagonal and grid patterns produced compound deformation involving both axes simultaneously.

Among TPU-SMP specimens, the 90° linear pattern (C-TPU-3) produced the highest κ_{max} of 0.848 mm^{-1} , indicating extreme localized curvature deformation with structural collapse. Because 90° filaments drive bending along the long axis, the greater span amplifies the released strain into concentrated local buckling rather than distributed bending, resulting in a localized collapse zone. This suggests that highly directional patterns oriented along the longer specimen dimension are prone to deformation instability, which could potentially be mitigated through selective local reinforcement of the wall thickness in collapse-prone regions.

The grid pattern (C-TPU-4) produced the lowest A_r among pattern variants (56.32%) alongside a notably high κ_{mean} (0.034 mm^{-1}), suggesting a more spatially distributed multi-axis deformation. This is visually corroborated by the physical specimen, which exhibits compound curvature with simultaneous bending and lateral spread. The 0° pattern (C-TPU-1) and 45° pattern (C-TPU-2) produced intermediate deformation levels with dominant lateral bending and diagonal curl respectively, reflecting how filament orientation directly controls the principal direction of pre-strain release. Of particular note, cross-diagonal specimens across both materials consistently exhibited asymmetric deformation with a preferential right-up/left-down warping orientation, despite the nominally symmetric $\pm 45^\circ$ filament arrangement. The underlying mechanism of this process-induced asymmetry has not been conclusively determined and is identified as a subject for further experimental investigation, potentially involving

controlled variation of printing path sequencing.

For PLA, infill pattern variation produced a consistent but comparatively mild range of responses. Notably, the 90° pattern (C-PLA-3) generated the highest deflection among all PLA specimens ($\delta_{max} = 19.78$ mm, $A_r = 77.16\%$). This is directly attributable to the bending axis effect: 90° filaments induce bending along the long axis, and the greater span of the long axis translates the released pre-strain into a larger absolute deflection. This confirms that the choice of bending axis, is a more influential determinant of deflection magnitude than material stiffness alone, at least within the PLA parameter space. The grid pattern (C-PLA-4) remained near-flat ($\delta_{max} = 5.38$ mm, $A_r = 92.33\%$), producing the most pronounced material contrast with its TPU-SMP counterpart ($A_r = 56.32\%$), demonstrating that grid topology amplifies the performance gap between materials and is therefore a sensitive configuration for comparative assessment.

3.3 Design Principles

The experimental results collectively demonstrate that fabrication parameters: thickness, infill ratio, and infill pattern, provide a viable and controllable means of programming deformation behavior in SMP-based 4DP elements without altering material composition. Each parameter operates through a distinct mechanical mechanism: thickness modulates global bending rigidity, infill ratio governs internal strain density, and infill pattern controls the directionality and concentration of pre-strain release. The main design principles are concluded:

- (1) *Thickness*: 1.2 mm is the practical minimum. The thicker the specimen, the higher the stiffness, leading to less bending deflection.
- (2) *Infill Ratio*: Higher infill increases stiffness, less shrinkage suppressing strain release and minimizing deformation.
- (3) *Infill Pattern*: Bending axis is always perpendicular to filament orientation. Two-direction perpendicular infill (e.g., grid) increases structural stability,

Across both materials, infill pattern emerged as the most influential parameter in terms of deformation diversity, producing distinct deformation modes (e.g. lateral bending, diagonal curl, sharp local curvature, and compound multi-axis deformation, etc.) within a single material system. A practical parameter selection principal logic can be proposed for façade design applications. **Infill pattern should be treated as the primary design variable for directional control, while thickness and infill ratio serve as secondary tuning parameters for magnitude.**

3.4 Discussion: CAF Integration

Material Selection

The contrast between TPU-SMP and PLA underscores the importance of material selection at the system level. TPU-SMP consistently produced larger deformations, lower coverage area ratios, and higher shrinkage area ratios, confirming its suitability as the active material for CAF applications. PLA, while capable of programmed deformation, exhibited deformation levels that may be insufficient for meaningful modulation at architectural scales without further optimization.

Coverage Area Ratio and Openness

The coverage area ratio (A_r) established in this study provides a direct quantitative link between specimen-level deformation and façade-level shading performance. Across TPU-SMP specimens, A_r ranged from 53.70% to 69.93%, corresponding to an intrinsic opening ratio range of 31% to 46% achievable through parameter selection alone.

Temperature Compatibility

As discussed in the literature review (Section 2.4.2), a critical design parameter for façade deployment is the activation temperature threshold, which must align with the thermal microclimate of the building envelope. Façade surface temperatures under direct solar radiation frequently exceed ambient air temperature by 20–40°C: dark-colored metal or polymer surfaces in temperate climates can reach 50–70°C even when ambient temperatures are 25–30°C (Hens, 2017; Yi & Kim, 2021a). This thermal gradient is sufficient to trigger the SME in materials with a glass transition temperature (T_g) between 45°C and 65°C without auxiliary heating.

The TPU-SMP used in this study ($T_g \approx 55^\circ\text{C}$) falls within this operational window. Compatibility can be further extended through deliberate surface treatment: applying a dark-colored coating to the panel surface increases solar absorptivity, elevating surface temperature above ambient by a greater margin and providing a reliable thermal trigger even in climates where peak surface temperatures would otherwise fall short of the activation threshold.

For broader climatic applicability, particularly in moderate or maritime climates where peak surface temperatures are lower, materials with T_g in the range of 35–45°C would be preferable. Such materials are achievable through adjustment of the polymer synthesis process, with printing parameters adjusted accordingly, and represent a natural next step in material selection for architectural deployment.

Adaptive Diurnal Cycle and Shape Memory Effect Mechanism

A practical constraint in deploying FDM-printed SMPs in façade applications is their inherently one-way actuation behavior, as discussed in Section 2.4.2. Thermal activation drives deformation from the as-printed flat state to a programmed curved configuration, but autonomous recovery requires either two-way SMP formulations, antagonistic material pairings, or supplementary mechanical actuation. Resolving this limitation falls outside the scope of the current study; the parameter-to-deformation relationships established here constitute the necessary foundational layer for either approach.

Potential of Bilayer Design

The differential T_g values of TPU-SMP ($\approx 55^\circ\text{C}$) and PLA ($\approx 65^\circ\text{C}$) also suggest a further design opportunity: bilayer configurations in which both materials are co-printed within a single element. At temperatures between the two T_g values, only the TPU-SMP layer would undergo the glass transition and release internal strain, while the PLA layer remains rigid and acts as a structural constraint, inducing curvature through differential stiffness, analogous to a bimetallic strip. Preliminary multi-material printing was conducted using the Bambu Lab X1-Carbon with AMS, confirming that co-extrusion of TPU-SMP and PLA is technically feasible within a single print (Figure 37). However, reliable interlayer bonding requires an interlocking interface geometry to prevent delamination under repeated thermal cycling; without such a mechanism, layer separation was observed intermittently. This approach remains promising but requires further systematic validation before it can be considered a reliable fabrication strategy.

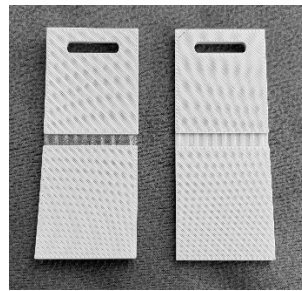


Figure 37 Preliminary multi-material printing sandwich hinge structure: (left) PETG:TPU-SMP:PETG=1:1:1 with gap 6mm ; (right) PETG:PLA:PETG = 1:1:1 with gap 6mm. Total thickness of 1.8 mm

4 Façade Implementation and CAD Tool

This chapter focuses on the connection of material behavior with façade design application, addressing the second research sub-question: how these programmed deformations be translated into effective CAF. Drawing inspiration from the movement typologies identified by (Tabadkani et al., 2021), basic movement, folding structures, and biomimetic skins, three implementation concepts are explored how the deformation behavior can be translated into functional façade applications. The chapter then introduces a developed Computer-Aided Design (CAD) tool that enables façade designers to interactively explore the target geometry, visualize both the rest and deformed states, evaluate the climate performance of the integrated façade system, and automatically generate fabrication files for printing.

Based on the previous chapter, TPU-SMP is selected as the primary material for façade implementation due to its greater deformation relative to PLA across all tested parameter configurations. For the design implementation and the developed tool, an ideal two-way SMP and SME are assumed. Due to commercial availability constraints, the laboratory experiments were conducted using a one-way SMP, while the performance model operates under the idealized assumption of a fully autonomous and reversible two-way SMP.

4.1 Design Exploration

The first and second concepts operate through intrinsic material bending, in which thermally activated deformation directly controls aperture openness or blade shading angles. The third concept integrates SMP actuation with an origami-based compression mechanism, engaging both folding structure logic and basic rotational movement to produce a reversible façade system.

4.1.1 SMP Panel Module

Drawing on the relationships between parameter and deformation established in the pervious chapter, a façade panel system is proposed in which thermally activated deformation directly controls aperture size. Each panel consists of two fabrication zones: a rigid perimeter frame (e.g., 2.0 mm thickness, 85% infill, cross-diagonal pattern) acting like a fixed end that remains stable upon thermal activation, and a central active zone (e.g., 1.2 mm thickness, 70% infill) serving as a free end. The active zone is divided by a central cut and printed with symmetric infill along the y-axis. Upon thermal activation, the two halves of the active zone deform outward symmetrically, expanding the central aperture from a closed slit to an open configuration (Figure 38a).

The aperture geometry is directly governed by fabrication parameters. By varying infill pattern, thickness, and infill ratio across the active zone, designer controls the degree, direction, and curvature of opening. Further variations in gap orientation (vertical, diagonal) and active zone geometry could expand the design space, producing distinct opening characters across the façade surface (Figure 38b).

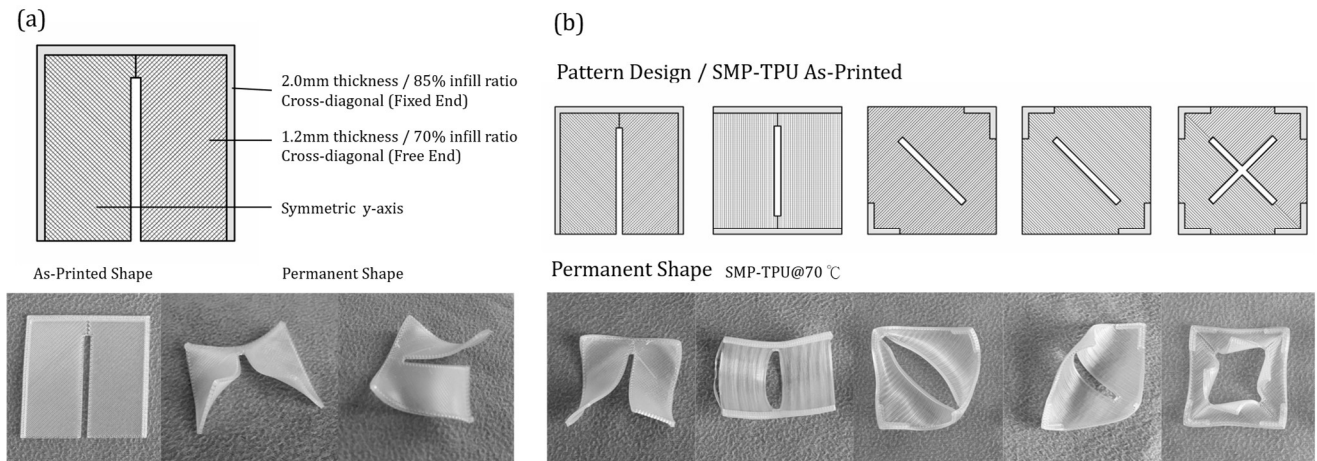


Figure 38 SMP Panel: (a) parameter configuration diagram and as-printed flat state and thermally activated permanent shapes; (b) pattern, gap orientation (vertical, centered, diagonal) and infill direction design variations

4.1.2 SMP Louver

Based on previously established parameter and deformation relationships, the SMP passive louver utilizes thermally induced curvature combined with strategic anchor positioning to achieve self-changing orientation angles (θ or $-\theta$). Instead of relying on conventional motorized rotation, rising ambient temperatures trigger intrinsic curving deformation in the blade segments., allowing shifts between the shading state (e.g., from 0° to 30°) passively. This system effectively blocking direct daylight and managing solar heat gain without external energy consumption.

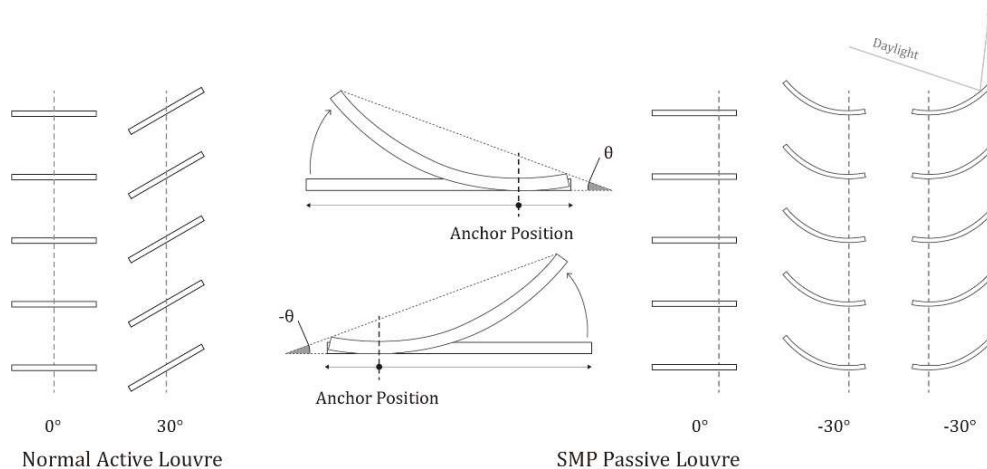


Figure 39 SMP Louver: mechanism and comparison between active and passive louvers.

4.1.3 SMP Hinge

The third design extends the parameter and deformation logic into a 3D structural system by integrating SMP-based actuation with a compressive origami mechanism. The unit consists of a polygonal SMP hinge structure combined with planar rigid face panels mounted to a façade substrate. The geometry of the hinge, including the number of sides, height, and pre-encoded rotation angle, directly governs its torsional behavior and the range of panel rotation achievable under loading (Figure 40).

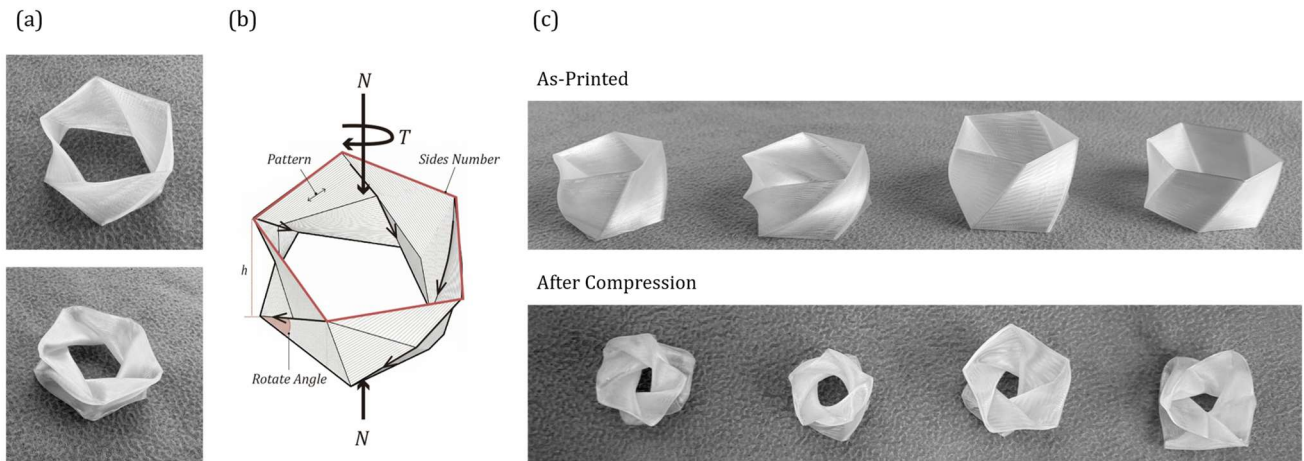


Figure 40 SMP Hinge: (a) as-printed geometry; (b) mechanical force and geometric design parameters; (c) as-printed variants with different polygon configurations and corresponding compressed states.

As noted in the discussion, the SMP used in the experiment exhibit inherently one-way actuation. In this design, a further reversible panel system of SMP hinge acting as a façade composition controller was developed. A cable threaded through the panel system provides the compression force from the rear of the façade. During cooler periods, tension is applied to the cable, compressing the SMP hinge vertically and driving rotational displacement of the face panels, opening the aperture, increasing ventilation, and expanding outward views. The degree of rotation, and therefore the size of the opening, is directly controlled by the magnitude of applied tension. Once cooled below T_g , the TPU-SMP hardens and locks the rotated geometry in place, eliminating the need for continuous force application. This means a single tensioning event is sufficient to set the panel position for the duration of the cool period. The degree of openness could also be adjust according to the force applied, larger force creates larger rotation angle. As temperatures rise, the SMP hinge softens above T_g and thermally expands back toward its as-printed geometry, rotating the face panels back to their closed, overlapping configuration and restoring shading to the façade surface. In this way, the SMP hinge functions as a thermally controlled rotational latch: the cable provides the mechanical drive for opening, while thermal activation governs closing (Figure 41).

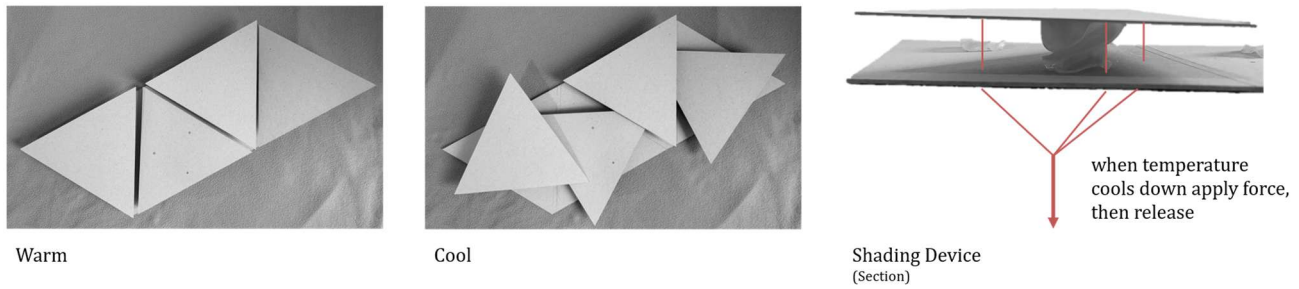


Figure 41 SMP Hinge: warm state - SMP hinge in as-printed open geometry, face panels separated; cool state - face panels overlapping after compression and thermal locking; cable-driven compression mechanism.

4.1.4 Concept Selection: SMP Panel & SMP Louver

“SMP Panel” and “SMP Louver” are selected as further implementation concepts because both clearly demonstrate how 4DP can encode spatially differentiated behavior through fabrication parameters within a single printed element. In the SMP Panel, different regions of each panel are assigned varying infill patterns, thicknesses, and infill ratios, resulting in deformation that changes across the surface. In the SMP Louver, spatially defined anchor positions translate a uniform printed curvature into controlled shading angles. In both systems, each panel or blade in the façade array can be individually programmed, with parameters such as pattern, gap orientation, anchor position, and zone geometry directly defined as design inputs.

In contrast, the SMP Hinge is mainly governed by the automatically generated slicing printing path of a hinge structure, where the overall geometry defines folding direction and torsional behavior, but local deformation cannot be independently programmed within a single unit. Its customization is therefore limited to geometric selection rather than spatial parameter distribution. While the SMP Hinge remains a valid reversible shading strategy, it is less suitable for demonstrating the spatial programmability central to this research and is retained only as a secondary reference in the design exploration.

4.2 How a Façade Designer design with SMP materials?

The research on 4DP SMP in architectural applications has mainly followed a linear workflow (Yoon, 2019; Niazy et al., 2021). As identified in the previous literature review (Section 2.4.2), most studies define several sets of printing parameters, fabricate components, test the best-performing parameters under thermal activation in laboratory conditions, and conclude with a single specialized prototype derived from the specimen. While this approach is important for understanding fundamental material behavior, it offers limited scalability for architectural design. It is still difficult for designers to connect material behavior with different geometric typologies or evaluate responsive systems under different climatic conditions.

For façade designers, a single prototype tested in a controlled environment provides limited design flexibility. Buildings must respond to changing environmental conditions, solar orientations, spatial programs, and aesthetic requirements. Therefore, designers need more than an optimized component; they require **an interactive design framework** that links printing parameters, material deformation, geometry generation, and environmental performance within the same workflow. However, the relationship between printing parameters and final deformation behavior is often highly non-linear and difficult to predict. Small changes in toolpath orientation, infill density, or layer thickness can significantly alter the deformation mode and façade performance. Without an integrated computational workflow, designers cannot efficiently understand these behaviors or evaluate their impact on indoor environmental quality (IEQ), such as daylight, glare, and ventilation performance. As a result, design iteration still relies heavily on slow and repetitive physical prototyping.

To address this gap, this research proposes a computational workflow tool that links experimentally derived material behavior with parametric geometry generation and façade design. The tool builds a mapping between printing parameters (infill ratio, infill thickness, infill pattern) and resulting deformation (e.g., curvature), enabling a support for design based on experimental data. In this way, the workflow allows designers to define a desired target deformed form and automatically generate corresponding fabrication parameters, supporting the exploration of adaptive SMP façade systems across different geometric configurations. The workflow also integrates basic climate performance evaluation to enable iterative feedback, allowing users to refine the design based on simulation results.

4.3 Computer-Aided Design (CAD) Tool

4.3.1 Overview Framework

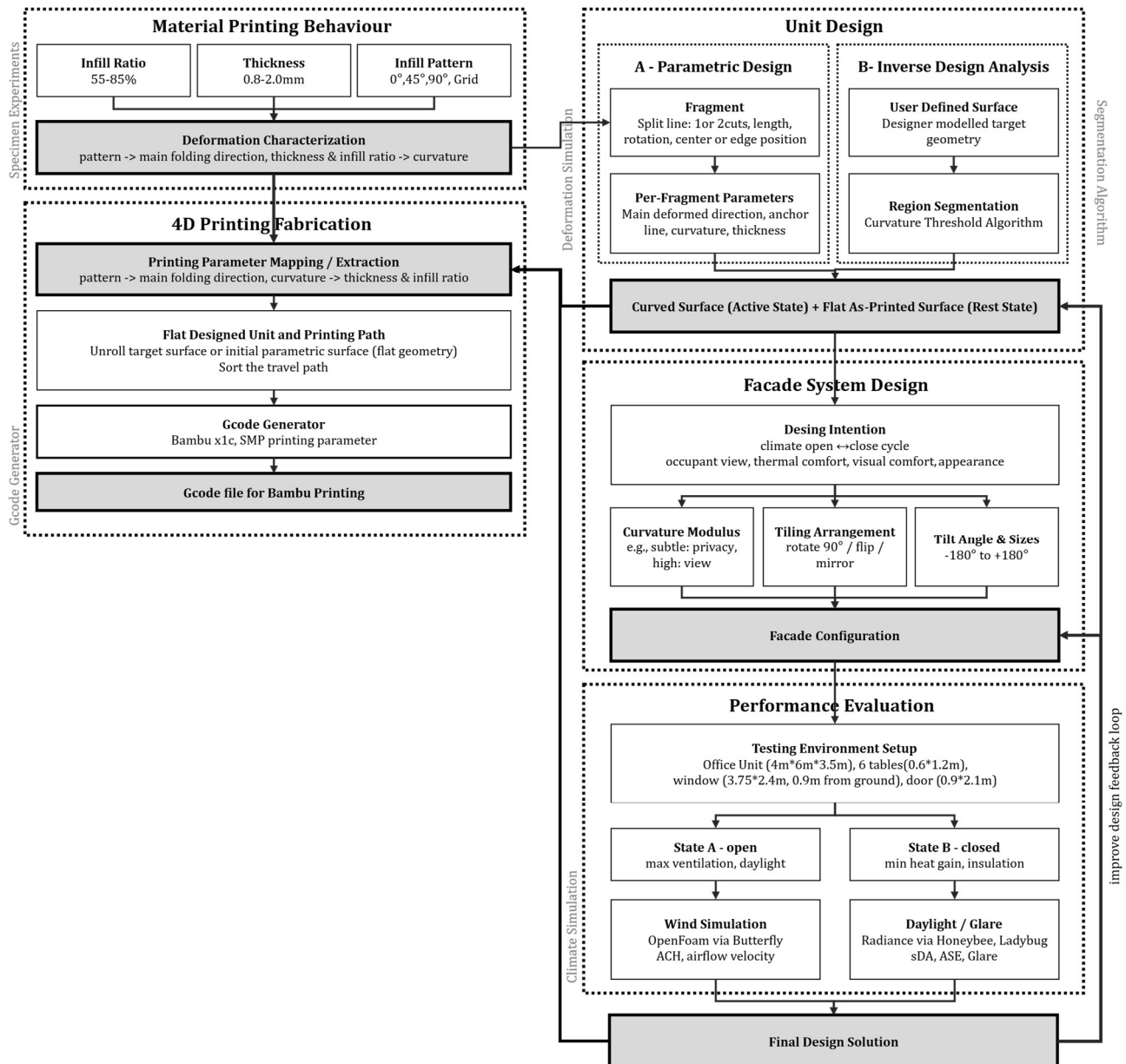


Figure 42 Framework of CAD tool.

To acquire immediate consequence feedback, an interactive computational design tool was developed in the Rhinoceros and Grasshopper environment. Rather than treating material behavior, geometry generation, and performance evaluation as separate stages, the tool integrates them into a closed-loop workflow (Figure 42). The workflow is structured into five interconnected modules, forming a continuous process from empirical material data to façade design and fabrication.

Module 01: Material Printing Behavior

This module functions as a material knowledge base derived from experimental results in Chapter 3. It defines the relationship between key printing parameters and resulting deformation behavior, enabling rapid estimation of infill thickness, infill ratio and infill pattern.

Module 02: Unit Design

This module translates material behavior into façade unit design. Designers can either define a parametric component or start from a desired deformed geometry. The system then links geometry and material response through the established material mapping.

Module 03: Façade System Design

At the system scale, individual units are aggregated into a façade configuration. Designers can control spatial distribution and orientation to adapt the façade to different architectural and environmental requirements.

Module 04: Performance Evaluation

The generated façade system is evaluated under simplified environmental conditions to provide feedback on daylight, glare, and ventilation performance. Designer can iterate the design components on Module 02 and Module 03 to improve the evaluation result.

Module 05: Fabrication

The final module translates the validated design into data ready for fabrication, linking geometric output with corresponding printing parameters for 4DP production.

4.3.2 Material Behavior Module

Material Behavior Module implements an inverse lookup function that translates target deformation behavior into corresponding fabrication parameters. Instead of assigning printing parameters and observing outcomes, the system allows designers to define a target curvature value, which is then mapped back to feasible material configurations based on experimental data as established in Table 5, Chapter 3. According to the experiment results concluded in Chapter 3, infill pattern direction controls the principal orientation of deformation and is aligned with the intended bending direction defined at the design stage. Thickness regulates structural stiffness and bending resistance, while infill ratio determines the magnitude of deformation response. The inverse computation is executed through a deterministic lookup and interpolation process:

ALGORITHM: Inverse Lookup Function

```
INPUT:
    target_curvature  $\kappa^*$ 
    deformation_axis_vector V_axis

DATABASE:
    empirical_samples = { $\kappa$ , pattern_direction, thickness, infill_ratio}

STEP 1 – Geometric Axis Alignment
    extract V_axis orientation from geometry
    pattern_direction* = V_axis + 90°

STEP 2 – Find nearest data bounds
    ( $\kappa_{low}$ ,  $\kappa_{high}$ ) = findBoundingSamples( $\kappa^*$ , database)

STEP 3 – Interpolate fabrication parameters
    thickness* = LERP( $\kappa^*$ ,  $\kappa_{low}$ ,  $\kappa_{high}$  → thickness)
    infill*     = LERP( $\kappa^*$ ,  $\kappa_{low}$ ,  $\kappa_{high}$  → infill_ratio)

STEP 4 – Apply fabrication constraints
    thickness* = clamp(thickness*, 1.0, max_limit) [FDM lower limit for structural
                                                    stability]
    thickness* = round_to_step(thickness*, 0.2) [Discrete layer height normalization]

STEP 5 – Check extreme deformation zone
    if infill* < 0.55:
        flag = "EXTREME ZONE"
        activate structural warning

OUTPUT:
    fabrication_parameters (thickness*, infill*, pattern_direction*)
    curvature_prediction  $\kappa^*$ 
    design_flag (safe / warning / extreme)
```

4.3.3 Unit Design Module

Following the establishment of the material behavior lookup matrix, the Unit Design Module translates deformation logic into architectural geometry. The module operates through two pathways. Pathway A supports parametric generation for façade component exploration, while Pathway B performs inverse geometric analysis to reconstruct geometry for fabrication from user-defined freeform surfaces.

Pathway A — Forward Parametric Generation

In Pathway A, the designer generates a target curved surface directly from a standard polygon. The workflow previews how the initially flat SMP panel deforms after thermal activation while automatically extracting surface properties required for printing parameter generation and G-code production. By implementing the core design logic of the SMP Panel (Section 4.1.1), the workflow enables the generation of diverse responsive geometries through parameter control (Table 6).

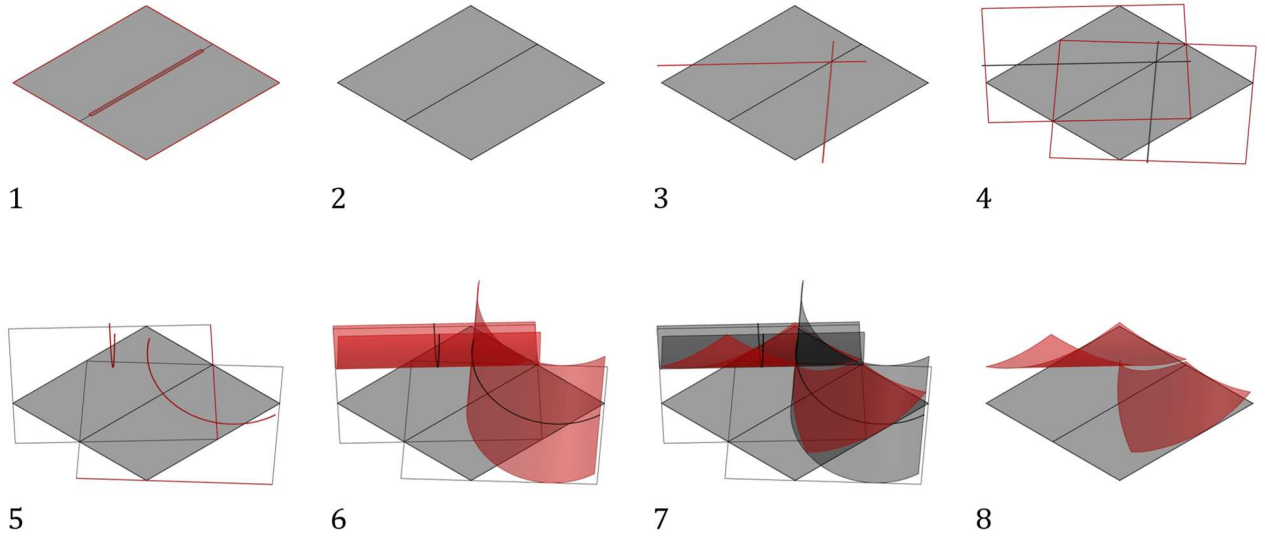


Figure 43 Pipeline of Pathway A: Parametric generation and forward geometric construction

The forward parametric workflow consists of eight steps (Figure 43):

- (1) **Base Shape Initialization:** The algorithm first defines the outer polygon boundary and split lines, supporting parameters such as single or dual, center or edge, length, position and rotation angle.
- (2) **Fragment Segmentation:** The panel is divided into fragments through split lines.
- (3) **Folding Axis Setting:** User set the main guiding fold axis of each segment, controlling directional deformation behavior.
- (4) **Reference Bounding Box and Frame Extraction:** Local orientation frames according to folding axis are extracted and bounding box of each segment along the local frames are generated.
- (5) **Target Arc Profile:** To preserve material length and avoid stretching, the arc length S must match the length of each flat segment's bounding box L . Given a user-defined target curvature κ , the geometry of the deformed arc can be defined by its radius R and angle θ as follows:

$$R = \frac{1}{\kappa}, \quad \theta = \frac{S}{R} = L\kappa$$

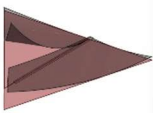
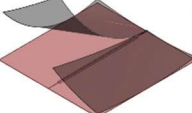
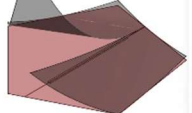
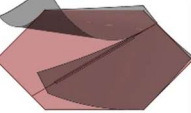
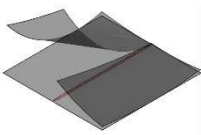
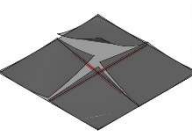
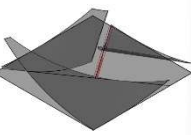
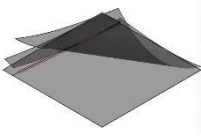
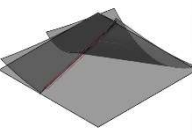
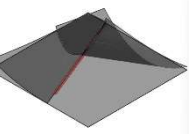
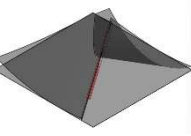
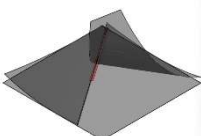
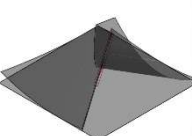
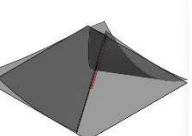
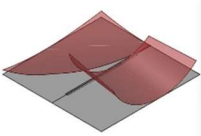
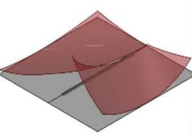
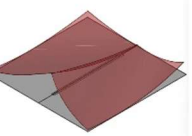
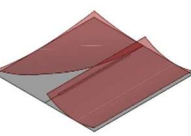
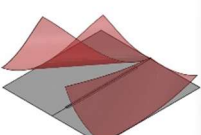
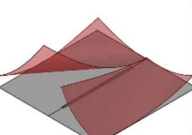
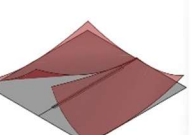
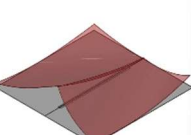
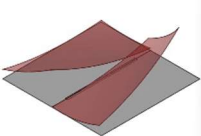
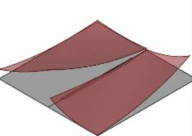
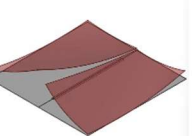
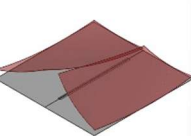
User-defined anchor position defines the intersection point where the arc meets the World XY plane.

- (6) **Target Surface Extrusion:** A localized cylindrical surface is then generated, with its extrusion length equivalent to the width of each flat segment's bounding box.

(7) Cylindrical Surface Morphing (Sporph): A Sporph function maps the flat geometry onto the curved target surface with the reference bounding box.

(8) Final Deformed Shape.

Table 6 Unit Parametric Design Morphological Chart

shape				
cut pattern				
	single center cut	two cuts	edge cut	edge 90° cut
cut rotation (per cut)				
edge cut position (per cut)				
rolling direction (per segment)				
curvature (per segment)				
anchor position (per segment)				

Pathway B: Freeform Surface Inverse Analysis and Geometric Deconstruction

Pathway B addresses reverse design workflow. When a designer inputs an arbitrary developable freeform curved surface representing the desired morphed façade state, the system analyzes the geometry to reconstruct the corresponding flat 2D fabrication state.

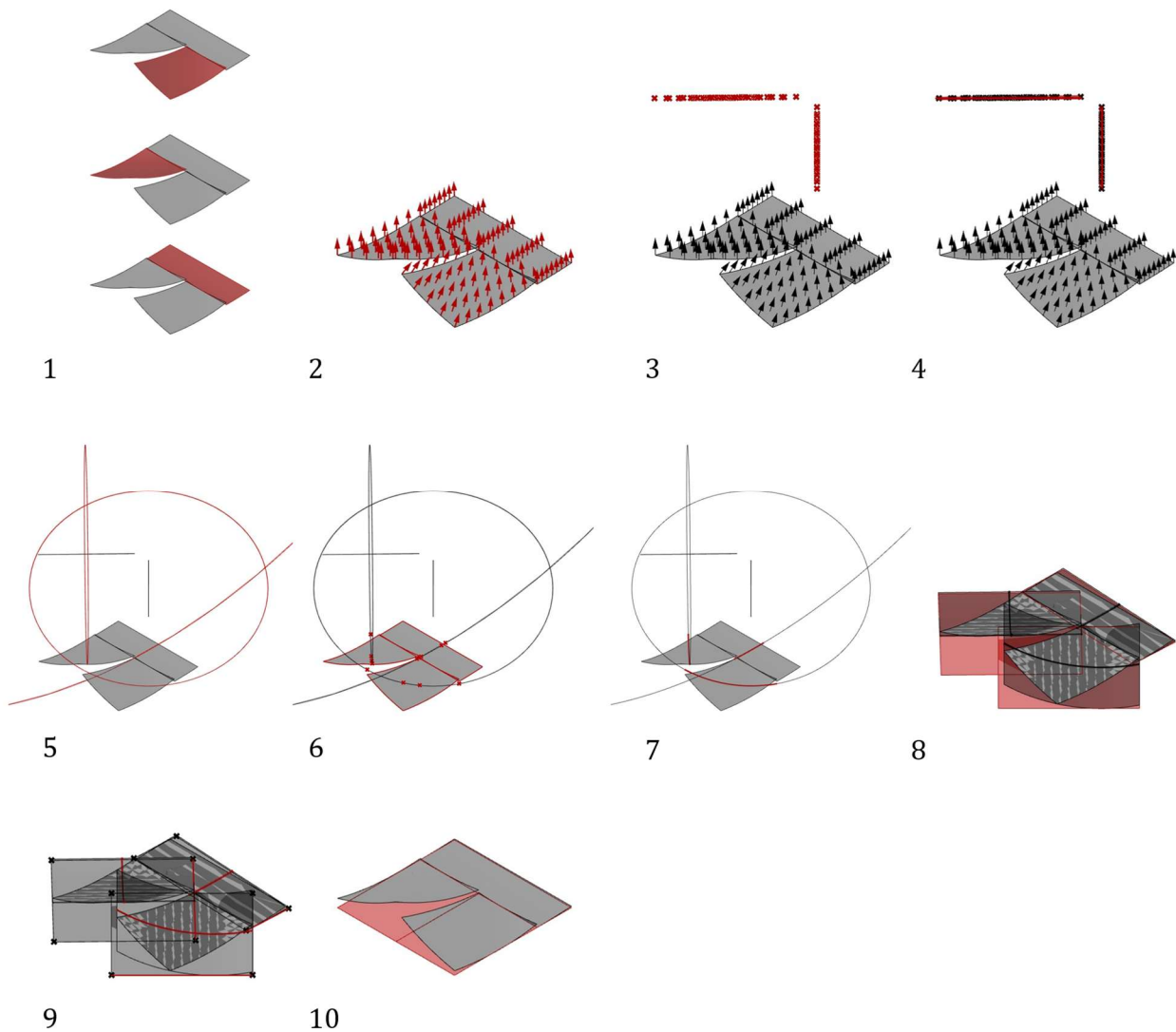


Figure 44 Pathway B Pipeline: Inverse analysis and geometric deconstruction of freeform surfaces.

The inverse geometric deconstruction workflow consists of ten steps (Figure 44):

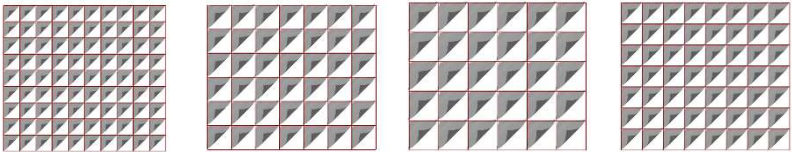
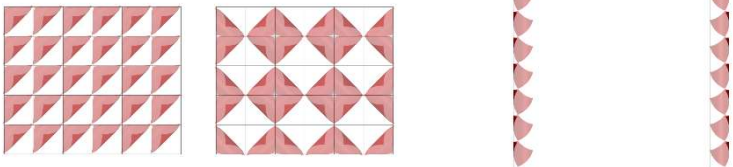
- (1) Surface Segmentation: The target mesh is segmented into regions based on curvature continuity.
- (2) Surface Point and Normal Extraction: For each curved fragment, the algorithm extracts sampled surface points (e.g., $u:v = 5:8$) and corresponding normal vectors.

- (3) Core Projection Analysis: Based on the evaluated average surface curvature κ , the corresponding transformation radius is $R = \frac{1}{\kappa}$. Surface points are then projected along their normal vectors by distance R to estimate the rotational center associated with cylindrical bending behavior.
- (4) Rolling Axis Reconstruction: A linear regression fitting process reconstructs the principal rolling axis from the projected vector intersections.
- (5) Radius and Curvature Profiling: The perpendicular distance between the reconstructed rolling axis and surface points defines the localized transformation radius distribution across the surface.
- (6) Boundary Extremum Extraction: By finding the closest point of each vertices of the fragment, extreme min, max value identifies the start and end boundary points of the curved shell segment.
- (7) Reference Arc: A transformation arc is constructed between the boundary extrema.
- (8) Reference Surface: The reference arc is extruded along a length equivalent to the width of the bounding box, creating the reference surface for the geometric transformation.
- (9) Target Rectangle: A target flat rectangle is constructed along the rolling axis, with its length equal to the reference arc length and its width equivalent to the bounding box width.
- (10) Inverse Cylindrical Surface Morphing (Sporph): Through mapping from the curved reference surface, the deformed geometry is flattened into an undistorted 2D fabrication target rectangle on the World XY plane.

4.3.4 Façade System and Climate Performance Module

The Façade System and Performance Evaluation Module links single-panel behavior to building-scale envelope performance. Due to the customizability of 4DP, the façade system could be designed as a heterogeneous, responsive skin in which geometric variation directly corresponds to architectural intentions and environmental performance. The module enables designer control over façade assembly, including panel size, tiling strategy, and tilting angle, allowing configuration to be tuned according to spatial requirements such as visual permeability, daylight access, or shading control. (Table 7)

Table 7 Façade system variations.

size	
louver tilt angle	
tiling arrangement	

The generated façade configuration is then evaluated within a simplified environmental context, assessing both airflow and daylighting performance.

- (1) Computational Fluid Dynamic (CFD): The workflow parameterizes the facade geometries as aerodynamic boundaries and interfaces them with OpenFOAM via the Butterfly plugin. The simulation pipeline executes sequentially through computational domain generation (*blockMesh*), boundary-fitted meshing (*snappyHexMesh*), and solution initialization. The solver tracks internal velocity vectors to calculate localized airflow velocity and Air Change Rates per Hour (ACH). Finally, simulation results are post-processed and visualized through *load probe value* at designated target points.
- (2) Daylighting and Luminance: The facade geometries are converted into Honeybee optical objects with specific material reflectance properties and exported directly into Radiance via the Honeybee and Ladybug plugins. Depending on the evaluation criteria, the workflow initializes either point-in-time or annual daylight analysis recipes. The Radiance ray-tracing engine then executes spatial calculations to evaluate daylight availability and visual comfort, computing metrics such as Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Daylight Glare Probability (DGP)

Simulation outputs are directly visualized within the design environment as spatial performance maps. This allows immediate adjustment of key parametric variables such as infill orientation, curvature intensity, or panel density. As a result, the workflow establishes a feedback system in which geometric configuration and environmental performance are iteratively optimized prior to fabrication.

4.3.5 Fabrication Module

Before parametric geometries can be translated into machine-readable motion instructions, the continuous surface representations must undergo a structured toolpath decomposition process. Conventional slicing software generates uniform horizontal layers from solid meshes, which removes localized printing variations such as infill ration and infill pattern. Therefore, a custom toolpath generation function is implemented directly within the CAD environment. This function restructures geometric curves into a multi-zone, layered data hierarchy prior to machine-level translation.

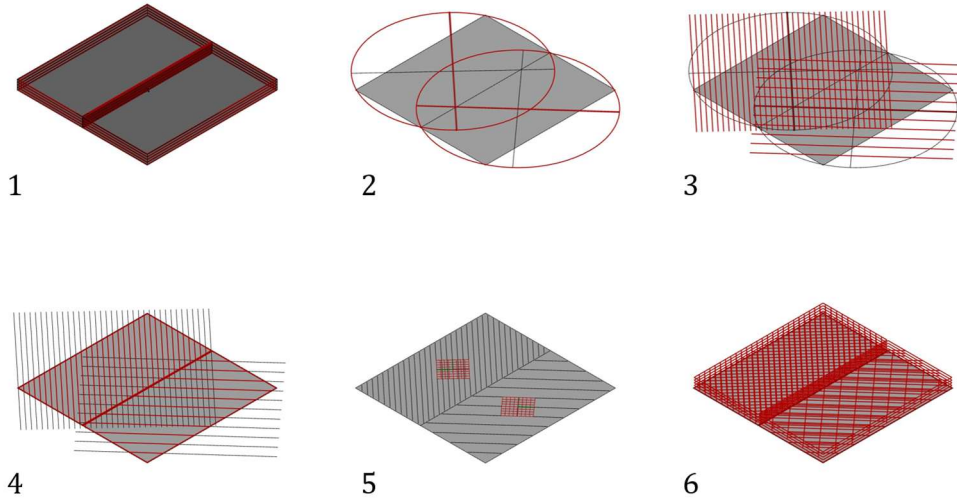


Figure 45 Fabrication pipeline: Toolpath planning.

The workflow of toolpath planning is divided into six sequential steps (Figure 45):

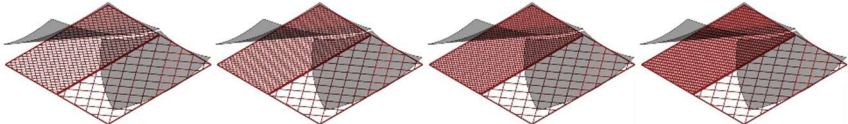
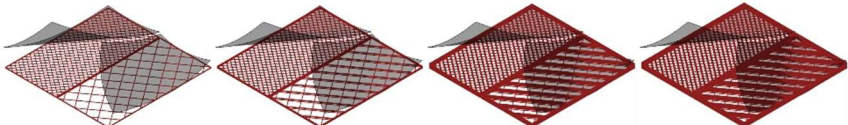
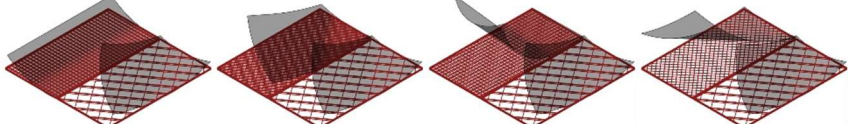
- (1) Slicing: Each zone is discretized into horizontal layers using a fixed layer height ($\Delta z = 0.2 \text{ mm}$), forming the base stacking structure for additive fabrication.
- (2) Zone-based Orientation Assignment: Each zone is assigned a directional orientation derived from the parametric design stage.
- (3) Infill Path Generation and Mapping: Infill paths are generated as offset trajectories aligned with the primary directional axis. Infill ratio are assigned according to localized structural requirements and the experimentally validated Material Behavior Module. The offset distance d is determined by the infill ratio and the nozzle width ($w = 0.4 \text{ mm}$), calculated as:

$$d = \frac{w}{\text{infill_ratio}}$$

- (4) Boundary Trimming: All infill paths are clipped and constrained by the contour of each zone.
- (5) Directional Infill Sorting: Within each rolling direction plane, infill paths are sorted based on their spatial x -coordinate. A zig-zag flipping strategy is applied every two consecutive lines to minimize non-printing travel distance.
- (6) Hierarchical Toolpath Structuring: All curves are compiled into a Grasshopper DataTree structured as {Layer_Index ; Zone_Index}, ensuring hierarchical execution from lower layer to higher layer.

The corresponding printing parameter space, including infill ratio and directional patterns, is summarized in Table 8.

Table 8 Printing parameters variations.

infill ratio (per segment)	
thickness (per segment)	
infill pattern (per segment)	

Following toolpath generation, the system directly converts the structured curves into machine-readable motion instructions within the Grasshopper–Python environment. The resulting toolpath is encoded into standard G-code motion commands (G1), where each command simultaneously defines spatial movement and coupled extrusion control.

In particular, the parameters correspond to:

- X, Y, Z: spatial position of the nozzle in machine coordinates
- F: feed rate controlling printing speed
- E: cumulative extrusion length derived from the volumetric deposition model

G1 X120.450 Y95.320 Z0.200 F2700 E1.4582 ; Active print movement

G1 X145.800 Y95.320 Z0.200 F2700 E2.6451 ; Continuous deposition

This fully automated pipeline eliminates the need for external slicing software, mesh export, or manual toolpath assignment. Machine start and end routines are integrated within the script, enabling direct generation of print-ready G-code from parametric geometry. The resulting G-code can be either directly sent to the printer or visually inspected through slicing preview software (Figure 46), ensuring both fabrication readiness and geometric verification.

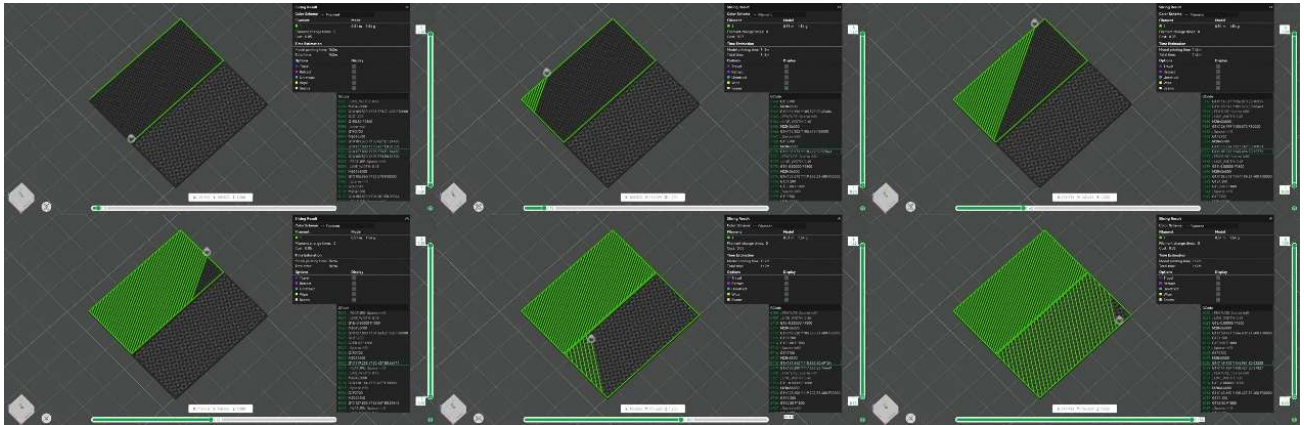


Figure 46 Preview visualization of the generated G-code travel sequence and print quality in Bambu Studio.

5 Environmental Performance

This chapter evaluates the performance of the proposed 4DP SMP façade system in a building scale, addressing the third research sub-question: how adaptive SMP façades influence Indoor Environmental Quality (IEQ) performance. To assess the IEQ impact of the responsive behavior, the study simulates the geometric transition between the thermally activated curved state (State A) and the cool resting flat state (State B) under varying climatic conditions. As discussed in Section 2.2.3, a comprehensive PMRF includes five criteria: thermal comfort, daylight level, glare control, view-out quality, and energy-oriented metrics (Tabadkani et al., 2020). The evaluation of our workflow focuses on the two performance criteria that most significantly influence IEQ: (1) *ventilation*: evaluating airflow behavior and indoor air exchange driven by designed geometry, affecting thermal comfort; (2) *daylighting*: balancing daylight availability while reducing glare and excessive solar exposure.

Subsequently, this chapter demonstrates a comparative case study analyzing these performance behaviors under the distinct temperate and subtropical environmental conditions of Delft and Taipei. Through this simulation framework, the design workflow extends beyond geometric design and fabrication into a performance feedback loop, linking material behavior, façade morphology, and environmental performance.

5.1 Evaluation Methods

5.1.1 Simulation Setup and Design Matrix

To evaluate the natural ventilation performance of the responsive SMP façade, a CFD simulation environment was established using OpenFOAM through the Butterfly interface. A representative office module ($4.0 \times 6.0 \times 3.5$ m) is structurally embedded as a critical mid-zone spatial cell within a multi-story, multi-bay building envelope framework to accurately mimic real-world boundary layer pressures. (Figure 47).

To avoid unrealistic velocity acceleration near the façade opening, an extended computational domain was adopted with sufficient upstream and downstream offsets. A uniform inlet velocity of 1.2 m/s was applied perpendicular to the south façade, while airflow exited through an interior door opening, establishing a single-inlet/single-outlet ventilation pathway for tracking indoor airflow distribution and air change performance.

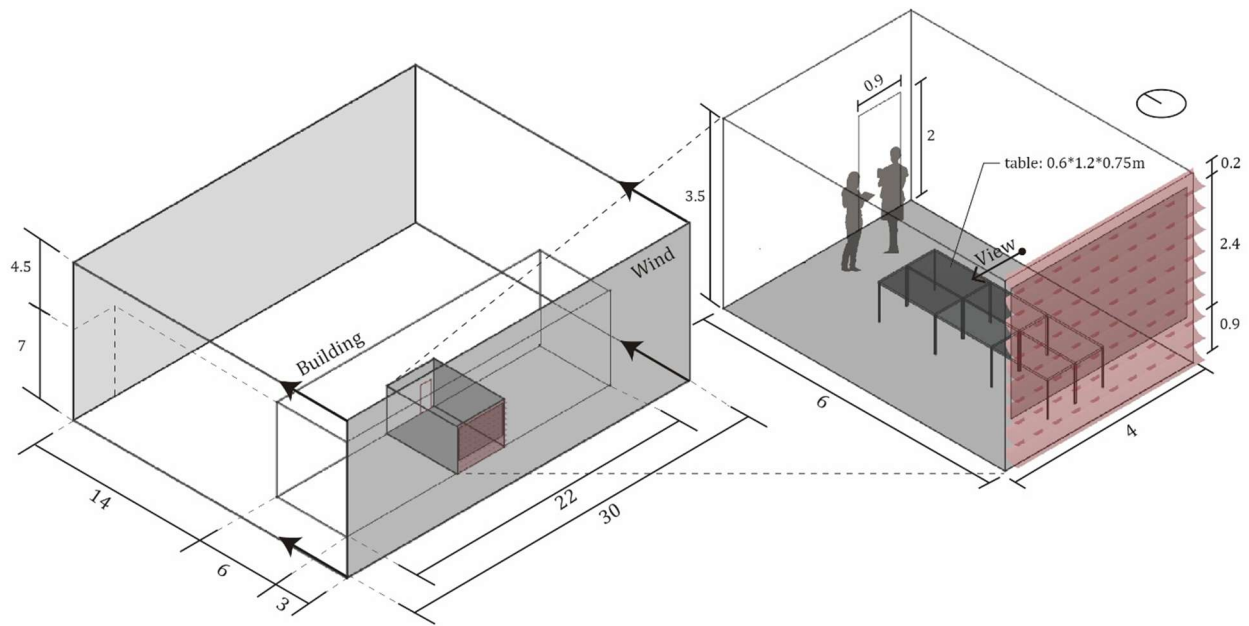


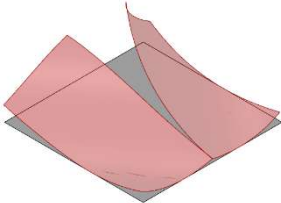
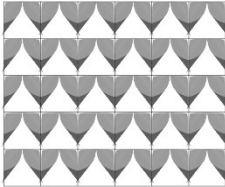
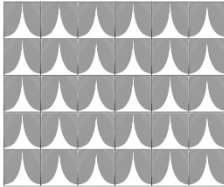
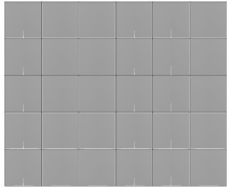
Figure 47 Simulation testing office room environment setup.

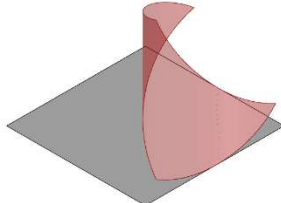
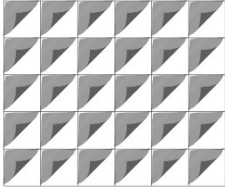
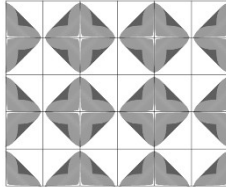
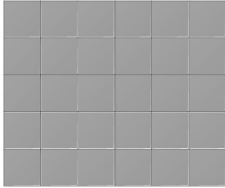
Daylighting and visual comfort simulations were conducted using Radiance-based workflows within a standardized office layout with façade facing south (Figure 47). The evaluation incorporated two thermally responsive façade states: (1) State A: curved/activated morphology above the SMP transition temperature; (2) State B: flat/resting morphology under cooler conditions. Because continuous thermodynamic shape transitions cannot be simulated within a single integrated workflow due to Honeybee Radiance software limitations, the study utilizes a comparative evaluation of static states. Consequently, each state was analyzed through discrete static simulations to investigate the independent geometric impacts on performance. To approximate the optical behavior of the TPU-SMP, the façade geometry was assigned a calibrated translucent material modifier with a diffuse reflectance of 0.40, diffuse transmittance of 0.30, and 0 specular transmittance.

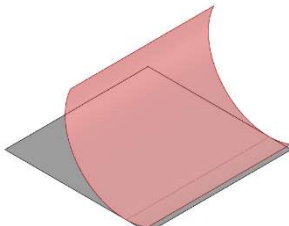
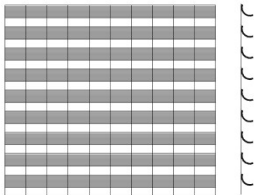
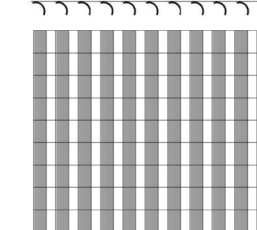
To evaluate the relationship between geometric parameters and environmental performance, three adaptive façade typologies were tested against an unshaded glazing baseline (Table 9):

- (1) *Variable Curvature*: Evaluates how curvature depth controls ventilation circulation and solar exposure reduction.
- (2) *Tiling Arrangement*: Investigates how diverse façade pattern influence view permeability and shading distribution.
- (3) *Dynamic SMP Louvers*: Testing different tilt angle louvers for solar control and daylight redirection.

Table 9 Experiment design matrix.

Design 01		Parameters		
Options		Cut count: 1 Cut Edge position / angle parameter: 0.625, 0° Curvature: (0.1428, 0.1428) Thickness (Left, Right): (1.2, 1.2) mm Infill ratio: (30%, 30%) Infill pattern: (52°, -52°) Anchor location: (-0.25, -0.25)		
				
	01-A	01-B	01-C (closed)	
Curvature	(0.1428, 0.1428)	(0.1000, 0.1000)	(0.0050, 0.0050)	

Design 02		Parameters		
Options		Cut count: 0 Curvature: 0.0714 Thickness: 1.6 mm Infill ratio: 30% Infill pattern: 45° Anchor location: -0.25		
				
	02-A	02-B	02-C (closed)	
Configuration				

Design 03		Parameters			
Options		Cut count: 0 Curvature: 0.0526 Thickness: 1.6 mm Infill ratio: 40% Infill pattern: 0° Anchor location: -0.34			
					
	03-A	03-B	03-C	03-D	
Tilt Angle	45° (0)	27° (-18)	0° (45)	Vertical 45° (0)	

5.1.2 Metrics

This study evaluates the performance of the façade system through a multi-criteria simulation framework integrating CFD and daylighting analysis. Ventilation performance is assessed using CFD-based airflow fields extracted at a vertical sectional cut through openings and a horizontal breathing-height plane at 1.2 m, quantifying indoor air velocity distribution and Air Changes per Hour (ACH) (ANSI/ASHRAE, 2023; ASHRAE, 2022). Daylighting performance is evaluated on a 1.0 m work plane using coupled Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) metrics to capture both useful daylight availability and excessive solar exposure (ANSI/IES LM-83-23, 2022). Visual comfort is further assessed through hemispherical fisheye renderings from occupant viewpoints on a working table on December 21st 11:00 coupled with Daylight Glare Probability (DGP) (NEN-EN 17037, 2019). Together, these spatially resolved metrics enable a consistent comparison between façade states and parametric configurations across ventilation, daylighting, and glare performance. (Table 10)

Table 10 Indoor Quality Assessment Metrics.

Metrics	Symbol	Definition	Target Threshold	Standard
Airflow Velocity	V	Indoor air velocity generated by airflow through the adaptive façade openings.	0.5 - 1m/s to maintain ventilation while avoiding draft discomfort.	ASHRAE Standard 55
Air Changes per Hour	ACH	Hourly rate of indoor air replacement through natural ventilation.	≥4–6ACH for occupied office environments.	ASHRAE 62.1
Spatial Daylight Autonomy	Sda _{300/50%}	Percentage of floor area receiving at least 300 lux for 50% of annual occupied hours.	≥55% for acceptable daylight availability.	IES LM-83-12
Annual Sunlight Exposure	ASE _{1000,250}	Percentage of floor area exposed to direct sunlight above 1000 lux for more than 250 hours annually.	<10% to reduce overheating and glare risk.	IES LM-83-12
Daylight Glare Probability	DGP	Probability that an occupant experiences visual discomfort due to uncontrolled luminance contrast.	< 0.35 for imperceptible glare boundary during peak radiation hours.	EN 17037

5.2 Case Study: Delft & Taipei

To evaluate climatic adaptability, the system was tested under two contrasting environmental conditions: (1) Delft: 52°N representing temperate northern-European daylight conditions with low winter solar angles. (2) Taipei: 25°N representing subtropical high-radiation conditions with intense solar exposure. (Figure 48)

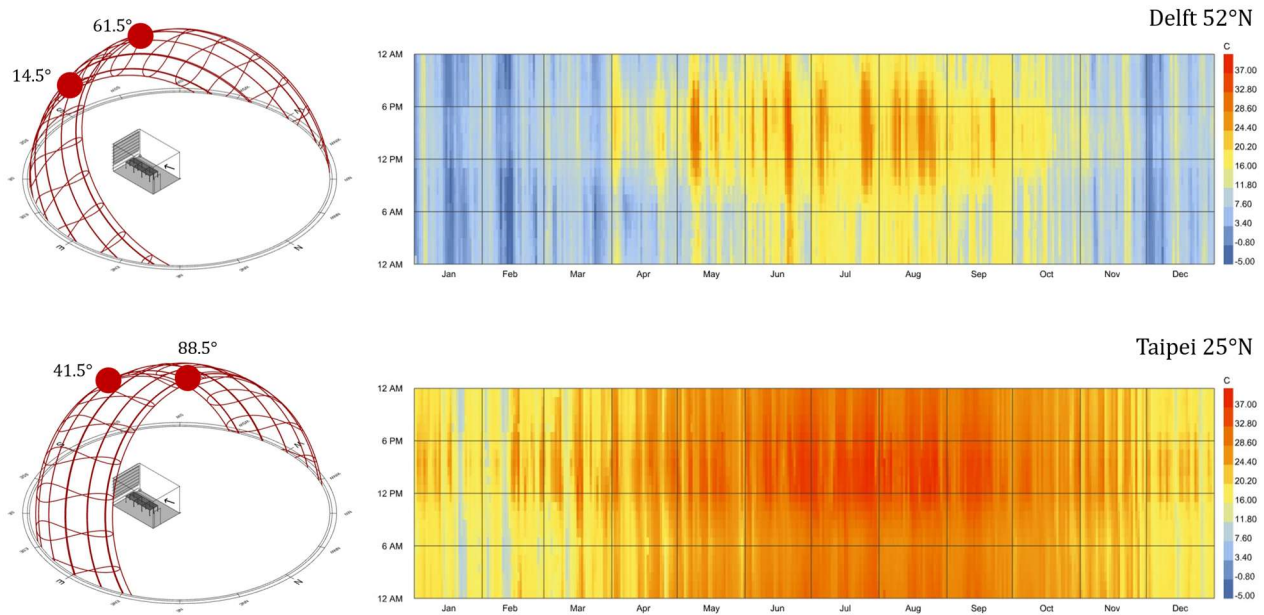


Figure 48 (a) Delft, The Netherlands 52°N, and (b) Taipei, Taiwan 25°N Climate: Annual hourly dry bulb temperature profiles (°C) and localized 3D stereographic sun path vectors.

5.2.1 Natural Ventilation Performance

The results of ventilation simulation results are summarized in Table 11. The comparison of the CFD yields insights into how parametric geometry functions as a fluid deflector, fundamentally re-shaping the interior thermal comfort.

Curved Aerodynamic: (Design 01)

The upward-warped profiles within Design 01 function as an aerodynamic scoop, forcing the incoming fluid vectors toward the upper boundary layer to trigger a strong ceiling jet mechanism. This behavior routes high-velocity air masses directly across the ceiling plane, successfully maximizing thermal flushing to evacuate hot air strata accumulated at the upper volume (Etheridge, 2012). This also create a vertical air convection, resulting in better air quality.

However, a performance threshold is reached as the curvature decreases. In Design 01-B, the reduced curvature causes the fluid profile to undergo a pronounced upward deflection. This geometric constraint drives the ACH to increase significantly from 68 to 92, signifying a substantially higher volume of induced ambient air and an elevated stream velocity within the indoor space. This detachment disrupts momentum exchange within the lower occupied zone, causing the local velocity at the standard 1.2m work plane to experience an abrupt stagnation drop near the center of the room, failing to achieve the uniform fluid distribution observed in larger curvature.

Turbulent Diffusion: (Design 02)

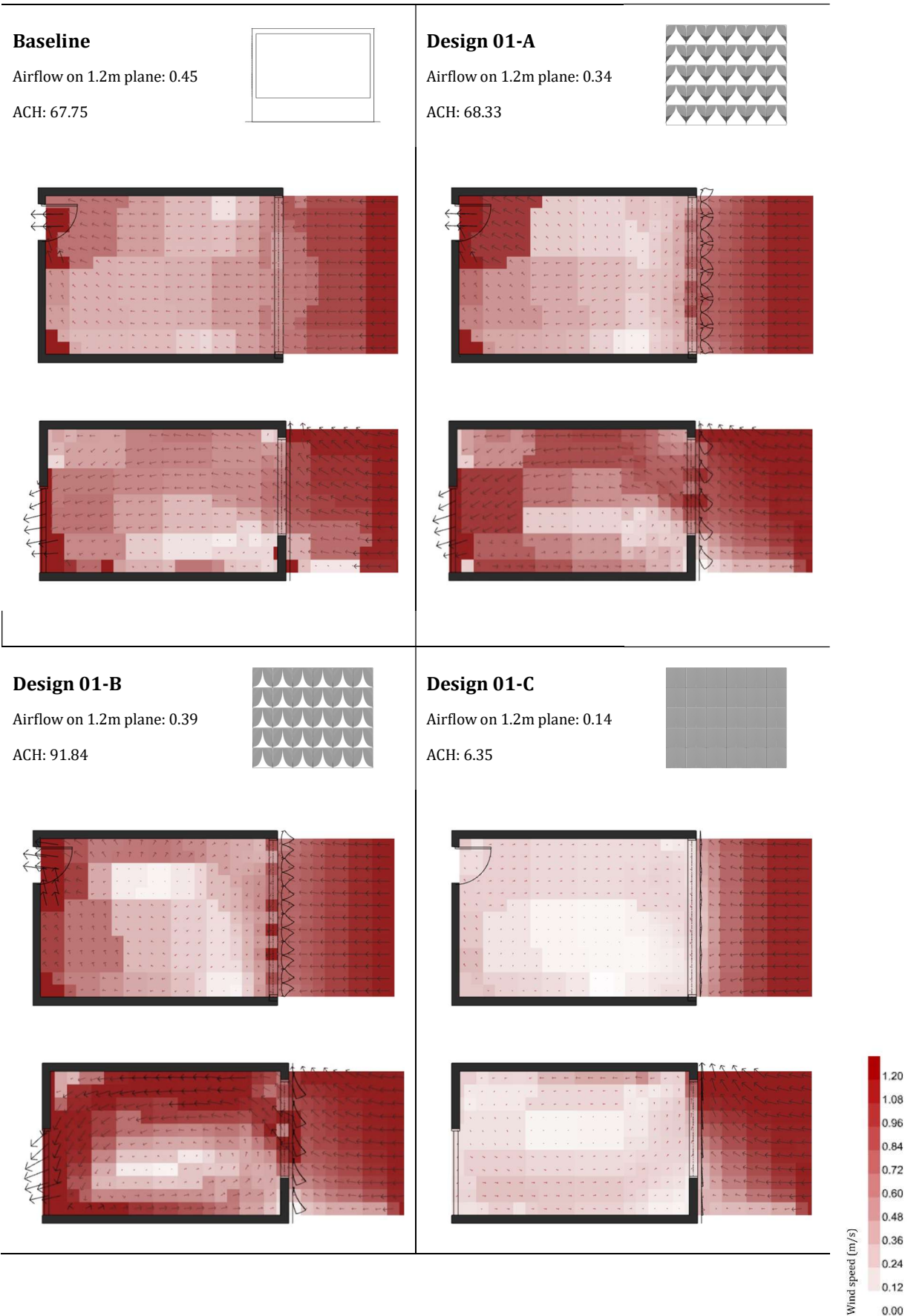
Conversely, the asymmetrical matrix of the Design 02 series provides a different fluid typology. While Design 02-B maximizes view outside, its multi-directional facets induce structural flow collisions. The incoming vectors are fragmented upon impact, generating localized, chaotic macro-turbulences. This fluid fragmentation mitigates high-velocity drafts but creates decentralized low-speed stagnant pockets across the intermediate spatial grid. This decentralized low-speed stagnant pockets could also be observed in 02-A.

When transitioning into the flat resting configurations (Design 01-C and 02-C), the unsealed perimeter tolerances between adjacent physical patches leads to air infiltration, yielding ACH of 6 and 26, respectively. Although minor residual airflows persist through these seams, they function effectively as a static pressure buffer block, assuming the structural window frame behind provides the definitive thermal airtight sealing required for winter heating retention.

Axis Dependency in Louvers: (Design 03)

- (1) *Horizontal louvers* (Design 03-A~C): The blind configurations systematically force an upward vertical deflection. While mid-angle setups like 03-B establish a highly stable indoor circulation, the linear slates restrict the horizontal dispersion of the incoming wind, forcing the fluid path into a strict, unidirectional track.
- (2) *Vertical louvers* (Design 03-D): Aligning the slats vertically reshapes the spatial distribution of the fluid. The vertical physical boundaries guide incoming wind to propagate evenly across the horizontal domain, maximizing 1.2m work plane coverage with velocity of 0.58m/s, which is highest among all designs. Nevertheless, this configuration constrains vertical buoyancy flow, yielding little vertical air exchange and reducing the mean kinetic velocity relative to horizontal louver systems. As a result, the ventilation performance degrades from 67 to 50 ACH, which sits below the alternative solutions' average of 60 to 70 ACH.

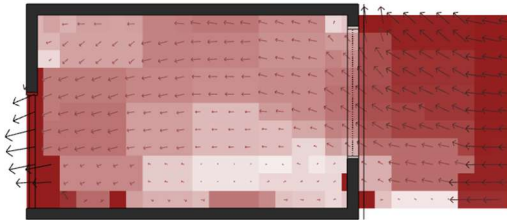
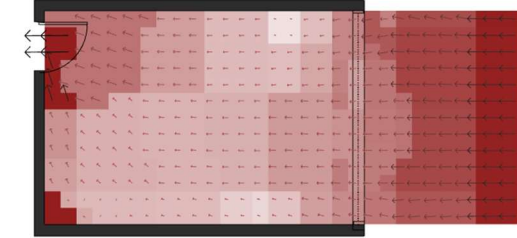
Table 11 Ventilation Performance Results. (Airflow: m/s; ACH: h⁻¹)



Baseline

Airflow on 1.2m plane: 0.45

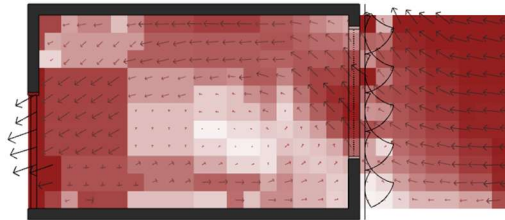
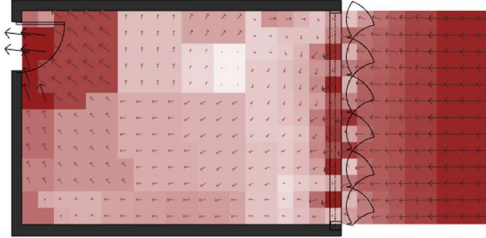
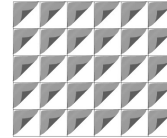
ACH: 67.75



Design 02-A

Airflow on 1.2m plane: 0.42

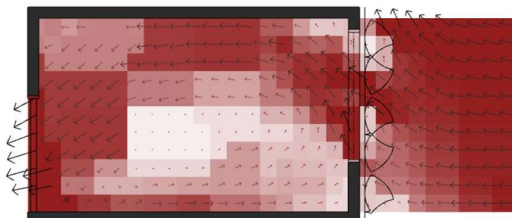
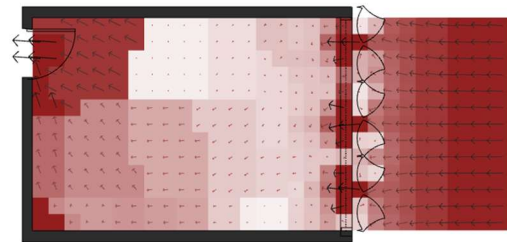
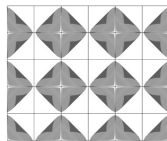
ACH: 57.77



Design 02-B

Airflow on 1.2m plane: 0.37

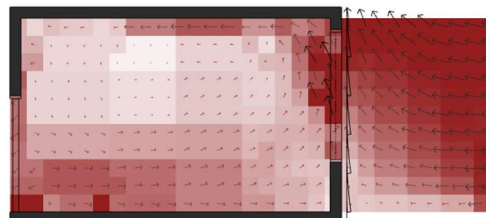
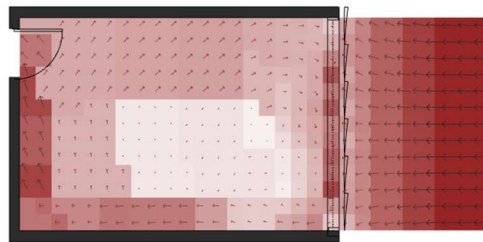
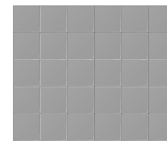
ACH: 71.80



Design 02-C

Airflow on 1.2m plane: 0.37

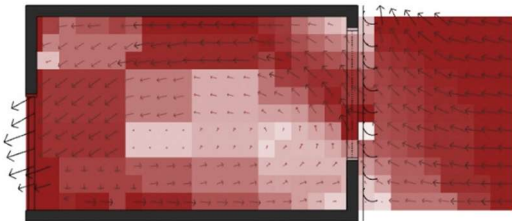
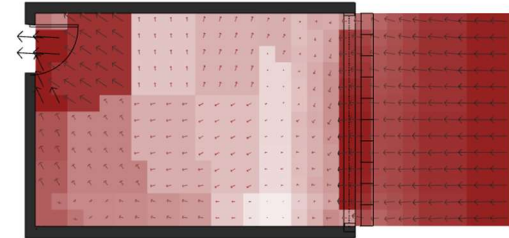
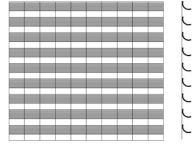
ACH: 26.34



Design 03-A

Airflow on 1.2m plane: 0.43

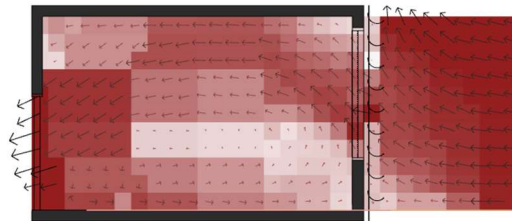
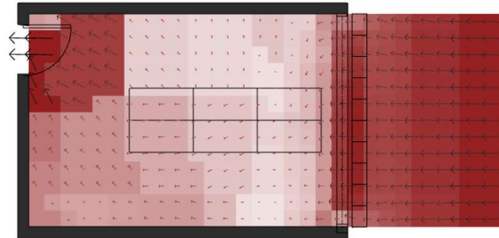
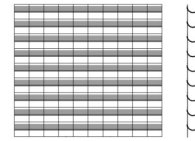
ACH: 69.45



Design 03-B

Airflow on 1.2m plane: 0.38

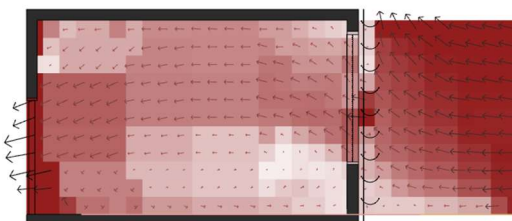
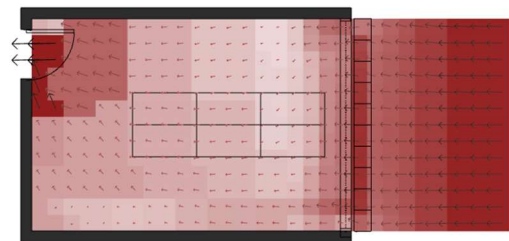
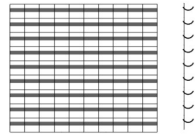
ACH: 69.32



Design 03-C

Airflow on 1.2m plane: 0.43

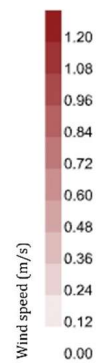
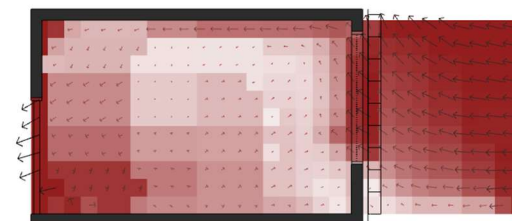
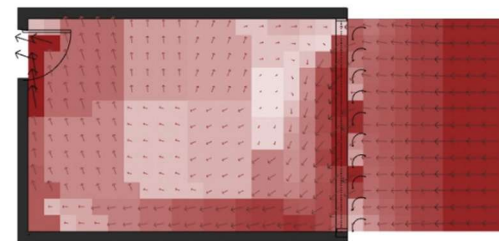
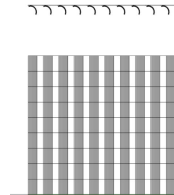
ACH: 67.46



Design 03-D

Airflow on 1.2m plane: 0.58

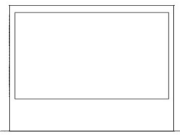
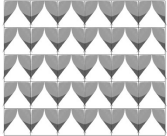
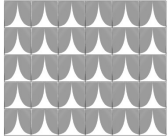
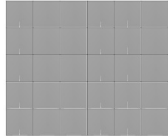
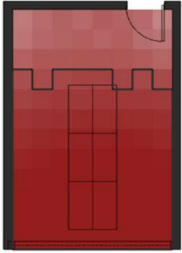
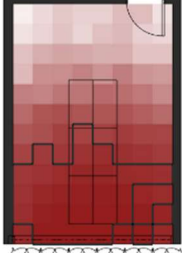
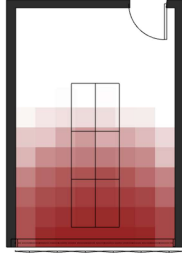
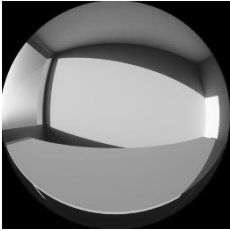
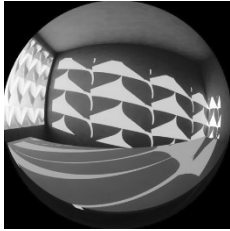
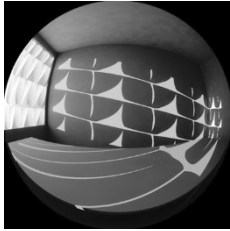
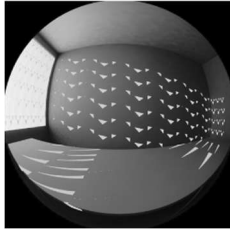
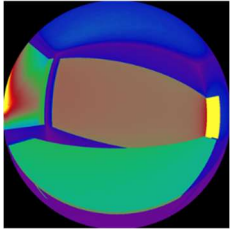
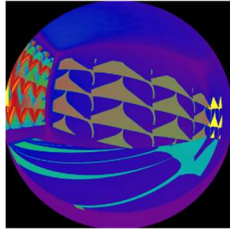
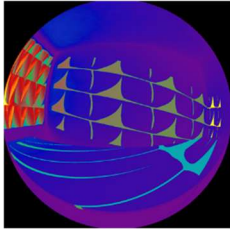
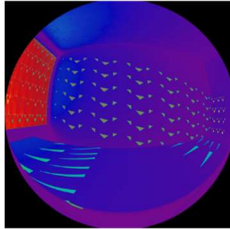
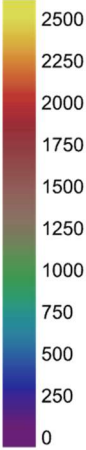
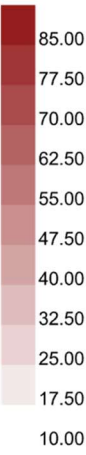
ACH: 49.78



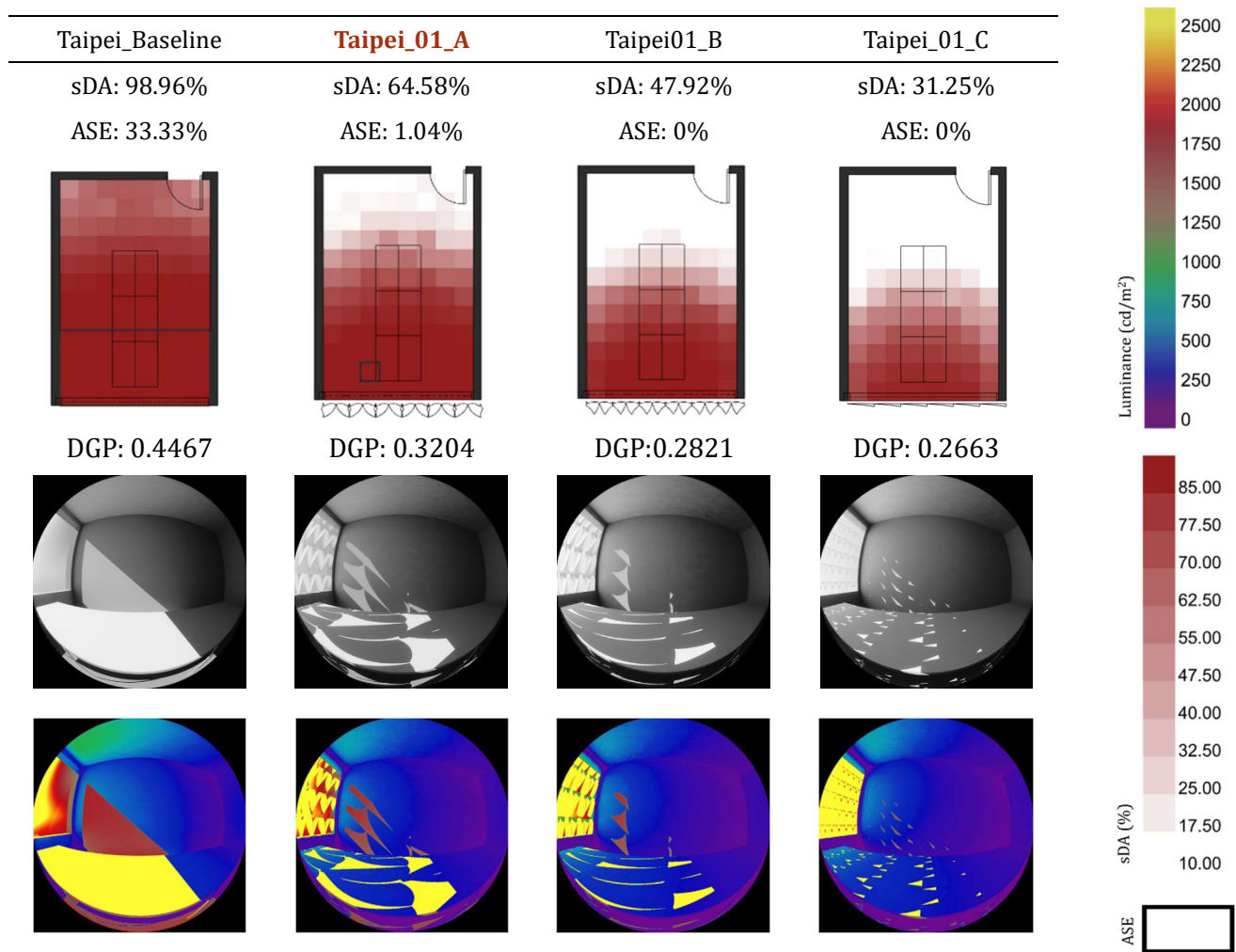
5.2.2 Visual Comfort Performance

The results of daylight analysis are shown in Table 12, Table 13 and Table 14. The comparison across two distinct latitudes shows how different geometries act as physical filters to reshape daylighting, solar heat gain, and visual comfort.

Table 12 Design 01 Visual Comfort Performance Results.

Baseline	Design 01-A	Design 01-B	Design 01-C (closed)
			
Delft_Baseline	Delft_01_A	Delft_01_B	Delft_01_C
sDA: 100%	sDA: 61.77%	sDA: 50%	sDA: 35.42%
ASE: 71.88%	ASE: 31.25%	ASE: 1.04%	ASE: 0%
			
DGP:0.3012	DGP: 0.2382	DGP: 0.2213	DGP:0.2128
			
			
  			

Note: Highlighted in red indicates optimal daylighting performance that satisfies standard green building criteria, defined here as sDA > 55% combined with ASE < 10%.

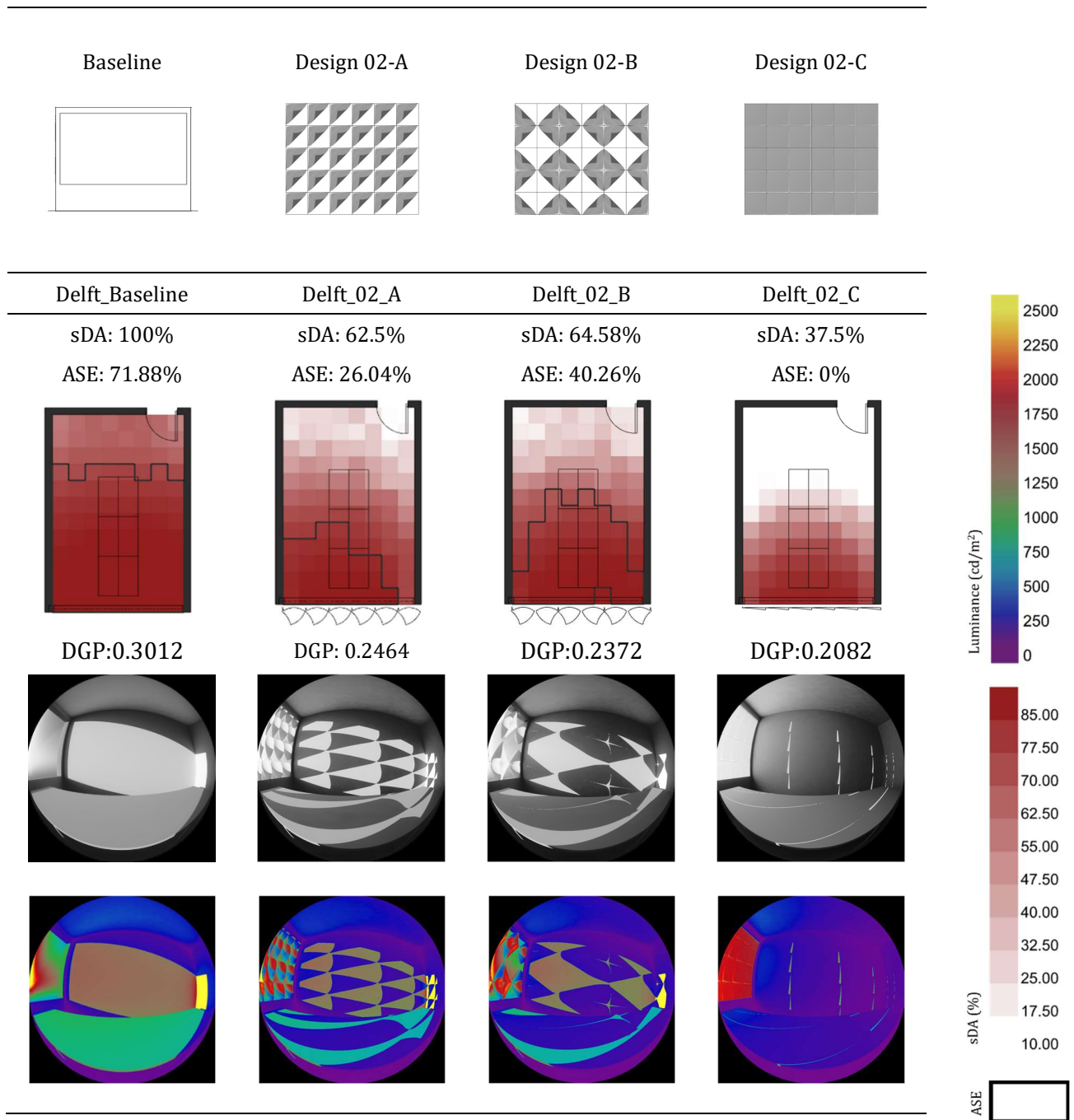


Effect of Curvature Level

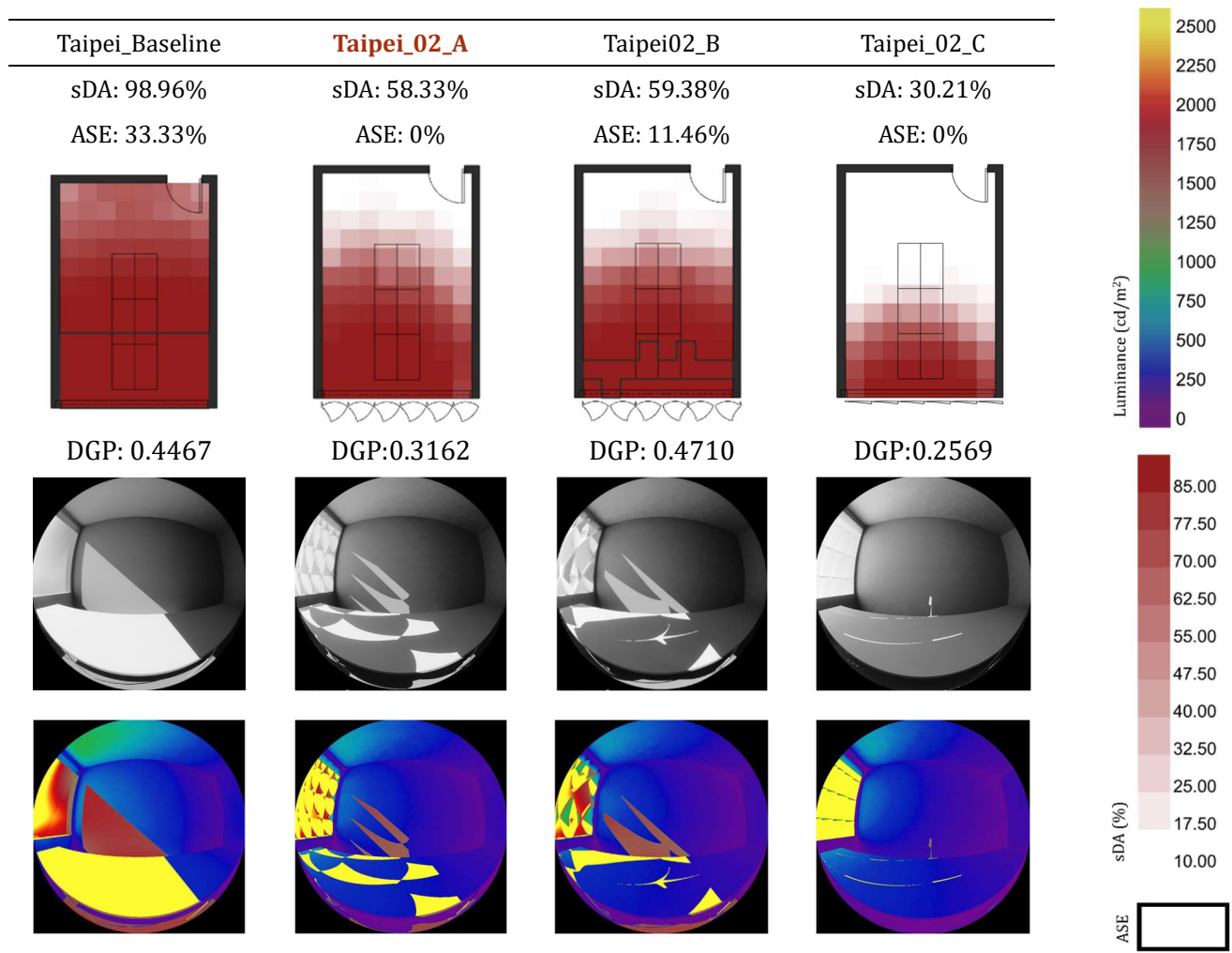
The performance of Design 01 shows a clear relationship between the curvature level of the 4DP elements and the indoor environment. (Table 12)

- (1) *Delft*: High curvature (01-A) maintains a good daylight level, with sDA at 61.77%. However, because the winter sun angle is extremely low (14.5°), the low-angle sun rays easily pass through the wide curved openings, leading to a high ASE of 31.25%. This creates a clear trade-off that keeping the facade open protects daylight but allows too much direct solar penetration.
- (2) *Taipei*: High curvature (01-A) is an ideal configuration. Because Taipei has a higher winter sun angle (41.5°), the upward-curved profiles act like a series of mini-overhangs. This geometry perfectly blocks the strong direct solar rays, dropping ASE from 33.33% to an impressive 1.04%, while allowing high-quality ambient daylight to enter deep into the space, keeping sDA at 64.58%. As the curvature decreases to 01-B, the daylight drops slightly.

Table 13 Design 02 Visual Comfort Performance Results.



Note: Highlighted in red indicates optimal daylighting performance that satisfies standard green building criteria, defined here as sDA > 55% combined with ASE < 10%.

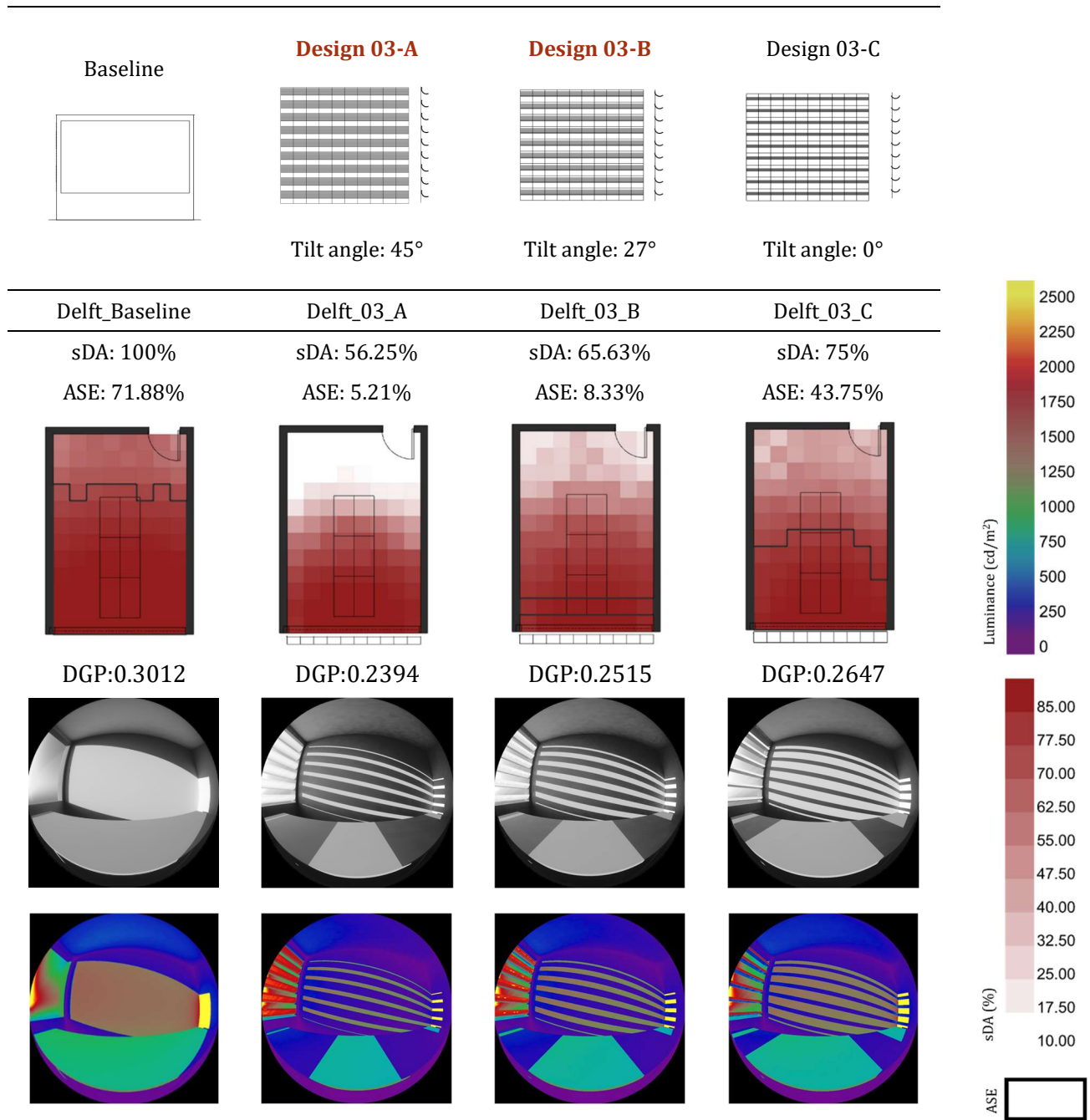


Effect of Tiling Arrangement

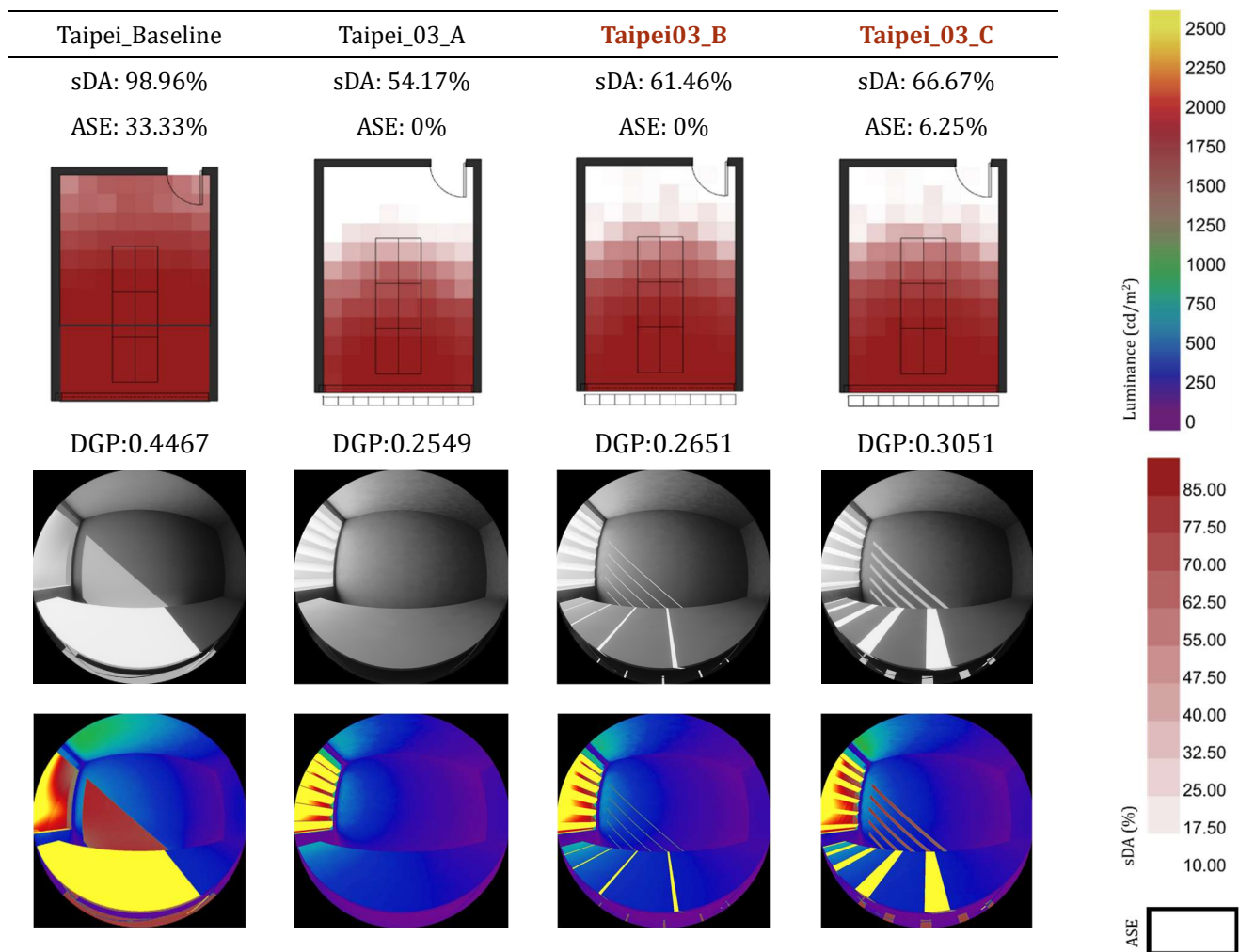
Design 02 provides an interesting visual appearance and good daylighting, but it performs poorly in glare control due to low-angle sun positions. (Table 13)

- (1) *Delft*: The asymmetrical panels offer weak defense against the low winter sun, resulting in a very high ASE (40.26%) and failing to reduce glare effectively.
- (2) *Taipei*: A critical issue occurs in Design 02-B, where the DGP rises sharply to 0.4710. The false-color render displays a concentrated high-luminance yellow and red spot on the left side of the room. This proves that under Taipei's 41.5° winter sun, the specific angles of the asymmetrical panels create an accidental concave mirror effect, bouncing intense direct sunlight directly into the user's view. This secondary reflection causes severe visual discomfort. On the other hand, 02-A lies in a good option according to sDA and ASE value, but the cause of mirror effect should also be carefully assessed across the whole year.

Table 14 Design 03 Visual Comfort Performance Results.



Note: Highlighted in red indicates optimal daylighting performance that satisfies standard green building criteria, defined here as sDA > 55% combined with ASE < 10%.



Effect of Tilting Angle

Horizontal louvers prove to be highly effective for high-latitude environments. (Table 14)

- (1) *Delft*: Design 03-A and 03-B both show great performance in balancing sDA and ASE. Specifically, Design 03-B (27° tilt) performs the best because it distributes and scatters daylight most evenly across the entire room. When the louvers flatten completely into Design 03-C (0° horizontal), the wide openings cause a localized overexposure near the window. However, in Delft's cold winter, this extra direct sunlight is still acceptable because the glare remains in a safe range (DGP 0.2647) and the sun capture provides helpful passive solar heating to warm the building.
- (2) *Taipei*: The flatter louver configurations (03-B and 03-C) achieve the most balanced daylighting performance for subtropical conditions. Unlike the steeper 45° configuration (03-A), which excessively reduces deep-plan daylight penetration, 03-B and 03-C effectively suppress ASE to 0% and 6.25% while maintaining sufficient diffuse daylight sDA > 60%.

Flat Closed State

When the elements completely flatten into the closed state (01-C and 02-C), the fish-eye false-color renders capture an optical phenomenon, the translucent material functions as a passive diffusion shield. Instead of creating a complete blackout, the closed state allows a safe amount of diffuse light to pass through, sDA of 35.42% in Delft 01-C and 31.25% in Taipei 01-C. In the false-color images, the window area turns entirely yellow. This indicates that the material successfully breaks down the highly concentrated, blinding solar disc and spreads the light uniformly across the window surface. By removing the extreme brightness contrast between the window and the dark interior walls, the DGP drops to a perfectly safe, imperceptible range in both climates.

5.2.3 Design for Climate

For Delft, **Design 03-B (Horizontal SMP Louver)** provided the most balanced environmental performance for the Dutch context. Its 27° tilted horizontal configuration maintains stable airflow distribution and indoor air circulation while delivering effective shading and mitigating summer glare. During colder winter periods, the localized anchor positions allow the louver to revert to its flat, 0° horizontal rest state. This flat transition maximizes direct winter solar heat gain, which is highly beneficial for passive heating in high-latitude regions (reference result from Design 03-C). For temperate maritime climates like the Netherlands, utilizing an SMP material with $T_g = 35\sim 40^\circ\text{C}$ would align the system's operational surface temperatures. (Figure 49)

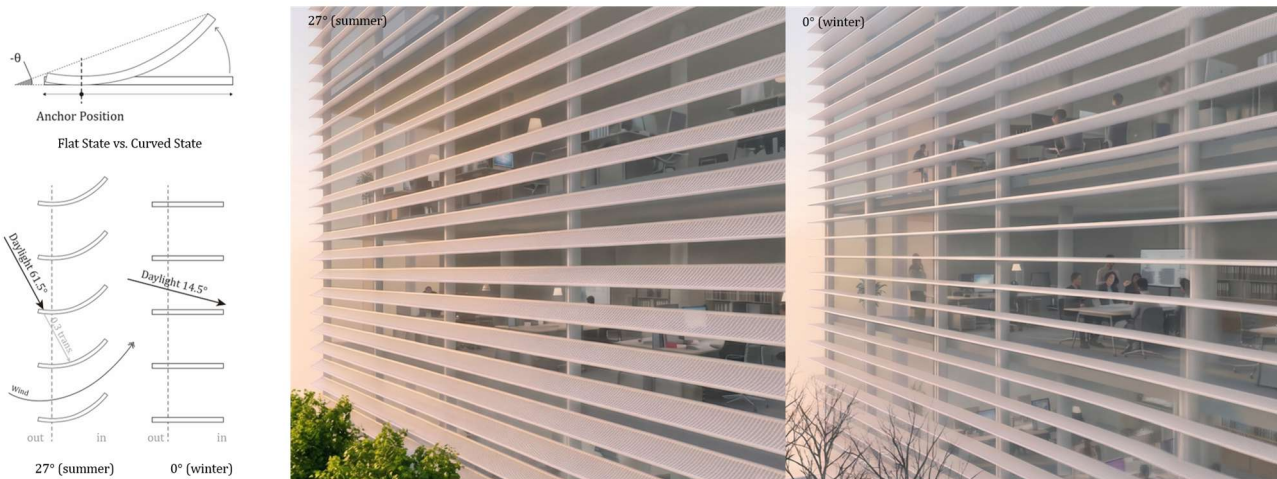


Figure 49 Design 03-B louver prototype for temperate climate: (left) thermally activated curved state during peak solar loading, providing adaptive shading; (right) flat rest state 0° during cooler periods, maximizing direct solar penetration for passive heating. (Model built by author, rendered by Gemini AI.)

For Taipei, **Design 01-A (SMP Panel)** demonstrated the strongest overall performance for subtropical conditions. Its highly curved active geometry effectively reduces intense solar exposure while preserving adequate daylight penetration. Crucially for hot climates, it promotes upward convective airflow, which enhances indoor heat dissipation. When summer façade temperatures exceed the TPU-SMP activation threshold ($T_g \approx 55^\circ\text{C}$), the active zone deforms to expand the aperture, driving natural ventilation and convective cooling during peak thermal loading. Conversely, as temperatures drop in the evening or during cooler seasons, the panel returns to its closed configuration, minimizing unintended air infiltration and improving the building envelope's thermal insulation. As an alternative subtropical solution, the flatter horizontal louver configurations (Design 03-B and 03-C) also performed reliably, maintaining low ASE values while preserving sufficient daylight and stable ventilation. (Figure 50)

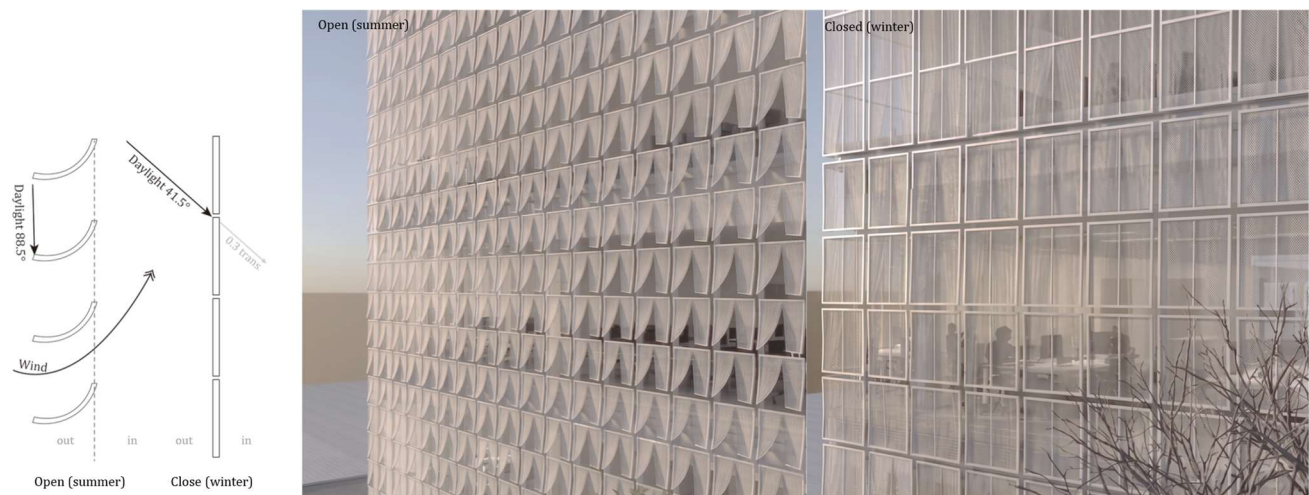


Figure 50 Design 01-A panel for subtropical climate: (left) thermally activated open state during peak solar loading, enhancing shading and natural ventilation; (right) recovered closed state during cooler periods, providing thermal insulation. (Model built by author, rendered by Gemini AI.)

5.2.4 Façade Detail

To demonstrate the architectural scalability of the programmed smart material systems, a unitized curtain wall detail is proposed (Figure 51). The structural grid relies on standard aluminum mullions (50×100mm), which are rigidly anchored to the concrete floor slabs via mullion fixing brackets. The 4DP Panels (600×600mm) are mounted directly onto the primary mullion profiles using panel clamps. Crucially, these clamps are aligned precisely with the *anchor axis* defined by the designer. By strictly restraining the panel along this designated linear boundary while leaving the active zones unconstrained, the connection detail ensures the shape-shifting behaviors, such as aperture opening or louver curvature transformation. Furthermore, this adaptive shading skin functions as the outer layer of a double-skin

facade, where the inner glazed window maintains the building's air tightness in the winter, while the programmed dynamic buffer zone optimizes natural ventilation in summer and daylight control.

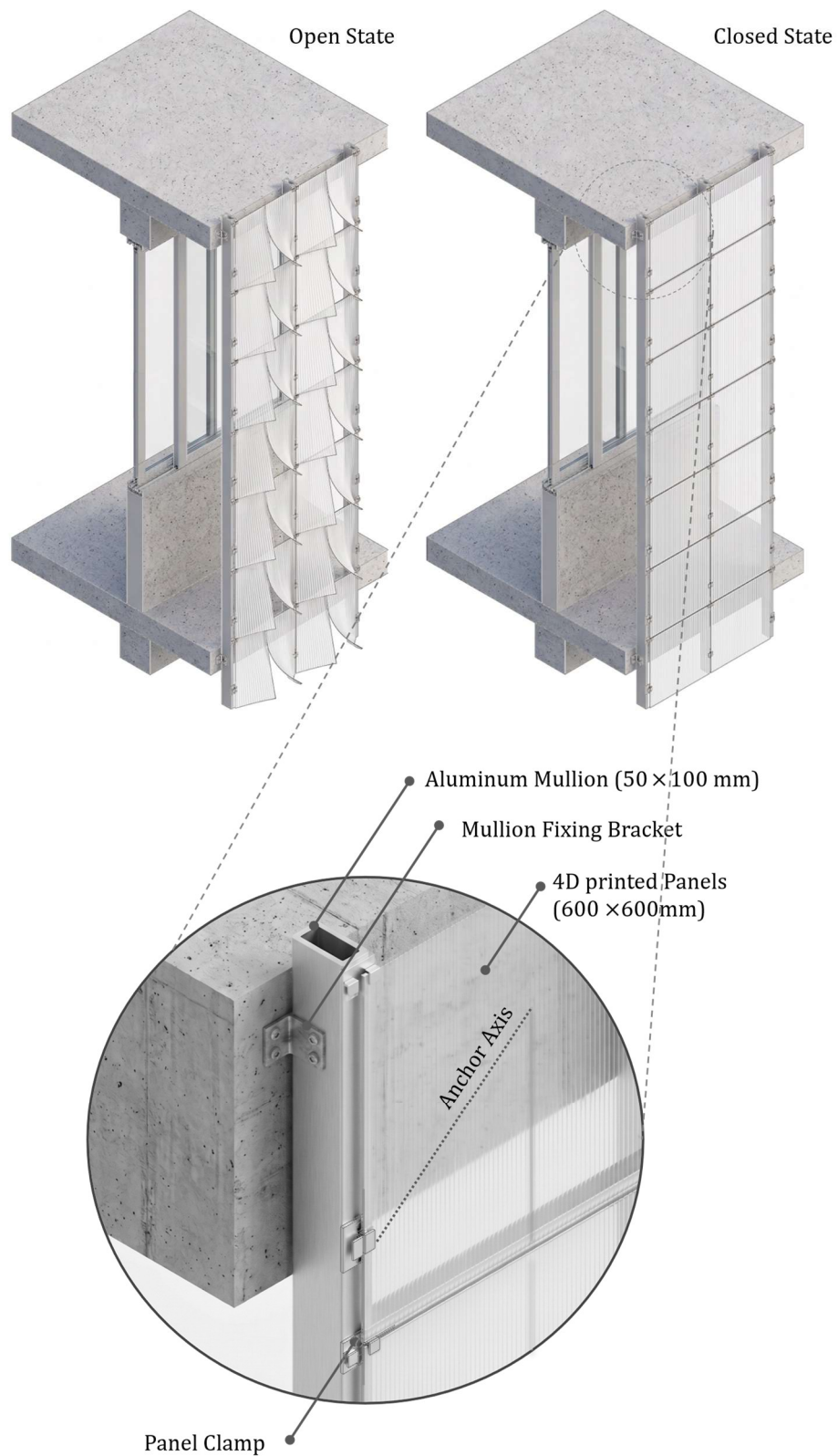


Figure 51 Façade section detail. (Model built by author, rendered by Gemini AI.)

5.2.5 Prototype Models

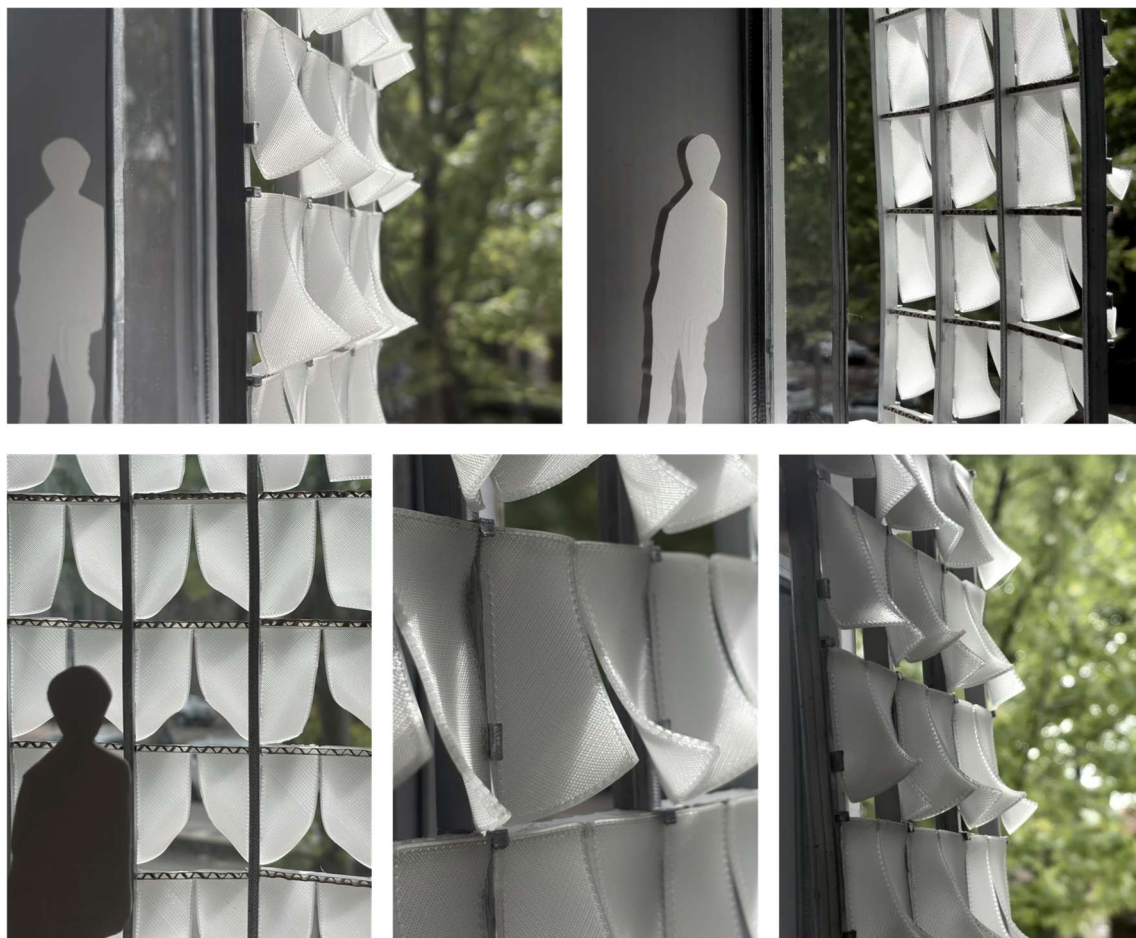


Figure 52 1:12 Façade Model.



Figure 53 Panels changing from closed state to open state.

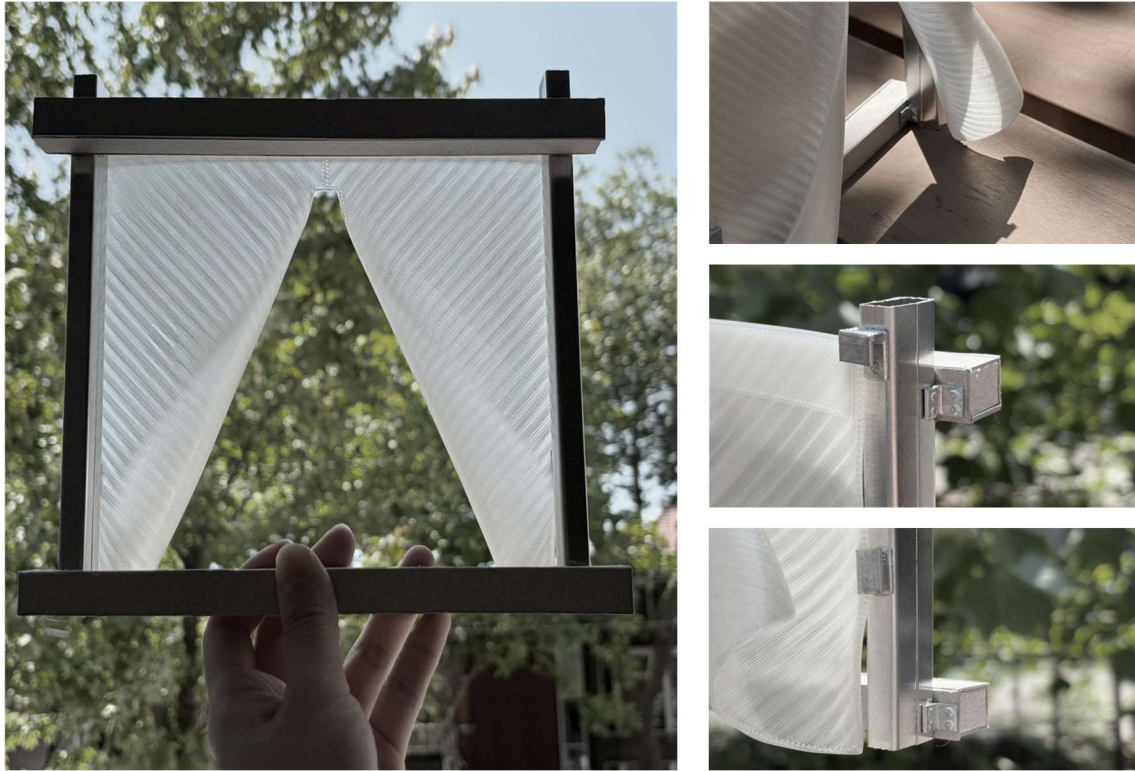


Figure 54 1:3 Scaleup Model.

Figure 52 and Figure 54 show close-up details of the façade module with scale 1:12 and 1:3 respectively. Figure 53 shows the same installation at three different moments, illustrating how the petals shift from fully closed to progressively opened, demonstrating the device's dynamic shading behavior over time.

6 Limitations & Future Work

While the 4DP SMP responsive façade tool successfully demonstrates a diverse design workflow, several critical boundaries must be contextualized.

Geometrically, the algorithmic generation is bounded by developable surfaces to align with planar-to-curved 4DP fabrication logic, leaving true double-curvature shells unachieved. Furthermore, because the shape-morphing physics are computed through isolated patch proximity visualization rather than a continuous façade skin, the tool remains a geometric abstraction. Future iterations should integrate realistic mathematical models of material deformation to bridge this gap.

Environmentally, ray-tracing could only be applied to one discrete state at a time, meaning that dynamic, two-way behaviors could not be simulated simultaneously within a unified loop. Developing an automated co-simulation workflow that seamlessly alternates between these states remains a critical trajectory for future research. Additionally, due to severe computational bottlenecks in DGP processing times, glare mapping was strictly limited to winter south façade conditions, leaving critical low-angle summer evening western tracks open for future investigation. Finally, design typologies and state behaviors must be critically reviewed across different climate zones, as this thesis serves as an initial hypothetical study focusing primarily on temperate and subtropical archetypes.

In terms of applicability, constraints in commercial availability meant that physical laboratory experiments utilized a one-way SMP, whereas the CAD tool and performance model operates under the idealized assumption of a fully autonomous, two-way reversible SMP. This gap between experimental reality and design assumption is the most consequential limitation of this thesis. The parameter-to-deformation relationships established in Chapter 3 are valid for the initial activation cycle, but the reversible diurnal behavior assumed in the façade design and environmental simulation has not been physically validated. Any deployment scenario that relies on autonomous daily cycling would require either a verified two-way SMP formulation or an antagonistic material system, neither of which has been tested here.

Furthermore, the long-term material durability against ambient degradation, such as UV exposure, moisture ingress, and thermal cyclic fatigue, remains untested. Repeated heating and cooling cycles may progressively reduce the shape recovery ratio of TPU-SMP, degrading actuation performance over time in ways that the current study cannot predict. Finally, scaling the design to an architectural reality introduces additional uncertainties that the specimen-scale experiments do not address. A preliminary 1:3 scale-up test was conducted to verify that the curling deformation behavior persists at a larger size, and the results confirmed that the actuation effect remains present at this intermediate scale. However, full panel scale and further testing across the full range of material properties is still required. Future work is required to evaluate the true lifespan and sustainability of these 4DP components, to validate scaling behavior from

specimen to panel, to address actuation force limitations under wind loading, and to develop fabrication protocols for optimized SMP materials tailored to specific climatic conditions. Future investigations should also address the influence of panel mounting constraints on free deformation, as the anchor axis connection detail proposed in Chapter 5 has not been physically tested at scale.

7 Conclusion

This thesis investigated how 4DP SMP can be used to design a passive, climate-responsive façade, which responds autonomously to thermal stimuli without mechanical actuators or electronic control systems. The main research question is **“How can 4D-printed SMPs be used to create a passive, climate-responsive façade?”** The research addressed a gap identified in the literature, while existing studies acknowledge the potential of FDM-printed SMPs for adaptive façades, few have systematically mapped fabrication parameters to deformation outcomes, few have linked that material behavior to concrete façade design strategies, and fewer still have evaluated such systems against real environmental performance criteria at the façade scale. This thesis addresses that gap through three interconnected research questions.

Q1: “How do 4DP parameters affect the deformation behavior of SMP elements?”

Empirical results on TPU-SMP and PLA show that deformation behavior can be systematically controlled through three fabrication parameters alone, without altering material composition. Infill pattern governs deformation directionality. The bending axis runs perpendicular to the principal filament direction, giving designers direct control over which way a panel curves. Thickness modulates global bending rigidity, with 1.2 mm producing the largest deflections and 1.6–2.0 mm providing more stable, controlled responses. Infill ratio adjusts deformation magnitude, with lower ratios increasing overall deformation, though ratios below 55% risk geometric instability as curvature becomes too concentrated to produce controlled bending. Across all parameter groups, TPU-SMP exhibited substantially greater actuation capacity than PLA, confirming its suitability as the active material. Together, these three parameters constitute a programmable deformation vocabulary that can be spatially distributed across a single panel to encode zones of controlled curvature directly into the fabrication process.

Q2: “How can these programmed deformations be translated into effective passive adaptive façade mechanisms?”

An iterative design process explored three façade concepts: the SMP Panel, the SMP Louver, and the SMP Hinge. The SMP Panel divides each element into active and passive zones defined by differentiated parameter sets. Upon thermal activation, the active zones deform outward, converting closed slits into open apertures. The SMP Louver uses spatially defined anchor positions to translate a uniform printed

curvature into controlled shading angles. The SMP Hinge integrates SMP actuation with a compressive origami mechanism, achieving reversible panel rotation. Of the three, the SMP Panel and SMP Louver were selected as the primary implementation concepts because both clearly demonstrate how 4DP can encode spatially differentiated behavior through fabrication parameters within a single printed element, with parameters such as pattern, gap orientation, anchor position, and zone geometry directly defined as design inputs. To operationalize this translation for design practice, a parametric CAD tool was developed. The workflow integrates material behavior data, component geometry, fabrication output, and climate performance simulation, allowing designers to move from a target deformed geometry to fabrication-ready G-code without external slicing software.

Q3: “What performance improvements in IEQ can be achieved through such systems?”

CFD and Radiance-based simulations evaluated three façade configurations against an unshaded baseline across two climate contexts. In Taipei (25°N subtropical), the curved SMP Panel (Design 01-A) performed best. Upon thermal activation, the active zones open to reduce ASE from 33.33% to 1.04%, maintain sDA at 64.58%, lower DGP from 0.45 to 0.32, and direct airflow upward for natural ventilation. As temperatures drop, the panel recovers toward its closed configuration, shifting from solar control to passive thermal insulation. In Delft (52°N temperate), the horizontal louver system (Design 03-B 27° tilt) delivered the most balanced performance, providing stable airflow and controlled glare in summer, while its flat winter rest state welcomes low-angle solar penetration as a passive heating benefit.

Answering the main research question, this research demonstrates that a passive, climate-responsive SMP façade is achievable through a three-step design logic. First, select an SMP whose glass-transition temperature matches the target façade surface temperature ($T_g \approx 35\text{--}40^\circ\text{C}$ for temperate climates, $T_g \approx 55^\circ\text{C}$ for subtropical climates). Second, program and design deformation behavior spatially through fabrication parameters. Third, select the activated geometry based on climate-specific performance simulation. The result is a façade whose responsiveness is embedded at the point of fabrication, activated when the environment demands and return back to the rest state when conditions permit.

Contributions

This thesis establishes a reproducible design-to-evaluation framework for SMP-based 4DP façade elements, with three concrete contributions. First, it systematically identifies how three fabrication parameters, infill pattern, infill ratio, and thickness, each independently influence the deformation behavior of FDM-printed SMP elements, establishing an empirical parameter-to-deformation map that gives designers a quantitative basis and understanding for programming material behavior. Second, it demonstrates a set of façade application concepts, the SMP Panel and SMP Louver, in which spatial parameter distribution within a single printed element produces climate-responsive aperture behavior;

showing that the same fabrication platform can serve different climates simply by adjusting parameter configurations. Third, it introduces a parametric CAD tool that integrates the full design chain, from material behavior lookup and geometry generation to fabrication-ready G-code output and environmental performance evaluation, within a single iterative workflow. Crucially, the tool is not material-specific: as long as a parameter-to-deformation mapping is established for a given SMP, the same workflow applies, meaning the framework can accommodate future materials or updated formulations without rebuilding the design logic from scratch.

Societal Impact and Implications

The proposed framework carries broader implications for the building industry and sustainable development. As buildings account for a substantial share of global energy consumption, passive adaptive façades that respond autonomously to climate stimuli represent a meaningful step toward low-energy building envelopes. Unlike conventional adaptive systems that depend on sensors, actuators, and maintenance-intensive control units, the SMP-based approach embeds responsiveness at the point of fabrication, reducing both operational complexity and long-term energy demand. From a sustainability perspective, the use of FDM-printed thermoplastic SMP materials offers advantages in geometric customization over traditional façade manufacturing. However, full life-cycle assessment and long-term durability validation remain necessary before deployment. Biobased printable SMP could also be considered and evaluated in the future.

Reflections

This thesis is positioned at the intersection and integration of material science, design informatics, and climate performance evaluation. The research process was not linear. Material procurement was costly and difficult for a student, and the absence of commercially available two-way SMP formulations remained a persistent constraint that shaped every downstream decision. The first thermal activation experiment, watching a flat printed specimen deform in hot water, excitedly proved the initial assumption that the behavior was controllable. The next important decision to develop a CAD tool emerged from an intuition that the material findings needed a design interface rather than proceeding directly to simulation. This later proved to be the most demanding and most rewarding phase of the work. The environmental simulation phase produced unexpected results during some trial-and-error testing, which reinforced the value of integrating simulation into the design loop rather than treating it as a final evaluation step. Overall, the findings have demonstrated that a deployable SMP façade panel is a realistic prospect, contingent on the material validation and scaling studies identified in the limitations chapter.

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Declaration on the Use of Artificial Intelligence (AI) Tools

In the development of this thesis, ChatGPT, Claude, and Gemini were utilized to support specific tasks, while all core concepts, brainstorming, research logic, experiment, and final implementations remain the author's original work.

- (1) *Text Refining & Language Support:* As English is the author's second language, ChatGPT, Claude and Gemini were used to refine the grammatical quality and narrative of the writing without changing the original arguments.
- (2) *Computational Design & Coding Support:* Claude was employed to co-develop an initial 2D conceptual CAD tool via vibe coding with the author; however, due to limitations in generating 3D variations in Claude, the logical framework was successfully manually translated to 3D and reconstructed into Grasshopper (GH) by the author. Additionally, Gemini assisted in co-authoring scripts for hard-coded G-code generator in python GH and offered algorithmic debugging directions. The ultimate integration, logic connections, and final physical outputs within the Grasshopper environment were independently engineered by the author.
- (3) *Visual Diagrams:* Gemini was utilized to generate conceptual, high-level process diagrams to communicate baseline theories. All precision technical drawings, empirical data visualizations, and exact material behavior plots were manually drafted by the author due to the accuracy limitations of generative models.

Appendix

The source code, GH file and simulation models implemented in this study are publicly available in the GitHub repository at the following link: [https://github.com/ellen87713/4DP SMP Facade](https://github.com/ellen87713/4DP_SMP_Facade)

For reproducibility, detailed documentation on hardware configuration and dependency packages can also be found within the repository's README file.

Research Timeline

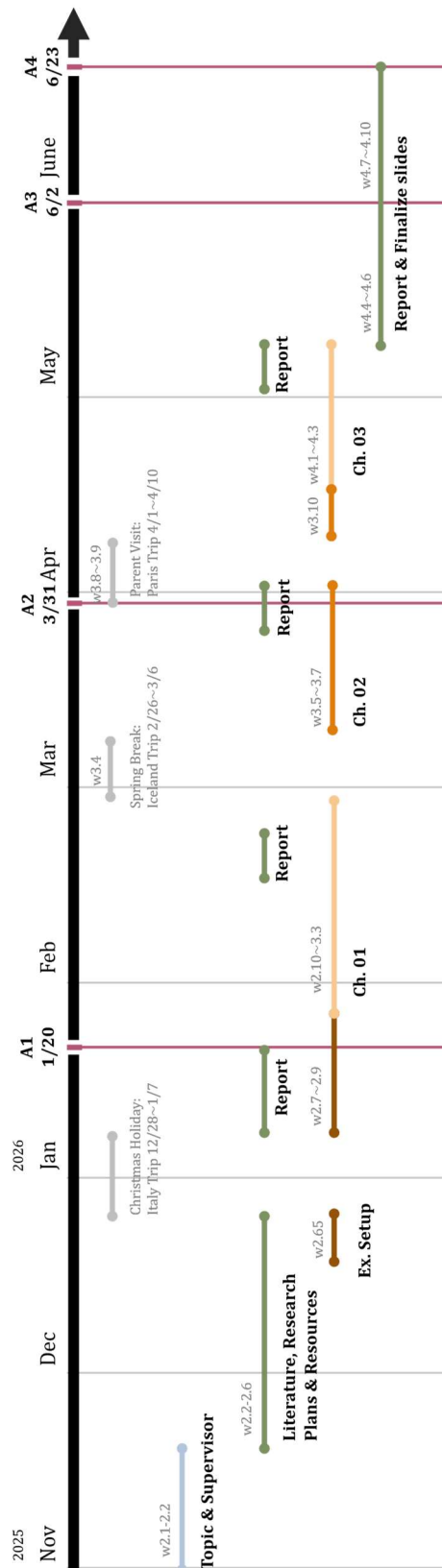


Figure 55 Research plan and timeline.

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DATA MANAGEMENT CHECKLIST

Instruction

This checklist is relevant for all graduation projects of the Master AUBS. The form is intended to highlight common aspects of graduation projects that require particular attention with regard to planning the research and data management. Relevant information and supplementary sources regarding each question are provided below each question.

With this checklist, the faculty wants to avoid that students unexpectedly find themselves in complex and stressful situations, in which ethical or privacy matters and/or other laws and regulations become an issue. In projects involving humans, certain types of data processing increase the risks to the human participants: planning such projects requires additional evaluations and advice from university staff before ethical approval can be received and the project can begin. In the case of a graduation project, obtaining additional advice or permits may delay the project with an extra education period or semester. To avoid this, it is recommended that students set up a graduation project with a low level of risk. Therefore, all students have to check their risk, by completing this checklist before their A1.

The first section of the checklist (A) should be completed by all students, together with their supervisor, during the planning of the graduation project, before the A1. It does not need to be submitted to anyone for review or approval. Please consider questions 1 to 3 carefully in relation to the intended graduation project, and answer with 'yes' or 'no'.

The second section of the checklist (B) should only be completed if the graduation project involves working with data from human participants. In that case, the student and their supervisor must apply for and receive ethical approval from the [Human Research Ethics Committee](#) (HREC) before the project can begin (see the paragraph 'Explanation and follow-up' after the questions). The student can submit the application to the HREC, but the supervisor is responsible for making sure that the project is compliant with relevant privacy regulations and ethical policies.

Section A. General considerations	yes	no
1. Is the graduation project conducted as part of an internship (at a company), or as part of a research project at TU Delft? If a student's graduation project is conducted at a company or as part of a research project at the university, questions of data ownership and intellectual property rights need to be addressed in a written graduation or internship agreement before the project begins. Students and their supervisor should consult the Intellectual Property Rights of Students webpage. Additional information can also be found in the Extended Personal Research Data Workflow.		✓
2. Does the project involve conducting (part of) the research outside the Netherlands? Students who intend to travel abroad (even to other EU countries) for study, exchange, research, internship, or graduation project purposes need to follow the Travel Safety Protocol. This includes attending a mandatory Travel Safety Training Session: see the Disclaimer.		✓
3. Will the research involve processing data from humans, such as running a survey, conducting interviews or workshops, collecting data through social media or internet forums, or re-using existing datasets about humans provided by a third party? (If 'yes', see follow-up questions 4 to 13 in Checklist B.) Students who work with data from human participants must complete the next section and apply for and receive ethical approval from the Human Research Ethics Committee (HREC) before conducting the research.		✓

Section B. Extended risk factors (only if question 3 has been answered with 'yes').	yes	no
4. Will the project involve participants who may be considered vulnerable, such as the elderly, refugees or asylum seekers, ethnic minorities, patients, or people with disabilities? Participants who may suffer very adverse consequences (for instance, due to discrimination) if their personal data became publicly available can be considered vulnerable.		✓
5. Will the project involve participants who cannot themselves give informed consent for taking part in the project, but for whom consent must be obtained from a legal guardian? Participants who cannot give informed consent can include, for instance, children or participants with intellectual disabilities, mental disorders, or dementia. Such participants are also considered vulnerable in the context of the General Data Protection Regulation (GDPR).		✓
6. Will the project involve processing any of the special categories of personal data below? - Race - Ethnicity - Criminal offence data - Political opinion - Union membership - Religious or philosophical beliefs - Sex life and/or sexual orientation - Health data (including measurements such as heart rate) - Biometric or genetic data (including fingerprints, iris scanning, facial recognition) The General Data Protection Regulation (GDPR) defines a stricter rules for processing special categories of personal data. If it is necessary to process these data in a project, it is important to provide additional safeguards.		✓
7. Will the project involve processing personal data that could be considered sensitive, such as the ones listed below? - Information about a person's income, debts, or other payments - Information about a person's (un-)employment status - Information about a person's performance at school or work - Information about relationship problems or (gambling) addiction - Information about poverty, domestic violence, or youth welfare/social work involvement Some types of personal data are considered sensitive, because they can have a high impact on the privacy of the data subject if other persons gain access to these data. Sensitive personal data should only be processed if necessary: in such cases, additional safeguards need to be put in place.		✓
8. Will the project involve processing video-recordings, or photographs of participants? TU Delft considers photographic and video-materials of research participants to be sensitive personal data. If such data need to be processed, additional safeguards must be put in place.		✓

Section B. Extended risk factors (only if question 3 has been answered with 'yes'.)		yes	no
9. Will the project involve sharing or transferring personal data between multiple partners or collaborating organisations involved, such as between TU Delft and an internship company? According to privacy law, sharing personal data between organisations requires a privacy agreement to be in place: setting this up takes time, and requires support from additional university staff. Furthermore, personal data sharing can potentially expose research participants to different types of risks: these risks must be considered in the ethical application.			✓
10. Will the project involve deception, or covert observation of participants? In some types of research, obtaining informed consent for processing participants' personal data is not an option: for instance, if the research involves deception, or the research is covert (conducted without participants knowing about it). In such situations, the steps to mitigate risks to participants are important, and an alternative legal basis for processing the participant's data needs to be established with the help of additional support staff.			✓
11. Will the project involve working with social media data? Social media data are personal data, but since it is usually not possible to ask for informed consent for processing social media data, another legal basis for processing the participant's data needs to be established. Processing of social media data also involves legal considerations related to terms of use of data from third-party platforms: therefore, research with social media data requires expert support on privacy, ethics, and legal matters.			✓
12. Will the project involve using learning algorithms or other AI to analyse, combine, or otherwise process data from participants? The use of AI in research involves many considerations in terms of data protection, ethics, security, and intellectual property: for more information, see TU Delft's Instructions for use of Generative AI.			✓
13. Will the project involve participants who are based in a country or countries outside of the EU? Students affiliated with TU Delft must comply with Dutch and EU regulations of personal data processing (GDPR). Furthermore, the student and their supervisor must make sure that the research complies with local (privacy) legislations of any foreign destinations. Additional support from an external (local) expert may be required.			✓

Explanation and follow-up

If you have answered 'no' to all questions 4 to 13, your project is likely to be considered low or minimal-risk: see the paragraph 'Projects with minimal or low-risk' on the next page.

If you have answered 'yes' to one or more of the questions 4 to 13, your research likely involves extended or high risks to participants, according to the [General Data Protection Regulation](#) (GDPR) and TU Delft's privacy and ethical policies: for information regarding such projects, see the paragraph 'Projects with extended or high-risk' on the next pages.

Additional support

Once the DMP has been compiled and reviewed by the supervisor, feedback should be requested from the Data Steward via DMPonline. After this, any other necessary support staff will need to be contacted. Crucially, if the project involves one or multiple ways of personal data processing that could result in high-risk to the participants according to the GDPR, the TU Delft Privacy Team must be consulted to establish whether or not a [Data Protection Impact Assessment](#) (DPIA) is required.

Additional resources

The HREC has guides available for [completing the checklist](#) and for compiling [informed consent materials](#). Additionally, the [Guide to the Extended Personal Research Data Workflow](#) has been created to help researchers and students who work with human participants comply with both GDPR principles and TU Delft's policies on Data Management and Human Research Ethics.

Timeline

It can take a long time to compile a complete research plan and HREC application for projects involving extended risks. DMP feedback from the Data Steward usually takes around 2 weeks, but can take longer during busy periods or holidays. Receiving additional support from other staff, such as the Privacy Team, can take anywhere from a few days to multiple weeks, depending on the project and capacity of university staff. If a DPIA is deemed necessary, it can take anywhere from 4 weeks to several months.

It is important to note that advice from the Privacy Team or other support staff, as well as any additional documents (such as necessary contracts, or a DPIA, if needed) must be in place before the application is submitted to the HREC. The initial evaluation by the HREC can be processed in 2 weeks, but may take longer during busy periods or holidays: see the [HREC website](#) for up-to-date information. Additionally, the application may require revisions before final approval is granted. If you do not receive an initial response about your ethical application after 4 weeks from the time of submission, you may follow up with the HREC to enquire about an update.

Considering the limited time available for students conducting their graduation projects, students working with data from human participants are strongly advised to prioritise low-risk research projects. If a student project necessitates processing data in ways that are considered extended or high-risk, both student and supervisor need to be aware of the extended processing times involved in obtaining ethical approval and beginning the graduation project.