

# Shape-morphing greenhouse: design of a thermally responsive transparent 4D-printed structure

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## Abstract

**Purpose** – Conventional greenhouse structures, particularly the multi-component assemblies of glass panels with rigid metal frames, face multiple limitations. Major advancements in FDM and four-dimensional (4D) printing offer a disruptive platform for macroscale responsive structure design. This project explores a proof-of-concept of using transparent polylactic acid (PLA) to create a single-part, thermally responsive greenhouse structure through 4D printing. The goal is to demonstrate the concept of passively opening at elevated temperatures, eliminating the need for complex assemblies with motors, sensors, and external control systems.

**Design/methodology/approach** – This research combines material characterization, bio-inspired ideation, and testing as part of the design methodology. Three actuation concepts, the pinecone, fish gills, and zero Poisson ratio (ZPR) mechanisms were developed and 3D printed. Each design was evaluated for optical transparency, structural stability, and thermal actuation.

**Findings** – Testing showed potential in using shape memory polymers for shape-morphing greenhouses, even though in this proof-of-concept there are limitations. PLA's relatively high glass transition temperature (63.5 °C) eliminates usage for real greenhouses, and opening was often gravity-driven rather than internal stress-induced. The pinecone design showed the most visible actuation but suffered from reduced transparency. The ZPR concept demonstrated potential for large-area openings but failed structurally.

**Originality/value** – The results highlight the potential of transparent PLA for 4D-printed responsive structures, enabling bio-inspired designs and morphing greenhouses. Recommendations include improving material responsiveness, integrating sealing features, optimising greenhouse parameters and further developing actuation mechanisms with modeling. This study provides an initial step toward scalable, electronics-free greenhouse ventilation systems.

**Keywords** 4D printing, Shape-memory polymer, Thermally responsive structures, Bioinspired design

**Paper type** Research article

## 1. Introduction

With intensifying extreme climates, growing crops in controlled environments becomes increasingly important for food security. However, conventional greenhouse design is limited by the use of a labor-intensive, glass panel and rigid metal structure. The use of flat glass panels limits the geometric design, possibly missing out on optimal energy capture. Furthermore, assembling greenhouses costs significant time and the multi-component design causes unneeded complexity and failure possibilities.

Addressing these limitations requires a fundamental shift in design and manufacturing approach. Recent research into 4D printing has shown its potential for creating structures that adapt over time in response to external stimuli. By integrating time as a design parameter, 4D-printed components can deform without active control, enabling new approaches in fields such



as soft robotics, biomedical devices, and responsive macroscale structures. This project explores the use of 4D printing to develop a thermally responsive, transparent greenhouse structure that passively opens at elevated temperatures.

The aim is to create a single-part, 3D-printed proof-of-concept using transparent polylactic acid (PLA), demonstrating passive actuation with temperature as stimulus. The focus lies on identifying effective actuation mechanisms, achieving sufficient light transmission, and ensuring basic structural performance.

The design is approached using the refined Double Diamond method, ensuring a structured yet iterative approach to problem solving and concept development (Pandey *et al.*, 2024). To support the development process, literature on PLA behavior, 4D printing techniques, and greenhouse requirements is reviewed. The design problem is then defined. Bio-inspired concepts are developed and tested for thermal response, optical clarity, and mechanical stability. The testing results are presented and used for recommendations. The result provides insight into the feasibility and limitations of 4D printing for meso-scale adaptive structures.

Four-Dimensional (4D) printing is a relatively new advanced manufacturing process, integrating time into three-dimensional (3D) printing. The material reacts to an external stimulus, deforming in a designed manner. The material can be thermo-, photo-, hydro- or magneto-responsive, with either a singular or multiple stimuli (Kortman *et al.*, 2024). The technique is used for a wide variety of applications, such as soft robotics, biomedical applications, self-assembly, and the aerospace and automotive sectors (Chen *et al.*, 2024a). As 4D-printed materials are pre-programmed and self-sensing and actuating, they eliminate the need for sensors and actuators and reduce the amount of parts and materials needed significantly. While a model-based method shows promise for designing morphing structures, it is kept as future work (Chen *et al.*, 2024b). The main materials already used in practical applications are hydrogels for biomedical use, nickel-titanium (NiTi) shape memory alloys for high-performance mechanical use and shape memory polymers (SMPs). The ease of use of polymers like PLA and PCL in 3D printers is a big advantage over other materials (Momeni *et al.*, 2017; Bodaghi *et al.*, 2024).

PLA is a common polymer used for shape-memory structures, due to its ease of use in 3D printers, and therefore it is an excellent option for this research. The stimulus for the shape memory of PLA is temperature. SMPs like PLA are easily deformed in their rubbery state, when the temperature is higher than the glass temperature  $T_g$ , which for PLA is 63.5 °C (Mehrpouya *et al.*, 2021). If the sample is cooled to  $T < T_g$  in deformed state, also known as programming, internal stress is present and the deformed state is locked. When the temperature is then raised above  $T_g$  the internal stresses resolve and the sample returns to its original shape. This behavior can be used to make one-piece adaptive parts.

To manufacture a feasible proof of concept, the PLA has to transmit enough light for plant growth. According to two leading companies in 3D printing equipment, printing vase mode (one layer wall thickness) with high layer height yields the most transparent results for PLA. Optimal layer adhesion is achieved by using a high printing temperature within the filament manufacturer's recommended range, minimal cooling, and a slightly increased extrusion rate (*Tips and tricks for easy printing with transparent PLA*, 2022; Ultimaker, n.d.). Additionally, reducing the printing speed to 20 mm/s further improves adhesion, which in turn enhances print transparency (*Tips and tricks for easy printing with transparent PLA*, 2022). Since improved adhesion correlates with increased tensile strength, the higher tensile strength observed for greater layer heights (75% of the nozzle diameter (Cahyati and Furqon, 2022)) suggests that increased layer height also improves transparency.

In addition to visual transparency, the light extinction coefficient  $\mu$  for the wavelength range of visible light (400–700 nm) is examined and it is found that the transparent PLA with a slight pink color has the lowest  $\mu$  for visible light (Amendola *et al.*, 2021). This means that less light gets absorbed or scattered and more light gets transmitted through the sample. These combined findings present PLA as a perfect candidate for the proof-of-concept design.

Besides light, plants' physiological processes, including photosynthesis and respiration, are highly dependent on other environmental factors, with temperature being one of the most critical. The plants taken into account in [Ponce et al. \(2014\)](#) use more sugar than they produce from 27 °C and stop both photosynthesis and respiration above 35 °C. Light in between 400 nm and 750 nm wavelengths is used for photosynthesis, with light between 600 and 700 nm being the most effective ([McCree, 1972](#)). In combination with the fact that PLA transmits most light in that range as well, it presents itself as a promising material.

The design of a traditional greenhouse is limited by the flat glass panels used, but inspiration can be taken from earlier geometric design research. The uneven-span design receives maximum solar radiation, making it the best suitable for 50 °latitude, capturing most of the sun's energy in the colder climate ([Sethi, 2009](#)). The gothic arch-shaped greenhouse is found to require less heating compared to even-span (gable) and quonset shapes. Furthermore, to further decrease the heating need the north wall can be made opaque and insulated ([Gupta and Chandra, 2002](#)). In general, east-west orientation is best for year-round applications ([Sethi, 2009](#); [Gupta and Chandra, 2002](#)). As uneven span and gothic arch designs are not tested directly, however it can be assumed that an uneven gothic arch with opaque north wall is most optimal greenhouse shape.

Automatic opening greenhouses exist, but they use multipart gas-filled cylinders, which can increase complexity. Using 4D printing for producing greenhouses could offer the solution to the complexity of the current design, integrating responsiveness and automatic opening in one part. To achieve this goal, inspiration will be taken from biology, where multiple adapting structure provide possible designs.

To the author's knowledge, no research has been done into large-scale SMP structures, a gap this paper aims to fill. Traditional greenhouses made of glass panels nowadays often have automatic opening mechanisms, however the added complexity diminishes reliability. 4D printing a transparent greenhouse would fill this gap, with an unrestricted shape as an additional benefit.

## 2. Conceptual design

In this section, the literature review and the bio-inspired design process come to the conceptual designs. Based on the design requirements, three designs are presented, with different bio-inspirations. Based on the preliminary research, PLA is selected as the working material due to its transparency and thermally responsive behavior, despite its relatively high glass transition temperature. Its properties are suitable for demonstrating passive actuation within the scope of a proof-of-concept, without being a realistic final material for cultivating plants. Industry-ready materials do exist, which are possible to be engineered to the desired properties. An uneven gothic arch geometry is considered the starting shape, inspired by its potential for maximizing solar capture in colder climates when combined with an opaque north wall. Literature research and early printing trials indicate that a single-line wall thickness offers the best transparency and clarity, this will be used for the south wall. These insights inform the direction of the first design iteration, which will be printed in an open position to allow opening under thermal activation, not using complex preprogrammed internal stresses during printing.

### 2.1 Design problem formulation

A greenhouse must maintain a stable internal environment to support plant growth. Traditional greenhouses rely on mechanical ventilation systems or manual intervention to regulate temperature. Wax-based mechanisms that open and close windows for ventilation exist, however, they are relatively heavy and contain multiple parts. A 4D-printed greenhouse offers a potential alternative, the structure can adapt passively, without multiple-part mechanisms or motors and sensors.

However, most 4D-printed applications rely on small-scale flexible or opaque structures, which are unsuitable for greenhouse applications that demand both larger scale mechanical stability and transparency. Additionally, the thermal response of affordable materials like PLA has not yet been fully explored in architectural contexts.

This project aims to develop a proof-of-concept greenhouse model that passively opens in response to heat using see-through PLA, fabricated in a single 3D-printed part. The focus lies on designing for thermal actuation and bio-inspired opening mechanisms, while reporting on visual transparency and structural load-bearing capacity. While the  $T_g$  of PLA is significantly higher than acceptable temperatures for plants, it is used for exploring the concept and methodology. The resulting mesoscale design will serve as a demonstration of feasibility for future scalable systems up to macroscale.

## 2.2 Design requirements

For this project, the requirements are the following:

Functional Requirements.

- (1) **FR1:** The structure must demonstrate observable deformation in response to temperatures above  $T_g$ .
- (2) **FR2:** The structure must fully close when programmed.
- (3) **FR3:** The actuation mechanism must be embedded in a single print (no assembly).
- (4) **FR4:** The structure must be printable using commercially available transparent PLA.
- (5) **FR5:** The prototype must demonstrate optical transparency by allowing measurable light transmission through the printed south-facing wall.

Performance Requirements.

- (1) **PR1:** The prototype must open visibly close to  $T_g$ , within a temperature range of 55–75 °C.
- (2) **PR2:** The south-facing wall must achieve 50% optical transparency under test conditions.
- (3) **PR3:** The structure must remain intact under a vertical load of at least 15 N (simulating snow).

Future Requirements.

Because the current goal is to prove the concept of a self-actuating greenhouse, the following requirements currently remain out-of-scope, but should be considered in future iterations to achieve a final working product.

Future requirements include achieving: cyclic loading and opening without significant performance deterioration; enduring water and weather effects; transmitting the required spectra and photosynthetically active radiation.

## 2.3 Design inspiration

To explore potential mechanisms for thermally actuated greenhouse openings inspiration is taken from nature, its material behavior, and structural transformation principles. A range of biological and mechanical systems were analyzed, and recurring themes were identified based on relevance to 4D printing, and reversible movement.

Three main concepts were selected for further development based on diversity in movement strategy and feasibility of implementation using clear PLA: the pinecone, fish gill and kirigami based design.

Firstly, the opening and closing of pine cones is a mechanism that uses humidity as an indicator of favorability for seeding. When the environment is wet, wind dispersion conditions

are not favorable and the pine cone closes. When it is dry, the seeds are released (Eger *et al.*, 2022). The reversible opening and closing of the bracts is used. Absorption of water causes the sclerenchyma fibers to soften and the sclereid layer to expand longitudinally. Together these two events cause bending of the bract.

The flexible armor of pangolins is an example how the design of a structure can protect its contents, while remaining flexible to open. The structure consists of overlapping hexagons which makes the design effective for keeping out the elements and other dangers (Wang *et al.*, 2016).

The design that follows is a roof with rhombus-like shape roof tiles that close to a solid roof.

The second design is based on fish gills, which are specialized respiratory organs that extract oxygen from water allowing breathing under water. They consist of thin, layered filaments covered in lamellae, which increase surface area for gas exchange. The gills are optimized for flow over their surface because of their overlapping structure. The flap-based structure provides directional control and modularity.

Gills are not only actuated by the fish's muscles, but also directed by the flow of the water between them. When the muscles relax, water opens them up. Similarly to this mechanism, wind could act for the design of the greenhouse, opening gill like structures for ventilation.

Thirdly, inspiration is taken from the art of Kirigami, where flat structures are cut with designed deformation as a result. It can be used to form auxetic (negative Poisson ratio) structures that, when expanded axially, also expand laterally. With traditional manufacturing processes, these structures are tedious to produce, but additive manufacturing provided a fast and reliable alternative (Joseph *et al.*, 2021). Combining kirigami and auxetic materials, bistable, out-of-plane deformations structure are produced with designs that enable tunable shape-morphing and predetermined transformation sequences (Kim and Park, 2025). Furthermore, the combination of auxetic shapes with SMPs has been investigated before, where great promise for reusable energy and impact absorbers was shown (Shadman *et al.*, 2025).

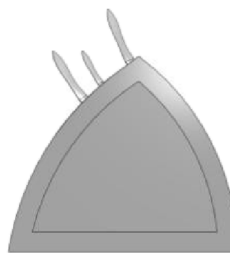
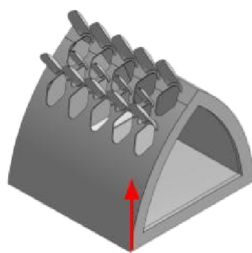
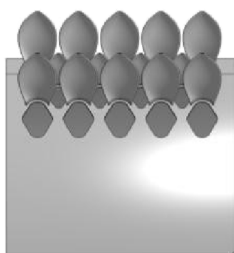
As the structure needs to close of a wall or roof completely, a rotating (semi-) rigid cell structure is used. The angle of the cells in the open position cannot exceed an overhang of 60° compared to the vertical because of printability. Perforated sheets can be seen as an extension of the field of rigid cell structures, with diamond shape perforated sheets closely resembling rectangular cells. The dimensions and resulting Poisson ratio can be seen in 1. From the Poisson ratio 0 and  $\theta = 70^\circ$  follows the ratio  $a/b \approx 0.7$ .

$$\nu_{xy} = (\nu_{yx})^{-1} = \frac{a^2 \cos^2\left(\frac{\theta}{2}\right) - b^2 \sin^2\left(\frac{\theta}{2}\right)}{a^2 \sin^2\left(\frac{\theta}{2}\right) - b^2 \cos^2\left(\frac{\theta}{2}\right)} \quad (1)$$

**Fundamental differences** As mentioned before, the first three design are fundamentally different, testing multiple concepts and mechanisms. The designs can be seen in Figure 1.

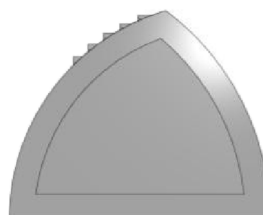
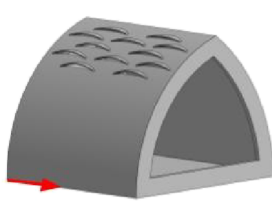
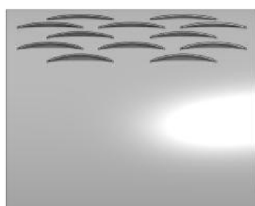
Firstly, the pinecone design differs from the others being a solid structure with opening bracts that open with a large deformation (more than 90°). The design has holes with multiple sizes. The fishgill design distinguishes itself from the others by being printed from the side instead of the bottom, having small slits as openings rather than large holes and the open-close deformation is much smaller.

Lastly, the zero Poisson ratio (ZPR) design is fundamentally different by fully opening the whole structure. The full north wall opens, pushing the south wall up and open. The side wall has to be printed at an angle to prevent it from intersecting the ZPR mechanism and thus also opens when the greenhouse is heated past activation temperature. Furthermore, the ZPR design opens on the opaque north wall, instead of the south wall the other designs open.



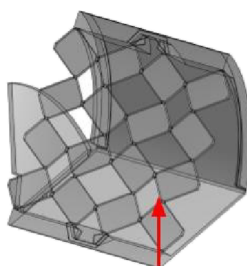
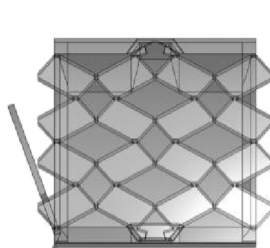
The pinecone design

(a)



The fishgill design

(b)



The rotating rigid cells with zero poisson ratio design

(c)

**Figure 1.** The first three CAD designs, with the red arrow showing the print direction. Source: Author's own work

### 3. Prototypes and testing

The designs are printed in PLA, and thereafter tested structurally, for clarity and opening.

The design are 3D printed in one piece using transparent PLA, on a footprint of 150 by 150 mm. If any are present, supports are removed and the sample is visually inspected for defects. After successfully manufacturing the prototypes, the tests are executed.

3.1 Fabrication parameters

To print the samples, the following parameters are used. A Bambu Lab X1 Carbon FDM printer is used, with Spectrum Premium Translucent PLA filament. For transparency, a larger 0.8 mm nozzle is used, flow ratio is heightened to fill any holes and layer height is increased. Nozzle temperature is changed to the maximum within the recommended range from the manufacturer and finally the cooling is set to 0% fan speed and outer wall speed is reduced to improve adhesion. Final settings can be found in Table 1, all other settings are kept at the default setting.

3.2 Testing protocol

To ensure experimental consistency, the testing protocol detailed in Figure 2 was developed.

Table 1. Final altered printing parameters

| Parameter          | Default (Bambu Studio) | Used    |
|--------------------|------------------------|---------|
| Flow ratio         | 0.98                   | 1.01    |
| Nozzle temperature | 220 °C                 | 215 °C  |
| Layer height       | 0.4 mm                 | 0.56 mm |
| Speed (outer wall) | 120 mm/s               | 20 mm/s |
| Cooling            | 100%                   | 0%      |

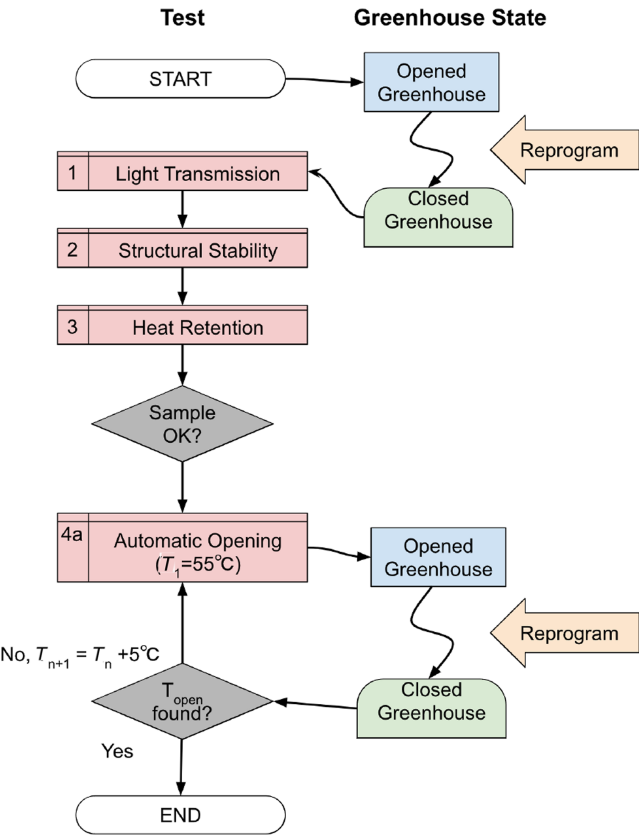


Figure 2. The full testing protocol in a flow diagram

**Sample Programming** To activate the sample, in other words close the greenhouse by deforming the printed part, the sample is submerged in hot water ( $>65^{\circ}\text{C}$ ) until the part is full past the  $T_g$ . The part is deformed and set to cool down to room temperature. Small local deformations can be made by heating up the area with the heatgun and deforming accordingly.

**Test 1: Optical Clarity Test** The objective of this test is to validate and compare light transmission through the greenhouse wall to evaluate suitability for plant growth and daylight entry. A flashlight with fixed distance from the sample is used to illuminate a lux sensor inside the sample.

**Test 2: Structural Stability Test** Next, to ensure the greenhouse remains stable under external forces, a structural test is executed. As snow is the riskiest weather influence, this is used to determine the load. To simulate a normative snow load, a vertical force of 15 N is used (scaled from a  $0.85\text{ kN/m}^2$  snow load using NEN-EN 13031-1 (NEN, n.d.)).

**Test 3: Heat Retention Test** To test how well the greenhouse retains heat, the sample is heated up and left to cool down.

**Test 4: Automatic Opening Test** To verify at what temperature the greenhouse opens, it is iteratively kept at an increasing steady temperature. Temperature, heating on/off and time is logged.

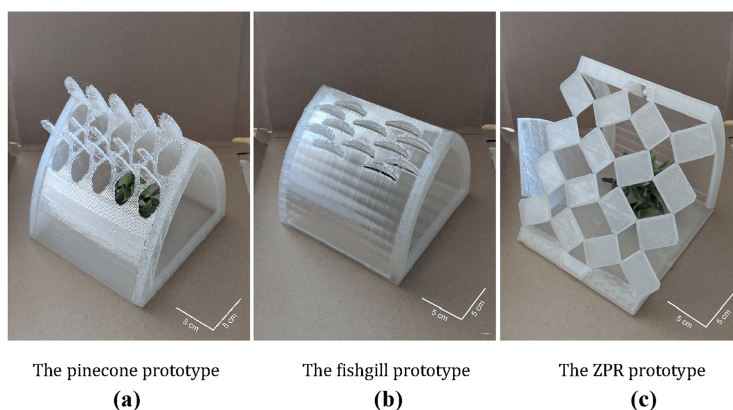
### 3.3 Printed prototypes

The printed prototypes can be seen in Figure 3.

### 3.4 Test results

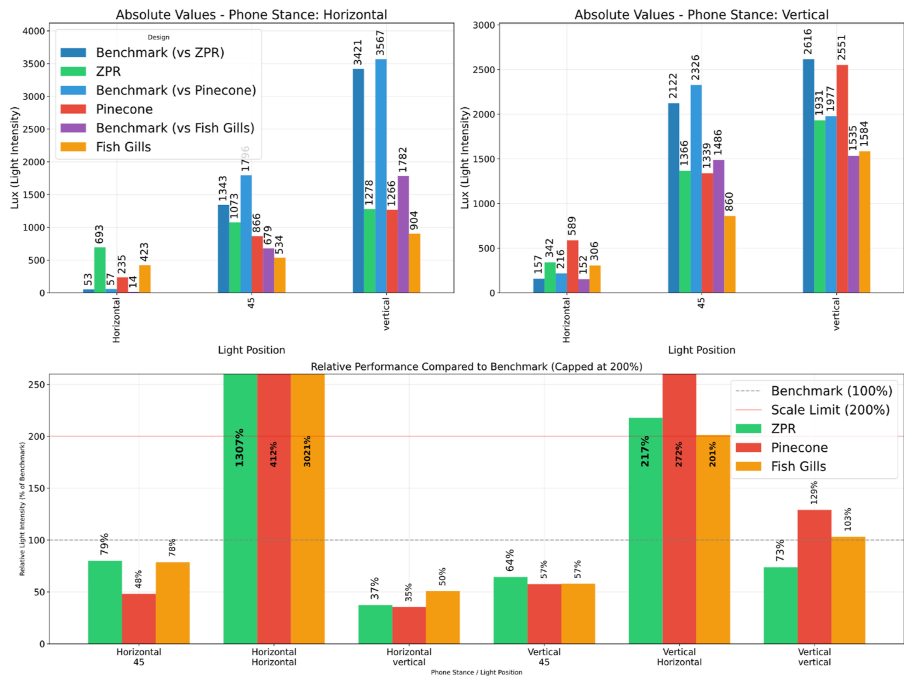
**Test 1: Optical Clarity Test** It can be seen in Figure 4 that in most phone stance and light positions the ZPR design has a better transmittance with the fish gill design as a close second, with the pinecone design being the worst light transmitter.

**Test 2: Structural Stability Test** All designs can withstand the load of 15N. Upon further loading the pinecone and fish gills designs do not deform significantly but the ZPR design deforms at the location of the hinge points of the rigid cell wall, out-of-plane.



**Figure 3.** The first three printed prototypes, scaled and from top front left view. Source: Author's own work

Greenhouse Light Intensity Measurements



**Figure 4.** The optical clarity test results, comparing the benchmark test done before each test. Source: Author's own work

**Test 3: Heat Retention Test** It can be seen in [Figure 5](#) that the pinecone design retains heat the best. All designs retain heat significantly better than open air.

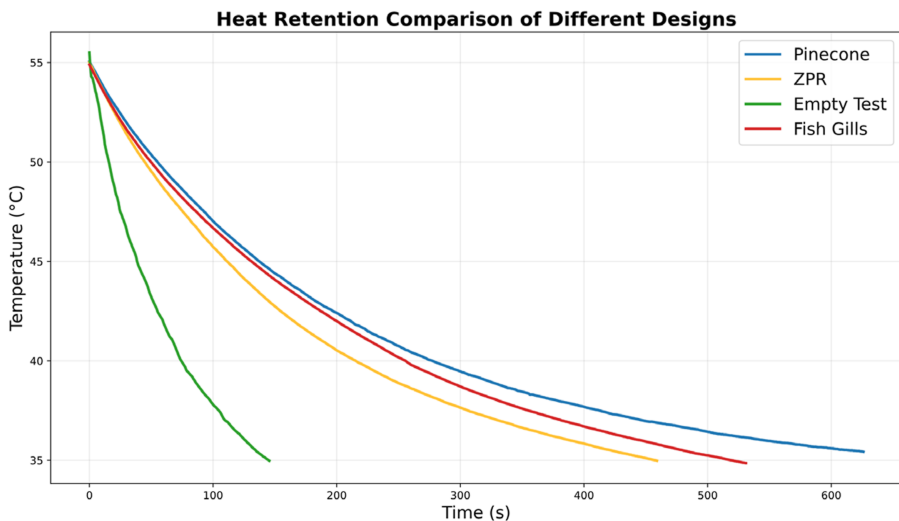
**Test 4: Automatic Opening Test** The results are best at  $T = 65^{\circ}\text{C}$ , which test is highlighted in [Figure 6](#). It can be seen that again, the pinecone design retains heat the best with a heater duty cycle of 23.1%. The heater is turned on less frequently and for a shorter amount of time in that test. At this temperature the ZPR design has opened most significantly, requiring a high duty cycle relative to the other designs compared to the other temperatures.

In [Table 2](#) it can be seen the pinecone design, from the top front right view opens up for the largest area, and has the largest percentual increase in area. The concepts start opening at different temperatures, with the pinecone and ZPR concept starting at  $65^{\circ}\text{C}$ , and the fish gill concept at  $70^{\circ}\text{C}$ .

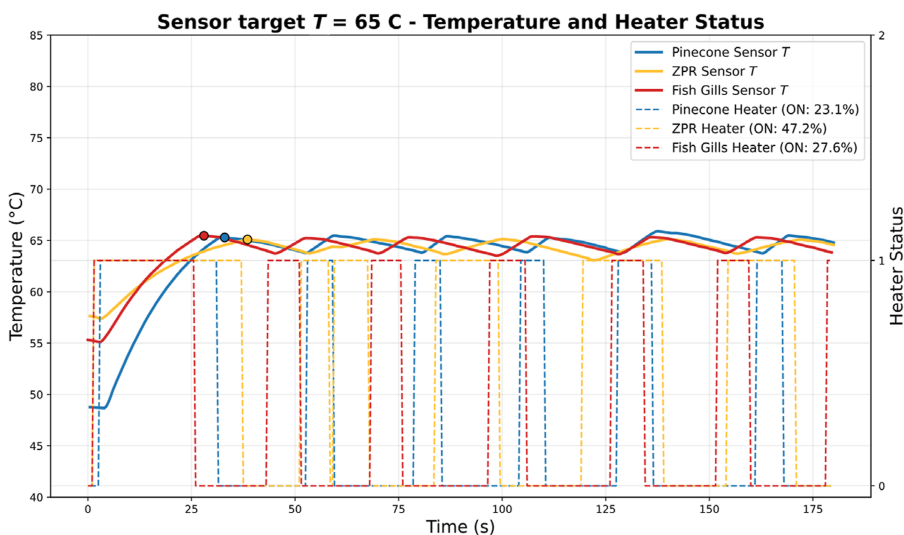
3.5 Discussion

This paper shows the potential of the use of 4D printing for thermally activated structures. Three bio-inspired designs were printed in PLA, a widely available shape-memory polymer. Two were based on biological mechanisms and the other on rigid cell auxetic structures. Tests were conducted in which multiple design objectives were met: light transmission, structural load capabilities and the single print objective. Observable deformations at test temperatures were also recorded.

Specifically, the pinecone concept showed significant deformation and good structural performance. The fish gill design provided improved transparency and rigidity. The ZPR



**Figure 5.** The heat retention of the different designs, from 55 °C. Source: Author's own work



**Figure 6.** Automatic opening test at  $T = 65$  °C. Source: Author's own work

design presented itself as the concept with largest potential for cooling the interior of the greenhouse fast.

However, the outcome falls short of other objectives, particularly in achieving reliable, passive actuation under real-world conditions. Each design presented trade-offs. The pinecone concept suffered from reduced optical clarity, while the fish gill design failed to deform significantly. The ZPR design, while conceptually promising in opening with a large surface, exhibited poor structural integrity and limited actuation due to rotating rigid cell also being the structural support for the south wall. Moreover, deformation in all designs was dominated by

gravity rather than internal stress release, indicating that the one-way shape memory behavior of PLA offers limited value when designed against gravity. Thus, when improving and scaling the designs from meso-to large-scale, the relative force exerted by shape memory needs to be improved and orientation relative to gravity of large-scale panels can be added as a design parameter.

Next to the designs, the material used was inherently flawed for the use case. While transparent PLA successfully transmitted light and softened under heat, the material’s relatively high glass transition temperature (63.5 °C) exceeded typical greenhouse conditions. Programming the designs was a tedious process due to the large amount of hinges or deformation areas.

The testing methods were insightful but constrained. Structural load testing was static and did not address cyclic or dynamic behavior. The area increases in Table 2 were taken from an angle that favors the bract design of the pinecone concept. Transparency testing lacked spectral sensitivity, photosynthetically active radiation testing and calibrated equipment and is therefore not repeatable. Environmental stress factors, including UV exposure, cyclic aging, moisture ingress and effects, and thermal fatigue, were acknowledged but not tested. Sealing performance, which is essential to greenhouse viability, remained entirely theoretical. For future versions, the testing protocol will significantly be improved, adding these changes to the tests.

Efforts to optimize transparency, such as using single-line walls, compromised both print consistency and mechanical stability. This resulted in fragile and inconsistent structures that undermined the core design objectives.

Finally, the reliance on manual actuation and the lack of two-way shape memory further limited the system’s autonomy. This autonomy was central to the original problem formulation.

4. Conclusions

This paper presents multiple responsive, 4D printed model greenhouses, which showcase the proof-of-concept for using this manufacturing process for large-scale structures. The conceptual designs draw inspiration from biology, with multiple adapting structures providing unique solutions with tailored behavior. The designs are intended for greenhouse usage, including temperature retention, opening mechanism and light transmission. This study addresses the gap of using 4D printing for larger-scale structure design and provides a novel approach to adapting buildings.

With this study it was shown that adaptive structures can be used for non-assembly greenhouses, with transparent 4D-printing allowing for complex bio-inspired shape-morphing structures. These designs allow optimisation for opening, energy absorption and plant respiration.

Transforming this meso-scale prototype into a deployable, large-scale solution necessitates further research focused on several key areas. Material selection should be reconsidered, to both provide a more suiting actuation temperature and increase the actuation force to

**Table 2.** Opening area from static photographs, with a top front right view. Area measures in amount of pixels (e3 pixels)

| Concept   | Programmed area | 60 °C | 65 °C | 70 °C | 75 °C | Max ^%        |
|-----------|-----------------|-------|-------|-------|-------|---------------|
| Pinecone  | 52              | 60    | 97    | 113   | 110   | +117% (70 °C) |
| Fish Gill | 28              | 29    | 29    | 36    | 36    | +28% (70 °C)  |
| ZPR       | 60              | 60    | 84    | 77    | 88    | +47% (75 °C)  |

counteract gravity. Furthermore, integrating a sealed design which opens with a larger area would increase the performance of the design. The testing protocol needs to be expanded to effectively test the iterated designs and modelling could be used for advanced designs (Chen *et al.*, 2024b).

Through targeted iteration, modelling and material innovation, the greenhouse application of 4D printing can provide a solution for decreasing greenhouse complexity and start a new generation of large-scale usage of 4D printing for adaptive structures.

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