Design and Computational Modelling for a Shape Memory Alloy-based Adaptronic Architecture

Student **Yufe Wong**
Number **4631579**

MSc Thesis P5 Presentation
2nd July 2018

Committee: **Peter Eigenraam, Serdar Asut, Kaspar Jansen, Marjolein Spaans**

Final Energy Use in the EU

Europe consumes **half of its energy** for heating and cooling purposes.

Most of this thermal energy is used in buildings and industry.

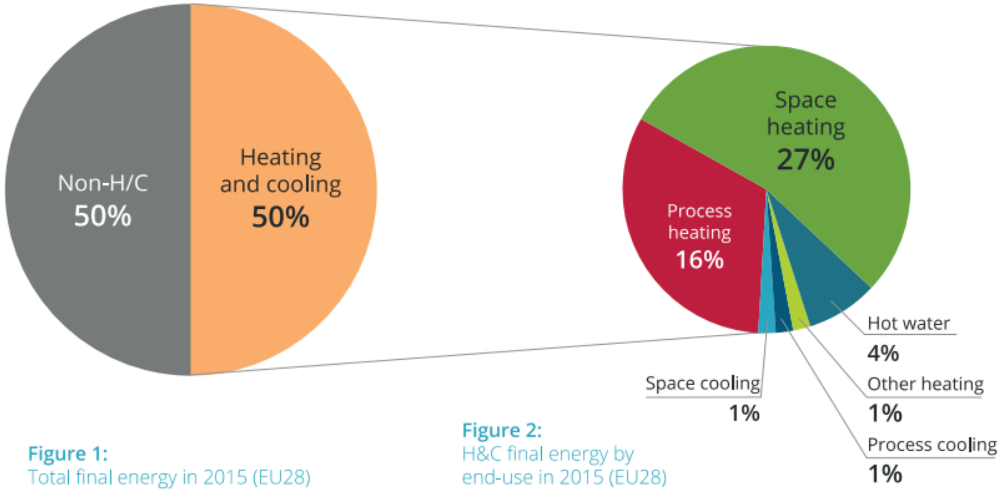
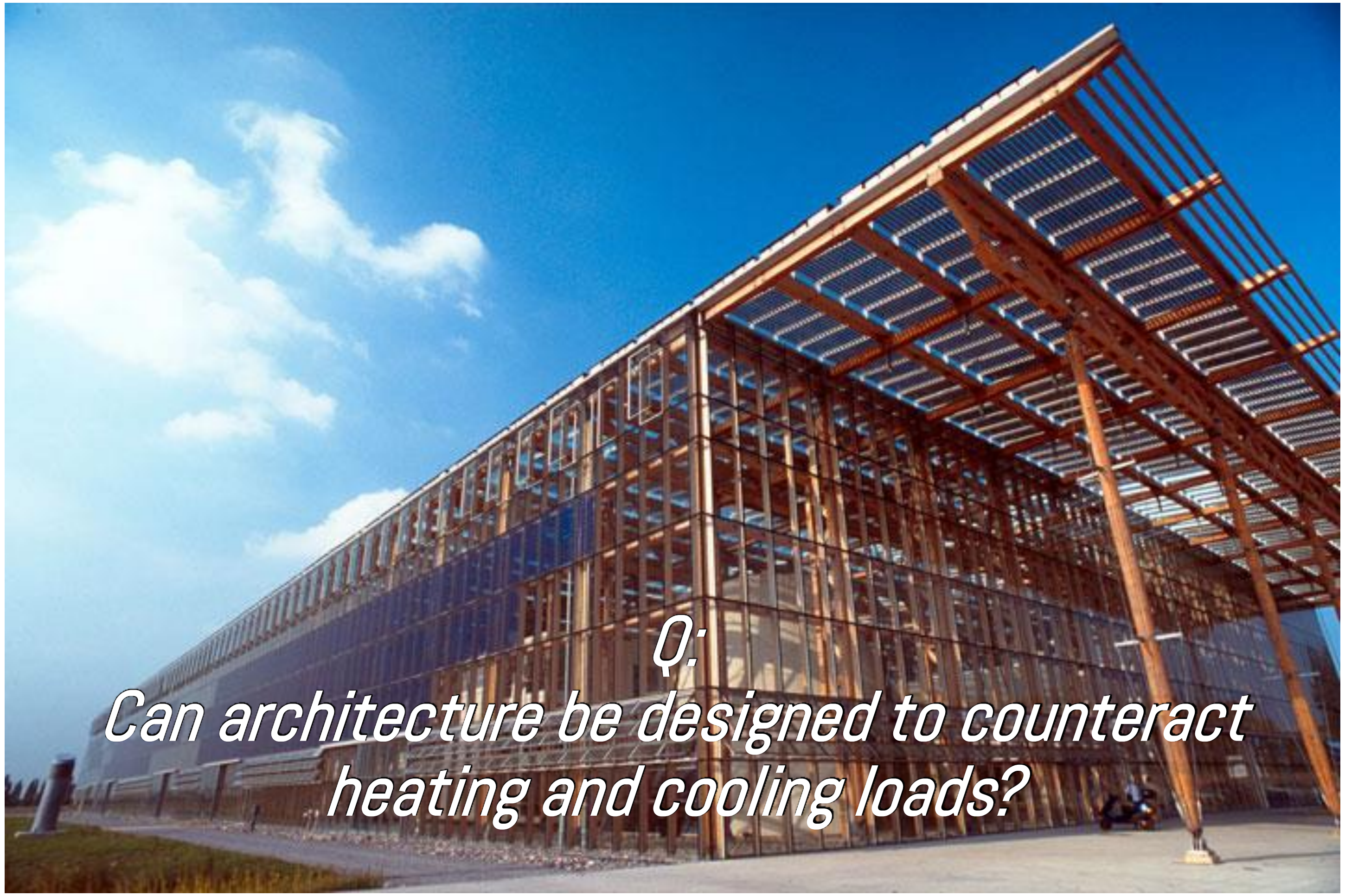


Figure 1:
Total final energy in 2015 (EU28)

Figure 2:
H&C final energy by end-use in 2015 (EU28)

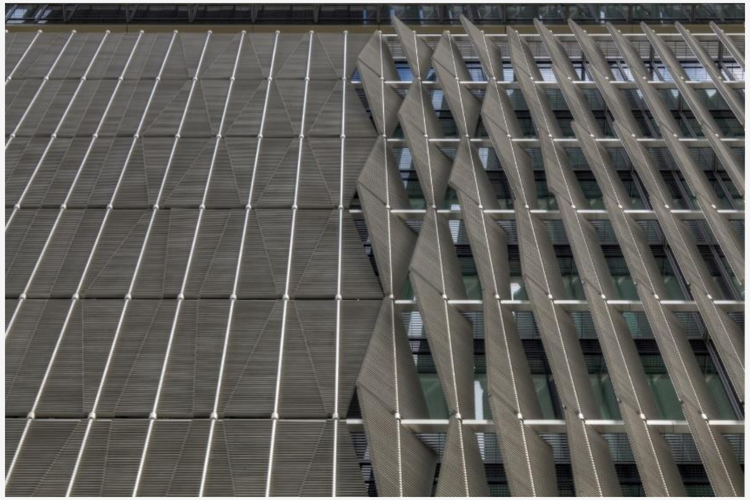
Source: Heating and Cooling Facts and Figures, Heat Roadmap 2017

14%



Academy Mont-Cenis Herne, Germany,
Studio Gang Architects

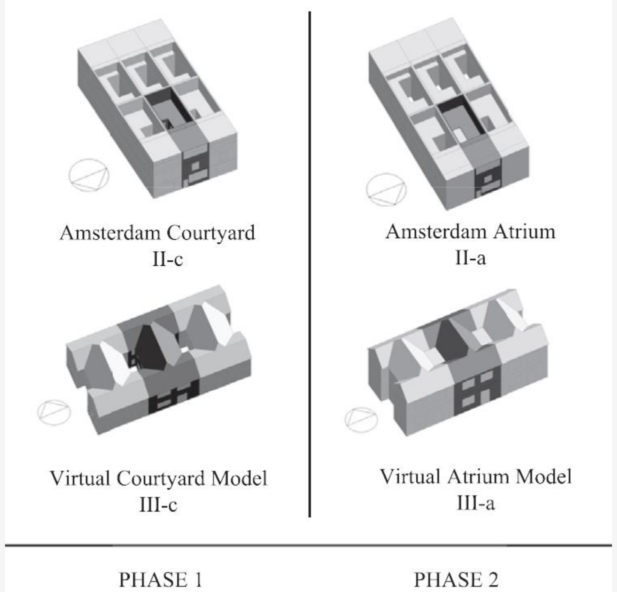
Conventional:
Seasonal shading



Summer: Shade the interior spaces from direct Sun
Winter: No shade

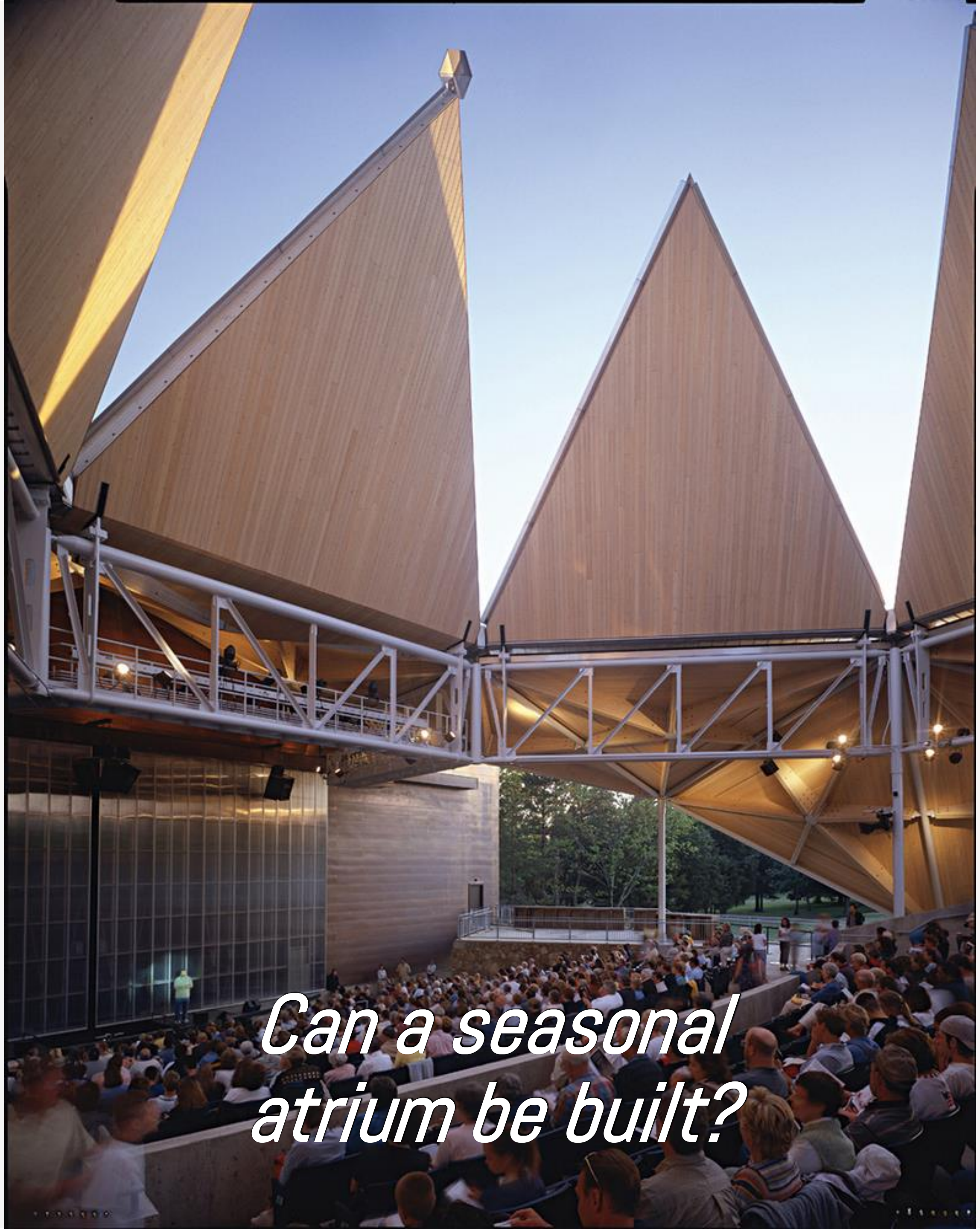
Yes.
Increase the solar thermal gain in the Winter times, and minimize it in the Summer times

Novel:
Seasonal glazing

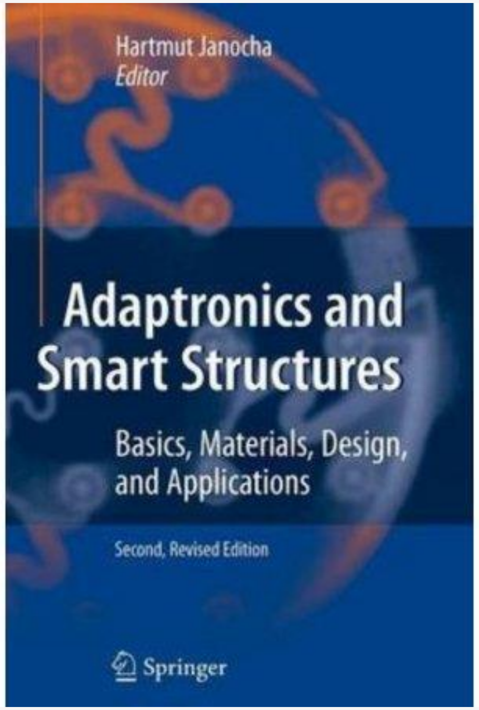


Summer: Open Courtyard
Winter: Atrium courtyard for greenhouse effect

Source: Energy performance and thermal comfort of courtyard-atrium dwellings in NL in the light of climate change, Taleghani et al., 2013



Bengt Sjostrom Starlight Theatre, Illinois,
Studio Gang Architects

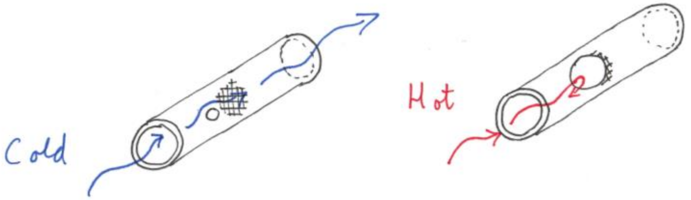


Adaptronics

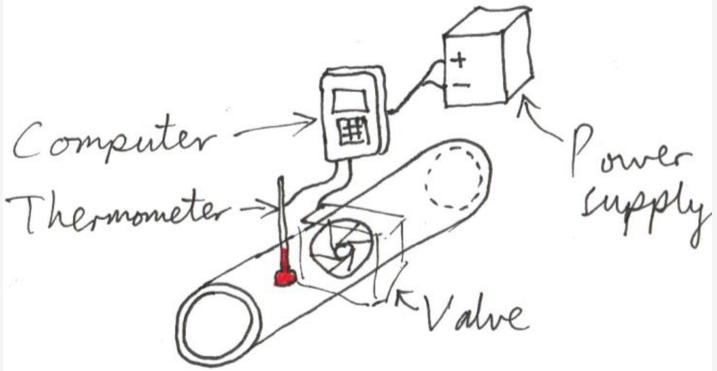
"the integration of actuators, sensors and controls with a material or structural component"

– Rogers and Giurgiutiu in *Adaptronics and Smart Structures (1999)*

Adaptronic method



Conventional method



Shape Memory Alloys (SMAs)

SMA petals

Cold

Heated

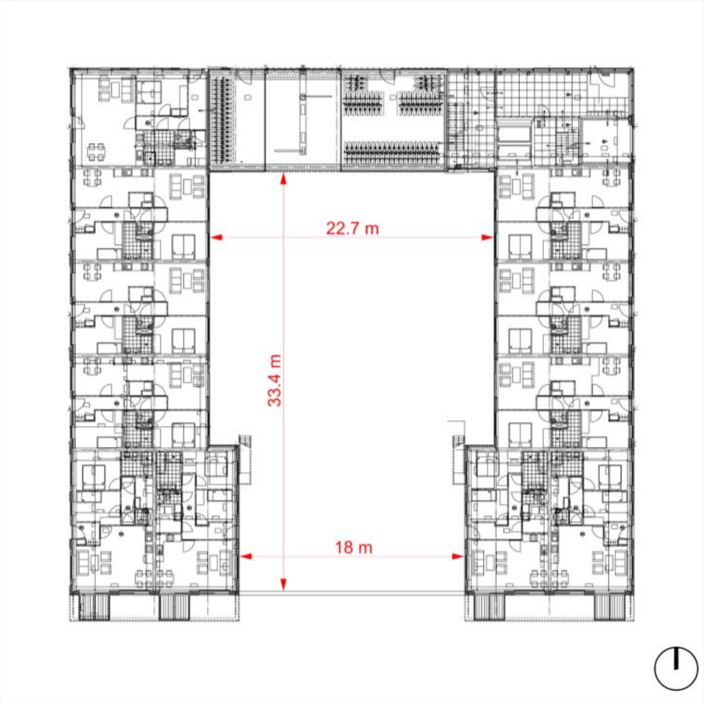
Source: University of Birmingham

Main Objective For Thesis


To investigate the feasibility and process of constructing an adaptronic façade module based on Shape Memory Alloy behaviour


Design Brief

Gerschwin Brothers Building, Amsterdam



An existing 7-storey residential building with a South-facing courtyard in Amsterdam Zuid

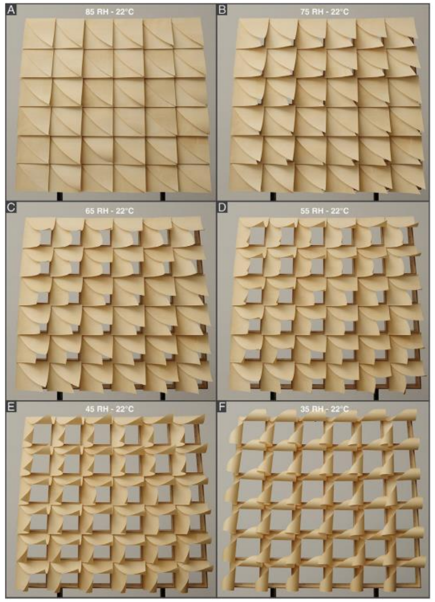
Output


1. Computational tool to help non-specialists model the behaviour of an SMA piece
2. Prototypes to validate the concept of the mechanisms
3. Design for an adaptronic façade module


Reference Projects

Adaptronic Facades

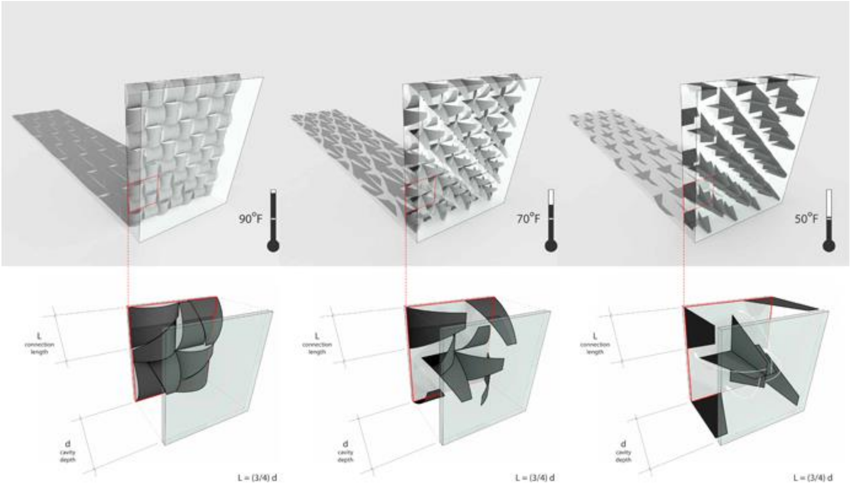
3D-printed cellulose fibres and polymer vents



Humidity causes vents to open

Correa et al., 2015

Bimetal shading between glazing



Direct sunlight causes shading to deploy

Doris Kim Sung, 2012

SMA-based shading between glazing

Direct sunlight causes shading to deploy

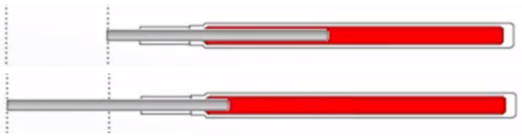
Fraunhofer Adaptronics Alliance

Adaptronic Energy-saving Facades: paraffin wax actuators

Christopher Leung, 2013

Actuated angle of 66 degrees achieved between temperature of 16.5°C and 35.6°C

Thermal expansion during phase change of paraffin wax used for auto-responsive actuation



Flexcover, 2017

Cavity ventilation enabled by temperature: saves 50% on cooling consumption

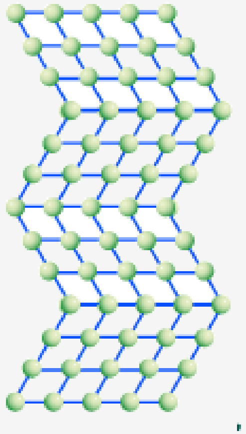
PhD paper by C. Leung 2013, Passive seasonally responsive thermal actuators for dynamic building envelopes

Philipp Molter, Technical University of Munich and Frener & Reifer Fassaden

Literature Study: Shape Memory Alloys

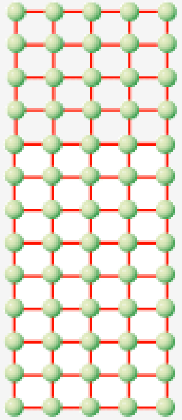
The Two Phases of SMAs

At low temperatures:
Martensite



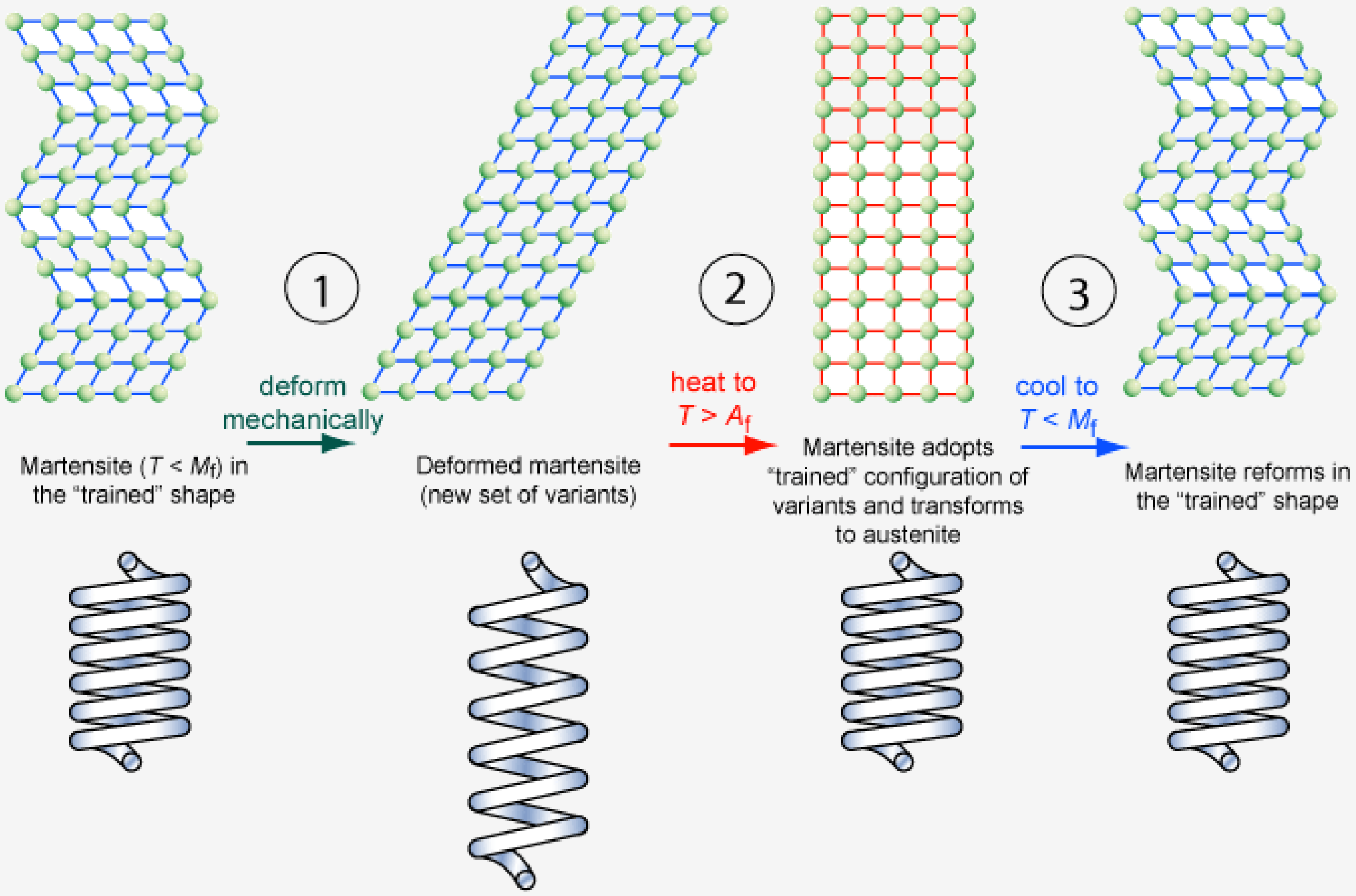
Easily deformed

At high tempertures:
Austenite



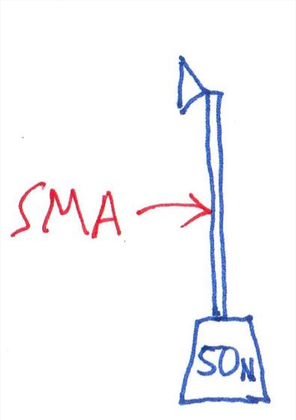
Much stiffer

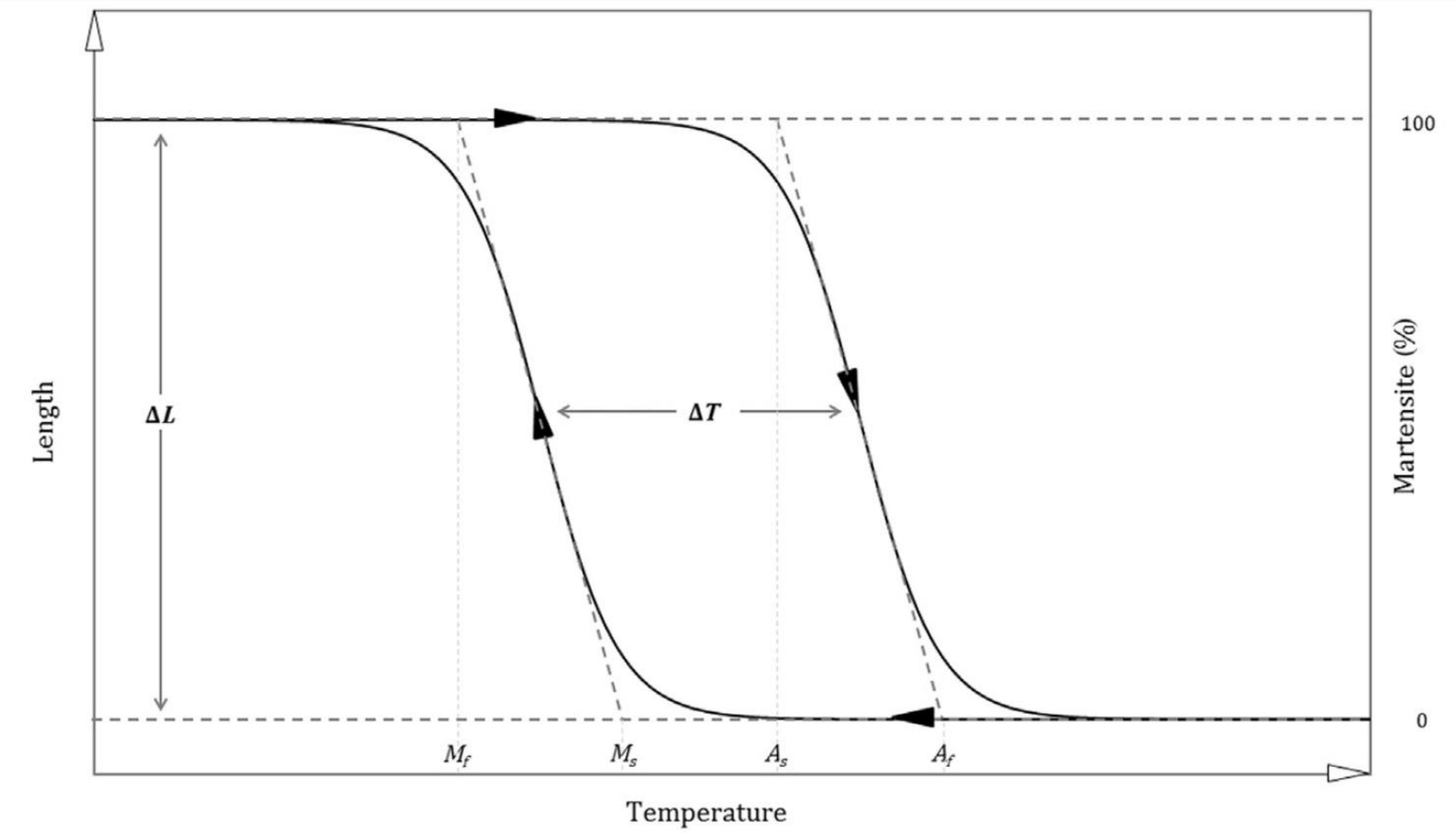
Shape Memory Effect



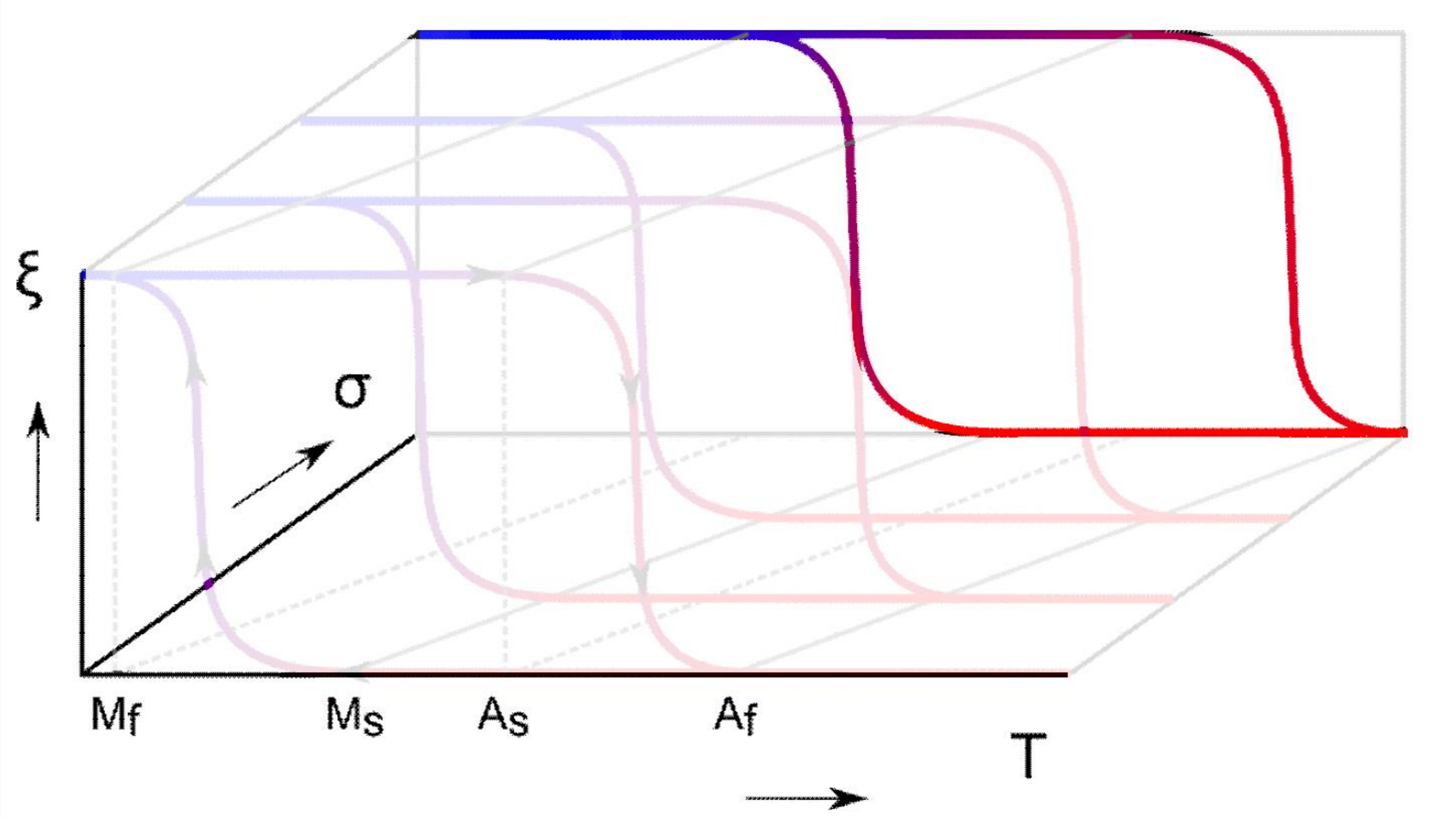
Transition Temperatures and Hysteresis

Length vs temperature for SMA wire with constant stress





Influence of Stress



Nitinol

Transformation temperatures (unstressed)	
As	75°C
Af	88°C
Ms	68°C
Mf	60°C

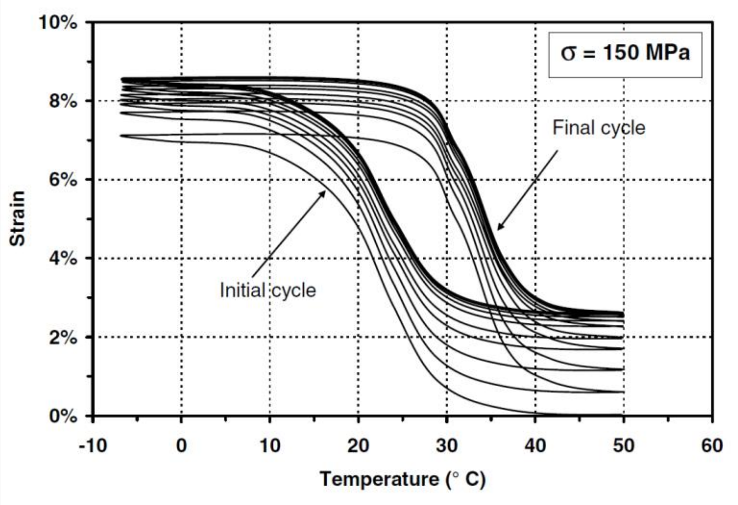
Source: Cianchetti 2013

Design considerations

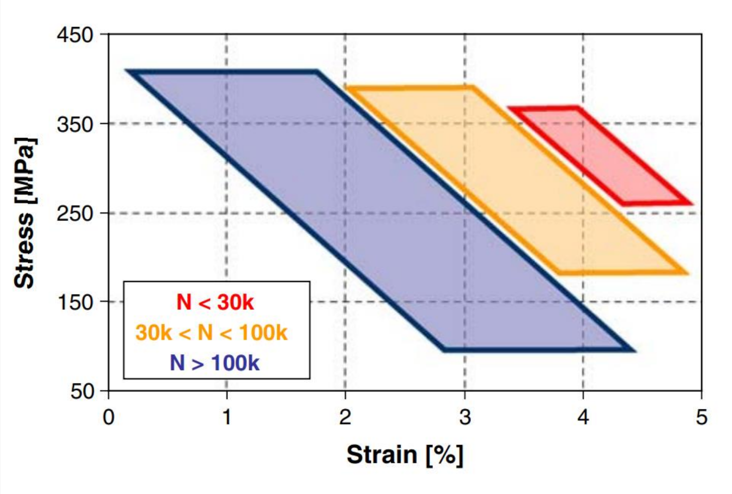
- The first times an SMA is thermally or mechanically loaded will have lower strains than later cycles. **It needs to be cycled a number of times to achieve a repeatable behaviour**

- **Both high stresses and high strains can greatly reduce the functional fatigue of SMAs.** Nitinol applications restrict it to man 4% strain to ensure long cycle life

- During a transition, the SMA is partially in both states at the same time, and material properties can be approximated by linear interpolation



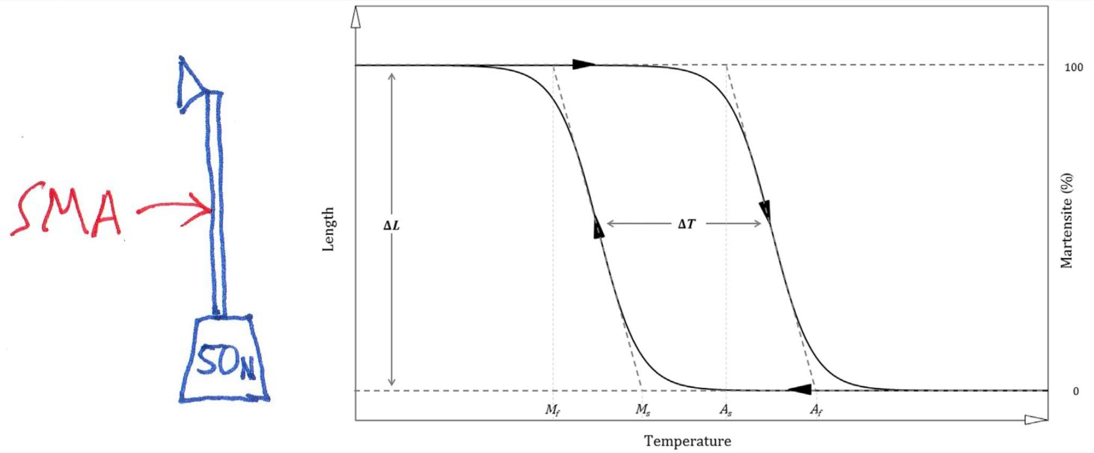
Source: Lagoudas, 2008



Source: Fumagalli et al., 2009

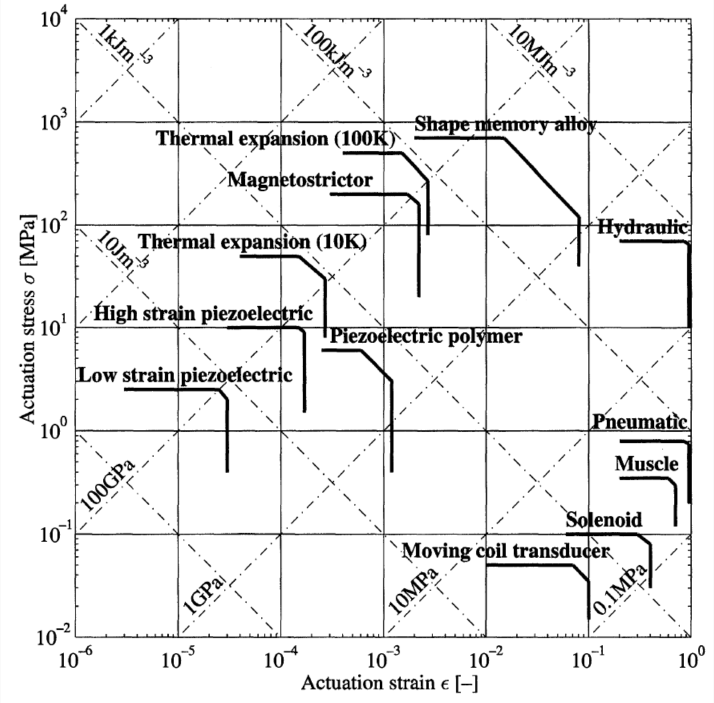
Computational Modelling of Shape Memory Alloys

SMA as Actuators

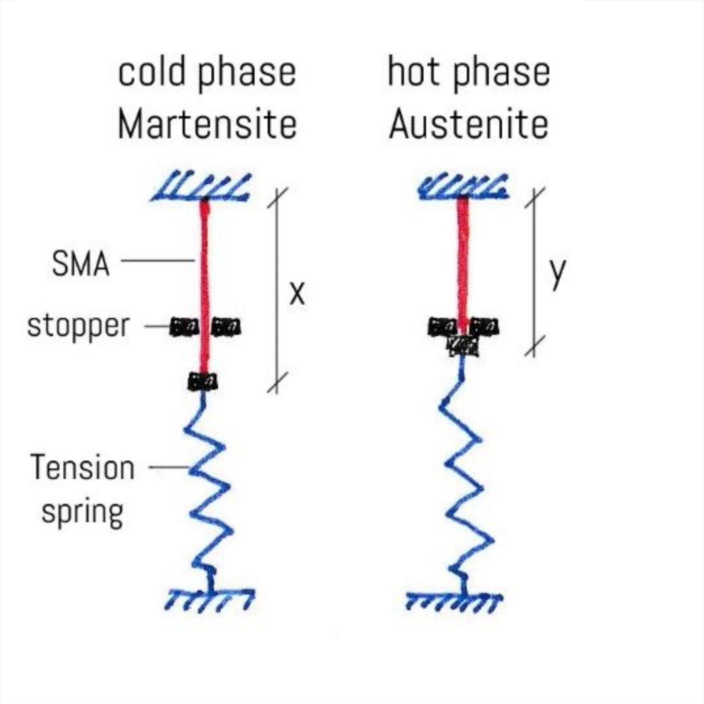


- Displacement of a stressed SMA can be determined by temperature, allowing it to be used as a linear actuator
- The counterweight acts as a bias force, but can also be replaced with a spring

SMA as Actuators



Tensile SMA wire actuator



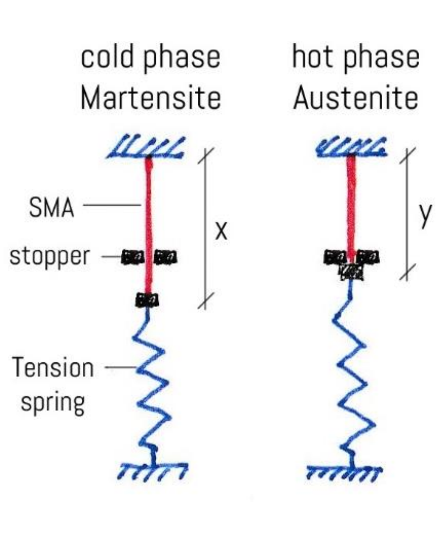
Advantages:

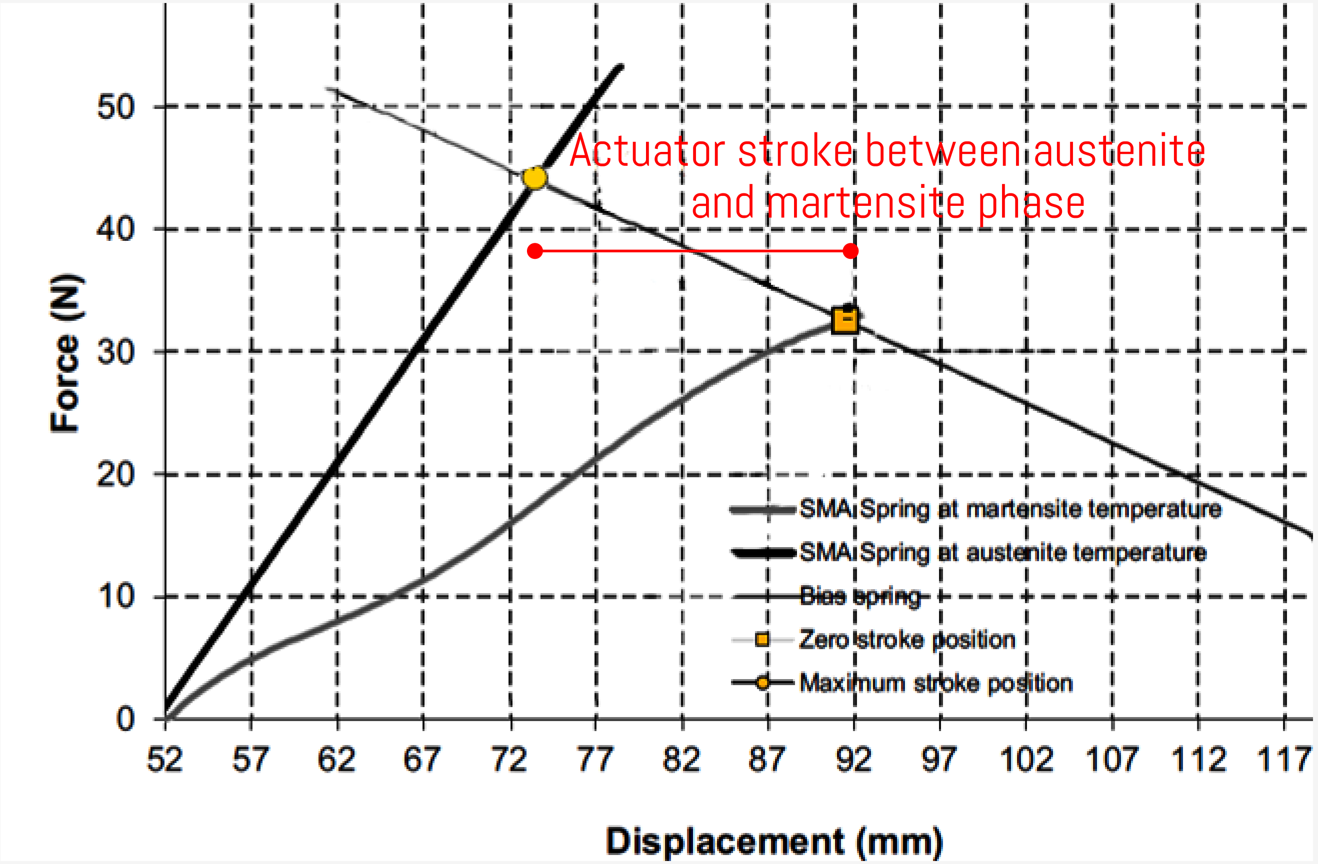
- Very weight and space-efficient
- Very simplistic design: its just a single wire

Disadvantages:

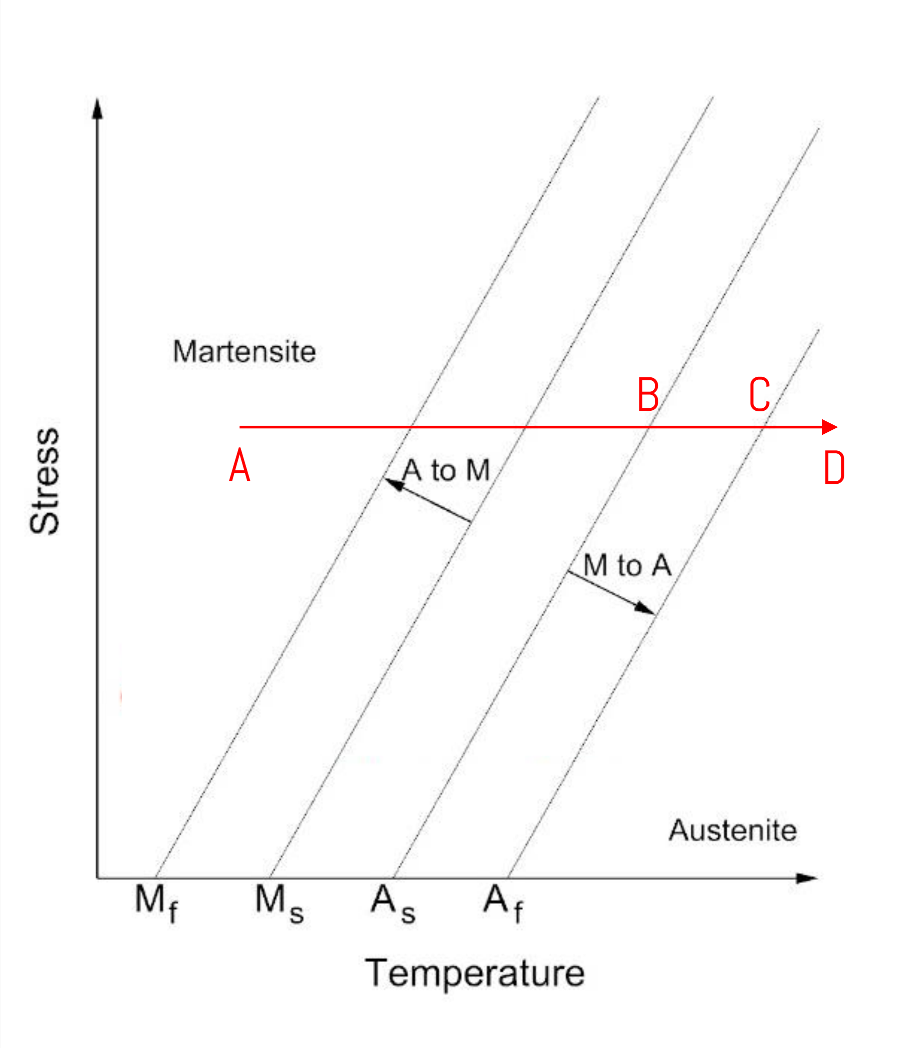
- Low energy efficiency: 2-3%
- Potentially long response times

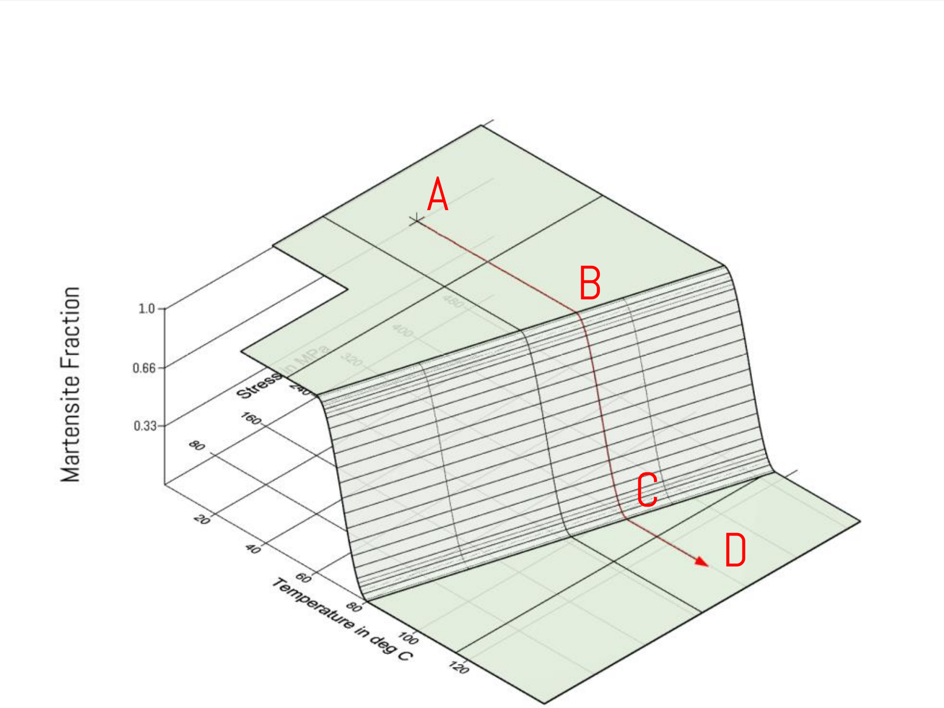
Force-Strain Matching method for finding displacement





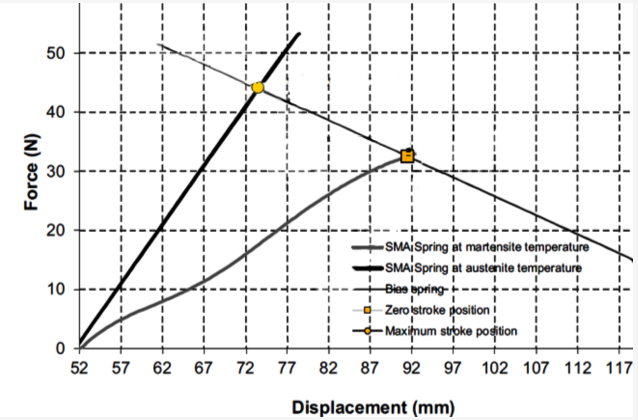
Phase Diagram to 3D graph

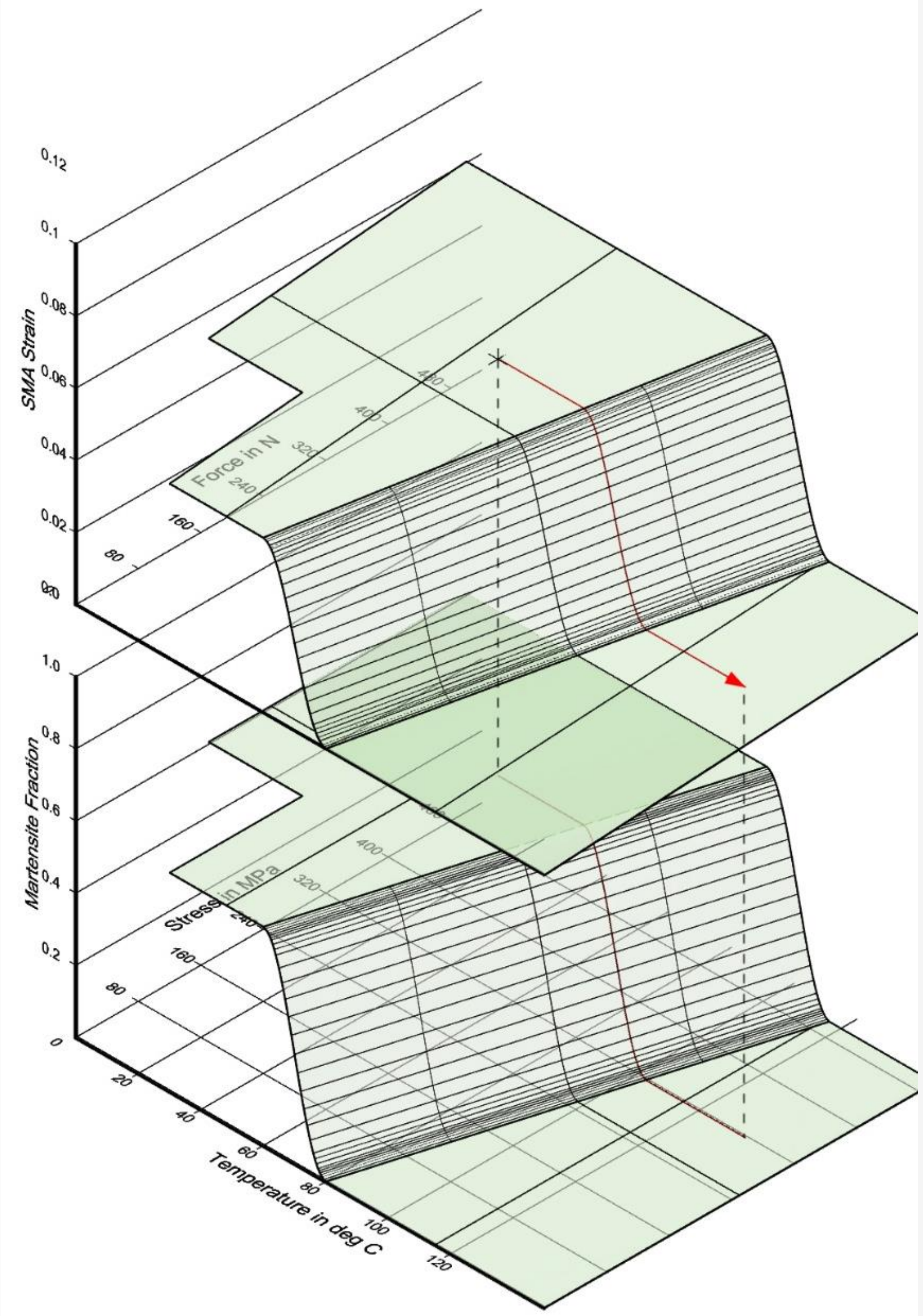




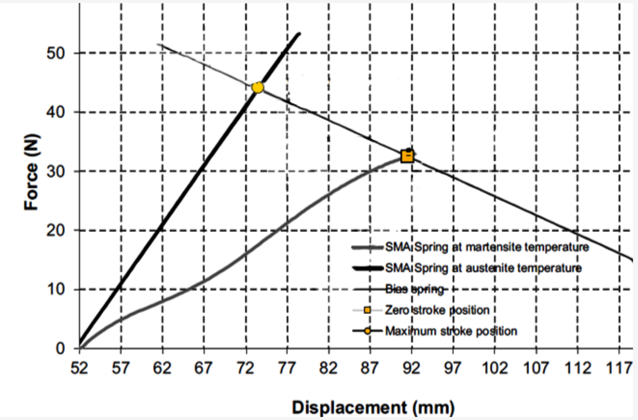
Mathematical model used: Brinson, 1993

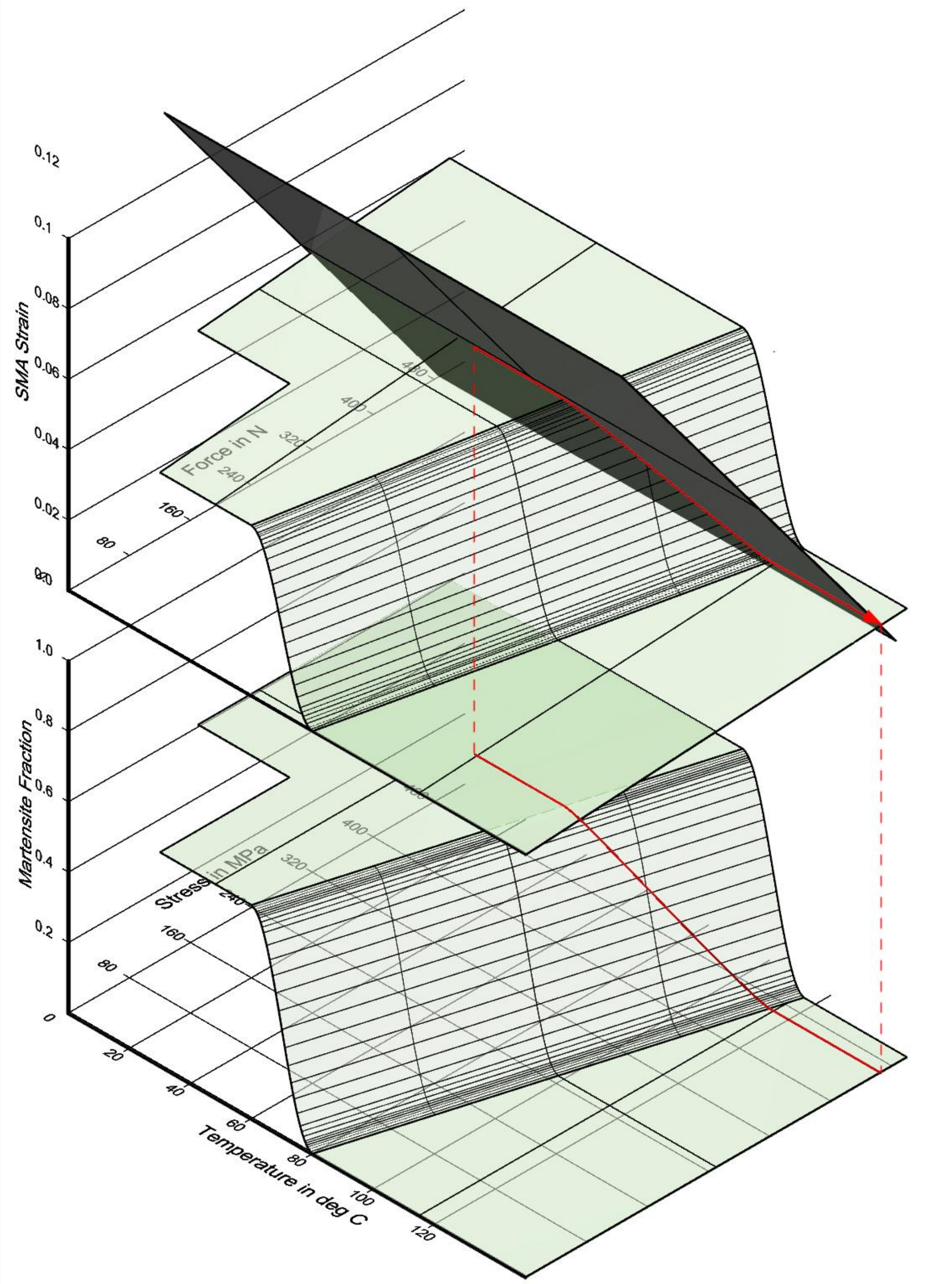
3D Graph


Force (N)
Displacement (mm)
SMA Spring at martensite temperature
SMA Spring at austenite temperature
Bias spring
Zero stroke position
Maximum stroke position

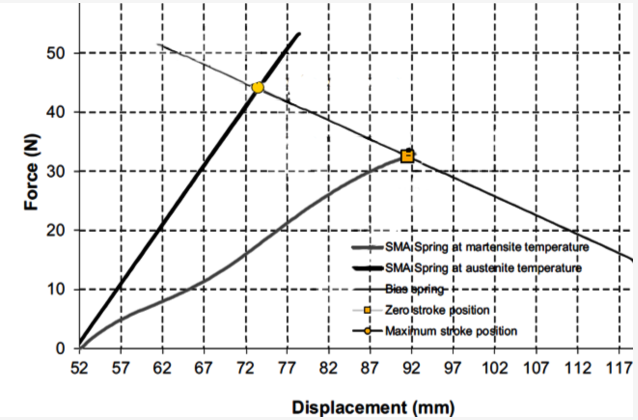

SMA Strain
Force in N
Martensite Fraction
Stress in MPa
Temperature in deg C

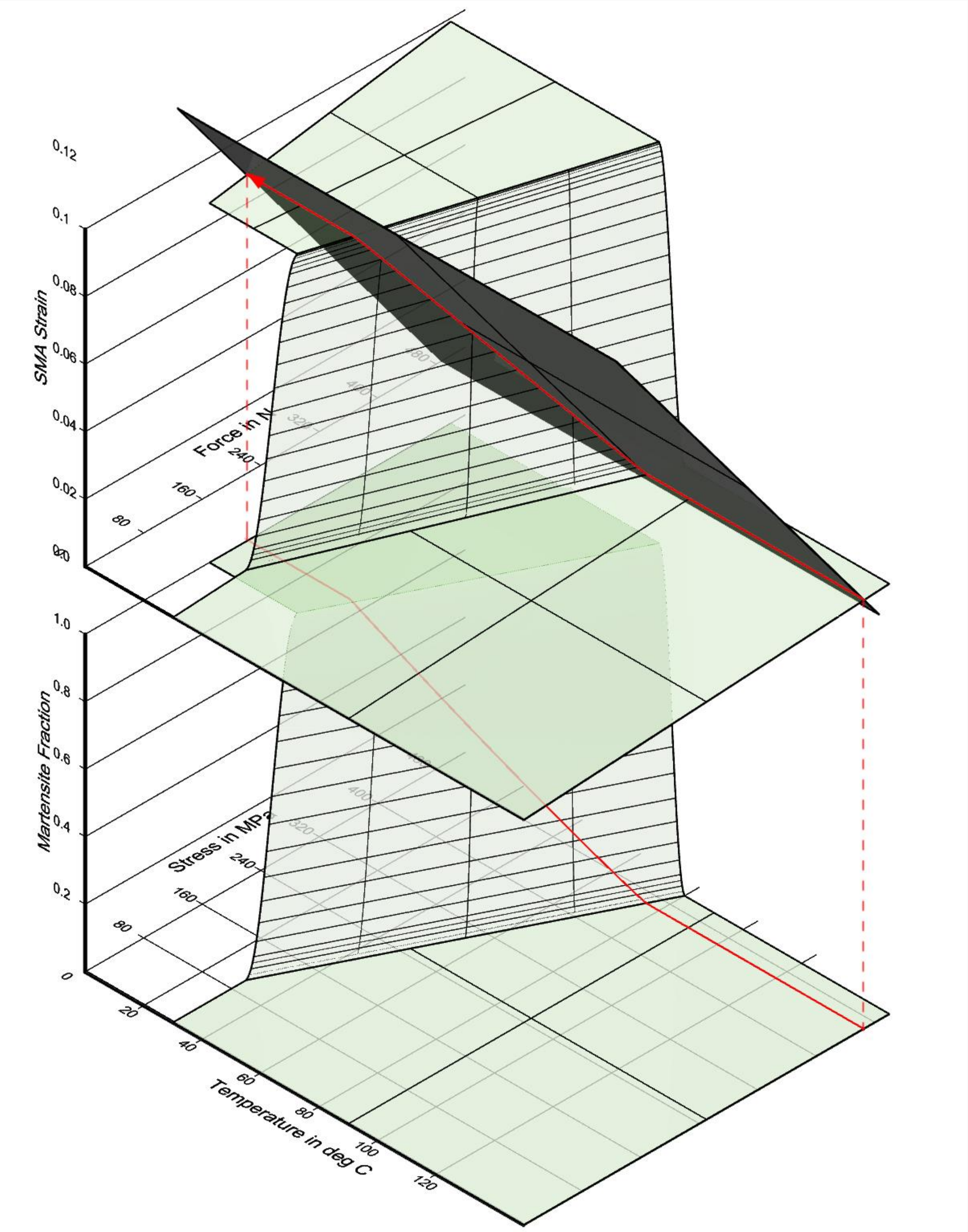
3D Graph


Force (N)
Displacement (mm)
SMA Spring at martensite temperature
SMA Spring at austenite temperature
Bias spring
Zero stroke position
Maximum stroke position

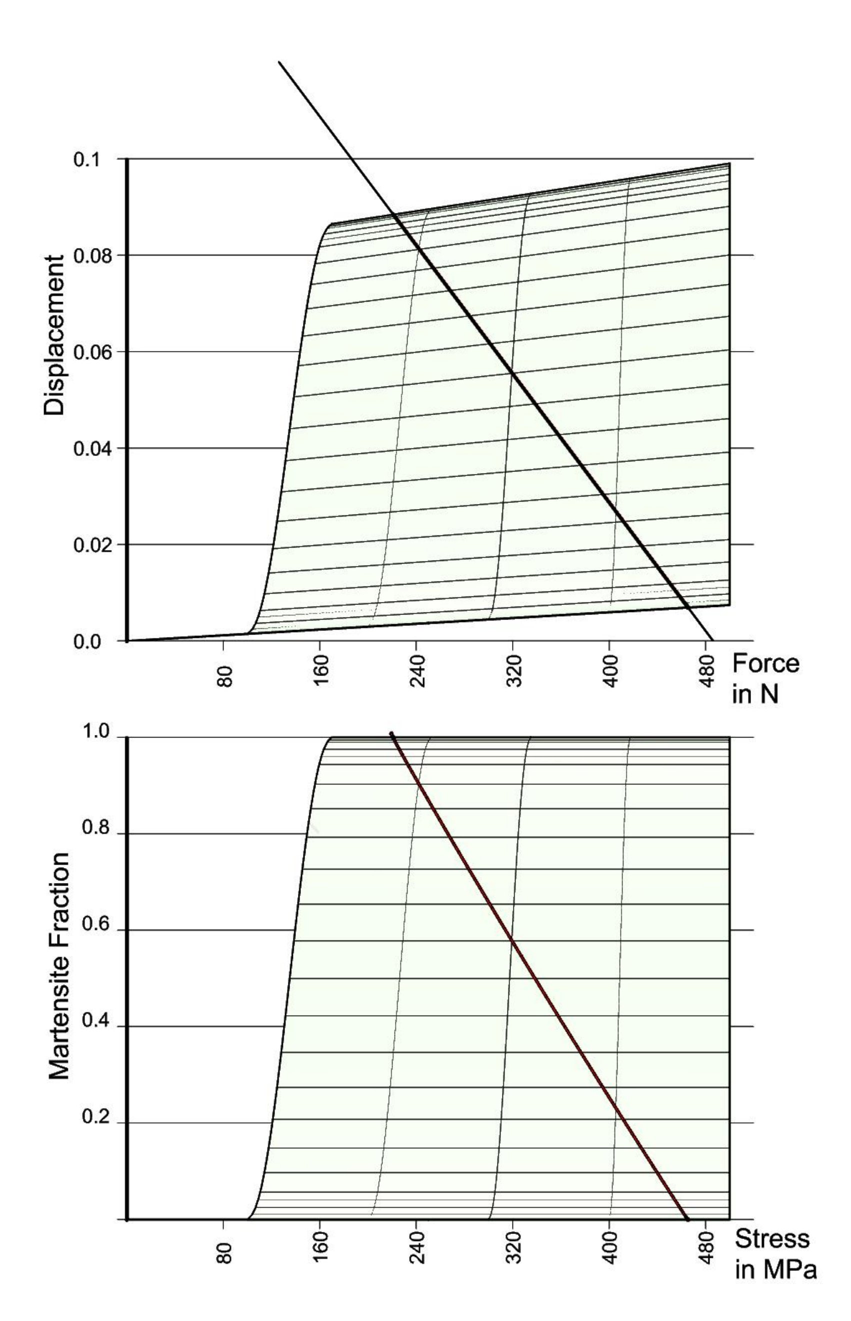

SMA Strain
Force in N
Martensite Fraction
Stress in MPa
Temperature in deg C

3D Graph


Force (N)
50
40
30
20
10
0
52 57 62 67 72 77 82 87 92 97 102 107 112 117
Displacement (mm)
SMA Spring at martensite temperature
SMA Spring at austenite temperature
Bias spring
Zero stroke position
Maximum stroke position

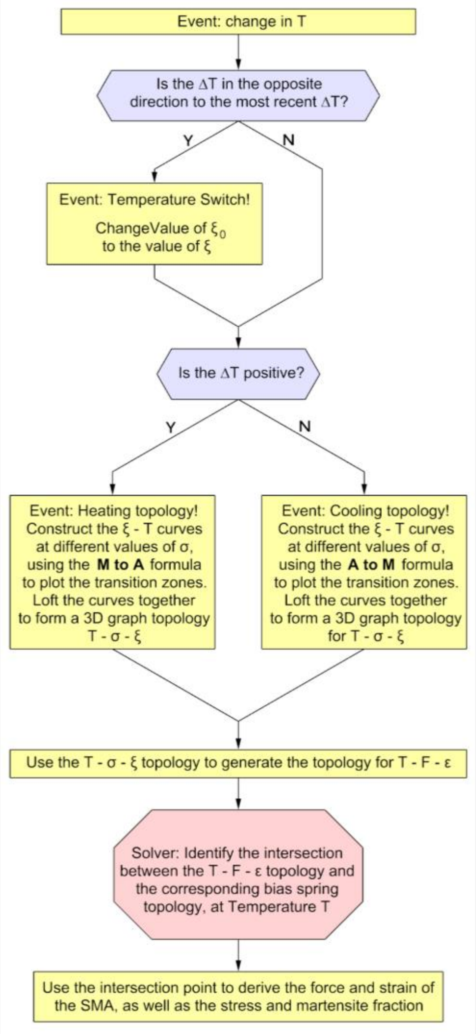

SMA Strain
0.12
0.1
0.08
0.06
0.04
0.02
Force in N
80
160
240
Martensite Fraction
1.0
0.8
0.6
0.4
0.2
0
Stress in MPa
80
160
240
Temperature in deg C
20
40
60
80
100
120

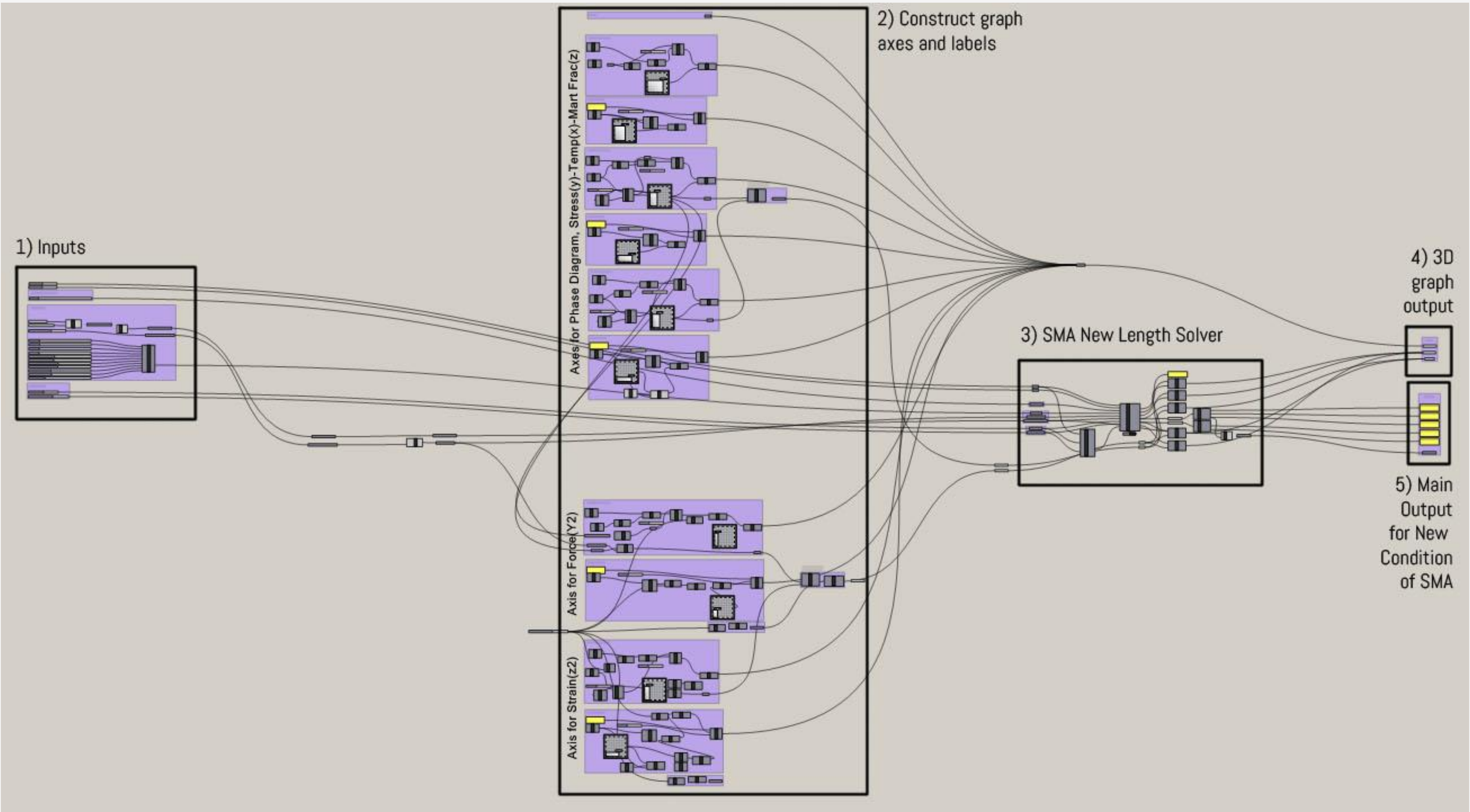
3D Graph Side View



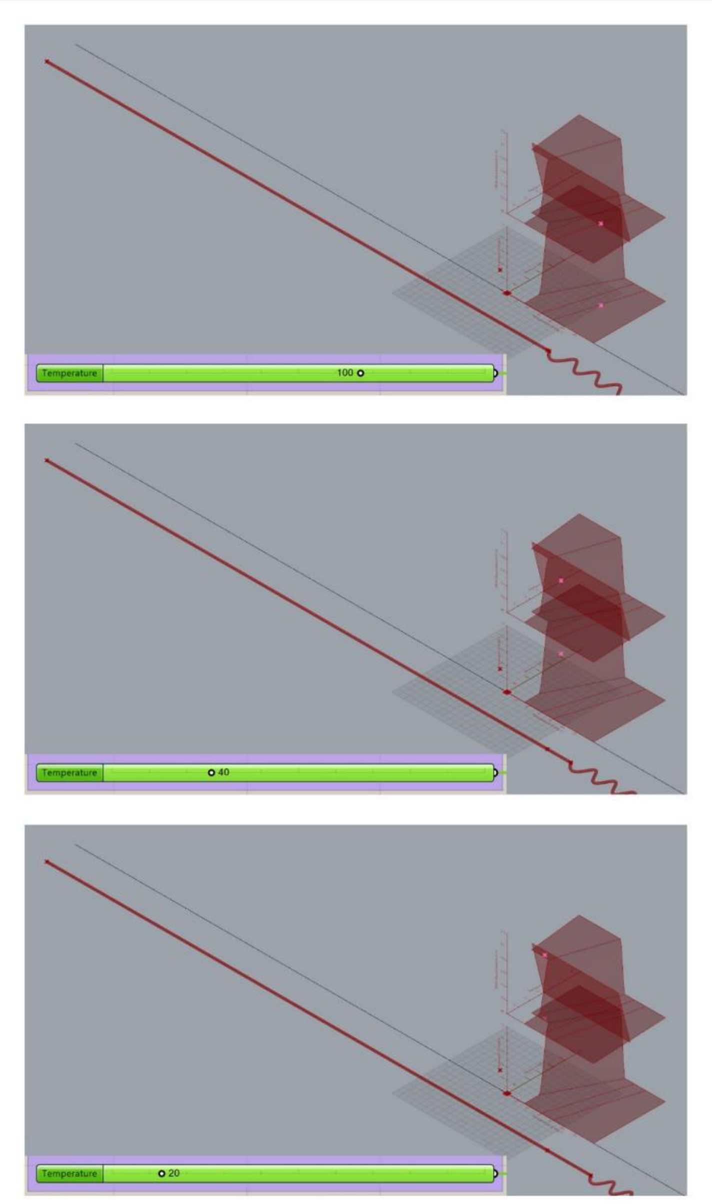
The difference in displacement at the temperature extremes will facilitate the actuator stroke

Summary of the software tool



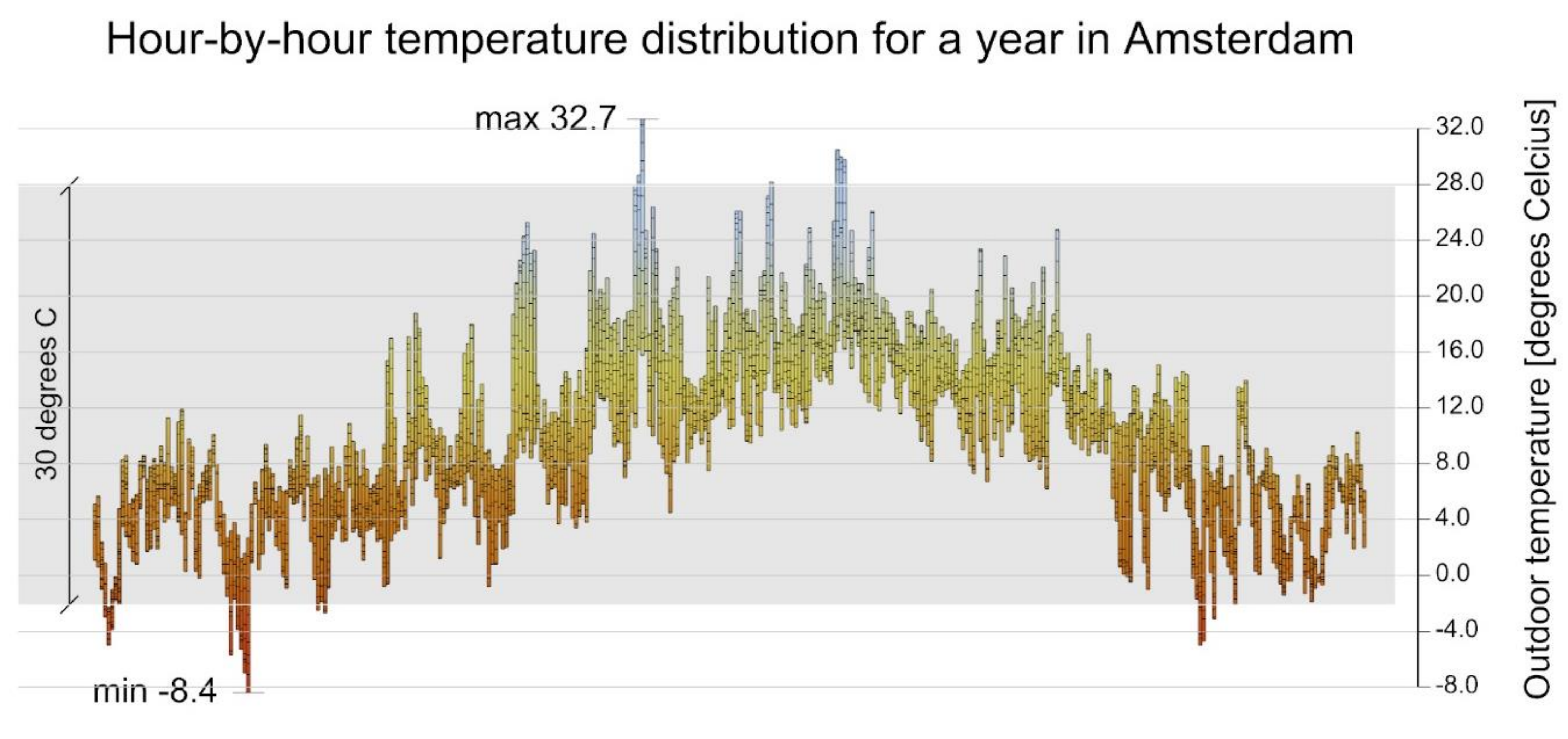


Example of Use



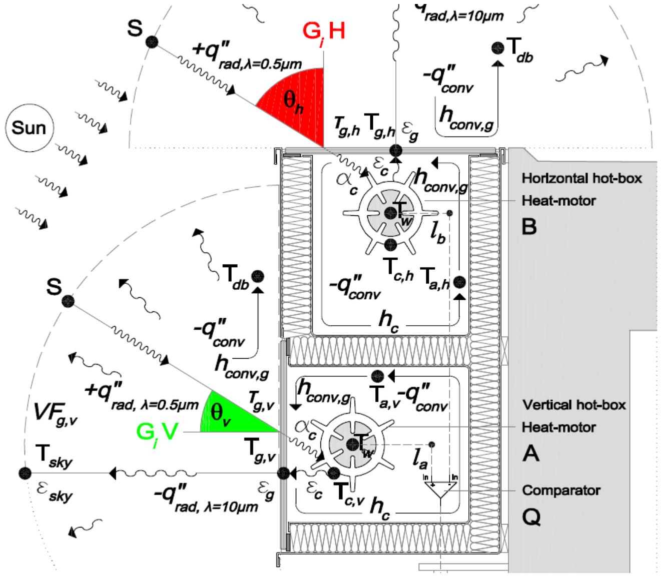
Concept and Exploration

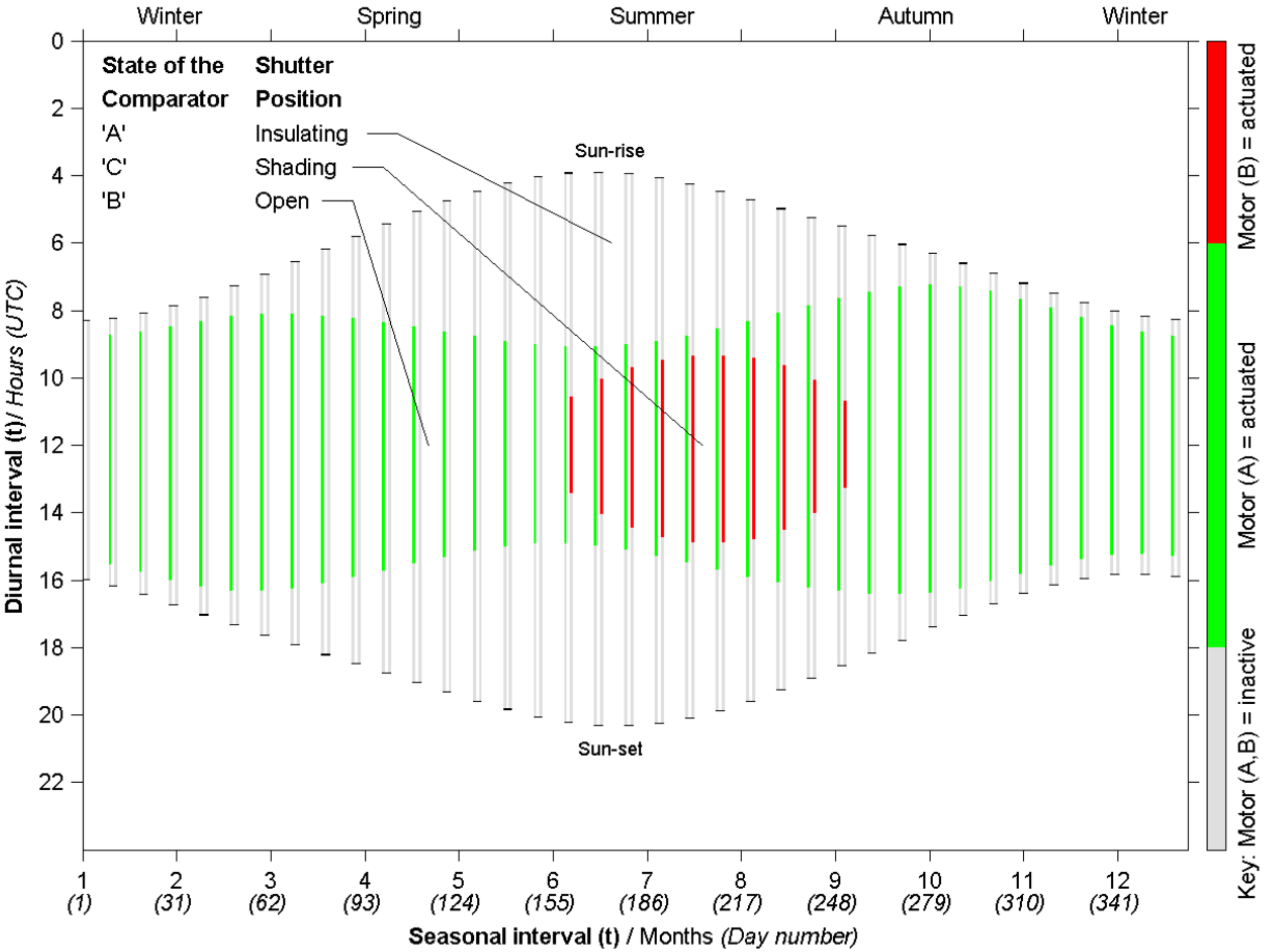
Heat provision



The grey area represents the size of the hysteresis; ambient temperature is not enough to actuate the device seasonally

Reference Project: C. Leung, 2013

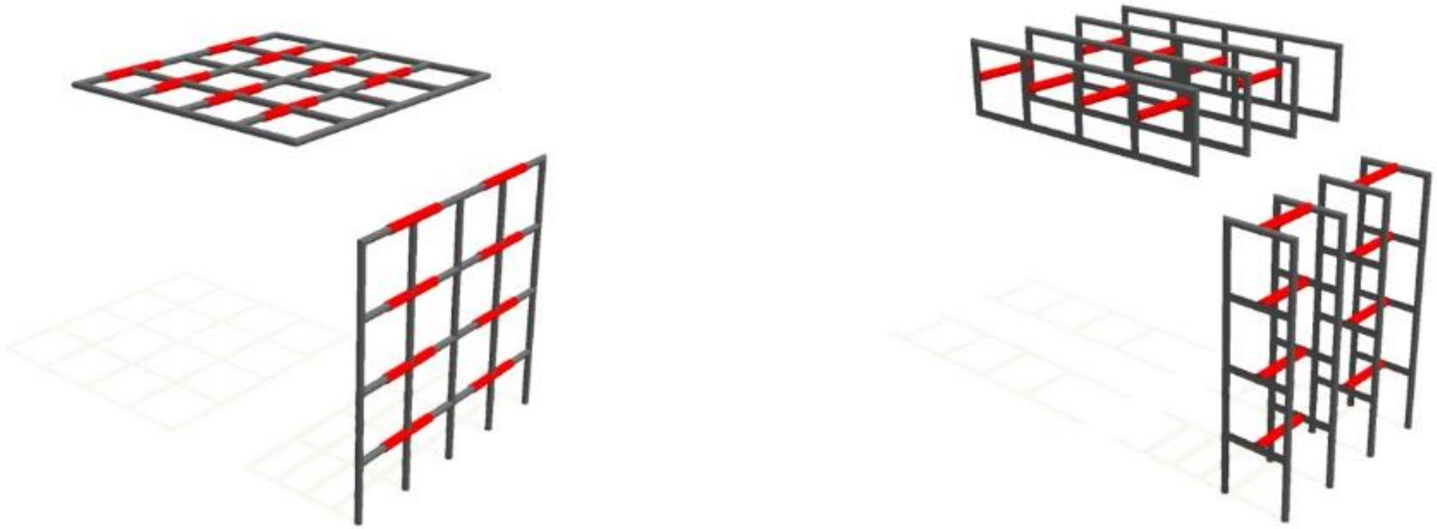




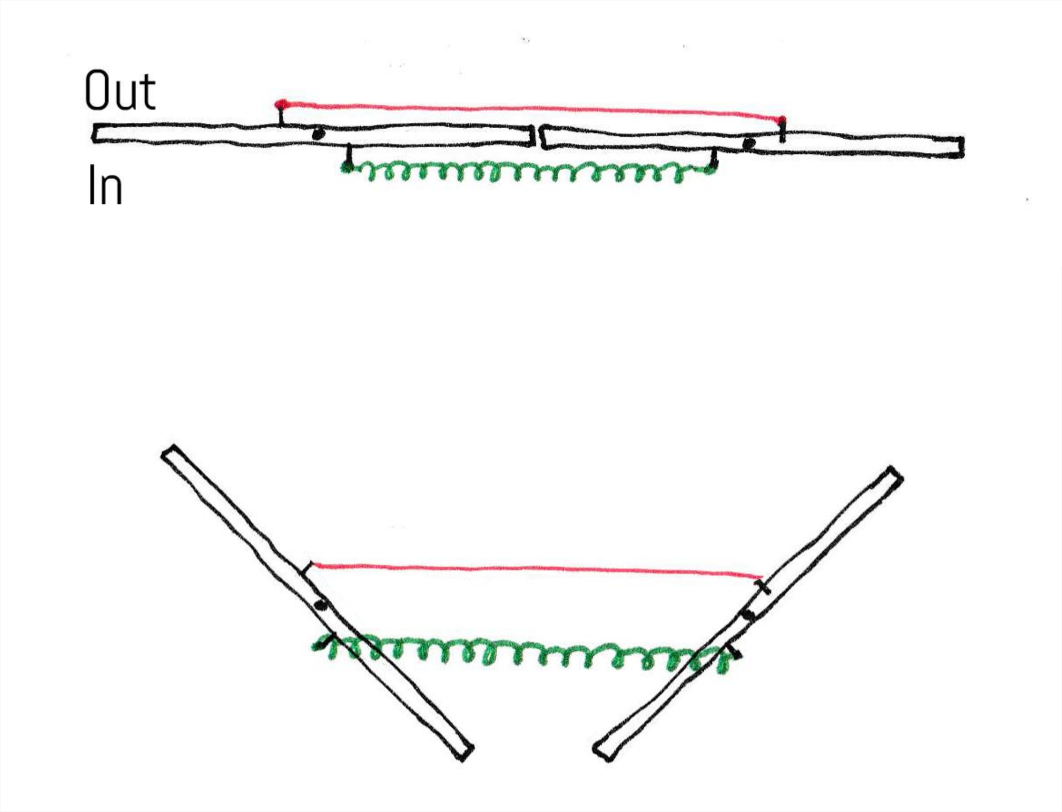
Source: PhD paper by C. Leung 2013, Passive seasonally responsive thermal actuators for dynamic building envelopes

Chosen concept design

For south facing facades and roof



Concept Module Development



Cold

Heated

1:10 Prototype

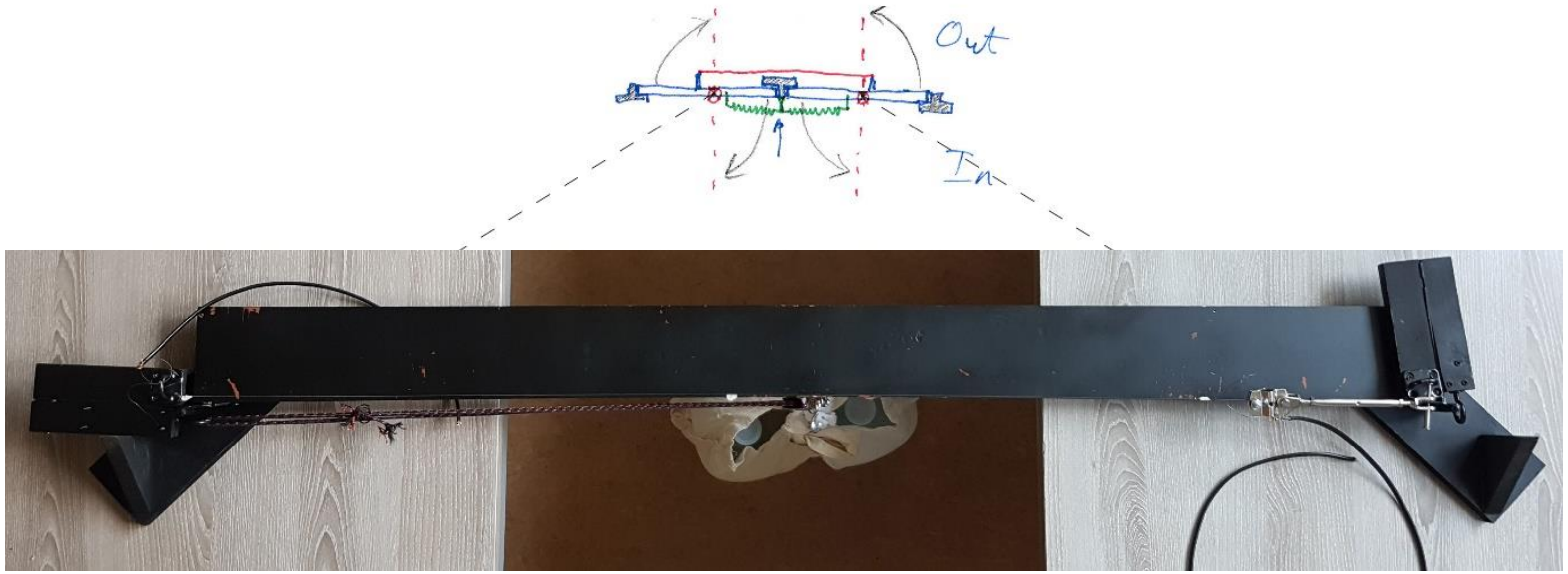
Views from interior: sequence of façade module opening

Findings:

- Careful placement of attachment points for SMA, spring and center of pivots are crucial for the mechanism to move as intended
- Body holding the pivot points in place must be very stiff, so the device will actuate instead of deform when the SMA activates

Engine Prototype

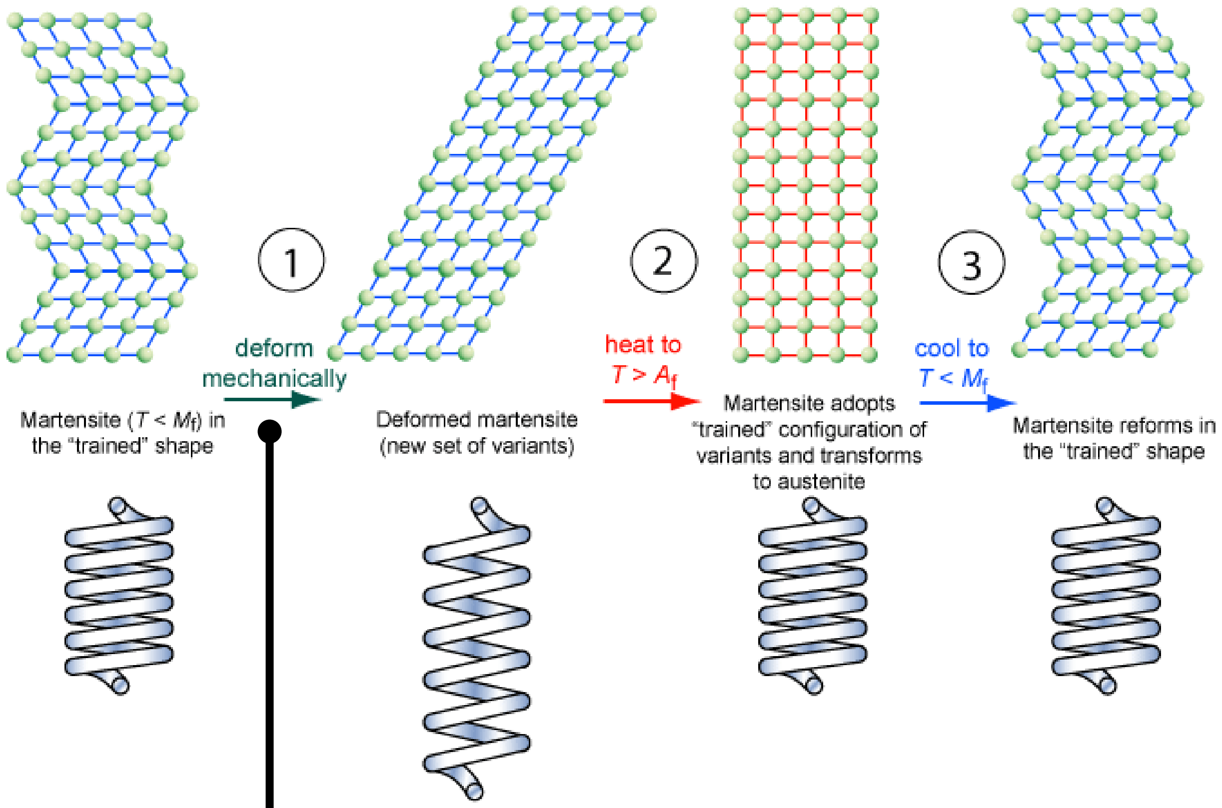
Engine Prototype



SMA:
Nitinol wire from *SmartWires*,
0.5mm diameter, 45ºC activation

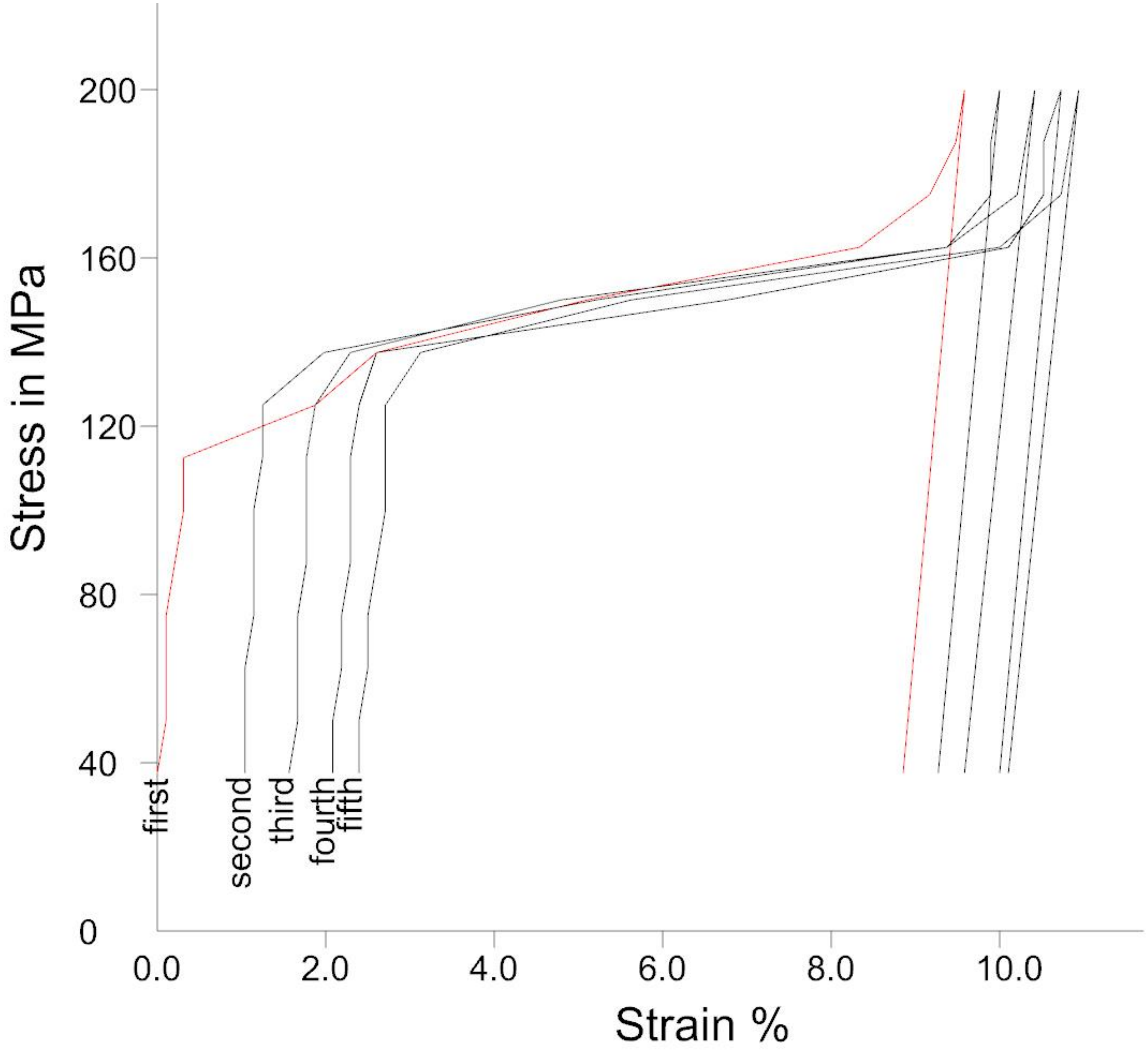
Testing Material to Interrogate the Shape Memory Effect

Material:
Nitinol wire from
SmartWires,
0.5mm diameter,
45^{o}C activation



What stress
level does this
deform at?

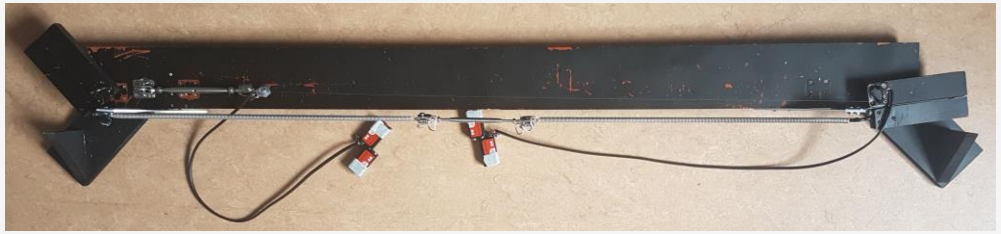
Critical Stress Experiment



Result:
σ_s at 125 MPa
σ_f at 175 MPa

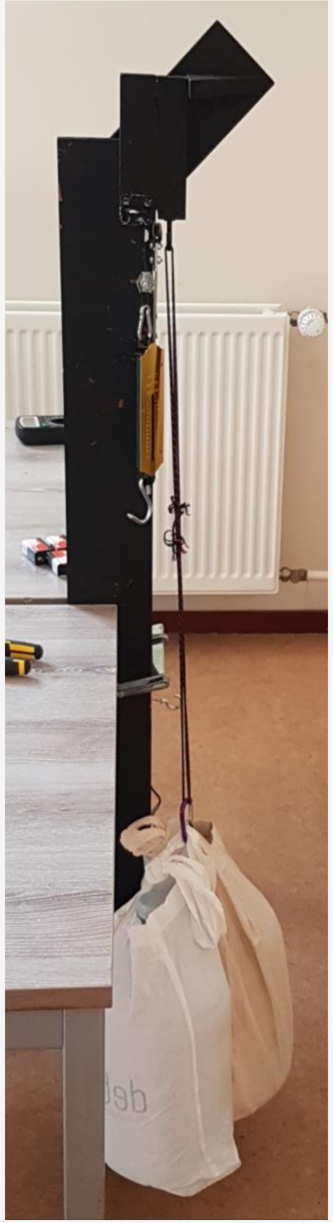
Stroke Angle Testing: alternatives

General set-up:
Electrically heat the SMA wire to make it contract against the bias object



Set-up 1:
Use springs as bias

Set-up 2:
Counterweight and pulleys
2.6% strain required for actuation



Set-up 3:
Vertical arrangement with counterweight
3% strain required for actuation

Result:

- Best actuation angle achieved of 65.9 degrees using the vertical arrangement, with a 6kg counterweight (58.9N) at ~25V, with 4-8mm prestrain in the SMA

Observations:

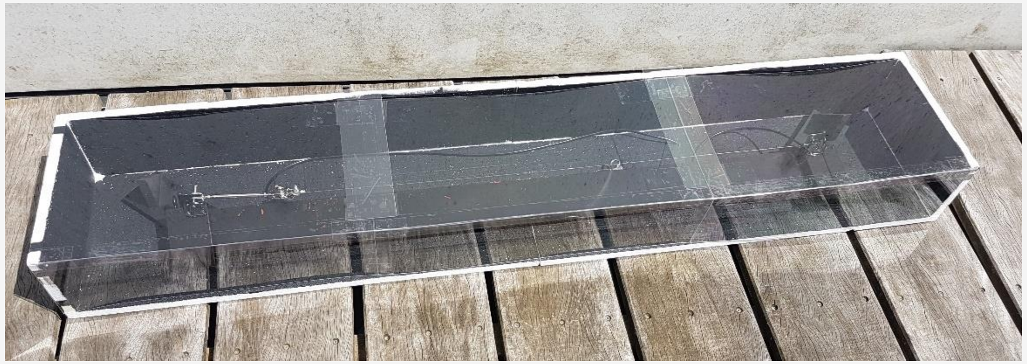
- Result can be improved by tweaking the prestrain and bias force, and the geometries of connections
- Issues with repeatability: the SMA appeared to still be getting longer after ~30 cycles

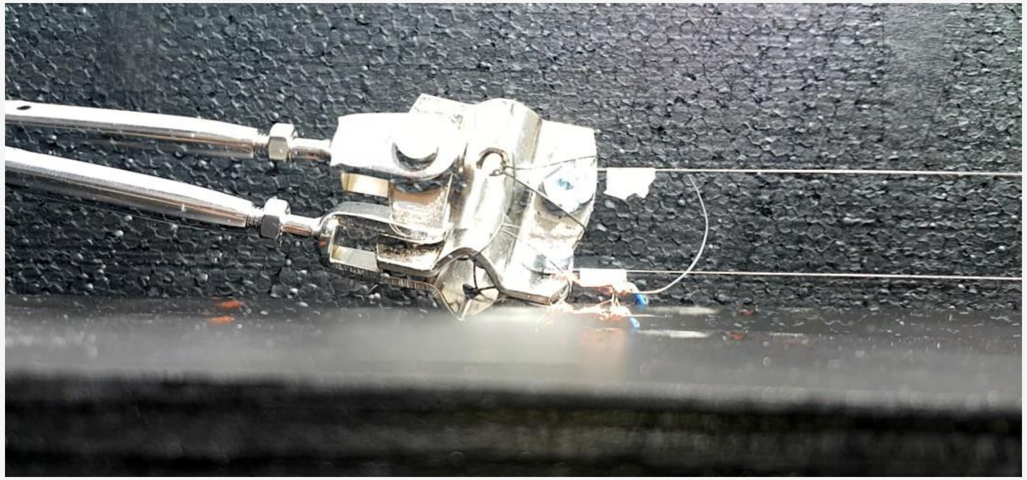
Heat Chamber

Testing for possibility of activation using outdoor conditions

Set-up:
Engine prototype placed in black box with transparent cover to absorb sunlight.

Weather condition:
(12th May 13:30 2017)
Sunny, 22^{o}C, sheltered from wind

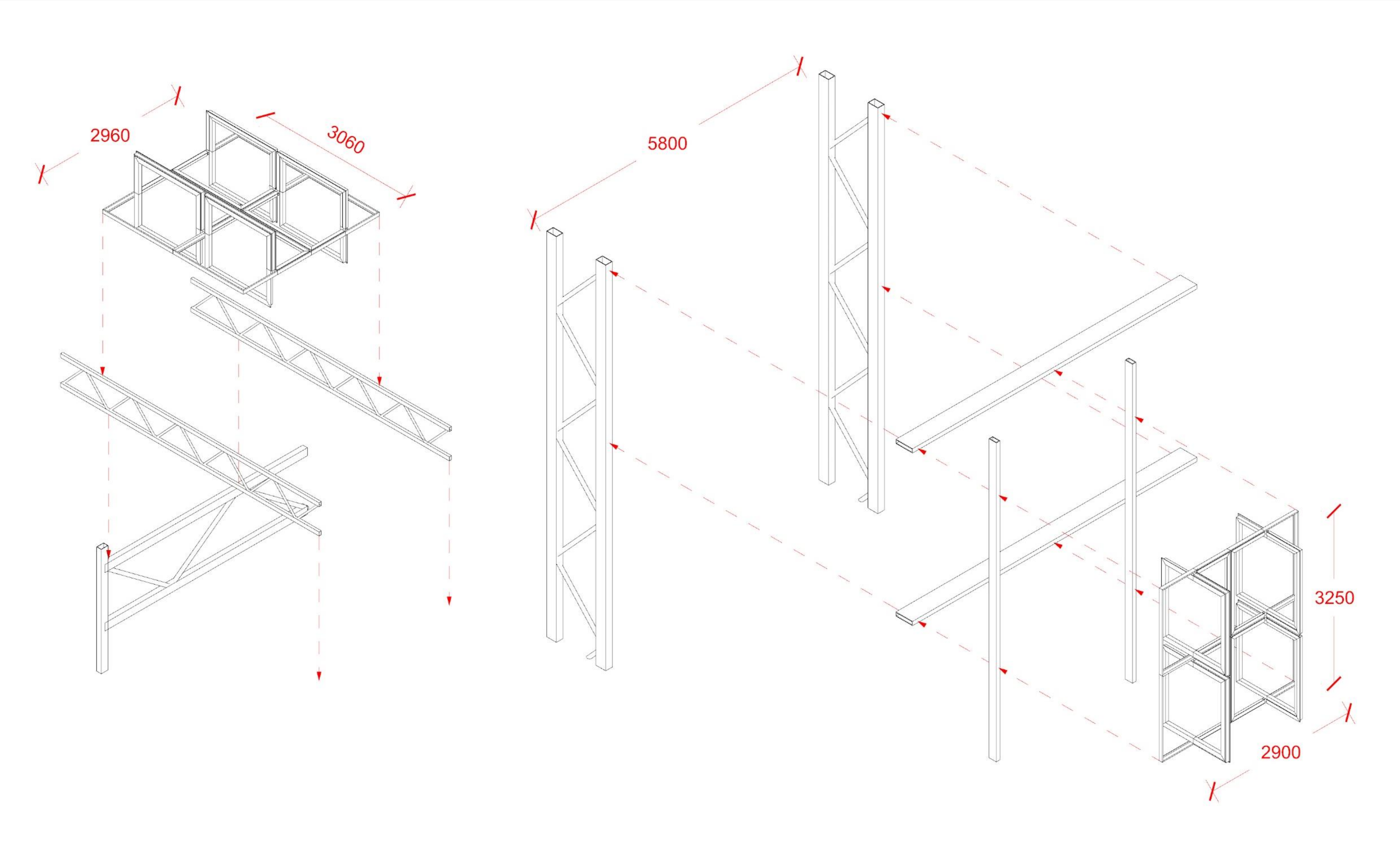




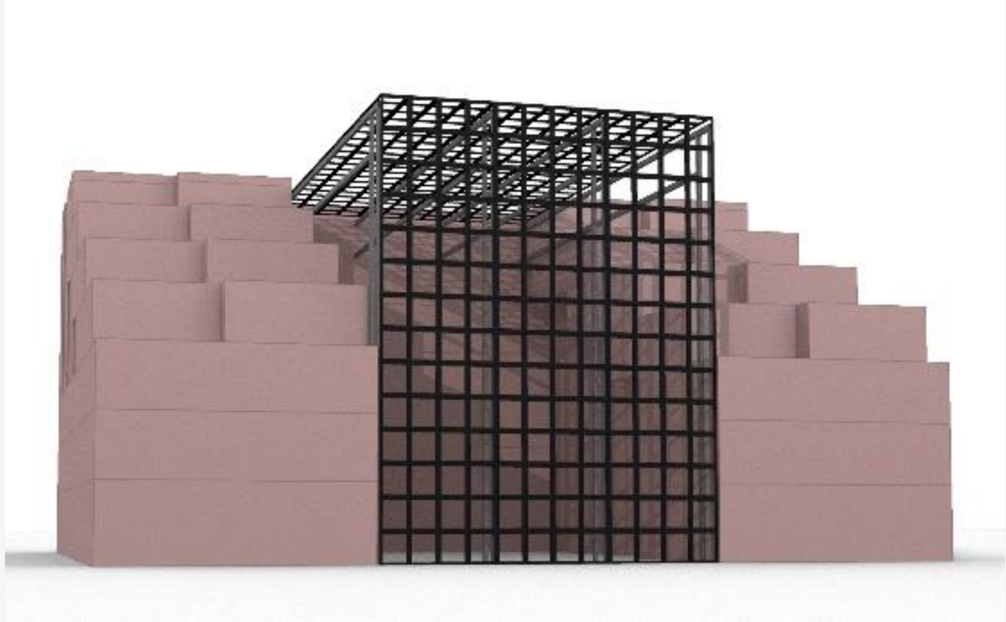
Result:
Instant activation after applying the cover; new position achieved after 80 seconds

Final Design

Atrium Structure and Grid Size

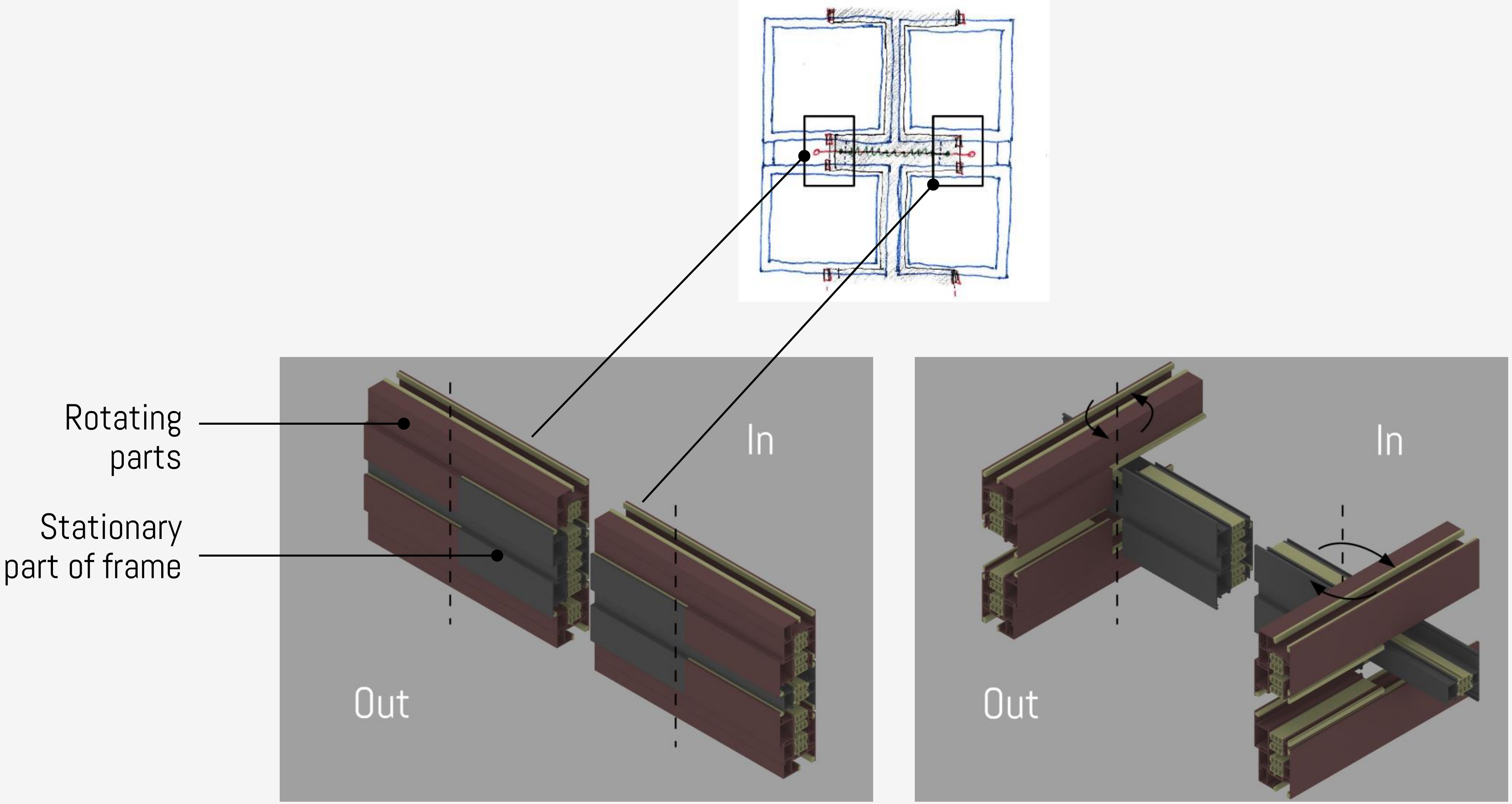


Atrium Structure and Grid Size

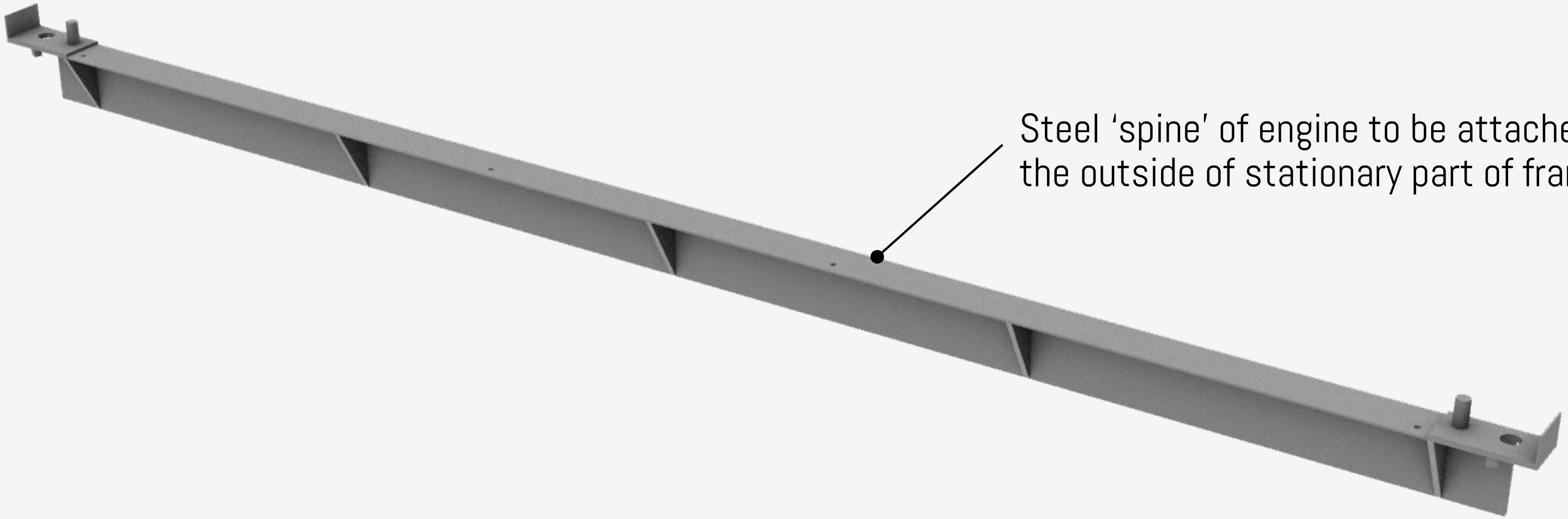


Standard Aluminium Profiles

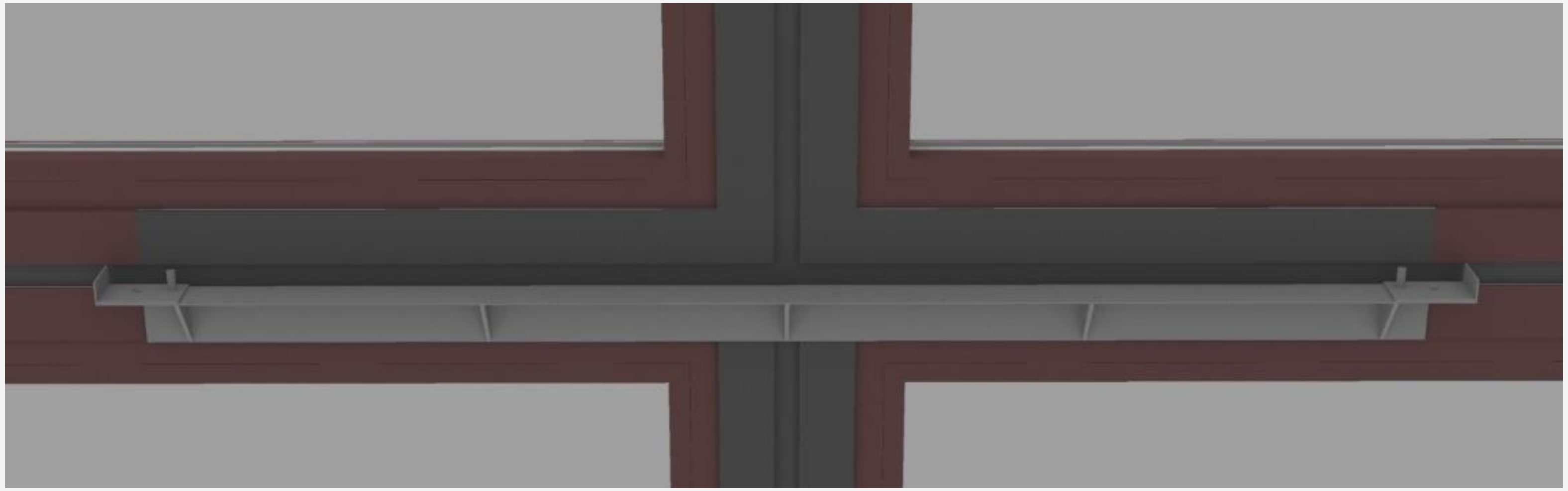
Raynaers aluminium CS77-012 center pivot frame



The Engine

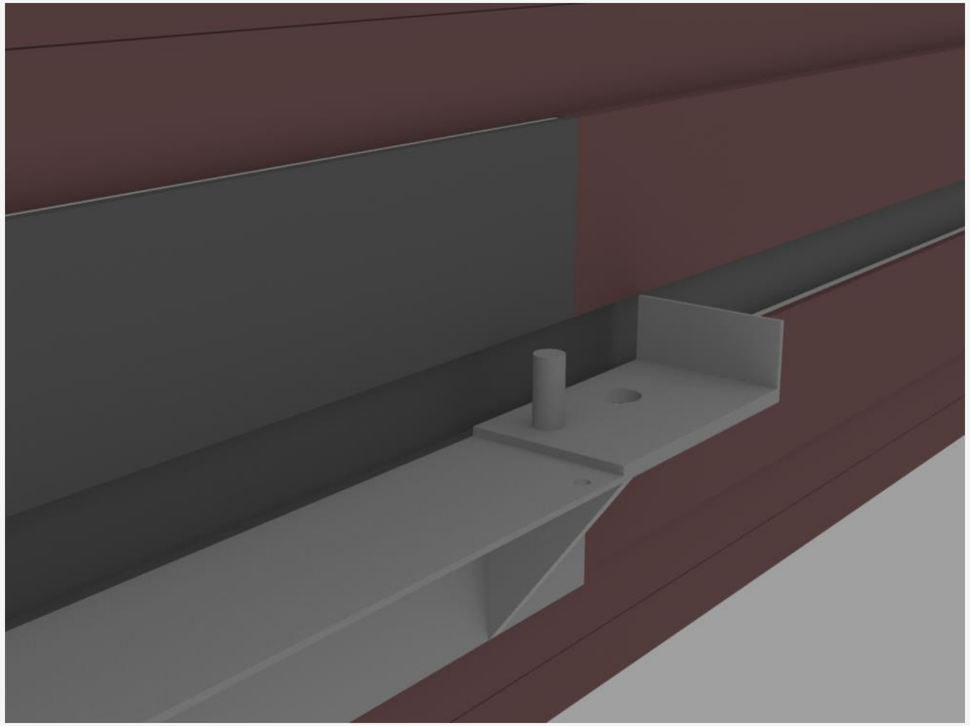


Steel 'spine' of engine to be attached to the outside of stationary part of frame



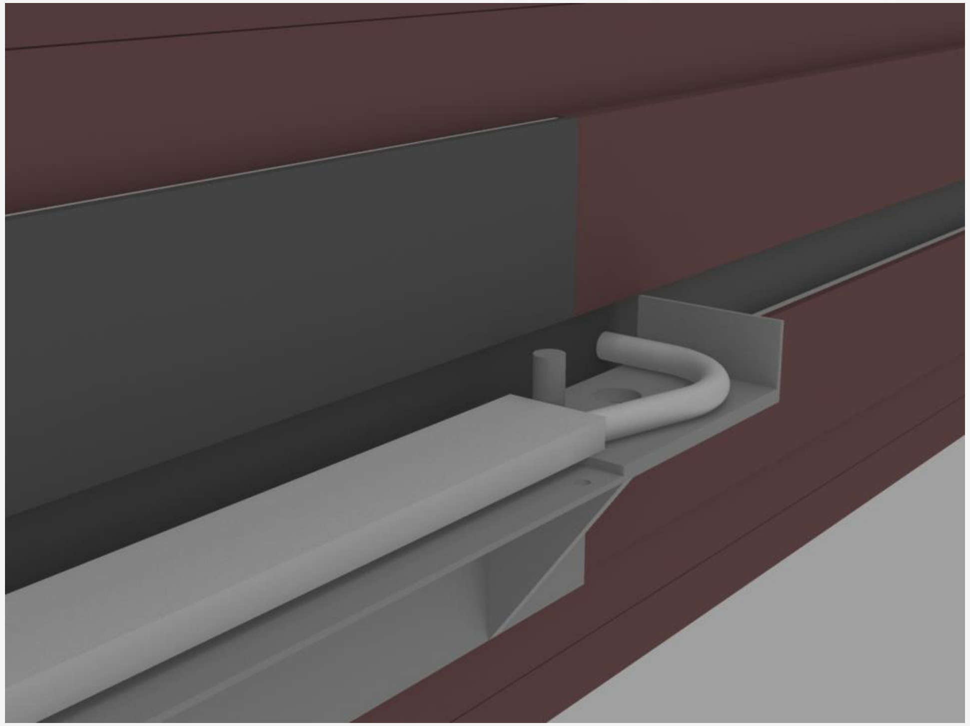
Steel 'spine' of engine screwed to outside of stationary part of frame

The Engine



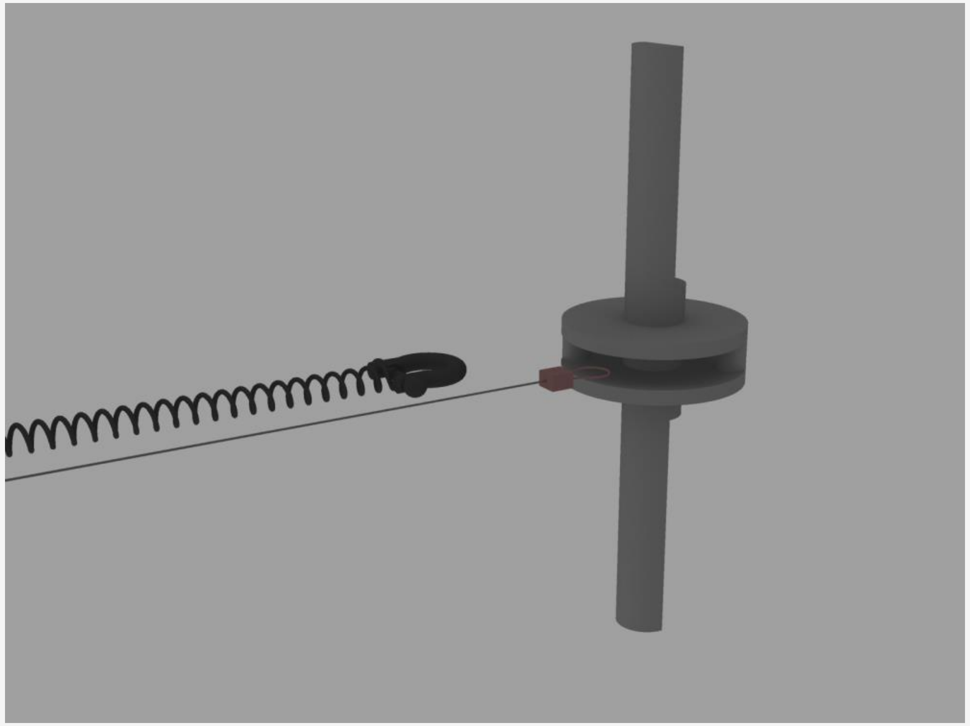
On the left and right ends of the spine are pre-drilled holes, in which the axle is inserted later on.

The Engine



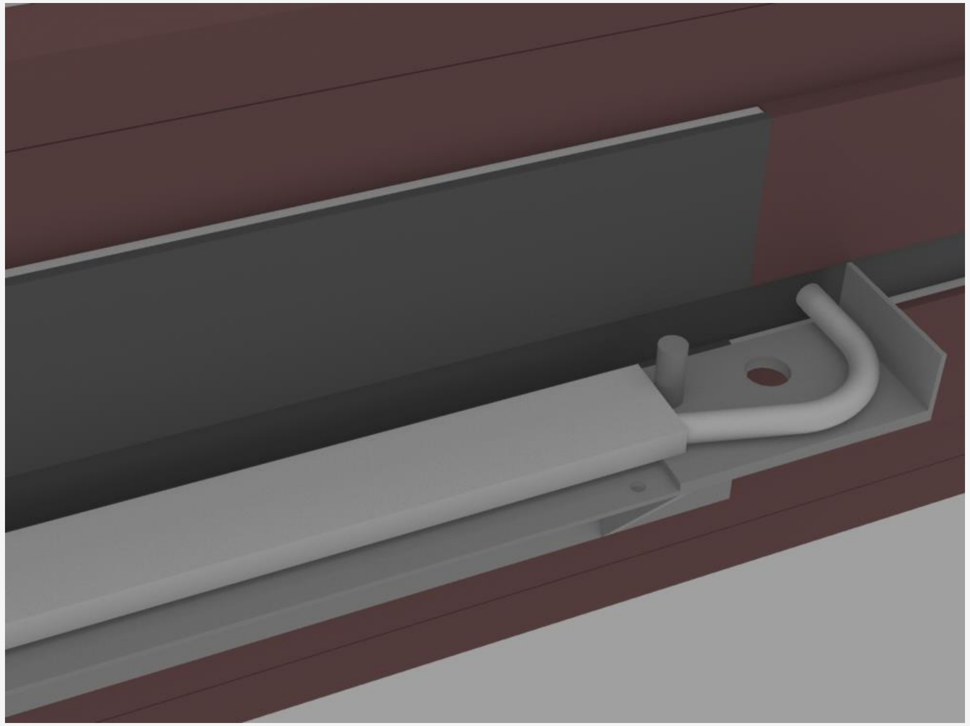
Plastic water tube and ‘radiator’ pipe fitted. It will allow cold water to be passed through

The Engine

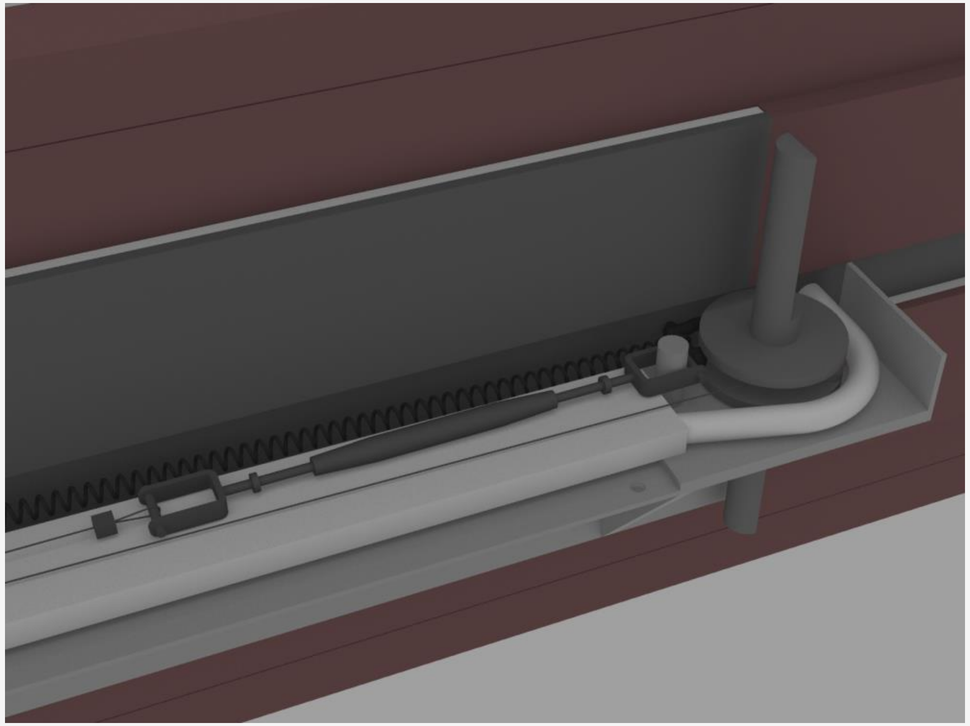


Spring and SMA wire is attached to
the axle

The Engine

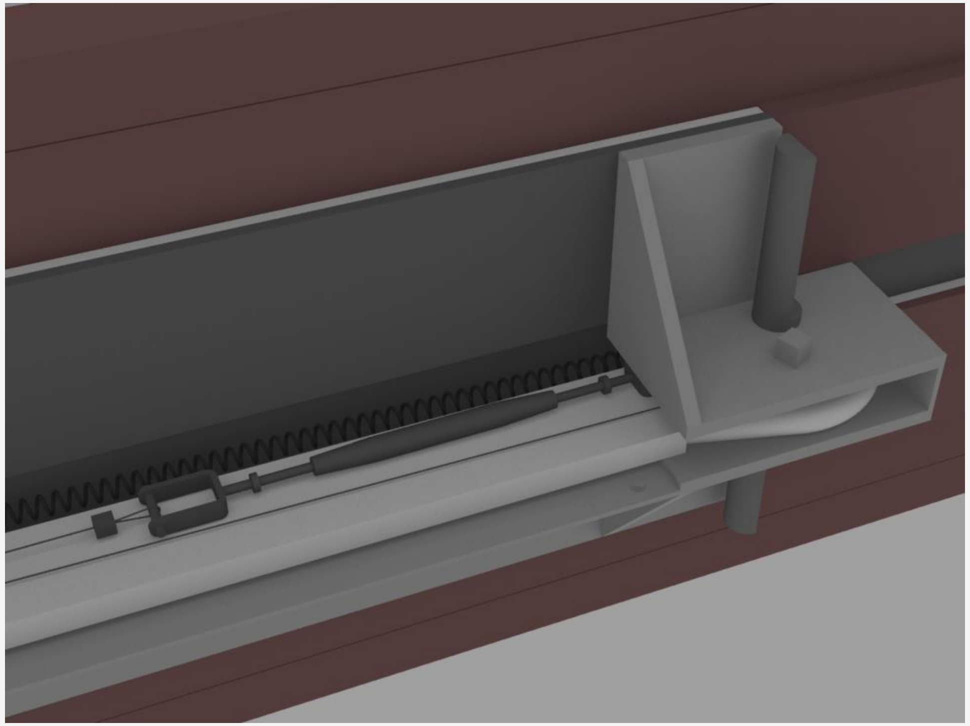


The Engine



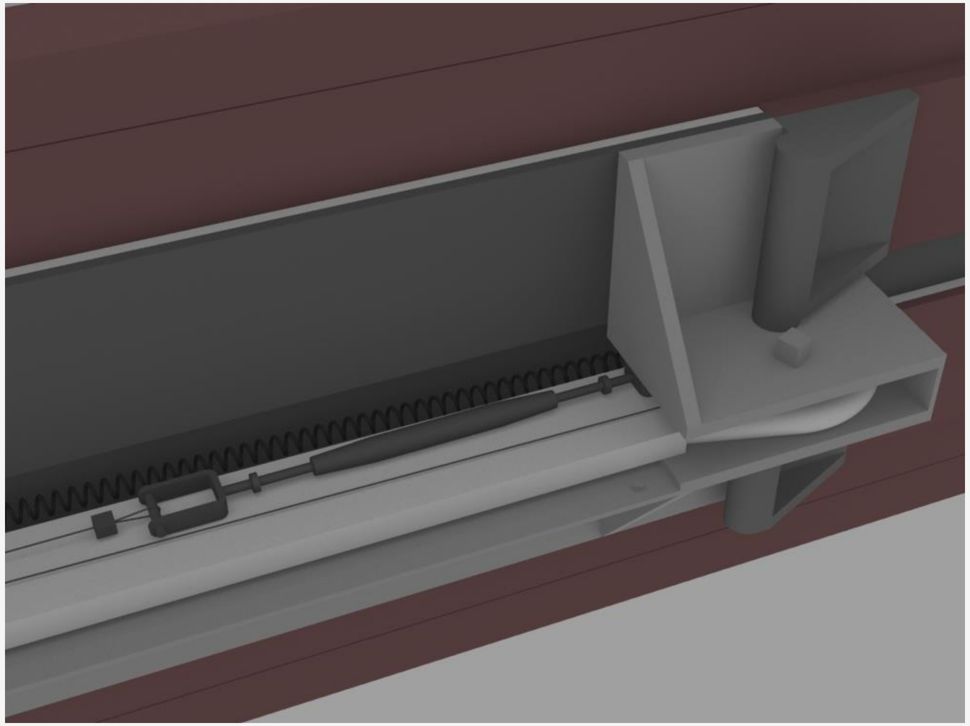
Axle inserted into hole in spine,
along with SMA wire and spring
Prestrain applied. Other SMA wire
end can be seen

The Engine



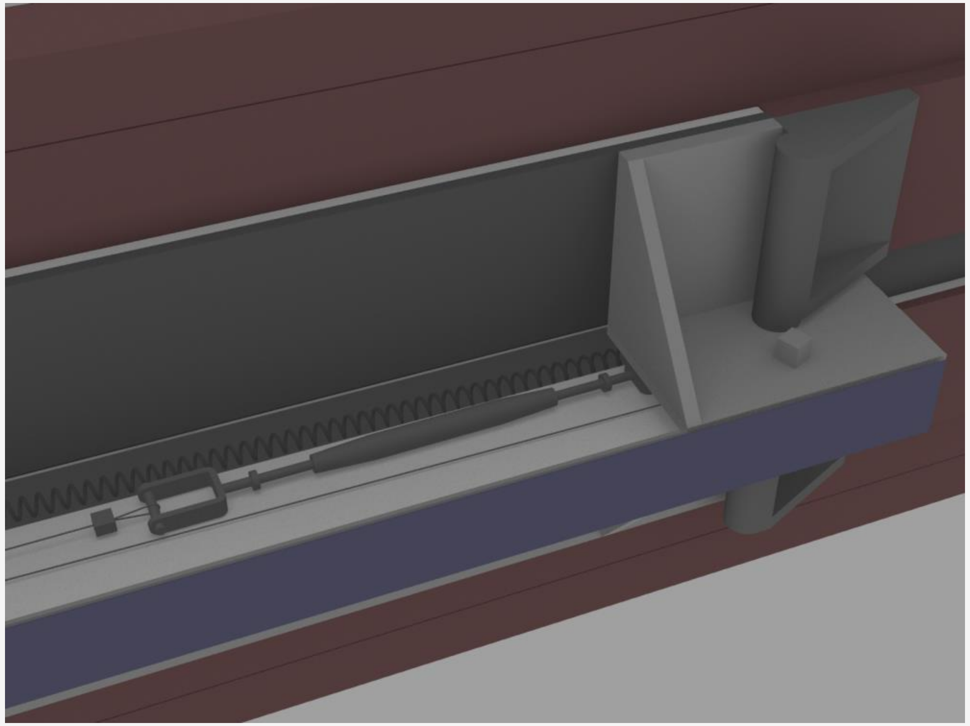
Top axle support is positioned to secure axle in place. It screws into the stationary part of frame

The Engine

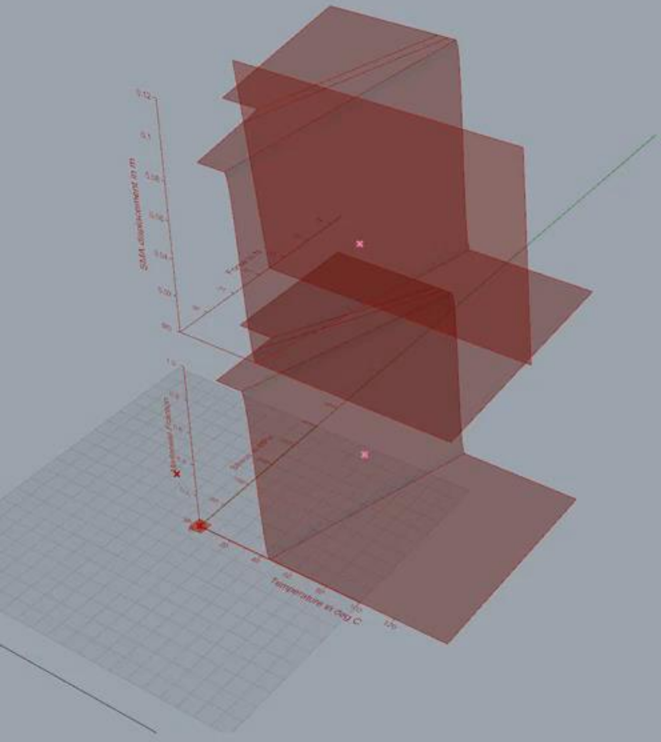


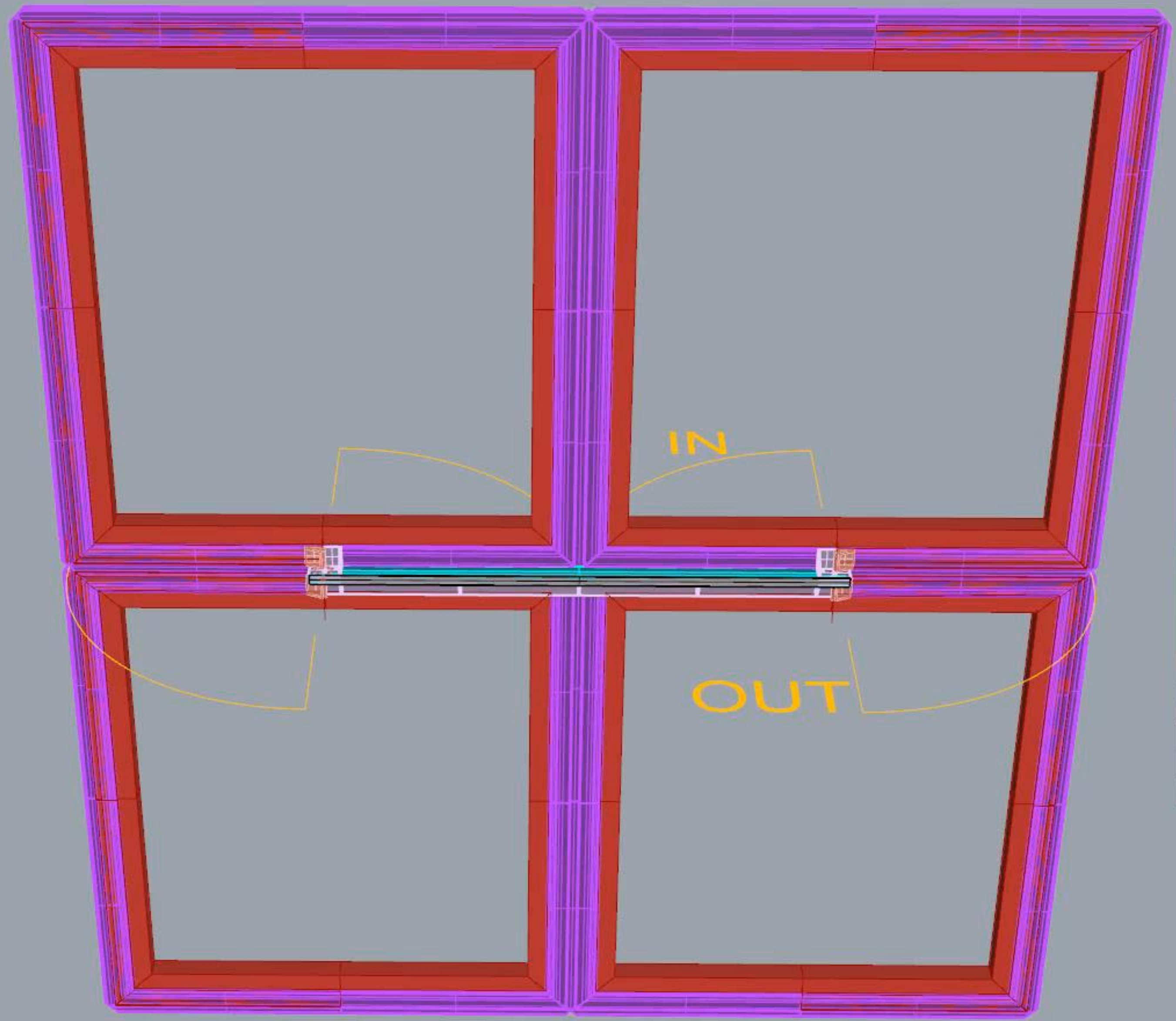
For each panel, the attachment between axle shaft and the moving part of the frame is screwed in

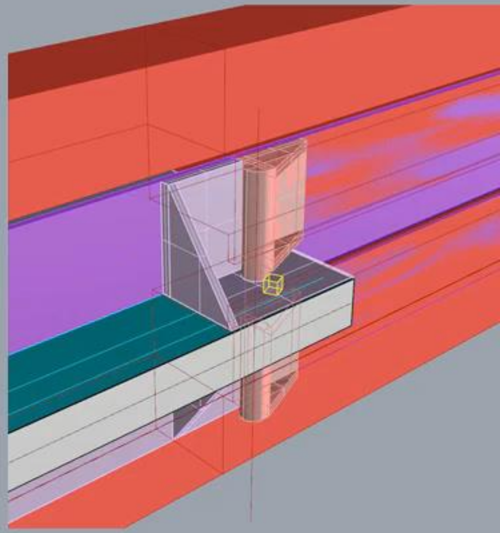
The Engine



Transparent polycarbonate cover is slid horizontally into the construction and blind-pop riveted from the bottom. Parts of it can be spray painted to exclude winter sun

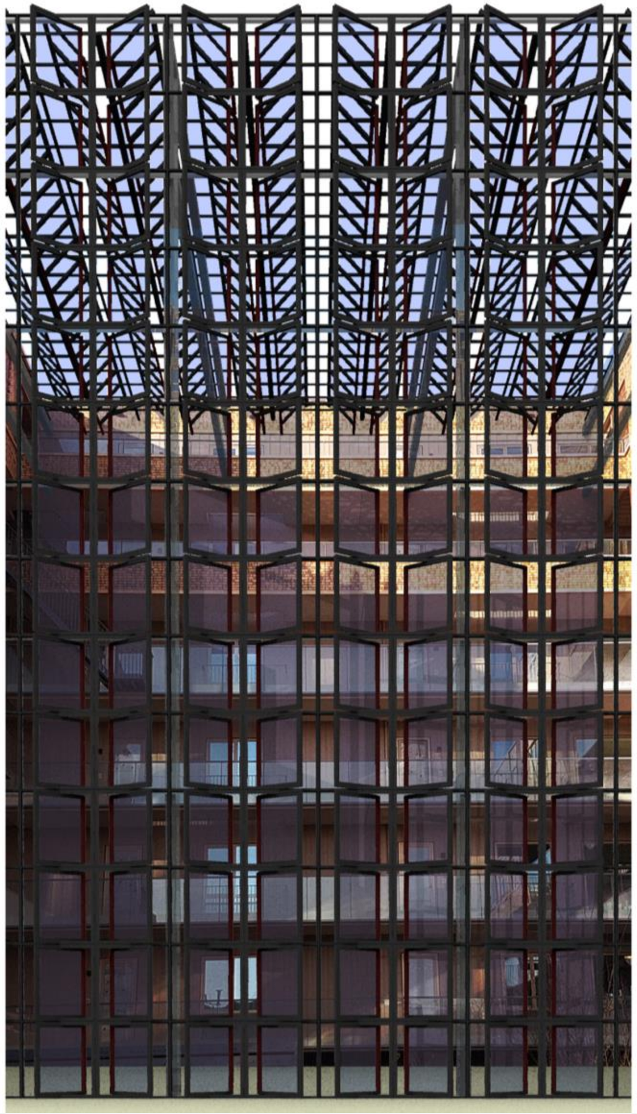

SMA displacement in m
Temperature in deg C


IN
OUT

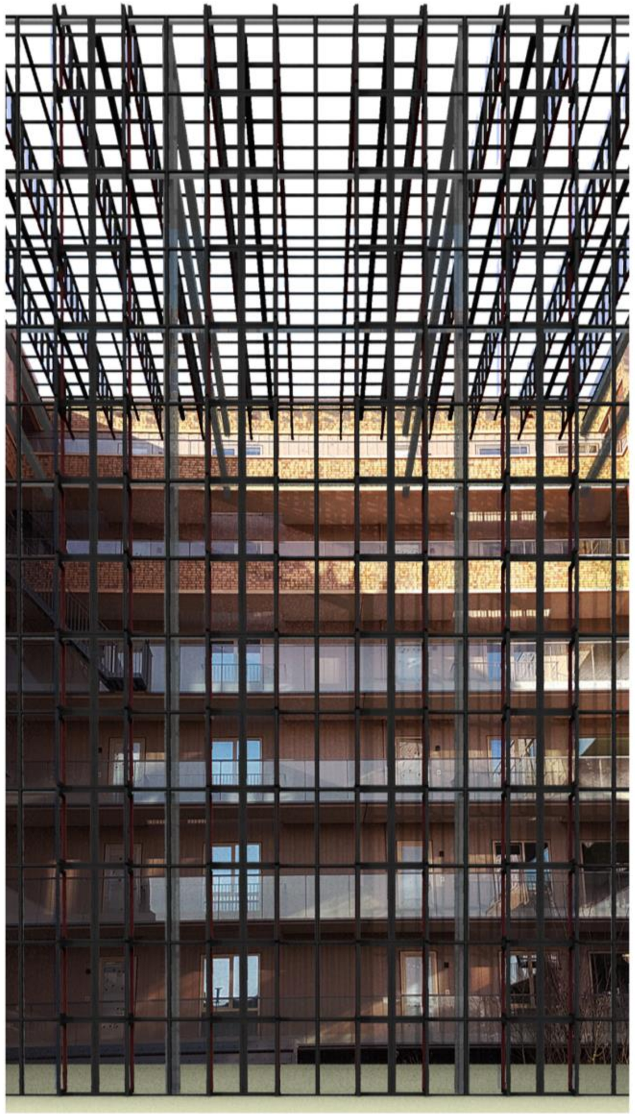


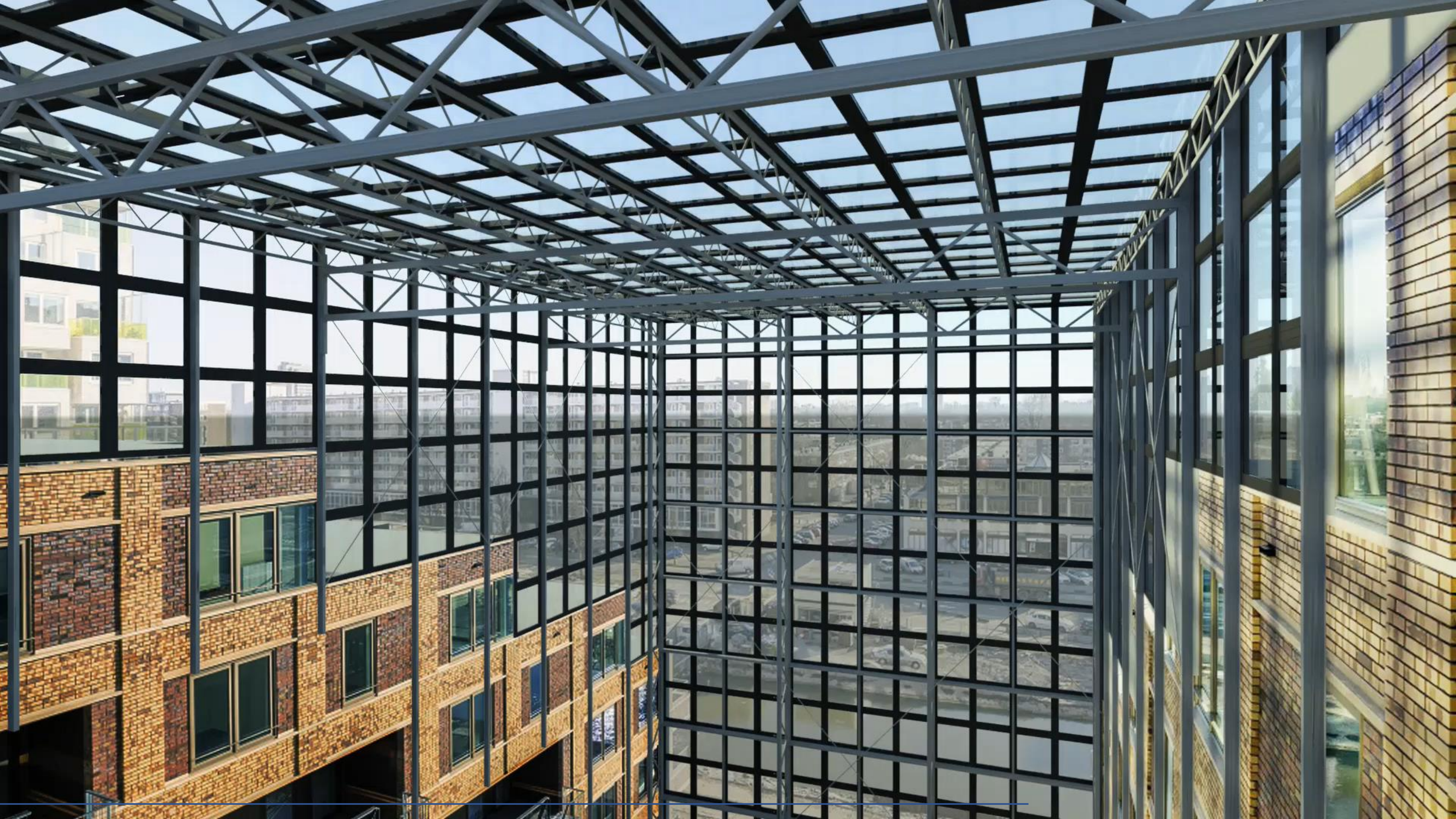
Closed

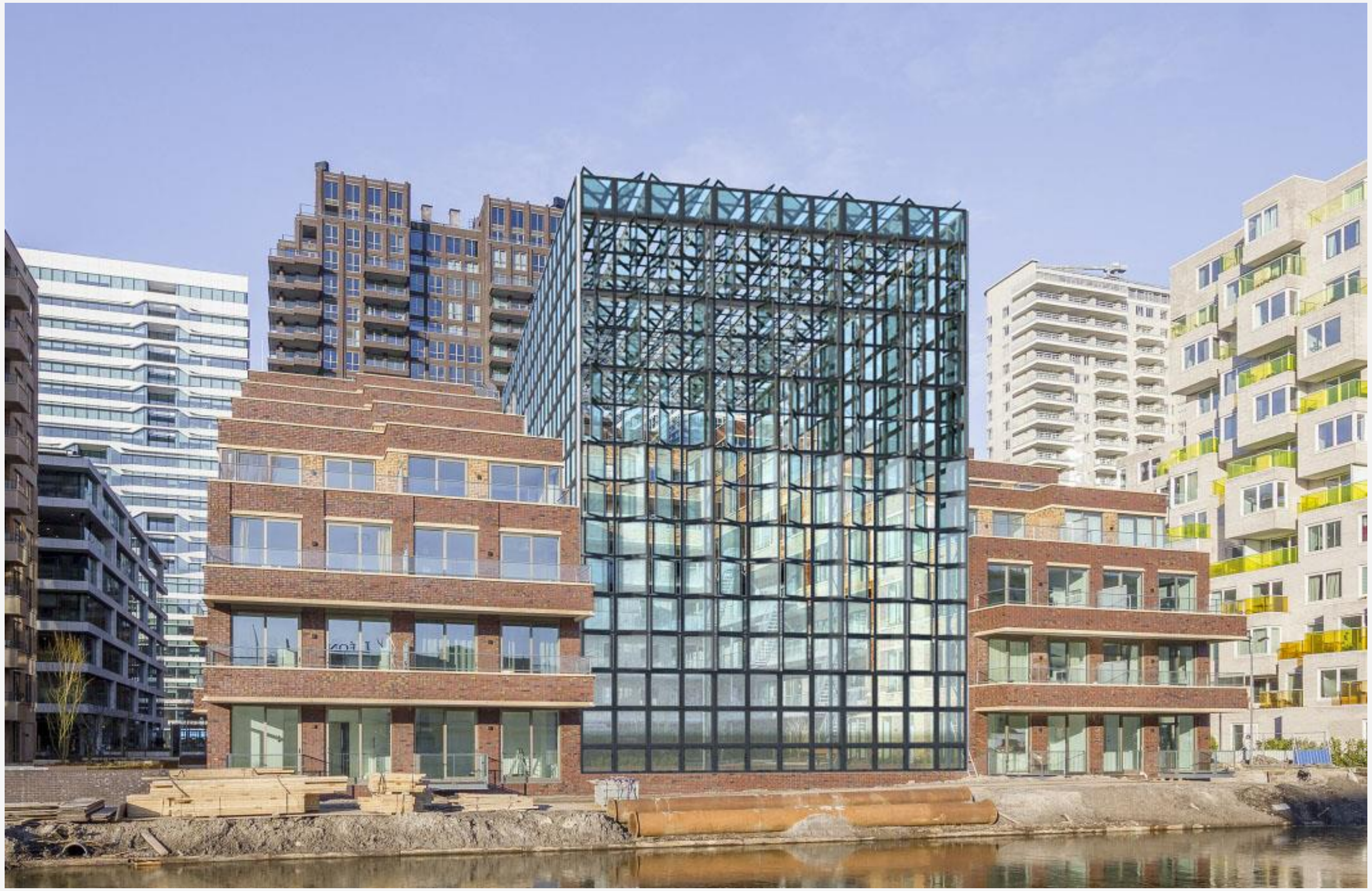
45^{0}



90^{0}







Recommendations and Conclusion

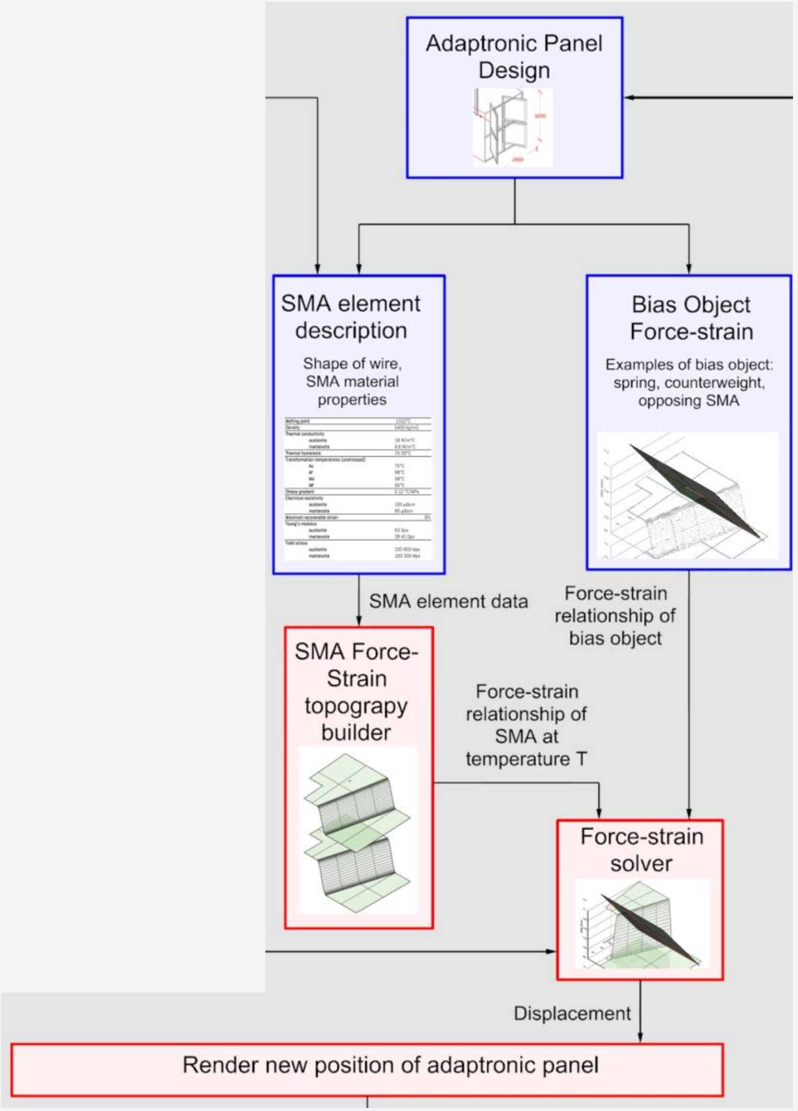
Furthering the design and study

- Tweaking the prototype bias force and geometry to achieve 90 degrees
- Analysis on the effect of wind and other external effects
- Further testing is needed to ensure stability of behaviour
- Atomic composition and material processing of Nitinol can be adjusted to ‘edit’ the temperature transitions. Other base alloys can also be experimented with
- Future outlook: Many different designs to achieve adaptronics is possible. It is a new genre of adaptiveness

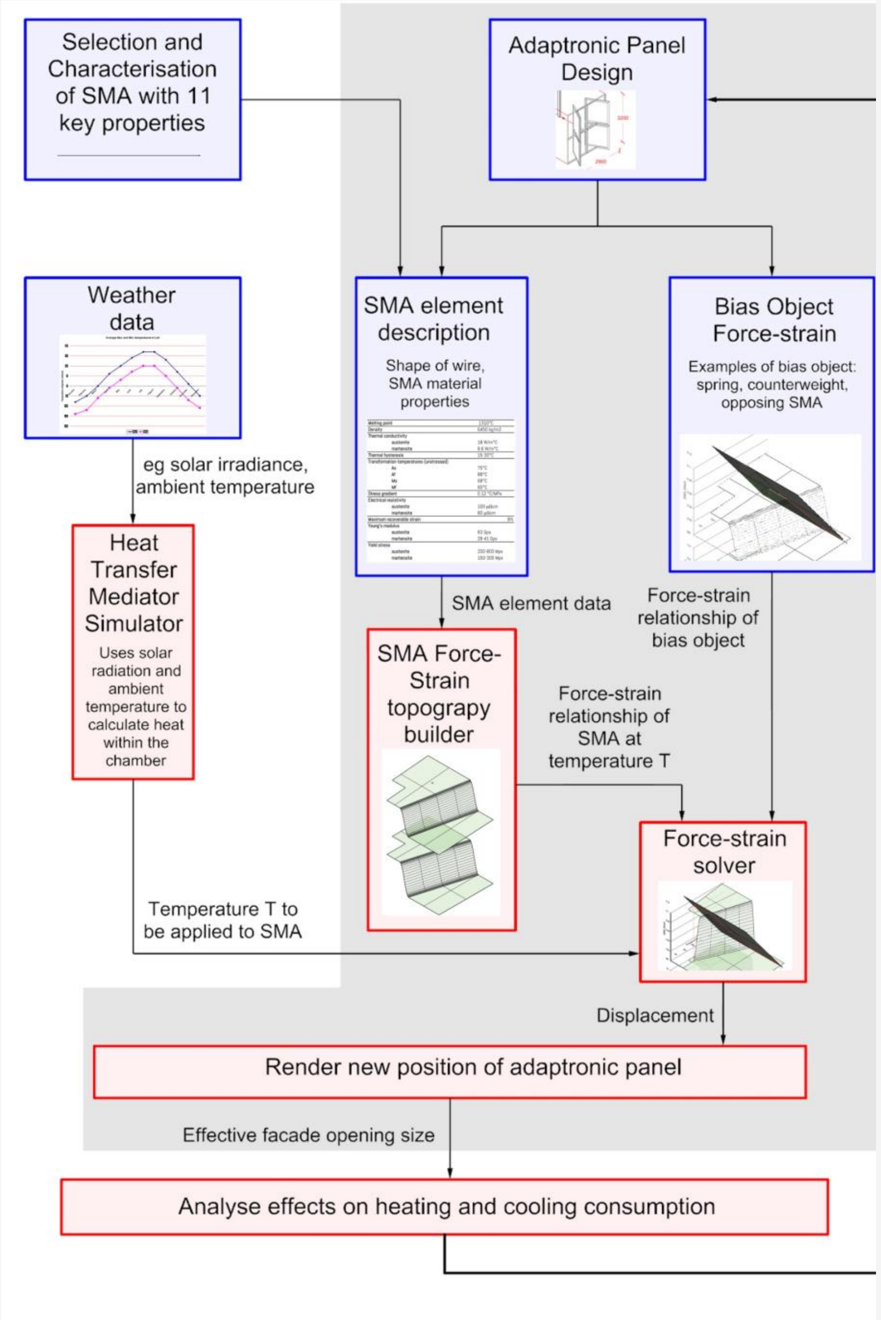
Summary

- **Adaptronics** is very recently gaining traction and has potential to deliver a self-powered and auto-responsive method for regulating indoor climate and building energy consumption
- **SMAs** can be useful for its temperature responsiveness, but are a complex material that are can be difficult to approach for a non-specialist
- **A seasonal atrium** has the potential to greatly decrease the heating load of a building
- **A software tool** was developed in Grasshopper to track the behaviour of an SMA-spring system as the temperature changes. It is designed to be accessible to non-specialists
- **Prototyping** was done to test the mechanism of a temperature-responsive engine that could be used for an adaptronic device
- **A design for an adaptronic module** for an atrium in Amsterdam was produced from the findings
- **Future studies** could analyze and fine-tune the design for enhanced response, and to optimize the design for reduction of heating and cooling loads

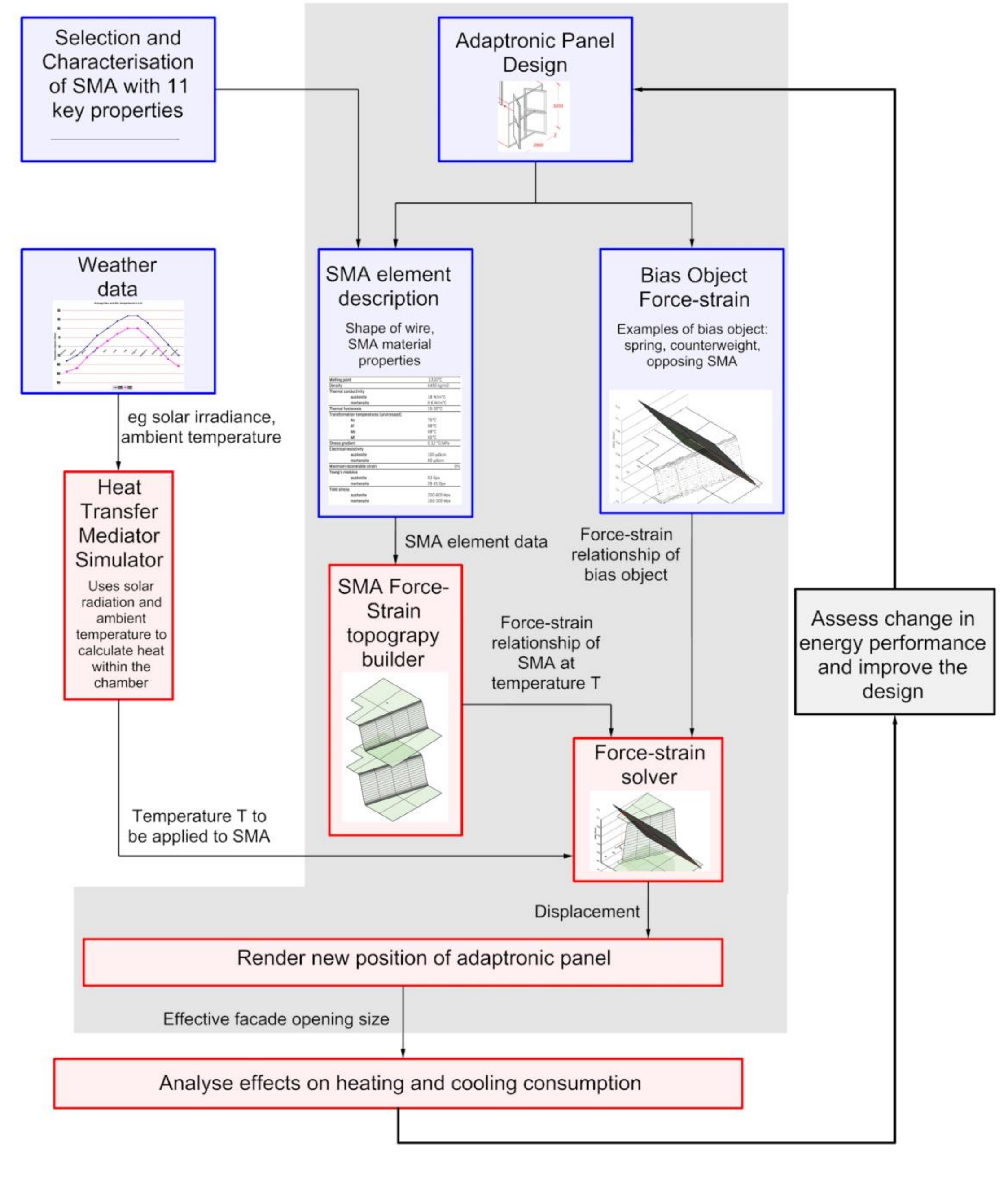
Recommendation: Framework for Energy Assessment



Recommendation: Framework for Energy Assessment



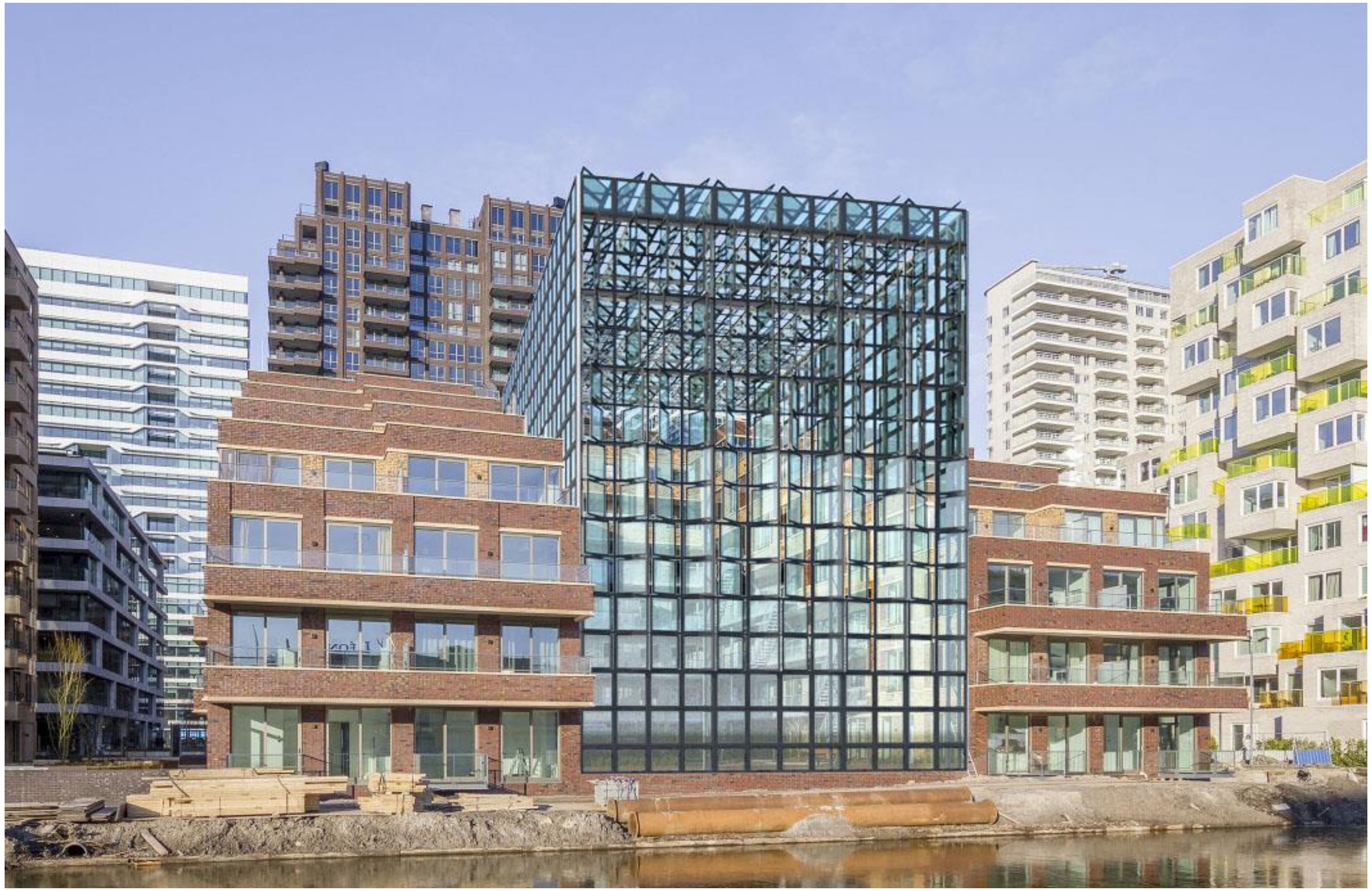
Recommendation: Framework for Energy Assessment



Conclusion

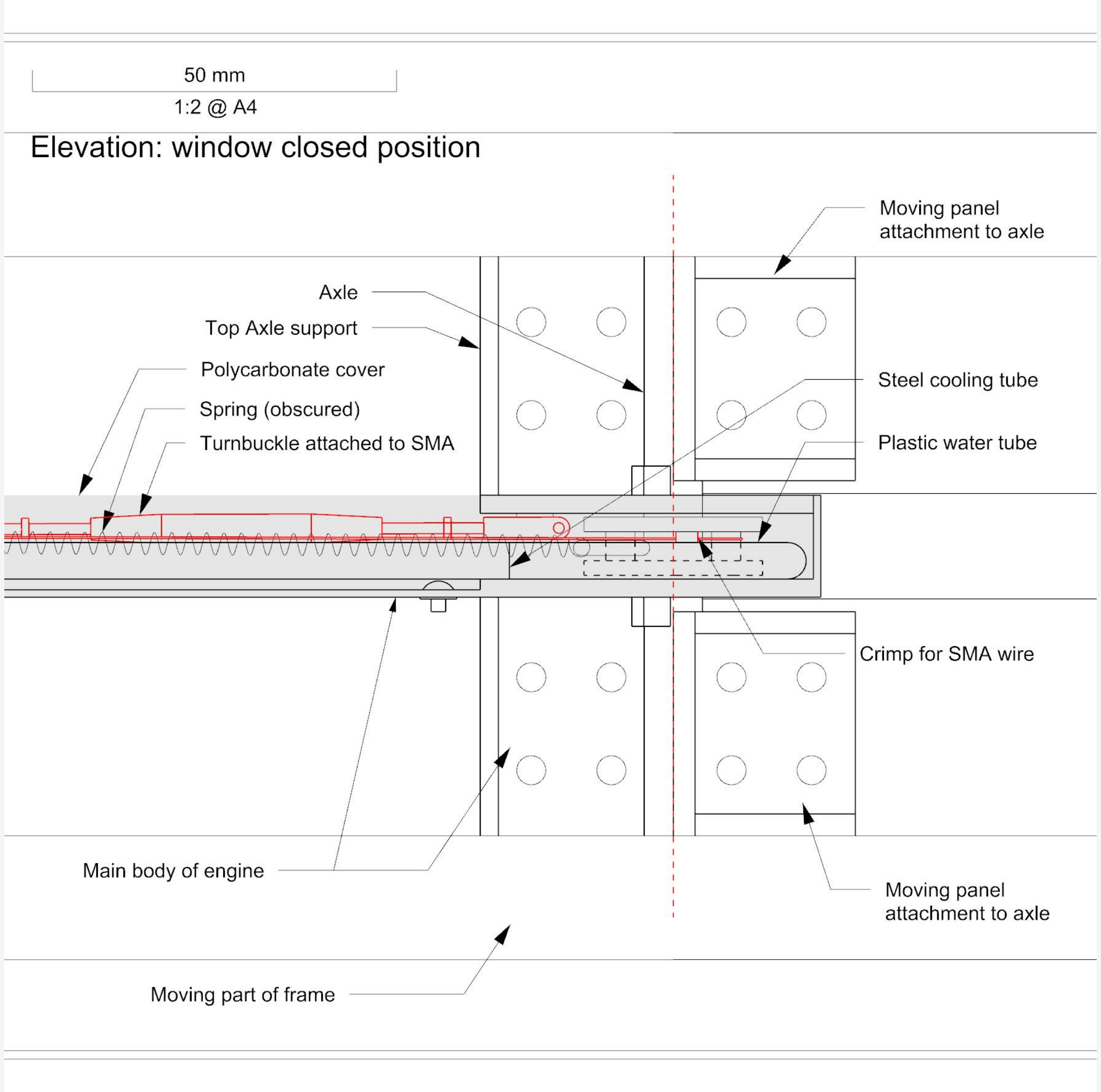
- It is possible to build an adaptronic atrium using an SMA-based contraption attached onto standard aluminium frames
- Such a device can self-open due to the outdoor environmental effects
- Further testing is needed on the material and with physical prototyping, to ensure stable repeatability in the long term and to see it behave in real life, especially against external forces
- In the longer term, the precise effect and potential benefit on the building energy consumption can be simulated with weather data and the design thereafter optimized
- The genre of architectural adaptronics is largely in its infancy; an abundance of potential emerging smart materials and designs await development in the longer term

Thank you

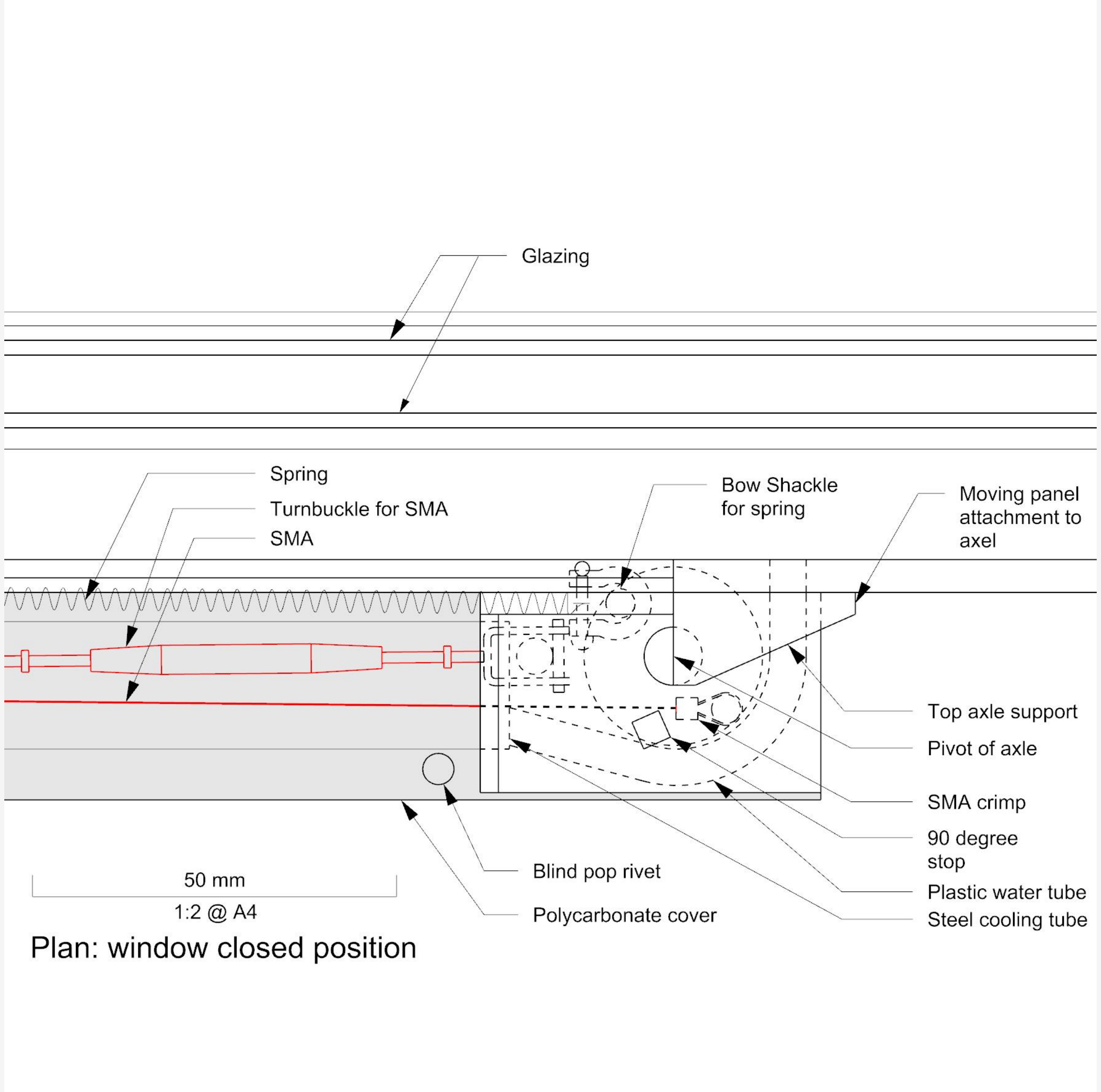


Appendix

Front Elevation Detail

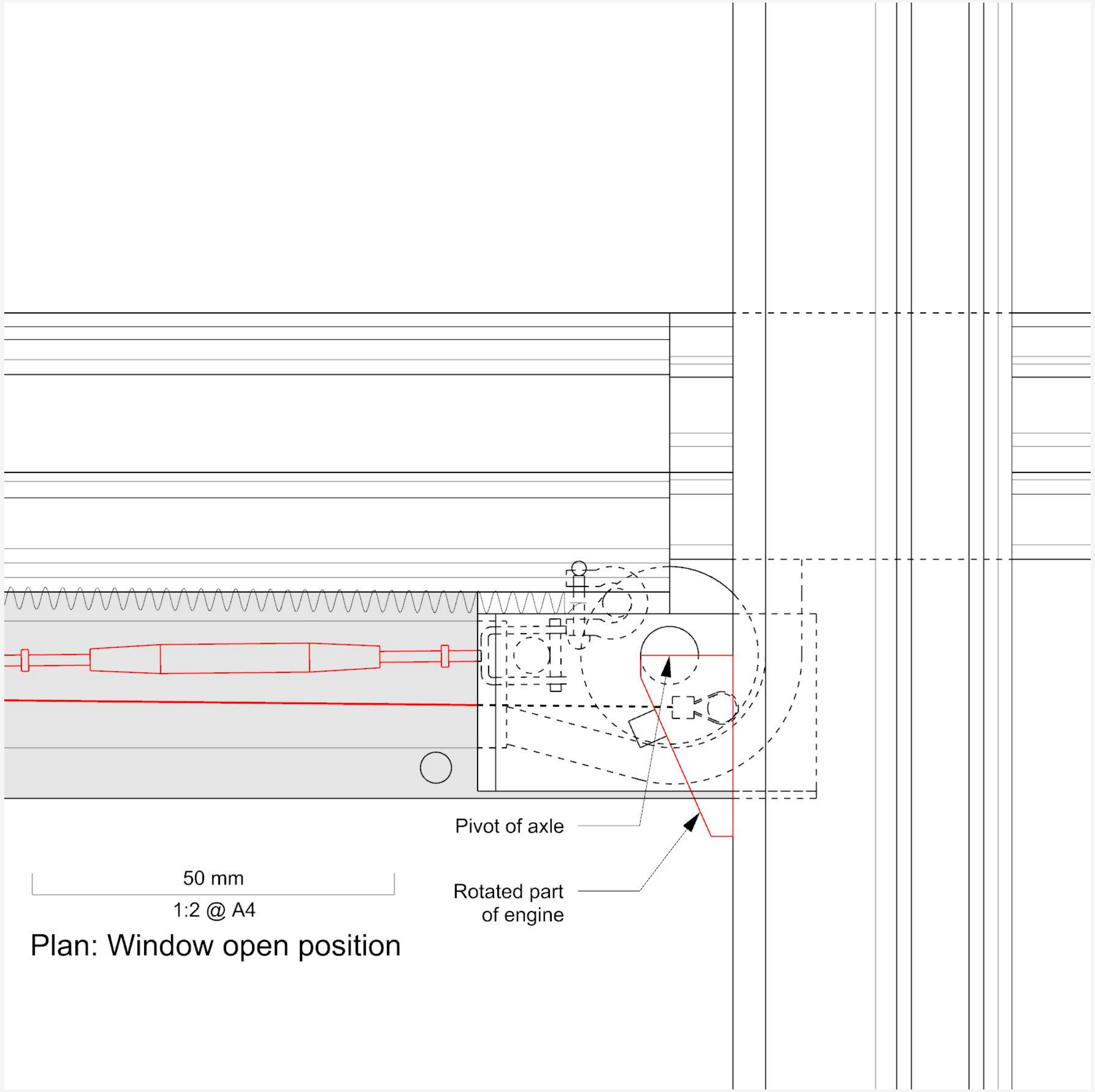


Plan Detail


Glazing
Spring
Turnbuckle for SMA
SMA
Bow Shackle
for spring
Moving panel
attachment to
axel
Top axle support
Pivot of axle
SMA crimp
90 degree
stop
Plastic water tube
Steel cooling tube
Blind pop rivet
Polycarbonate cover
50 mm
1:2 @ A4
Plan: window closed position

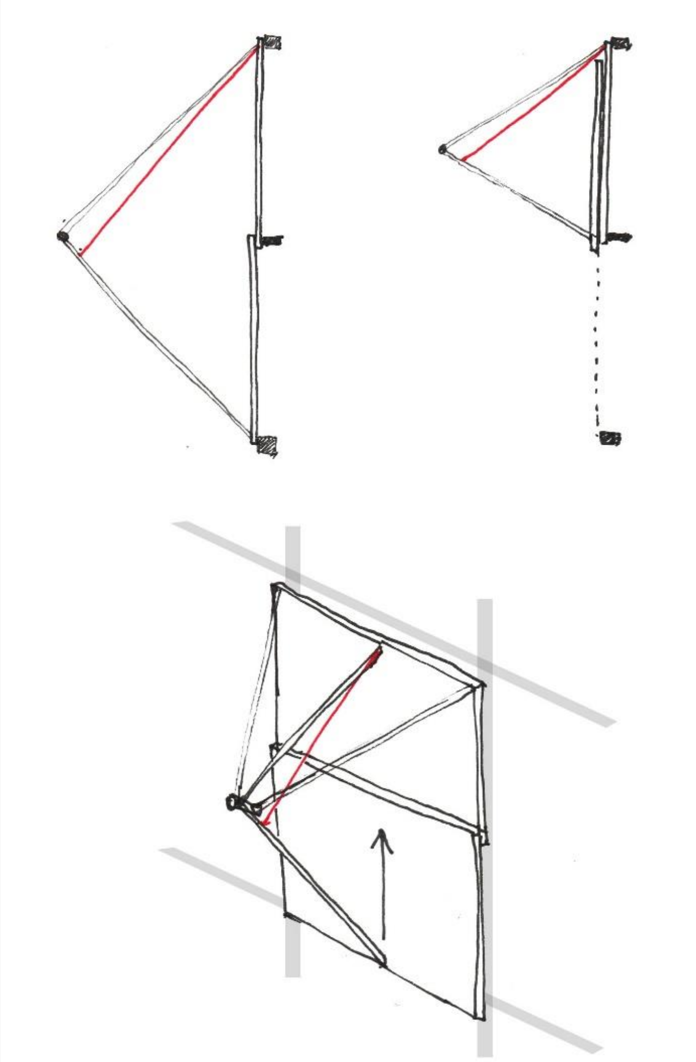
Plan Detail

Open position



Alternative design

- Sliding window panel
- SMA does not need counteract high wind forces
- SMA aligned North-South, which is better for Solar energy capture (solar collectors are normally North-South)



Reflection

Relevance to Sustainability Studio and Society

An agent against the highly intensive energy costs of HVAC

Scientific Relevance

Adaptronics: a new method for adaptive facades

Empowering the designer with Shape Memory Technology

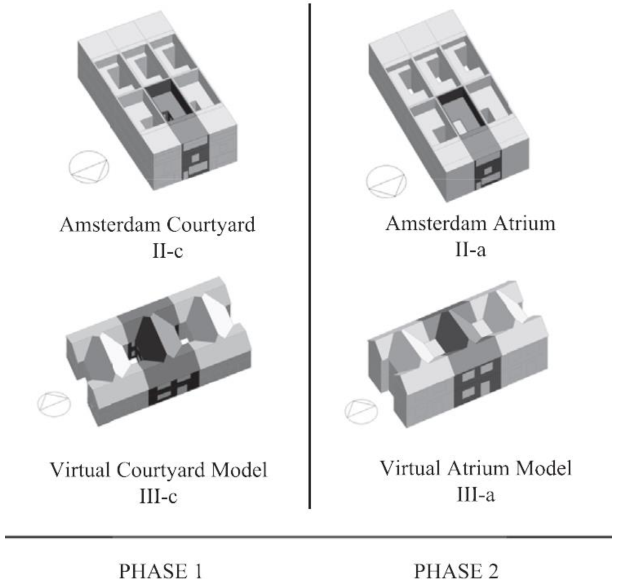
Melting point	1310°C
Density	6450 kg/m3
Thermal conductivity	
austenite	18 W/m°C
martensite	8.6 W/m°C
Thermal hysteresis	15-30°C
Transformation temperatures (unstressed)	
As	75°C
Af	88°C
Ms	68°C
Mf	60°C
Stress gradient	0.12 °C/MPa
Electrical resistivity	
austenite	100 μΩcm
martensite	80 μΩcm
Maximum recoverable strain	8%
Young's modulus	
austenite	83 Gpa
martensite	28-41 Gpa
Yield stress	
austenite	200-800 Mpa
martensite	150-300 Mpa

Energy Study: Atrium that only exists in the Winter

Taleghani et al., 2013

Set-up

A temporary glazed roof for the months Oct-Apr, and retain open courtyard for the rest of the year



Result

21-30% decrease in heating load and no increase to number of hot discomfort hours (which would have been a 75% increase for a permanent atrium)

Source: Energy performance and thermal comfort of courtyard-atrium dwellings in NL in the light of climate change, Taleghani et al., 2013

Problem Statement

- **Heating and cooling account for 14% of all energy consumption** in the EU, which is an immense amount for a single type of activity. It is 75% based on fossil fuels
- **Atria can be a great mitigator of high heating consumption** in the Winter, but poses a threat of high cooling loads in the Summer
- **Adaptronics can be an effective method for delivering 'passively responsive' façade systems** without the complexity of electrical sensors, microcontrollers, actuator and power source. method for designing the sensor, computer, actuator and power source all into the materials itself, and therefore removes many problems inherent with complex electrical-mechanical based systems of adaptive technologies. It has not been extensively utilized or researched in architecture yet
- **Shape Memory Alloys are a promising material for the 'passive actuation'** component of an façade device, but this material has also not been studied extensively in architecture

Main Question

In terms of structure and detailing, how can a Shape Memory Alloy-based adaptronic atrium be designed to self-actuate in response to external environmental conditions, for the purposes of energy consumption reduction, in temperate climate regions?

Research Questions

Sub-questions

1. **How can SMAs be used in building technology?** What are the conditions and limits when structurally incorporating Shape Memory Alloys into a façade module?
2. **How can the behaviour of an SMA element be modelled** computationally to predict the movement of the façade module given a stream of temperature data?
3. **How can an the module be designed to deliver the desired temperature-responsive change** of the façade module**?**
4. **How can a façade module incorporate the engine that delivers adaptronic abilities, and still function with all the usual requirements of a conventional facade? To what extent can it be done simply, with long-term reliability and with ease of manufacture/assembly?**
5. **To what extent can an adaptronic system deliver two extreme states of a fully transparent but insulated atrium to a fully open court, in response to a temperature change?**

Goal and Boundaries


Investigate the possibility of the adaptronic facade module, but not the fine-tuning for calculating the exact energy saving. Therefore, the focus is on the computational, feasibility and detailing aspects.


Contents

Premise for mathematical behaviour

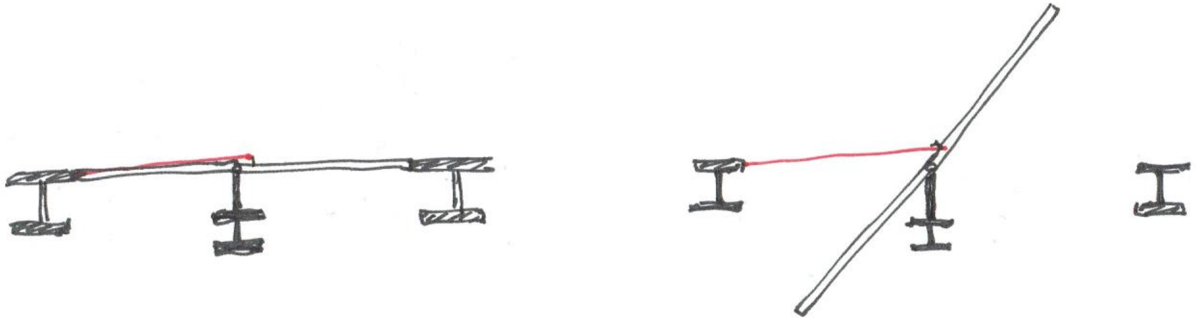
- Martensite state and Austenite state can be modelled as two conventional elastic-behaving materials with their own value of Young's Modulus and rest length
- During a transitional state, the Martensite fraction is a number between 0 and 1 to describe how much of the material is martensite; 0 is used for a fully austenite SMA, 1 for fully martensite
- The 'effective Young's Modulus' and 'current rest length' can be inferred from the Martensite fraction
- If the stress is known, it can be applied in conventional mechanical formulas with the effective Young's Modulus and current rest length to find the strain

Concept Designs

Concept 1

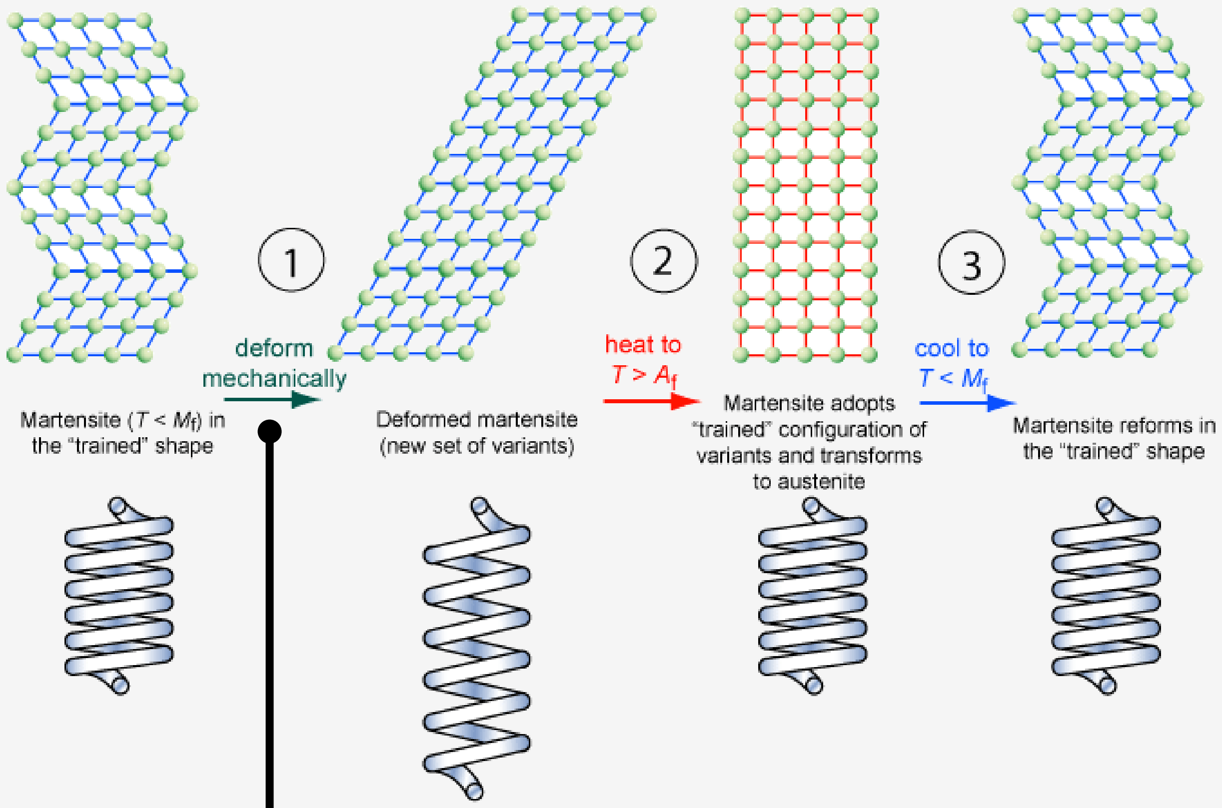
Concept 2

Concept 3



Testing Material to Interrogate the Shape Memory Effect

Material:
Nitinol wire from
SmartWires,
0.5mm diameter,
45ºC activation



What stress level does this deform at?