ThermoSense

Responsive Thermal Facade

RESPONSIVE THERMAL FAÇADE: MONO-MATERIAL FAÇADE WITH SWITCHABLE THERMAL RESISTANCE

Master Thesis

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ABSTRACT

This thesis presents an innovative façade element designed to significantly reduce a building's operational energy consumption while ensuring full recyclability. It achieves this by dynamically adjusting the thermal insulation of a mono-material facade element. Given the building sector's high global energy consumption and waste production, such innovations are critically needed.

The methodology consists of a literature review followed by three design phases: (1) conceptual design; (2) preliminary design; (3) final design. The iterative build–measure–learn cycle guided the development process.

Four different designs were developed for the switchable insulation: auxetic structure, soft robotics, doors and organic tree. The auxetic structure was selected to be further developed because of its low sensitivity to production errors and high thermal performance in the insulating state.

When it comes to the material, thermoplastic copolymer (TPC) was used for the facade, because of its flexibility, flame retardance, UV and moisture durability, compatibility with 3D printing, recyclability, and adherence to ISO and EU standards.

The final design achieves a Rc-value of 4.7 m^2K/W in its insulating state and 1.16 m^2K/W in its conducting state. Switching the state is done with a pneumatic actuator controlled by a rule-based system, making the facade responsive to its environment.

Future research should focus on optimizing the auxetic structure to reduce actuation force and exploring alternative sustainable materials compatible with the mono-material switching concept.

KEYWORDS
switchable insulation - mono-material - façade - responsive - additive manufacturing

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1. INTRODUCTION

INTRODUCTION

Background

Climate change is one of the most pressing global challenges of the 21st century, with human activities, particularly in urban areas, contributing significantly to greenhouse gas emissions. The built environment, encompassing buildings, infrastructure, and urban spaces, is a major contributor to climate change. The building sector accounts for about 30% of energy consumption worldwide and 26% of global energy-related emissions (IEA, 2023). As such, reducing energy consumption and improving the sustainability of buildings is critical for mitigating climate change.

Insulation plays a key role in reducing these energy demands by minimising heat loss during colder months and limiting heat gain during warmer months. Traditional insulation materials that do not adapt to environmental conditions are commonly used in building envelopes. However, fixed insulation materials are less effective at maintaining energy efficiency over time as they do not respond dynamically to changing temperature fluctuations and environmental conditions (Masoso & Grobler, 2008) (Pérez-Lombard et al., 2008). In contrast, switchable insulation systems, which can adjust their properties in response to external factors, have been shown to provide greater energy savings and improve indoor comfort compared to conventional fixed insulation (Cui & Overend, 2019).

Despite advancements in insulation technology, challenges remain in the long-term sustainability of building envelopes, particularly when it comes to recycling. Building materials are difficult to recycle due to the diverse and composite nature of the materials used in construction.
This problem is worsen by the fact that many building envelopes are composed of materials that cannot be easily disassembled or reused, leading to large quantities of construction and demolition waste that contribute to landfill burden (Finch et al., 2021). The lack of effective recycling methods for these materials presents a significant barrier to achieving circular economy goals and reducing the environmental footprint of the built environment.

This thesis aims to develop an easy to recycle building envelope that can enhance operational energy savings in a building. Easy recycling is achieved by making the envelope mono-material, enhanced energy savings is achieved by developing a switchable insulation. By addressing these issues, it is possible to not only reduce the environmental impact of buildings but also pave the way for more sustainable urban development in the face of ongoing climate change.

Problem statement

There is a goal to decrease the worldwide greenhouse gas emissions with 43% by 2030 ("Paris Agreement," 2016) and the building sector has a large share in the worldwide energy consumption.
Switchable insulation could be a promising solution for improving the energy efficiency of buildings. However, current building envelopes with switchable insulation are not designed with recyclability in mind and therefore are hard to recycle.

Objective

Main objective:
Developing a responsive façade element with switchable insulation that is easy to recycle

Subobjectives:
1. Define the optimal insulation range required for the switchable system

2. Identify the design requirements for the façade element

3. Determining the switching mechanism that is needed to change the thermal resistance

4. Select a suitable material that supports functionality and recyclability

5. Design the internal infill pattern to achieve the desired insulation range

6. Test if the desired performance range has been achieved

Research question
Main question
How to engineer a mono-material façade element that can adapt its thermal insulation value?

Sub-questions:
1. What is the required insulation range for the switchable system?

2. What are the design requirements for the façade element?

3. What switching mechanism is suitable for changing the thermal resistance?

4. What material supports both functionality and recyclability?

5. How should the infill pattern be designed to achieve the insulation range?

6. Has the desired performance been achieved?

Approach & Methodology
Phase 1: Literature review
In this phase knowledge is gathered on materials, requirements for façades, 3D and 4D printing techniques, mono-material façades, different patterns for infill (de Rubeis et al., 2024), and switchable insulations (Fawaier & Bokor, 2022). This knowledge serves as foundation for the design assignment of this thesis. Scopus and Google Scholar will be used to find suitable academic articles. For finding a suitable material the software ANSYS Edupack is being used.

In this phase the following sub-questions will be answered:
1. What is the required insulation range for the switchable system?

Phase 2: developing the conceptual design
In this phase the conceptual design is developed. This is done by first setting the design criteria. After that, some strategies are explored to change the thermal resistance of a facade in its application. Different strategies are explored to create flexibility. Finally, in this phase, a selection for material and actuator is made.

In this phase the following sub-question will be answered:
2. What are the design requirements for the façade element?

3. What switching mechanism is suitable for changing the thermal resistance?

4. What material supports both functionality and recyclability?

Phase 3: developing the initial design
This phase builds upon the knowledge gathered in the previous two phases. Using the conclusions from the previous phases, an different design strategies are developed.

Research by design is being done, meaning this phase is iterative in nature. It follows the following cycle: build, measure, learn by Ries (2011).

BUILD
Designing will be done through sketching and 3D modelling in Rhino3D. Prototyping will be done using a 3D printer in the LAMA Lab at the Faculty of Architecture and the Built Environment at Delft University of

Technology. The printing technique being used is Fused Deposition Modelling (FDM). The slicer software used is from Bambu Studio and Cura.
Testing the thermal conductivity will be done through a FEA simulation. For this, COMSOL Multiphysics is used.

MEASURE
After and during the building phase, the following questions will be asked:
- Does the prototype move like it was intended?
- How sensitive is it to production errors?
- What is the Rc value per 100mm?
- How long does it take to print it?
- Is there potential for a rapid production method (is it extrudable)?
- Does the design require a lot of energy in its application?

LEARN
This cycle ends with the learnings that will be taken into account in the next design iteration.

In this phase the following sub-question will be answered:
5. How should the infill pattern be designed to achieve the insulation range?
6. Has the desired performance been achieved?

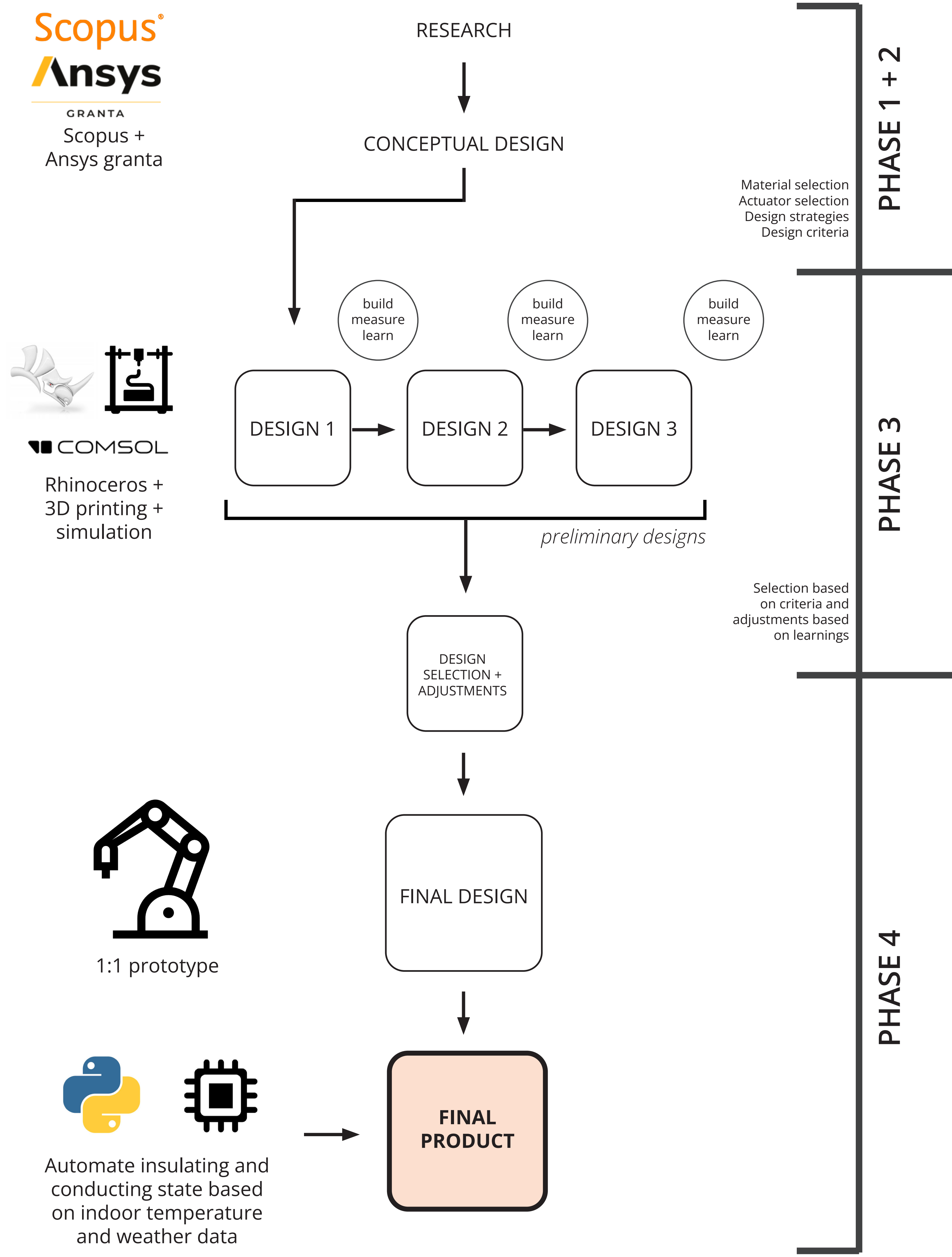
Phase 4: Final design
In this phase a selection is made from the developed design directions from the initial design phase. The selected design is further developed into a proof of concept.

This phase ends with a conclusion, reflection and recommendations for further research. The aim of this is to bring closure to the research project, while offering insights and directions for continued exploration and improvement in the subject matter.

Relevance
Society
The developed product in this graduation work aims to contribute to lowering CO2-emission by reducing energy usage in buildings. This is in line with the Paris Agreement to limit the temperature increase to 1.5°C above pre-industrial levels by decreasing the greenhouse gas emissions with 43% by 2030 compared to 2015 ("Paris Agreement," 2016). In addition, the product is easy to recycle, which is increasingly important in a circular economy. The societal impact has the potential to be great since the product developed is scalable in nature.

Science
Furthermore, this work introduces a novel way to create switchable insulation suitable to the circular economy by using auxetic structures. Therefore, a new application of auxetic structures is also shown. Additionally, the mistakes made in developing the product are valuable lessons for anyone working on a similar design task.

Industry
To conclude, this work introduces a new façade for the industry and shines light on the potential and advantages of switchable insulation for the built environment. Architects get a new tool to achieve sustainable buildings and comfortable indoor environments for the buildings they design.


Scopus
Ansys
GRANTA
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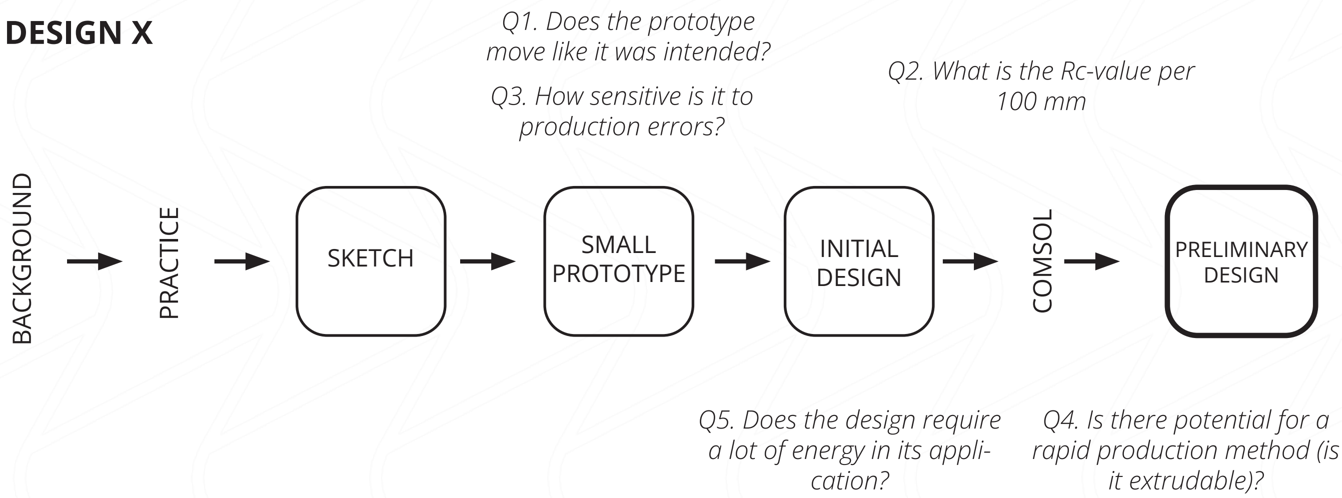
RESEARCH
CONCEPTUAL DESIGN
Material selection
Actuator selection
Design strategies
Design criteria
PHASE 1 + 2
build
measure
learn
DESIGN 1
DESIGN 2
DESIGN 3
COMSOL
Rhinoceros +
3D printing +
simulation
preliminary designs
PHASE 3
Selection based
on criteria and
adjustments based
on learnings
DESIGN
SELECTION +
ADJUSTMENTS
FINAL DESIGN
1:1 prototype
PHASE 4
FINAL
PRODUCT
Automate insulating and
conducting state based
on indoor temperature
and weather data

PRELIMINARY DESIGN

DESIGN X



2. LITERATURE REVIEW

LITERATURE REVIEW

The sources for this literature review were found using Scopus and Google Scholar. The search terms used were: dynamic insulation, switchable insulation, building envelopes, mono-material façades, 3D printing, additive manufacturing, and 4D printing. Most articles were found using the snowball method with the mono-material façade from Sarakinioti et al. as a starting point (Sarakinioti et al., 2018). Another source used was Granta Edupack (material database) to find a suitable material.

This literature survey serves as a base for further research on how to engineer a mono-material façade element with switchable thermal insulation.

1 Thermal insulation: static, switchable, and mono-material building envelopes
This section aims to explain the basic principles of achieving thermal insulation for static and switchable insulation as well as mono-material building envelopes. In section 1.1, basic principles of heat transfer for static building envelopes will be examined. In the following section (1.2), switchable insulation will be presented, and finally, in section 1.3, thermal insulation of mono-material building envelopes will be illustrated.

1.1 Basic principles of heat transfer for static building envelopes
Heat can move from one place to another in three ways: conduction, convection, and radiation (Sidebotham, 2015) (see figure 1). The generally accepted definition of heat is "energy transferred from one system to another solely by virtue of a difference in temperature" (Tripp, 1976). Conduction occurs when heat moves through direct contact between solid materials. Convection involves the movement of heat through fluids (liquids or gases). Radiation is the transfer of heat through electromagnetic waves and does not require a medium.

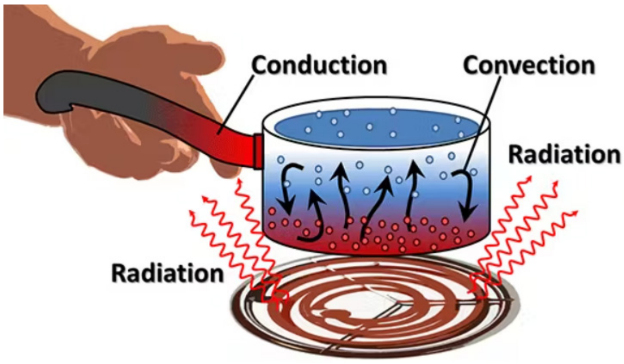


Figure 1. Three types of heat transfer mechanisms: conduction, convection and radiation, reprinted from (Machine Design, 2015)

When it comes to heat transfer in building envelopes with static insulation, conduction is the dominant factor. The law of Fourier is the basic formula of heat transfer through conduction:

$q = -\lambda * dT/dx$, where

- q is the heat flux [W/m^2]
- λ is the thermal conductivity of the material [W/m·K]

- dT/dx is the temperature gradient in the direction of heat flow [K/m], where
- dT is the temperature difference across the material [K or C]
- dx is the thickness or distance over which the temperature difference occurs [m]

As seen in the formula, heat transfer can only occur when there is a difference in temperature. Moreover, a lower thermal conductivity (λ) means less heat transfer.

Thermal conductivity is a material-specific property that influences the thermal resistance of a building envelope. Materials with lower thermal conductivity are more effective at reducing heat flow, making them preferable for insulation applications.

Other factors influencing material choice for thermal insulation are material cost, construction ease, safety and health issues, durability, acoustic performance, air tightness, environmental impact, and availability (figure 2) (Fawaier & Bokor, 2022).

1.2 Switchable Insulation Systems (SIS)
For this section the following search term was used in Scopus: "switchable insulation". There were 24 results, of which 6 were useful for this study: they were in the nature of switchable insulation types and strategies, energy saving and cost-benefit analysis.

Switchable insulation is the ability to change the heat transfer rate in a building envelope. Compared to static insulation, i.e., insulation material that cannot change the heat transfer rate over time, switchable insulation can save a lot of operating energy. According to a study in France, a residential detached house can save up to 63% of energy associated with heating and cooling if switchable insulation systems are used. For apartment units this is 82% annual energy savings (Valentin et al., 2022).

Changing the heat transfer rate of a building envelope would be particularly useful in the following scenarios:
- During summer nights, when it is colder outside than inside and there is a need

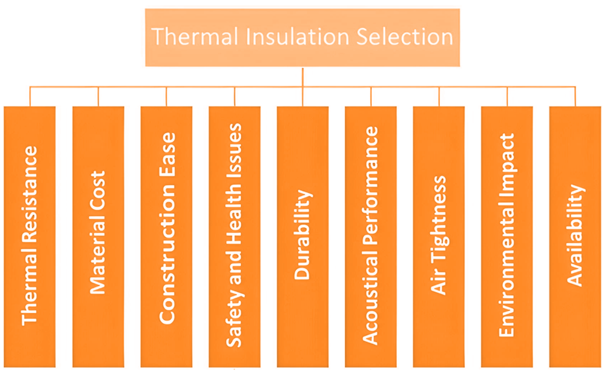


Figure 2. Factors influencing decision making in material for thermal insulation (Fawaier & Bokor, 2022).

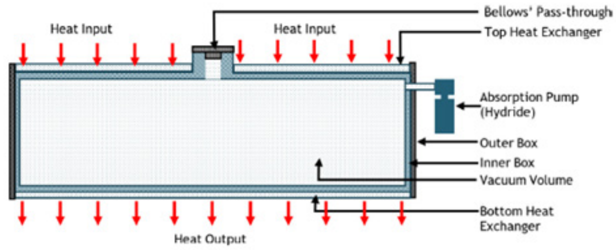


Figure 3. Active thermal insulation (Cui & Overend, 2019)

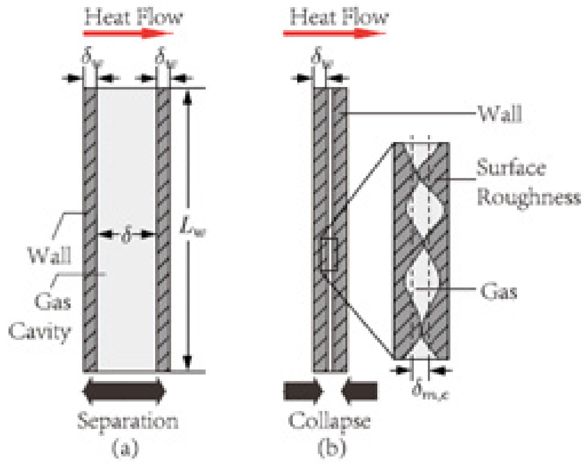


Figure 4. Mechanical contact switchable insulation (Cui & Overend, 2019)

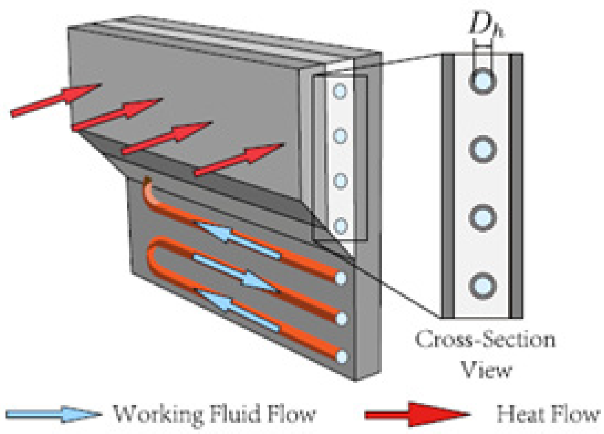


Figure 5. Pipe-embedded switchable thermal insulation (Cui & Overend, 2019)

to cool down the building. Decreasing the thermal resistance of the building envelope allows it to release heat to the outside.

- When there is undesired internal heat gain (e.g., during certain activities like sports), which results in a room with an uncomfortable temperature, and it is cool outside. Also in this scenario, decreasing the thermal resistance of the building envelope allows it to release heat to the outside.

According to Cui & Overend (2019), switchable insulation can be achieved through three different switching mechanisms:
- Carrier density transitions
- Carrier mobility transitions
- Carrier energy transitions

The first mechanism is about changing the amount of heat carriers in a medium. The more heat carriers you remove, the less heat transfer is occurring. Active vacuum thermal insulation (figure 3) falls under this category.

The second mechanism is about enhancing or hindering the mobility of heat carriers. This can be achieved through mechanical contact switchable insulation (figure 4), suspended-particle-based switchable insulation and pipe-embedded switchable thermal insulation (figure 5).

The third mechanism is about changing the energy density of the heat carriers. This can be achieved with phase-change switchable insulation.

Salah et al. (2024), on the other hand, also identified three types of switchable insulations but in a different way (see figure 6 and 7):
1. Dynamic panels/parts – which is about mechanically changing the position or configuration of the thermal insulation. This can be further categorised into movable insulation parts (e.g., rotating panels, vertically sliding panels and removable

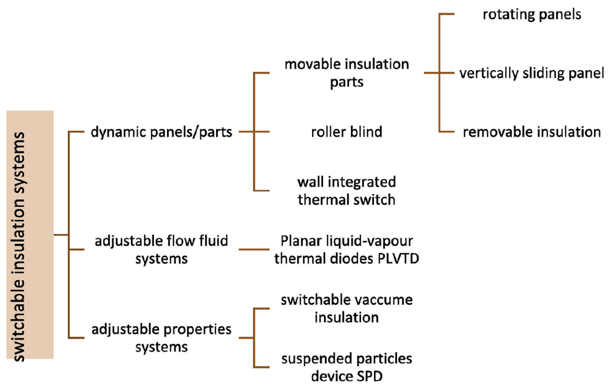


Figure 6. Types of switchable insulation systems (Salah et al., 2024)

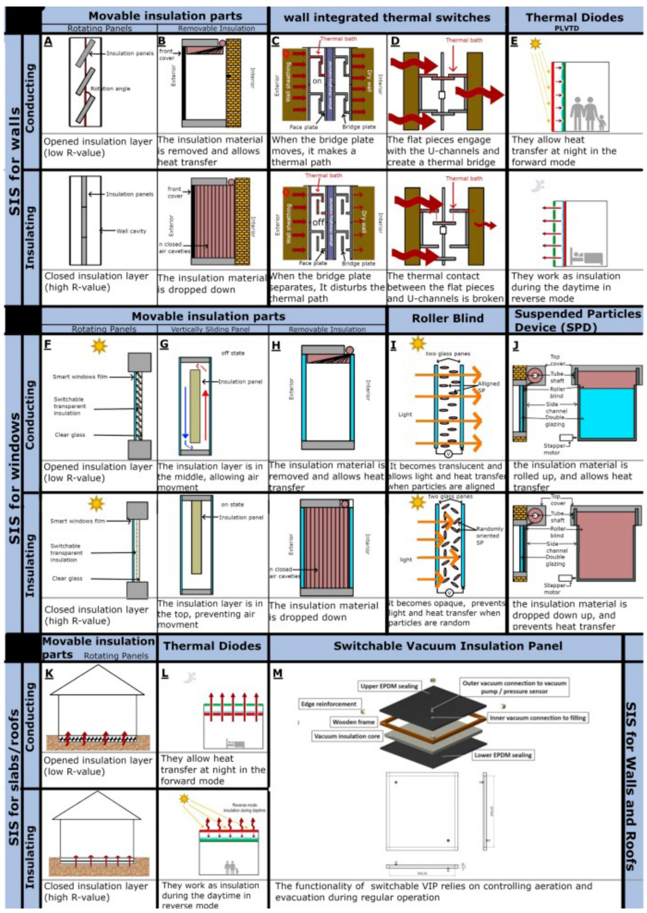


Figure 7. Types of switchable insulation systems (Salah et al., 2024)

insulation), roller blinds and wall-integrated thermal switches (this is similar to mechanical contact from Cui & Overend).

2. Adjustable flow fluid systems – this is about controlling the fluid flow and movement within a system to change the thermal insulation. This can be further categorised into planar liquid vapour thermal diodes (PLVTD) and pipe-embedded systems (this is similar to piped embedded systems from Cui & Overend).

3. Adjustable properties systems – this is about changing the properties of the whole system to change the thermal insulation. This can be further categorised into switchable vacuum insulation (this is similar to vacuum from Cui & Overend), suspended particles device (SPD) (this is similar to suspended particles from Cui & Overend), and phase change.

Although there are some similarities between the two studies, the review of Salah et al. gives a more complete overview.

All these switching mechanisms seem to be hard to recycle since they involve multiple materials, with some of them also involving mechanical and/or electrical devices.

Switchable insulation systems also have some logic behind them to control the thermal resistance of the building envelope. The control architecture of switchable insulation systems consists of:
- Sensor level – this is the 'sense' of the system. These are the devices that detect and monitor the physical environment. It can measure parameters such as temperature, solar radiance and humidity, which can be needed as input for the control strategy level.
- Control strategy level – this is the 'brain' of the system. Based on a certain logic, which

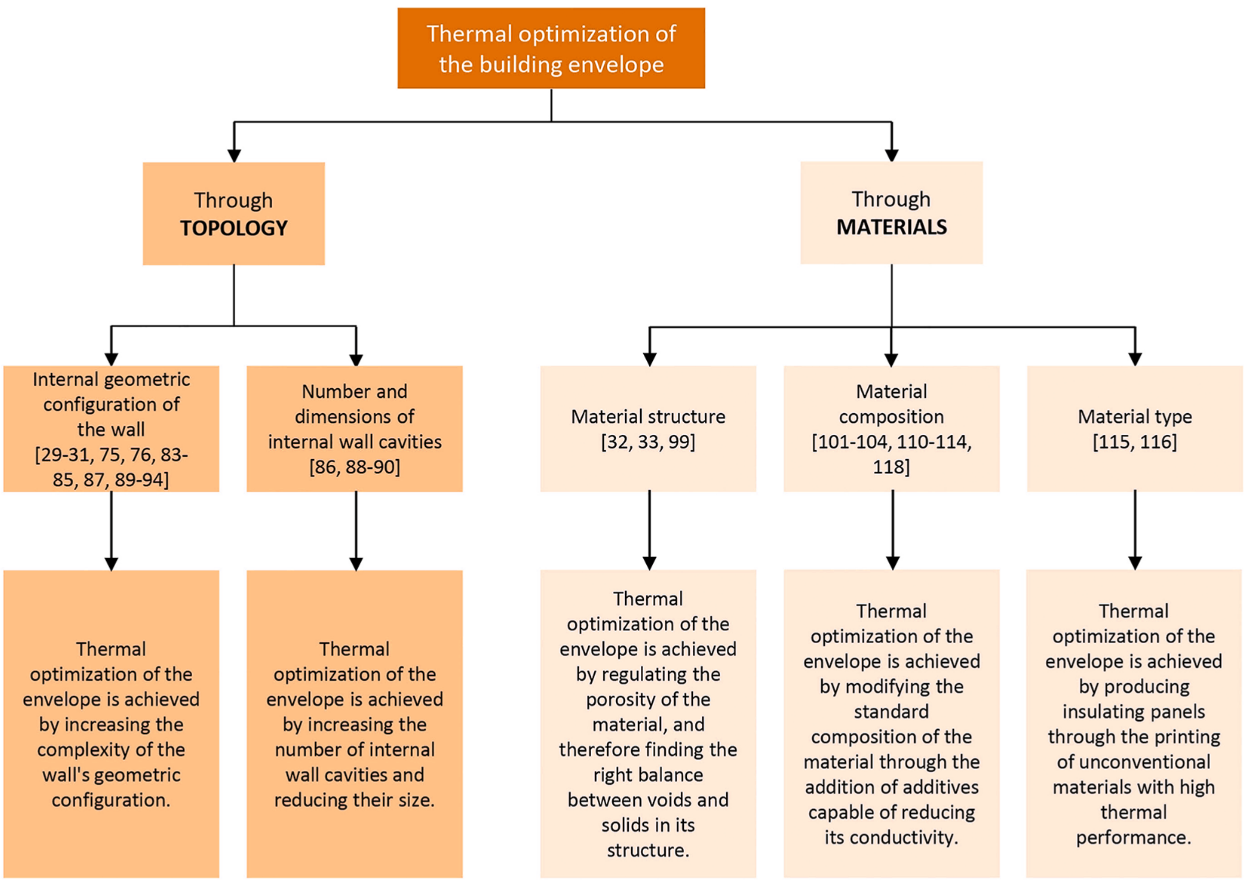


Figure 8. Ways to achieve thermal insulation with mono-material building envelopes (de Rubeis et al., 2024)

will be discussed in chapter 5.3, it decides when to switch the insulation.
- Actuator level – this is the 'muscle' of the system. It provides the force required to switch the insulation (more on the actuator level in chapter 3.2.4).

1.3 Thermal insulation of mono-material building envelope

Mono-material building envelopes are building envelopes that are made out of one material. Since they are made out of one material, there is no need to demount the façade to recycle it. Mono-material building envelopes are one of the two strategies to improve circularity for building envelopes (the other one is a clear design-to-disassembly strategy) (Cheibas et al., 2024).

A lot of research has been done on how to achieve thermal insulation with mono-material building envelopes. Current research shows that thermal insulation can be achieved through topology or materials (figure 8) (de Rubeis et al., 2024).

For the latter, the disadvantage is that these materials tend to be foamy and therefore unsuitable for facing the exterior. This means that it would be hard to achieve a mono-material façade.

Using topology for thermal insulation offers an opportunity to achieve high thermal performance with materials that are suitable for exterior use, even if they typically have high thermal conductivity (λ) and are not considered ideal insulators. In this case, high thermal performance can be achieved through increasing the complexity of the wall's configuration and/or increasing the number of internal wall cavities and reducing their size.

Heat transfers through these cavities are a result of solid conductivity, gas conductivity, radiation and natural convection (figure 9) (Briels et al., 2022). The optimisation of specific geometric attributes reduces

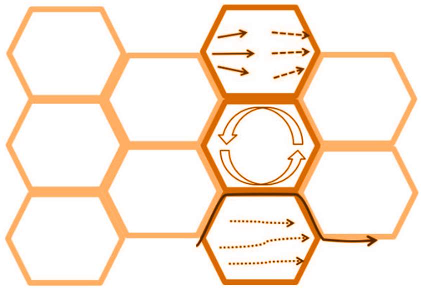


Figure 9. Heat transfer mechanisms in cellular structures, showing schematically radiative (red) and convective (green) heat transfer within the cells as well as conductive heat transfer (blue) through the gas (dotted line) and solid (continuous line) (Briels et al., 2022).

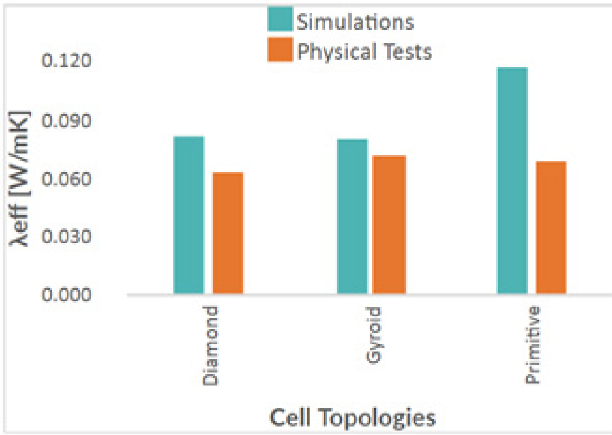


Figure 10. Comparison of simulations and physical tests results (Piccioni et al., 2020).

the total effective thermal conductivity ($\lambda tot,eff$) inside a cell structure (Gosselin et al., 2016). The formula for the total effective thermal conductivity would look like this:

$$\lambda tot,eff=\lambda rad+\lambda cond,gas+\lambda cond,solid+\lambda conv$$

with,
$\lambda tot,eff$ - total effective thermal conductivity
λrad - Radiation
$\lambda cond$,gas - Gas conductivity
$\lambda cond,solid$ - Solid conductivity
$\lambda conv$ - Natural convection

The biggest factors influencing the total effective thermal conductivity of these walls are the relative density (gas/solid) and cell diameter (Briels et al., 2022). To minimise convection, air cavities should be kept within small widths (Piccioni et al., 2020). The impact of convection can be neglected when the air cavities are below 10 mm (Briels et al., 2022).

Testing the thermal resistance for different cell topologies can be done through a simulation or a physical test. This physical test could involve a hot box. It is worth noting that simulations can significantly differ from physical tests, as seen in figure 10 (Piccioni et al., 2020). This is because the hot box test uses localised heat flux sensors while the structure with larger cells is inhomogeneous. This results in a less accurate prediction of the thermal resistance using the hot box test.

2 Additive manufacturing

This section aims to explain the basic principles of 3D printing and 4D printing as well as reviews some projects that use 3D printing to achieve thermal insulation. In section 1.1 a review on 3D printing will be done. In the following section (1.2) a review of projects that used 3D printing to create thermal insulation will be presented. In section 2.3 a review on 4D printing will be done, and finally in section 2.4 some practicality for additive manufacturing will be discussed.

2.1 Review on 3D printing

Additive manufacturing (AM) (or 3D printing) is, according to the standard ISO/ASTM 52900, a "process of joining materials together to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (Standardization, 2015).

The benefit of AM is that it can help decrease construction waste by 30-60% (Sakin & Kiroglu, 2017). Furthermore, AM allows for complex geometry with no additional costs compared to simple geometry (Seshadri et al., 2023).

There are many 3D printing (3DP) techniques as shown in figure 11 (de Rubeis et al., 2024), which will be examined in more detail in the next section.

2.1.2 3D printing techniques

There are multiple ways to classify additive manufacturing techniques (Gibson et al. 2021). One way to do this is based on the state of the raw material (Abdulhameed et al., 2019). These states can be solid, liquid or powder.

Additive manufacturing techniques using materials with a solid state are: Fused Deposition Modeling (FDM), Freeze-form Extrusion Fabrication (FEF), Laminated Object Manufacturing (LOM), Direct Ink Writing or Robocasting (DIW).

Additive manufacturing techniques using materials with a liquid state are: Stereolithography (SLA), Rapid Freeze Prototyping (RFP), Multi-Jet Modeling (MJM), Digital Light Processing (DLP).

Additive manufacturing techniques using materials with a powder state are: Inkjet 3D Printer (3DP), Electron Beam Melting (EBM), Selective Laser Sintering (SLS), Laser Engineered Net Shaping (LENS), Selective Laser Melting (SLM), Laser Metal Deposition (LMD).
A summary of this classification can be found in figure 12.

The most widely adopted techniques in the construction industry for large-scale objects are material extrusion and powder-based printing (Pshtiwan Shakor et al., 2022).

Material extrusion is a 3D printing method where material is pushed out of a nozzle in layers, following a digital design. This can be done using multiple systems: gantry systems, robotic arms, crane printers,

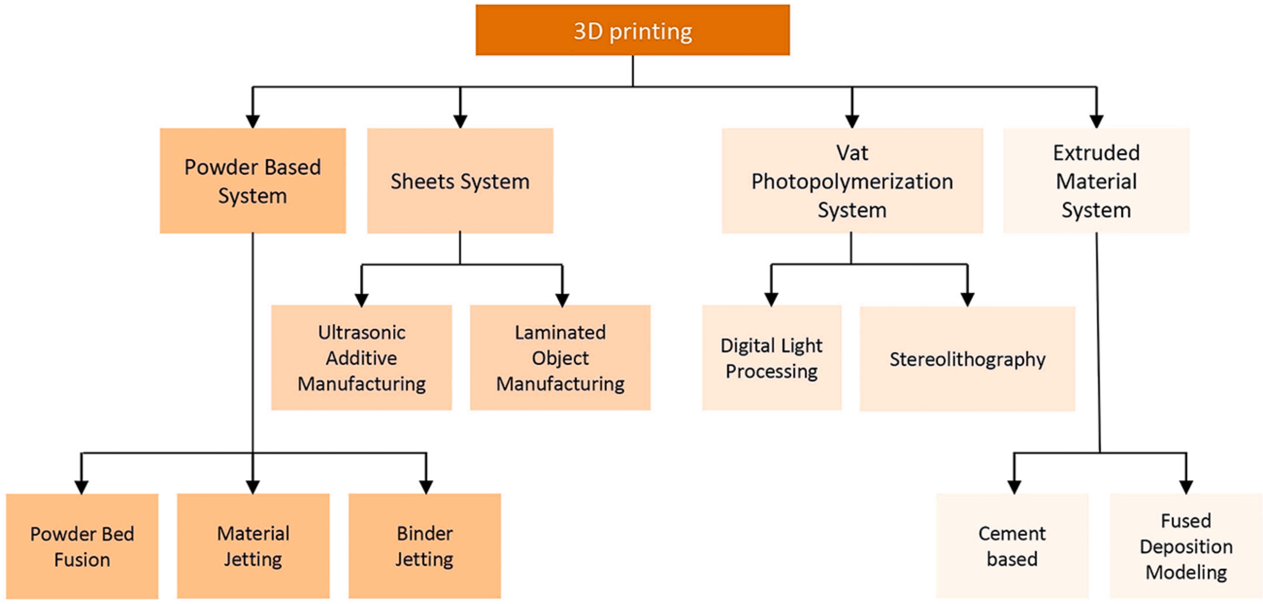


Figure 11. Types of 3D printing techniques (de Rubeis et al., 2024).

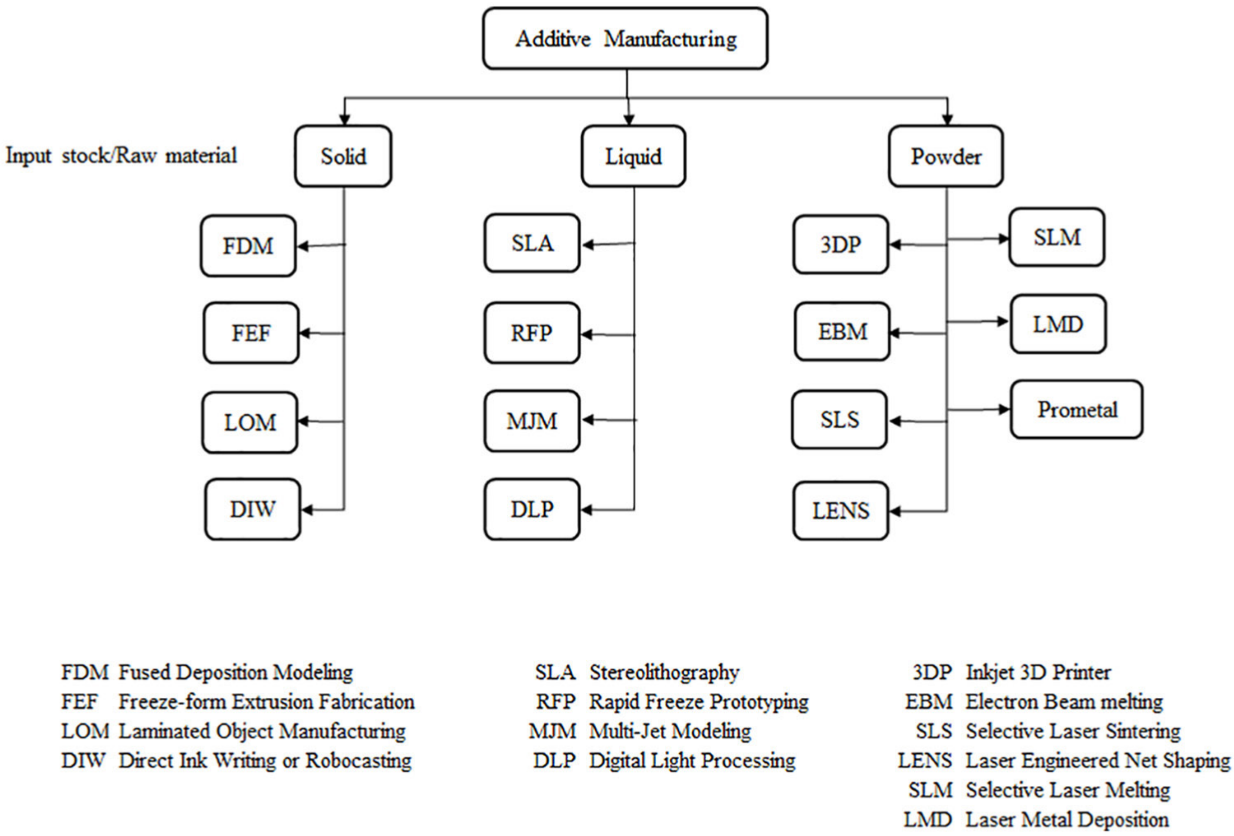


Figure 12. Classifying 3D printing techniques based on state of material (Abdulhameed et al., 2019).

particle-bed 3D printing, swarm printing, mobile truck printers, dome printers and off-world construction printers.

Advantages of material extrusion:
- Relatively low cost
- Safe and clean

Disadvantages of material extrusion:
- Rough surface finish
- Limited design freedom (compared to powder-based printing)

Powder-based printing is a process where liquid is poured on powder, which results in a solid state. There are multiple techniques for particle based printing. They all combine the same three elements: activator, aggregate and binder. They differ in which of these elements gets poured and which gets poured on. The element that is poured is always a liquid, whereas the element that gets poured on is in powder form.

Advantages of powder-based printing:
- Higher printing precision
- No restriction for form
- Very limited waste

Disadvantages of powder-based printing:
- Extensive post-processing required to remove excess powder particles
- Limited material choices
- Safety hazard, because of dust during the cleaning process

(Hassan et al., 2024)

2.2 Review of projects that used 3D printing to create thermal insulation

3D printing is a suitable production technique to optimise thermal resistance through topology because of its ability to create complex shapes. As discussed in chapter 1.3 creating topology is one of the strategies to create thermal resistance in a building envelope.

Several studies used 3D printing to create different cell topologies and showed that each has different thermal resistance. For example, De Rubeis et al. (2022) tested three different internal geometries: a. multi-

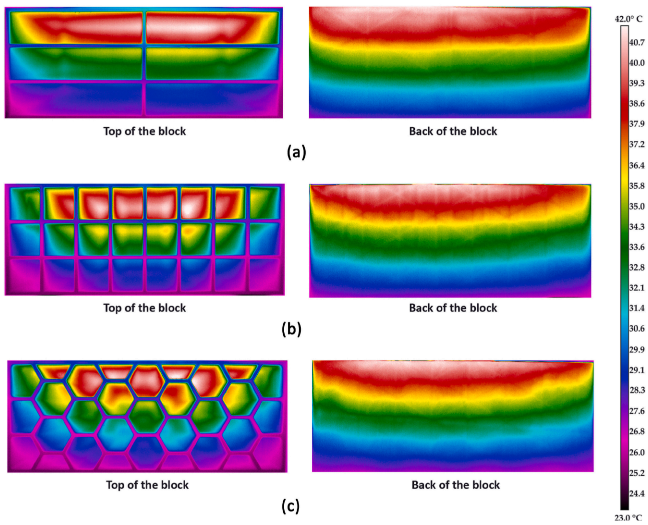


Figure 13. Different thermal resistance for different internal geometries (De Rubeis et al., 2022)

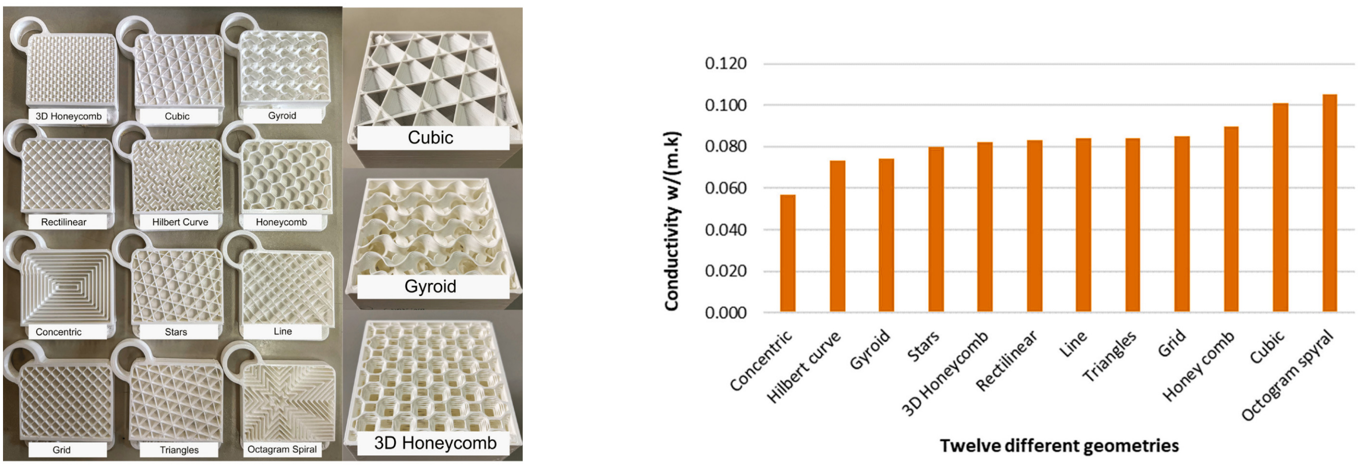


Figure 14. Different thermal resistance for different internal geometries (Lopes et al., 2023)

row structure, b. square structure and c. honeycomb structure. The honeycomb structure showed better thermal behaviour than the other two geometries (figure 13).

Lopes et al. (2023) took a step further and tested twelve different geometries and found out that out of the tested geometries, the concentric geometry had the least conductivity rate (figure 14). There were no significant cost differences between infill geometries except for the honeycomb and 3D honeycomb.

Furthermore, as seen in figure 15 the infill percentage also had a significant effect on the thermal transmittance.

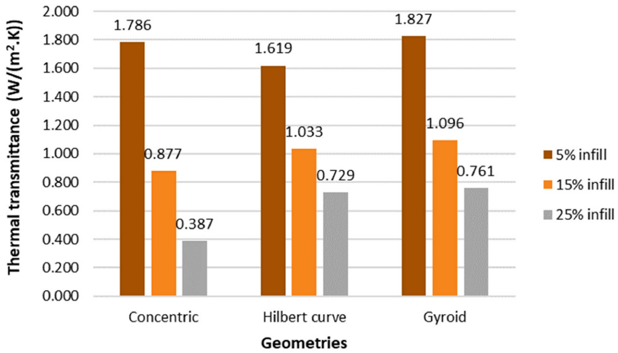


Figure 15. Different thermal transmittance for different infill percentages. Tested on three different geometries (Lopes et al., 2023).

2.3 Review on 4D printing

4D printing is the evolution of shape and functionality of a 3D printed structure with time when it is exposed to an external stimulus. This could be heat, water, light, electricity, pH etc. figure 17 shows different ways how this shape change could look like (Mallakpour et al., 2021).

Figure 16 shows different mechanisms for building responsive skins (Fattahi Tabasi & Banihashemi, 2022). 4D printing falls under the category where the mechanism is based on material properties or based on material properties with partial electrical or mechanical devices. This is a great attribute of 4D printing because it allows movement without complex mechanical or electrical designs.

There are several factors that need to be considered when designing with 4D printing. These are the AM process, material, type of stimulus and actuator.

The AM processes for 4D printing are the same as for 3D printing. Fused Deposition Modelling (FDM) is the most common one because it is simple, cheap and has a high printing speed (Ahmed et al., 2021).

Smart materials can be categorised in the following groups (figure 18) (Ahmed et al.,

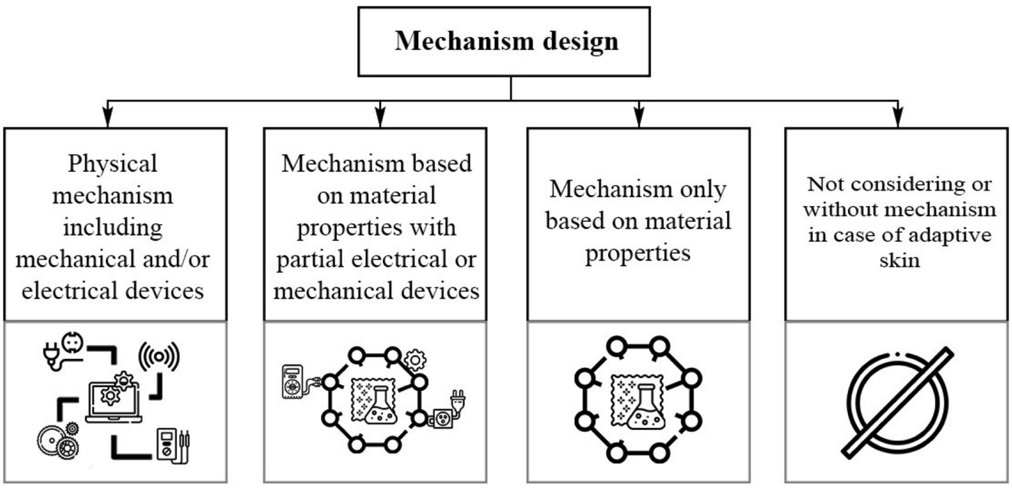


Figure 16. Different mechanism designs for building responsive skins (Fattahi Tabasi & Banihashemi, 2022).

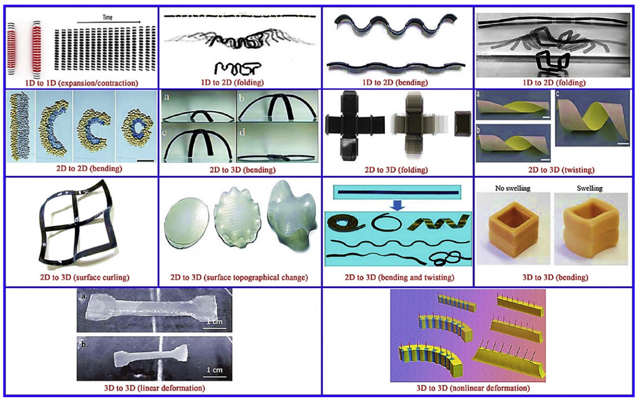


Figure 17. Different ways of shape change for 4D printing (Mallakpour et al., 2021).

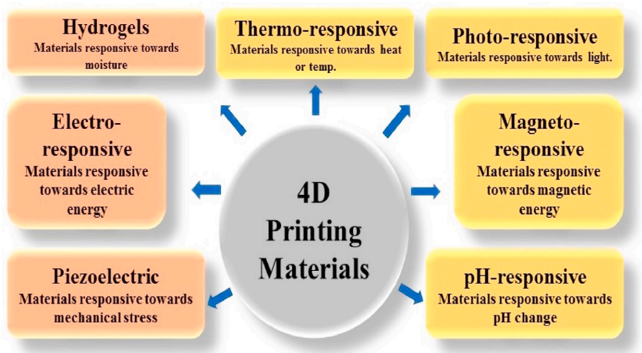


Figure 18. 4D printing materials (Ahmed et al., 2021).

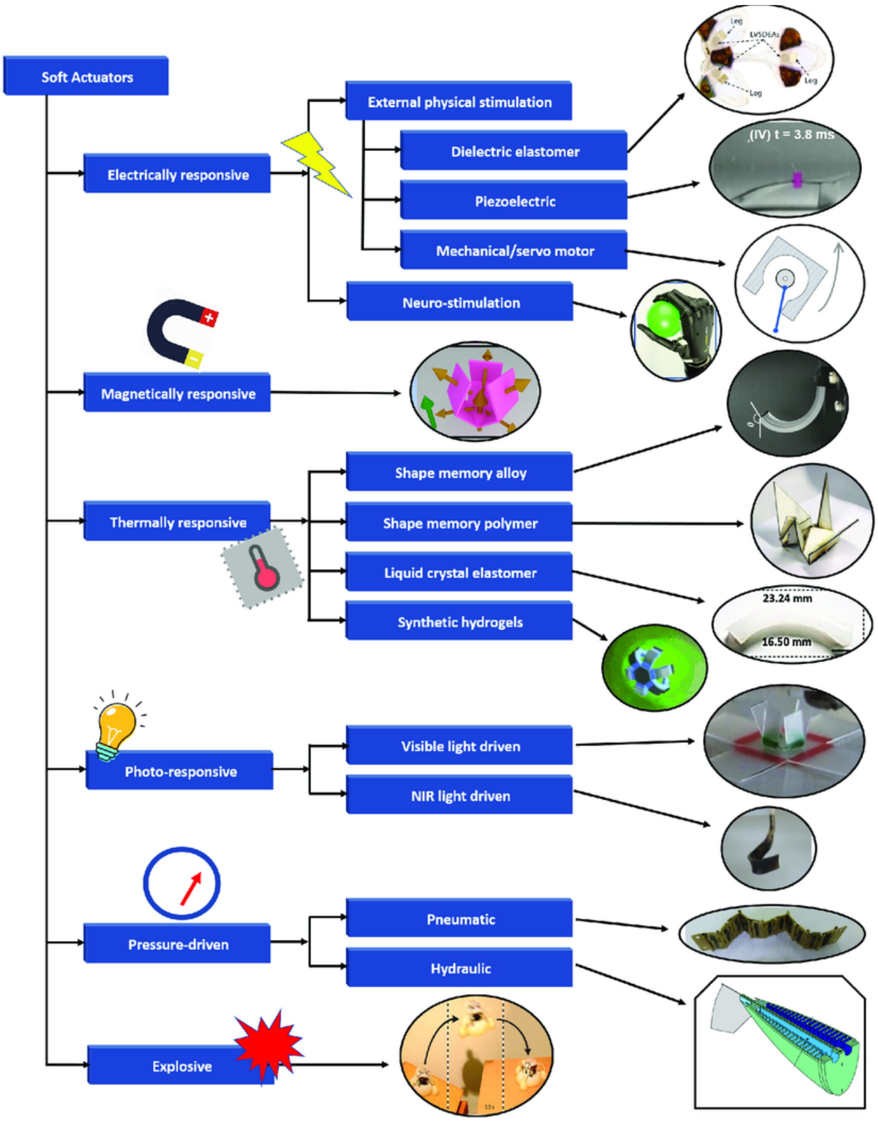


Figure 19. Different classes of soft actuators (El-Atab et al., 2020)

2021):
- Materials responsive towards moisture: hydrogels
- Materials responsive towards temperature: thermo-responsive (SMM, SMP + SMA)
    o One-way materials (cannot return to original shape)
    o Two-way materials
    o Three-way materials
- Materials responsive towards light: photo-responsive (indirect stimulus – generates heat)
- Materials responsive towards electric energy: electro-responsive (indirect stimulus – generates heat)
- Materials responsive towards magnetic energy: magneto-responsive (indirect stimulus)
- Piezoelectric materials
- Materials responsive towards pH

Soft robotics is a common application of 4D printing. The type of actuators found in literature for soft robotics is slightly different from the ones mentioned above (see figure 19) (El-Atab et al., 2020). Most notable are the pressure-driven and explosive actuators. Furthermore, the pH-responsive did not seem to be used for soft robotics applications.

2.4 Practicality

Filaments

When prototyping with a 3D printer (material extrusion), filament is needed. Filament is a long, thin strand of material (usually thermoplastic) that is wound onto spools and fed into standard 3D printers. These printers heat the filament and extrude it through a nozzle to build the object layer by layer. Filament typically comes in 1.75 mm or 2.85 mm diameter. It is fed into the printer through a direct drive or Bowden-style extruder that pushes the softened material into the heated head (see figure 21).

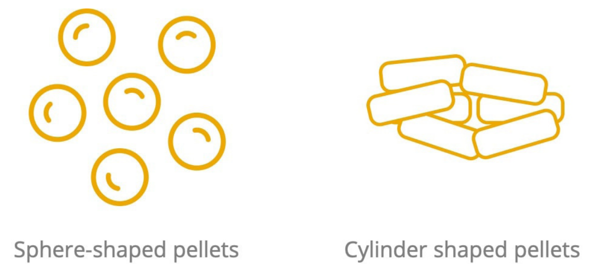


Figure 20. Pellet shapes (Pollen AM, 2025)

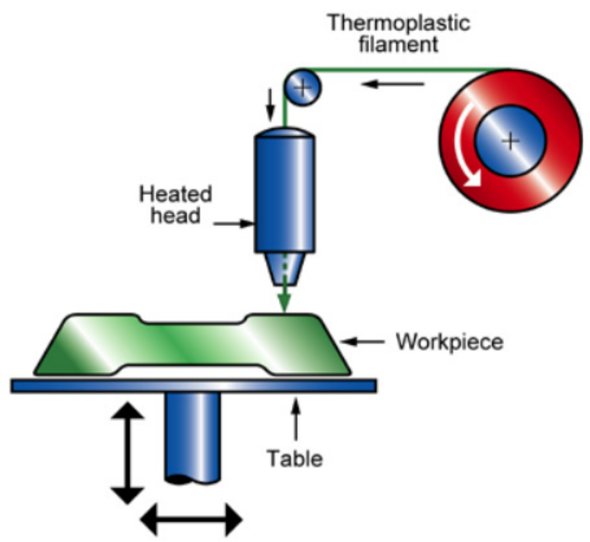


Figure 21. Material extrusion small scale (Ansys granta, 2023)

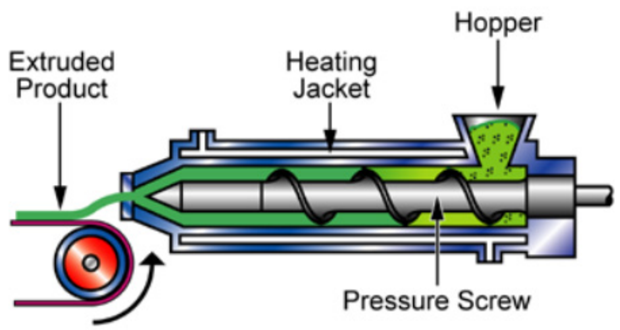


Figure 22. Material extrusion bigger scale (Ansys granta, 2023)

Pellets
When one wants to extrude material on a bigger scale, pellets are needed instead of filament. Pellets are small granules of a material. They come in sphere-shaped and cylinder-shaped (see figure 20). These pellets are loaded into a special extruder with a screw mechanism that melts and pushes the molten plastic through a nozzle (see figure 22).

Shore hardness
Shore hardness is a scale to measure material hardness. It is commonly used to describe the flexibility of rubber, elastomers and plastics. It is expressed in different shores:
Shore A is used for soft materials
Shore D is used for hard materials
Shore 00 is used for very soft materials, such as gel-like substances or very flexible elastomers

Next to that, there is also a number which indicates the flexibility of the material. A lower number indicates a higher flexibility. The shore hardness scale with some examples per value can be found in figure 23. For example, according to the scale, a rubber tyre has a shore hardness of around D15, which is similar to A70. These values are considered to be medium hard.

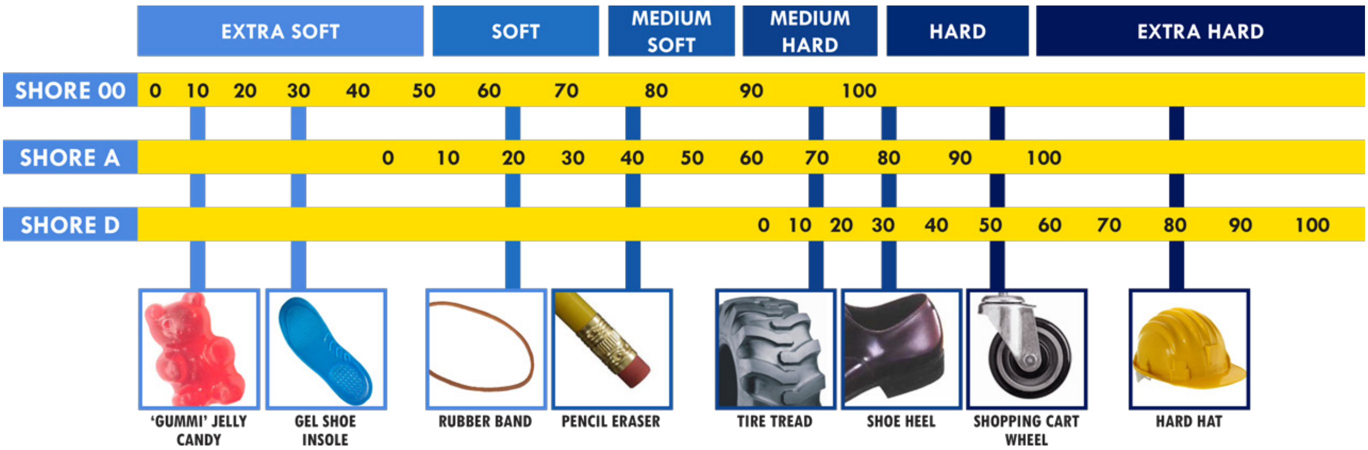


Figure 23. Shore hardness scale (Smooth-on, 2025)

3. CONCEPTUAL DESIGN

This chapter consist of the following parts:

3.1 workplan - where the high level goal is set for this project

3.2 conceptual design - where design criteria are set, thermal and flexibility strategies are explored and actuator and material is selected.

3.1 WORKPLAN

Objective
The objective of this chapter is to develop a conceptual design of the facade element, which serves as the foundation for the preliminary design stage.

This chapter covers design criteria, thermal insulation strategies, flexibility strategies, actuator selection, and material selection.

Vision
As stated in the introduction, the objective of this thesis is to develop a responsive façade element with switchable insulation that is easy to recycle. Therefore, a mono-material building envelope with a responsive switchable insulation layer will be developed.

The problem with static insulation facades is that they can keep heat inside when this is not desired, for example, during summer nights. In some cases you can open windows to release the heat. However, releasing the excessive heat through window openings can be slow. In other cases, opening a window may not be an option, and mechanical cooling is required, leading to high energy consumption.

There are more use cases where switchable insulation is well suited apart from the one mentioned above. These are spaces with high internal heat gains that need to lose excessive heat, like a data centre, factory, or gym. The latter has a high fluctuation in internal heat gain: in the winter during a group session, for example, a lot of heat is generated; this is where heat loss through the building envelope is desired. However, at any other time during the winter, a high thermal resistance is desired.

Lowering the thermal insulation in these cases would be beneficial, because it can reduce the energy usage of a building.
The three key elements of the product are mono-material, switchable insulation, and responsiveness. How each of these elements will be achieved is discussed below.

Switchable insulation
Thermal resistance is achieved by trapping air inside cavities as discussed in the literature review. By removing or enlarging the cavities, a lower thermal resistance can be achieved, thus achieving a switchable insulation.

Mono-material
The outer layers as well as the inner layers need to be of a single material that is suitable for the use case. Therefore, a material selection based on criteria will be made.

Responsive
The thermal resistance of the building envelope automatically adjusts based on local weather data and indoor temperature. This can be done by smartly interacting with the local outdoor environmental conditions.

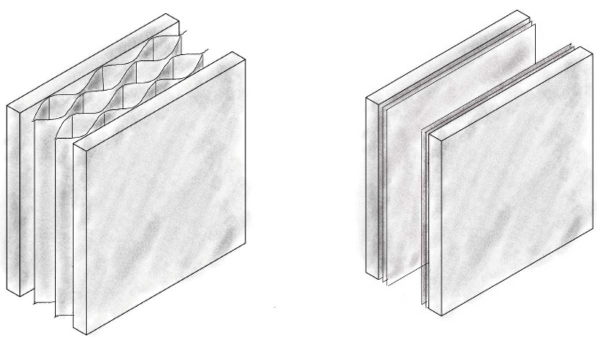


Figure 24. Artist impression

3.2 CONCEPTUAL DESIGN

3.2.1 Design criteria

To achieve the vision, it is important to set some boundaries. These are set using design criteria. This section explores the design criteria.

The final product will be a building envelope. There are a couple of requirements for building envelopes in the Netherlands. They need to be wind and water tight, fire retardant, structurally stable, and have a Rc value of at least 4.7 m^2 K / W. These are therefore included in the design criteria.

Moreover, in its application, the thermal resistance needs to change many times. When assuming that the building life span is around 60 years in the Netherlands (SEV, 2004) and that the thermal resistance needs to change on average four times in a day, this means the insulation needs to be strong enough to switch more than 87.000 times. Therefore, a durable material and system are important factors when designing the building envelope. Next to that, it is important to use as little energy as possible for the switching mechanism. This is therefore also added to the design

Design criteria	Why?	Element respon-sible for this
Minimal energy required for the switching mechanism	Goal of facade element is to reduce energy us-age of a building	Actuator + design
Minimal energy required during production	Goal of facade element is to reduce energy us-age of a building	Material + design
Durable switching mechanism	There is a high frequency of movement during its lifetime	Material + design
Recyclable	This is one of the ambitions of this thesis pro-ject	Material
3D printable	Complex configurations needs to be made to achieve thermal resistance	Material
Fire retardant	Requirement for facades	Material or design (sacrificial layer)
UV resistant	Material faces outside	Material or design (sacrificial layer)
(rain) water proof	Material faces outside	Material or design (sacrificial layer)
Fast production	Reduces energy (+costs)	Design
Insulating	Requirement for buildings in the Netherlands	Material + design
Switchable insula-tion	To improve energy efficiancy of the building envelope	Material + design

Table 1. Design criteria for wall

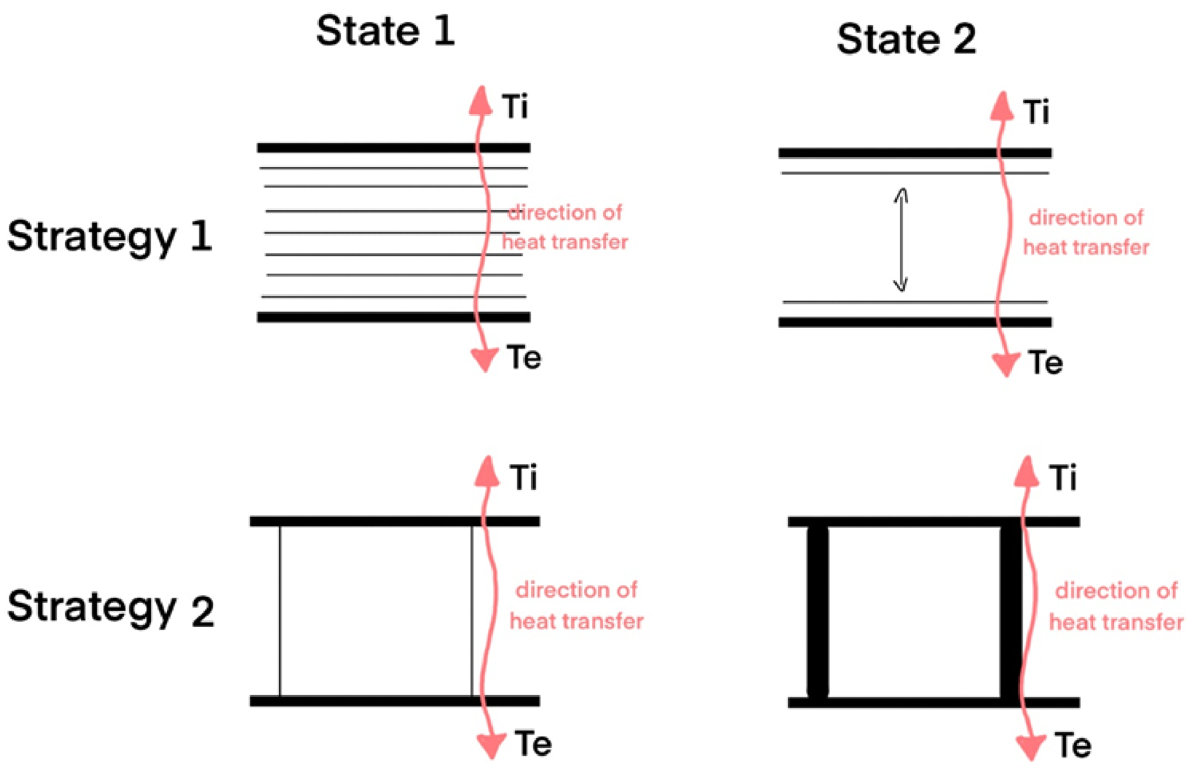


Figure 25. Thermal insulation strategies

criteria.

Finally, since the product aims to be easy to recycle, recyclable is also added as a design criterion.
A summary of all the design criteria can be found in table 1.

The final product can be divided into three elements: material, actuator and switching design. These three elements are responsible for achieving all the design criteria. In the same table for each design criterion is also stated which of these three elements has an effect on it.

3.2.2 Thermal insulation strategies

Looking at the literature, the following parameters seem to play a role when designing a wall configuration to achieve high thermal resistance:

- Height (direction of heat transfer)
- Cell shape
- Cell wall thickness

This is no surprise, since these parameters have a direct influence on the relative density of the configuration and the cell diameter, which, as mentioned earlier, have the highest influence on the total effective thermal conductivity ($\lambda tot,eff$).

Based on these parameters, the following strategies are formulated to change thermal resistance (see also figure 25):
1. Increasing/decreasing natural convection through height
2. Changing relative density by adding/removing material or expanding the material

These strategies require the system to be flexible. The following paragraph discusses how flexibility can be achieved.

3.2.3 Flexibility strategies

There are multiple ways to create flexibility in the insulation layer. These are:

- through shape - e.g. through a designed system like origami or kinetic art
- through amount - e.g. by processing the material like kerf structures
- through the material property (Young's modulus).

A designed system can have a lot of interdependent smaller parts, which makes the whole system more prone to defects. An example of a designed system that got a defect is the sunshades of the Institut du Monde Arabe (1987) in Paris by Jean Nouvel.

Processing the material by making some parts of the material thin is also defect prone. This is because a thin part can break more easily after it gets bent a lot of times.

Therefore, the latter strategy (creating flexibility through material property) was chosen for the development of the designs because it seemed to be the most durable.

3.2.4 Actuator selection

When selecting an appropriate actuator for the application, several factors were taken into consideration:

- Suitability for façade application
- Passive or active actuator
- If active: energy usage*
- Possibility for mono-material
- System complexity**
- Durability of complete system

Based on the decision matrix in table 2 the following actuators are considered suitable for the application:

- Visible-light actuator (photo responsive)
- Pneumatic (pressure driven)
- Hydraulic (pressure driven) (if fluid has a low freezing point)

For the visible-light actuator, the material can be rigid or flexible. The same goes for the pressure-driven actuators; however, it should be noted that if one wants to combine a rigid material with a pressure-driven actuator, the movement of the switchable insulation is achieved through a smart system design. As discussed earlier, these systems can be less durable. The hydraulic pressuriser can be less cost-effective, compared to the pneumatic actuator because of the special liquid that is needed.

Therefore, out of these actuators, the pneumatic actuator seems to be the most suited for the application.

3.2.5 Material selection

A material selection was done using Ansys Granta Edupack. The following criteria were set.

Must haves:
- durable switching mechanism
- recyclable
- easy to 3D print
- flexible: Young's modulus < 1GPa
- low thermal conductivity
- fire retardant

Nice to haves:
- UV resistant
- waterproof
- cheap
- low emissivity
- low thermal coefficient

The criteria under nice to haves are desired but not necessary since they can also be achieved in different ways. For example, a sacrificial layer in front of the facade makes the facade UV-resistant and waterproof. This is a thin layer in the same material that

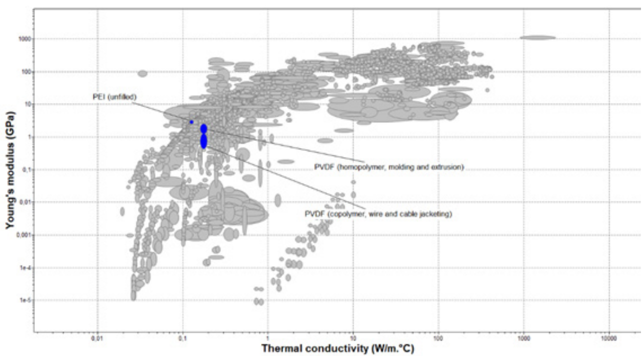


Figure 26. Youngs modulus and thermal conductivity for PEI and PVDF

Actuators	Note	Suitable for facade application?	passive or active?	If active: Energy use	Single-material possible?	System complexity*	Durability of complete system
Thermally responsive	You need a heat source	No - temperature gradient through insulation					
Moisture	degrading as a result of wetting and drying	No - water can freeze in winter					
Magnetically responsive		No - too much magnetic noise (in cities)					
Light (photo responsive)		Possible					
Visible-light		Possible	active	low	yes	medium	medium
Nir-driven		no	-	-	-	-	-
Pressure driven		Possible					
Pneumatic		Possible	active	low	yes	medium	High
hydraulic		Possible (but fluid with low freezing temperature)	active	low	yes	medium	Medium/ high

Actuators	Note	Suita-ble for facade applica-tion?	passive or ac-tive?	If active: Energy use	Sin-gle-ma-terial possible?	System complex-ity*	Dura-bility of complete system
Electrically responsive		No - not so safe for the applica-tion					
dielectric			active	Very high (kV)	yes	high	medium
piezoelectric			active	high	yes	high	medium
Mechanical Servomo-tor-Based			active	high	no	Very high	low
Neuro-Stimu-lation-Based			active	high	yes	high	medium

Table 2. Decision matrix for actuators

*Low, medium or high - these are relative to each other.
**with system complexity is meant if there are any additional hardware (e.g. sensors, pressurizer, tubes etc.) needed for it to be able to change in shape. Low complexity is when no additional hardware is needed.

Material	Heat chamber needed?	Price/kg ($) (fillament)	Flexibility (Young Modulus < 1GPa)	Note
PLA	no	30	rigid	
ABS	no	50	rigid	No sacrificial layer needed
PETG	no	30	rigid	
ASA	no	50	rigid	No sacrificial layer needed
NYLON	no	50	rigid	
Carbon fibre	no	80	rigid	
PVA	no	80	rigid	
HIPS	no	40	rigid	
Polycarbonate	no	40	rigid	No sacrificial layer needed
PC-ABS	yes	-	-	
Polypropylene (PP)	no	80	rigid	
TPU	no	30	flexible	

Table 3. New material decision matrix with softned requirements, which are already widely adopted

protects the material behind it and that needs to be replaced once it can no longer give full protection. This happens after the sacrificial layer got degraded.

Based on these criteria, the following materials were found:
- PEI
- PVDF

Looking at the thermal conductivity, both score quite well. It is similar to that of wood. However, when taking a closer look at the materials, it was found that they might not be suitable for this application. PEI and PVDF need a high printing temperature and heat chamber. This would cost a lot of extra energy, which goes against the ambition to reduce energy usage in the built environment. Moreover, it is reported that PVDF is highly toxic during printing and stable, which means that the material takes years to degrade and therefore remains in the environment for long periods.

To get a bigger pool of materials, the requirements for durability have been softened. Moreover, only materials that have already proven themselves and are widely adopted are taken into consideration. The potential new materials can be found in table 3.

ABS, ASA and polycarbonate do not need a sacrificial layer. Therefore, these materials would be interesting to look further into. As said earlier, in order to create movement for the insulation layer, a smart system needs to be designed for rigid materials.

When it comes to flexible materials, TPU is the only one considered flexible out of this list. This could be an interesting one for pressure-driven actuators where the movement is a result of material properties (and not the design). However, a sacrificial

Material	Toxicity	Biobased possible?	Fillament available?
PVC	High	No	No
MPR	Low	No	No
TPU	Moderate (use ventialtion)	Partially (Lubrizol, 2025)	Yes
TPV	Moderate (use ventialtion)	No	No
TPC	Moderate (use ventialtion)	Yes (Arnitel® Eco, 2025)	Yes
PVDC (TP)	High	No	No
PFA (TP)	High	Yes (Odiyi et al., 2023)	No
PA46, PA11, PA6, PA410	Moderate (use ventialtion)	No	No
SB (elastomer)	High	Partially (Sherman, 2023)	No

Table 4. Decision matrix for materials when only considering flexible materials (youngs modulus < 1GPa) that are suitable for 3D printing

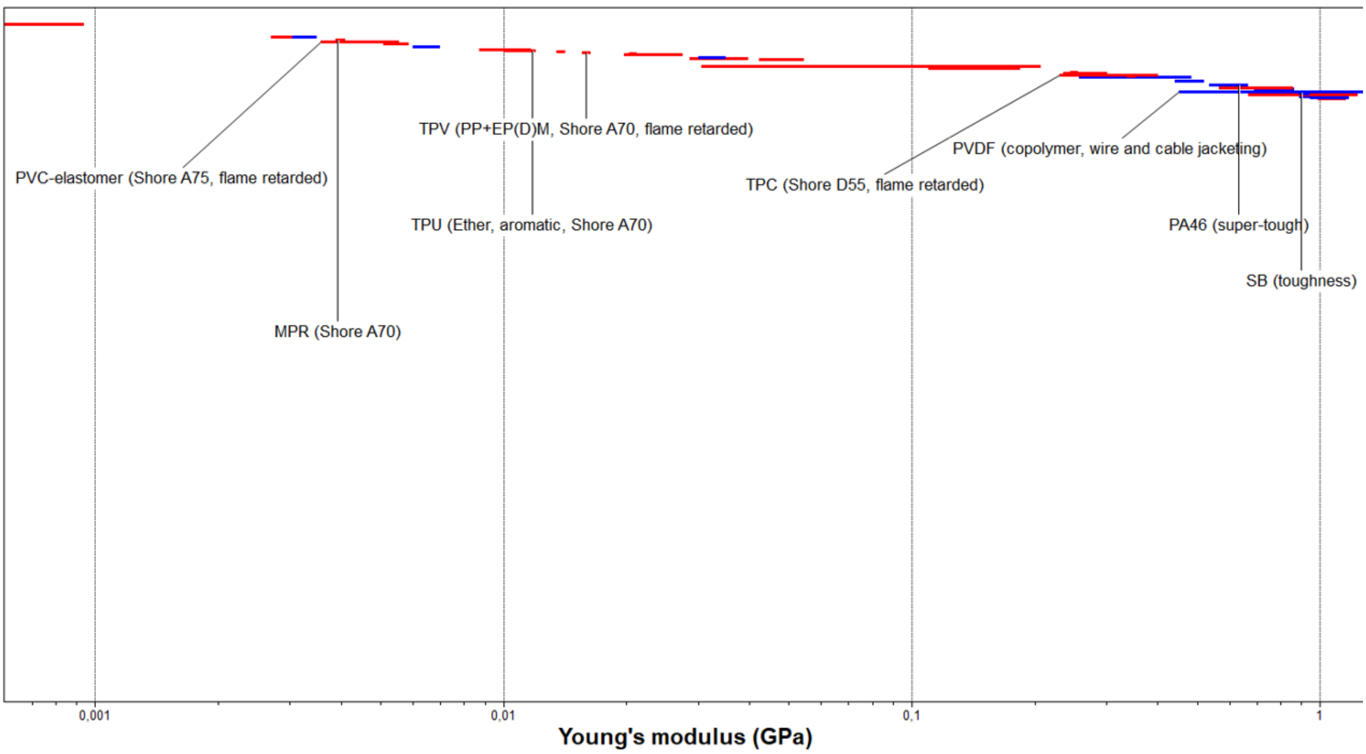


Figure 27. Youngs modulus of the materials from table 4

layer is probably needed for this material.

Flexible materials
Table 4 shows the materials that were found in Ansys Granta Edupack, when only considering flexible materials (Young's modulus < 1GPa) that are suitable for 3D printing, can be recycled and have reduced flammability. PVDF is kept away since it was concluded that it is too toxic. Figure 27 shows the corresponding scheme. For each material, toxicity and the option for biobased was explored as well.

Sustainability - toxicity and biobased
Sustainable materials include "those that are renewable or abundant, non-toxic, recyclable or compostable and that have little embodied energy or resources" (Faludi et al., 2015).

The materials found in Ansys Edupack which are shown in the table all seem to be plastics. This is because plastics are suitable for 3D printing. Only 6% of the material used in Europe is represented by plastics. This is about 60 million tonnes per year. Of that, 20.3 % is used for building and construction. This is the second largest application of plastics (figure 29) (van Wijk & van Wijk, 2015).

To understand if these plastics are sustainable, it is good to know the difference between biobased and biodegradable. Biobased refers to the origin of the material. A biobased material is a material which is (partly) made of substances derived from living (or once-living) organisms, such as plants, micro-organisms and animals. Biodegradable refers to the end-of-life of a material. A biodegradable material is a material that can naturally degrade to harmless elements by micro-organisms (like bacteria).

Plastics used to be biobased when they were invented. However, currently most plastics are fossil-based because they are cheaper. Currently, there are plastics that are (partly) biobased and/or biodegradable (see figure 28). These are called bioplastics.

This project aims to have an easy to recycle building envelope. This is the end-of-life strategy for the material. For the origin of the material a biobased material is preferred.
The reason why recycling is chosen over a biodegradable material is that the product

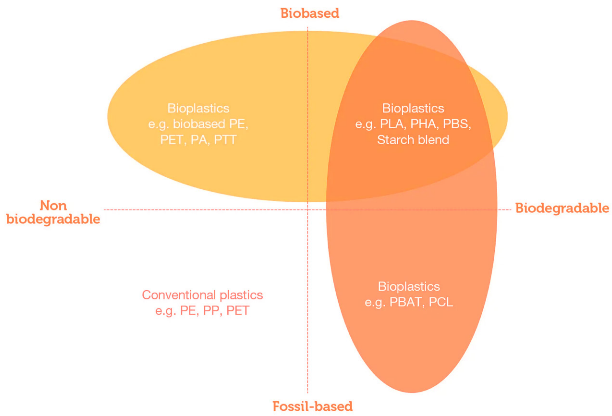


Figure 28. Types of plastics (Maguero, 2020).

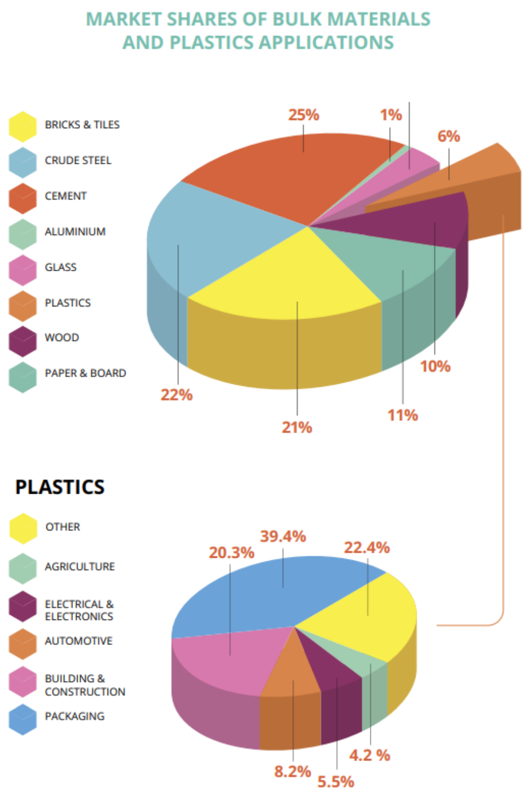


Figure 29. Market share of bulk materials and plastics (van Wijk & van Wijk, 2015).

needs to be around for a long time (>50 years).

3D printable - availability filaments
As mentioned earlier, the plastics in the table are all suitable for 3D printing. However, not all materials have a filament. Although, for the final production filament is not necessary, it is still useful if the material is available in filament to make prototypes on a small 3D printer. Moreover, it is preferred if the material is also cheap.

Considering all criteria, TPC is selected as the final material. TPC is a polymer material and more specifically a thermoplastic elastomer. It falls into the same category as TPA, TPU, TPO, TPV and TPS (figure 30). TPC is a flexible material that is partly biobased and durable (fire retardant, UV-resistant and water proof). Moreover, it is suitable for 3D printing, recyclable and does not need a heat chamber during production. Next to that, it is non-toxic (it passes the ISO irritation, ISO cytotox and the USP VI tests) and has an EU Ecolabel. The only downside is that the available filament for TPC (e.g. DSM Black Arnitel), is expensive compared to more widely adopted filaments like TPU, PETG and PLA.

3.2.6 Chapter conclusion
In this chapter a vision was set for the facade element. The goal is to create a responsive facade with switchable insulation that is easy to recycle. To achieve this, a list of design criteria are set:
- Minimal energy required for the switching mechanism
- Minimal energy required during production
- Durable switching mechanism
- Recyclable
- 3D printable
- Fire retardant
- UV resistant
- (rain) water proof
- Fast production
- Insulating
- Switchable insulation

Moreover, two strategies were formulated to achieve a changing thermal resistance:
1. Increasing/decreasing natural convection through cell height

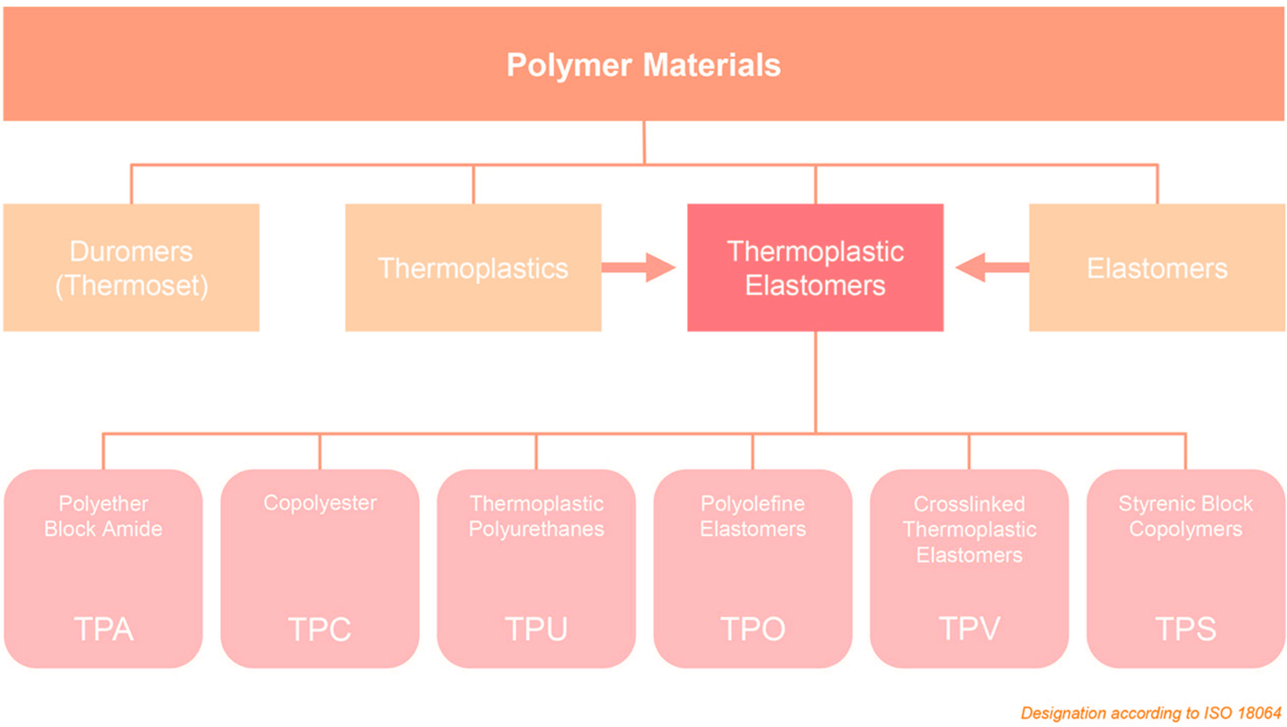


Figure 30. Type of thermoplastic Elastomers`(Kraiburg TPE, 2022).

2. Changing relative density by adding/ removing material or expanding the material

These strategies require flexibility. This chapter concluded that this flexibility should be achieved through the material (property).

To create movement, an actuator is needed. This chapter explored different actuators and concluded that a pneumatic actuator is most suitable given the design criteria.

Finally, different materials were explored in this chapter and assessed on suitability using the design criteria. It was concluded that TPC would be suitable for this application.

4. PRELIMINARY DESIGN

This section consists of the following chapters:

4.1 workplan - which elaborates on the plan and settings for the software used

4.2.1 design 1 - which explores the auxetic structure design

4.2.2 design 2 - which explores the soft robotic design

4.2.3 design 3 - which explores the doors design

4.2.4 design 4 - which explores the organic tree design

4.3 design selection - where we summarize the developed designs and select one of them to further develop

4.1 WORKPLAN

Objective
The objective of this section is to find a suitable preliminary design of the facade to further develop in the next phase.

This section explores different design directions and their implications for practice by building upon the literature review and conceptual design. The aim is to make a quick comparison between the design directions. Each design direction is explored with enough detail to allow for comparison between the developed designs. A more thorough elaboration will follow after the selection is made.

The goal is to find a design that achieves switchable thermal insulation, which:
- requires minimal energy for the switching mechanism
- has a durable switching mechanism

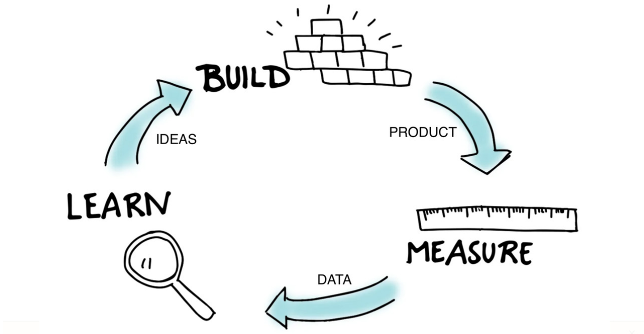


Figure 31. Build, measure and learn cycle (Ries, 2011)

(simplicity and not sensitive to errors)
- allows for fast production (see also design criteria from chapter 3.2)

Method
This is done by exploring four different switching designs following the build, measure and learn cycle developed by Ries (2011) (see figure 31).

Design criteria
Minimal energy required for the switching mechanism
Minimal energy required during production
Durable switching mechanism
Recyclable
3D printable
Fire retardant
UV resistant
(rain) water proof
Fast production
Insulating
Switchable insulation

MEASURE — BUILD

Design X	Answered through
Does the prototype move like it was intended?	PROTOTYPE
What is the Rc value per 100mm?	SIMULATION (COMSOL Multiphysics)
How long does it take to print it?	PROTOTYPE
How sensitive is it to production errors?	SKETCH + PROTOTYPE
Is there potential for a rapid production method (is it extrudable)?	SKETCH
Does the design require a lot of energy in its application?	SKETCH

LEARN

Table 5. Relation between design criteria and design. Each design criteria needs to be tested (MEASURE) through prototyping, simulations and sketching (BUILD). Valuable lessons are extracted from each design and carried forward into the next iteration (LEARN).

MEASURE
The following questions will be answered to measure the viability of the design:
Q1. Does the prototype move like it was intended?
Q2. What is the Rc-value per 100 mm?
Q3. How sensitive is it to production errors?
Q4. Is there potential for a rapid production method (is it extrudable)?
Q5. Does the design require a lot of energy in its application?

BUILD
The questions are answered through sketching, prototyping and simulations.

To answer the first and third questions, a prototype will be made. The prototype is made to test whether the switching mechanism works like intended. Question 3 examines to what extent a small error in the production process affects the functioning of the entire principle. The higher this is, the more faulty prints you get and the more you have to reprint (which increases the overall printing time). Through prototyping, the sensitivity to production errors becomes clear.

To answer the second question, which is about the Rc-value per 100 mm, the design will be simulated in COMSOL Multiphysics to get the heat flux for the design. Through a calculation the Rc-value can be derived.

Question 4 checks if the design principle is suitable for a cheaper production technique. This would be the case if the design is extrudable in one direction. In this case material extrusion on a big scale is possible (see also figure 22). A cheaper production technique increases the market viability. This question is answered through sketching.

Answering question 5 is hard without developing a 1:1 scale and testing it in a real life setting. Because of limited time and budget, the question is answered with

Parameters	Value
Infill	100%
Print Speed	10mm/s
Layer height	0.16mm
Bed heat	60C
Retraction distance	1.5mm
Printing Temperature	220C
Top/Bottom Pattern	Zigzag
Wall Thickness	1.2mm
Wall Flow	115%

Figure 32. 3D print settings using TPU 60A (Gaafar et al., 2024)

Build orientation	Horizontal
Nozzle diameter [mm]	0.4
Filament diameter [mm]	2.85
Layer thickness [mm]	0.2
Infill density [%]	100
Printing pattern	Linear
Material flow [%]	100
Nozzle temp. [°C]	220
Bed temp. [°C]	0

Figure 33. 3D print settings using vario-Shore TPU from Colorfabb (Lalegani et al., 2023).

Parameter	Value	Unit
Resolution settings		
Primary layer height	0.1	mm
First layer height	0.09	mm
First layer width	0.125	mm
Extrusion width	0.4	mm
Retraction settings		
Retraction length	4	mm
Retraction speed	40	mm/s
Speed settings		
Default printing speed	10	mm/s
Outline printing speed	8	mm/s
Solid infill speed	8	mm/s
First layer speed	8	mm/s
Temperature settings		
Printing temperature	230	°C
Heat bed temperature	32	°C
Cooling settings		
Fan speed	100	%
Infill settings		
Infill percentage	100	
Infill/parameter overlap	30	
Thin walls		
Allowed perimeter overlap	15	
External thin wall type	Perimeters only	
Internal thin wall type	Single extrusion fill	
Movements behavior		
Avoid crossing outline	Enabled	
Additional settings		
Extrusion multiplier	1.15	
Wipe nozzle	Disabled	
Support material	Enabled	

Figure 34. 3D print settings using TPU NinjaFlex Midnight from NinjaTek, USA (et al., 2021).

the best knowledge through a sketch and reasoning.

LEARN
After and during building and measuring, key lessons are extracted and taken with to the next design iteration.

Each design follows the following structure:
- Background information
- Practice
- Sketch of the switching principle
- Prototype
- Initial design
- Comsol Analysis
- Learnings

In this phase the prototypes are made using TPU instead of TPC. This is to reduce the costs of the prototype. TPU is similar to TPC. They are both thermoplastic elastomers (TPE). They are both flexible, have a high impact resistance and are suitable for 3D printing. However, TPC is better resistant to UV and can be more sustainable. The high UV resistance of TPC means that a sacrificial layer is not needed for the facade.

Since in this phase the movement is tested through prototyping, it is important that the TPU has a similar flexibility (or shore hardness) to TPC. The TPU used for the first prototypes had a shore hardness of 85A.

3D printing settings
The settings of a 3D printer have a big contribution to the end result. Therefore, it is important to carefully design the settings. Understanding which settings are suitable can be found in the literature. For example, in figure 32 to 34 the optimal printing settings for different research can be found. Slight changes can be seen in each parameter between these printing settings. In all this research the goal was the same: to make a soft robotic gripper. All used TPU, however, the company used a 3D printer and the flexibility of TPU differed from these researches. This is likely the reason why there are also slight differences between the optimal printing settings. It is therefore crucial to test and play around with the printing settings before making the prototypes.

This was done by 3D printing a simple object using a FDM printer. The initial settings were mostly derived from the research. The settings for the first test can be found under prototype 1 in table 7 After printing the first few layers, the object released from the bed. The adhesion was bad. A reason

Printing temperature	Increased
Bed temperature	increased
Printing speed	Decreased, and decreased more for the first few layers
Fan cooling	Turned off for the first few layers
Surface bed	Put a smooth clean glass plate on the bed
Bed height	Decreased distance between bed and noz-zle
Surface bed	Added pritt pen
Material	Bought new TPU: BASF Ultrafuse TPU 85A

Table 6. Summary of changes made to enhance printability of TPU for prototyping

could have been that the bed temperature and printing temperature were too low or that the printing speed was too quick for the first layers. Therefore these settings were adjusted. Moreover, the fan speed was set to 0% for the first layer and it gradually increased to 100% on the 5th layer. This allows the material to better attach to the bed. The changed settings are highlighted in orange under prototype 2 in table 7. Next to that, we made sure that we sprayed enough adhesion on the bed.

However, the cube still came off the bed after the first few layers. A reason could have been because the bed texture was too rough, making it hard for the material to attach. A clean glass plate was therefore put on the bed to correct this. This however, did not lead to any success.

After a closer inspection on the print quality of the first layer, it was found that there were small slits between the printing lines. Ideally a smooth surface is desired for the first layer. These slits exist because the distance between the nozzle and the bed was too high. Therefore, this distance was decreased so that the nozzle almost pushes on the bed, leading to more spread of the material. A smooth surface was achieved (figure 35), however the material still detached. Another attempt was made but this time Pritt pen was added on the bed to increase adhesion to the bed. However, this also did not work out (figure 36).

Because all these interventions did not work out, it was decided to get a new filament of TPU. It was thought that the used TPU might have been too old or contained too much moisture. The new TPU bought is BASF Ultrafuse TPU 85A filament Transparent 1.75 mm 0.75 kg from 123-3D.nl. The printing settings were set similarly to prototype 2, only the bed temperature was lowered to 40^{o}C degrees, as this was recommended by the manufacturer. The results were much better. The object (5cm x 5cm x 5cm cube) stuck to the bed during the whole process (figure 37).

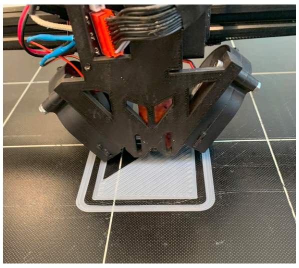


Figure 35. Smooth surface achieved

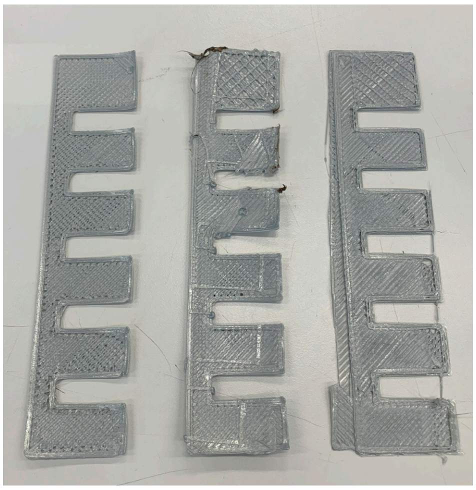


Figure 36. Results of prototype 1,2 and 3 (from left to right. All detached from the bed after the first few layers.

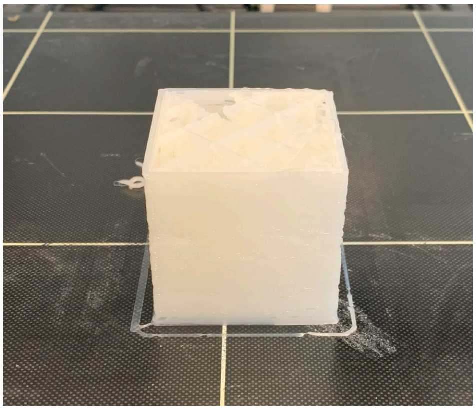


Figure 37. Result after buying new TPU (BASF Ultrafuse TPU 85A). The print remained attached to the bed throughout the entire process.

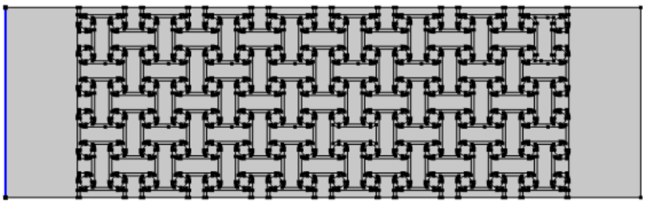
COMSOL Multiphysics settings

COMSOL Multiphysics is a Finite Element Analysis (FEA) software that can simulate how materials behave under certain

	Prototype 1	Prototype 2	Prototype 3
Profile	Draft - 0.3 mm	Draft - 0.3 mm	Draft - 0.3 mm
Layer Height	0.3 mm	0.3 mm	0.3 mm
WALLS			
Wall thickness	1.2 mm	1.2 mm	1.2 mm
Wall line count	1	1	1
TOP/BOTTOM			
Top/Bottom thickness	1.2 mm	1.2 mm	1.2 mm
Top thickness	1.2 mm	1.2 mm	1.2 mm
Top layers	4	4	4
Bottom thickness	1.2 mm	1.2 mm	1.2 mm
Bottom layers	4	4	4
INFILL			
Infill density	25%	25%	25%
Infill pattern	Zig Zag	Zig Zag	Zig Zag
MATERIAL			
Printing Temperature	200.0 ^{0}C	220.0 ^{0}C	220.0 ^{0}C
Build Plate Temperature	50.0 ^{0}C	60.0 ^{0}C	50.0 ^{0}C
SPEED			
Print Speed	40.0 m/s	40 m/s	20 m/s
Top/Bottom Speed	-	10 m/s	10 m/s

	Prototype 1	Prototype 2	Prototype 3
TRAVEL			
Enable retratction	Off	Off	Off
COOLING			
Enable Print Cooling	Yes	Yes	Yes
Regular Fan Speed	-	100%	100%
Initial Fan Speed	-	0.0%	0.0%
Regular Fan Speed at Layer	-	5	5
SUPPORT			
Generate Support	No	No	No
BUILD PLATE ADHE-SION	Skirt	Skirt	Skirt
DUAL EXTRUSION	None	None	None
OTHER			
Bed Surface	Regular	Regular	Glass
Use brim or raft	None	None	None
Z-offset	None	None	+0.45 mm (glass thick-ness)
	0.45mm		

Table 7. Development of printing settings



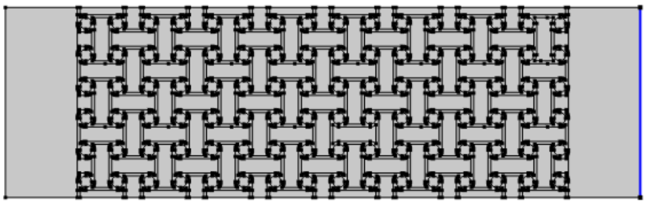


Figure 38. Selection (blue line) of boundary probe 1, heat flux 1 (left) and boundary probe 2, heat flux 2 (right)

conditions. COMSOL Multiphysics 6.2 Classkit was used. One possibility with this software is to simulate the thermal transmittance of an object. This is useful for this thesis to predict how certain designs affect the thermal resistance. Therefore, COMSOL Multiphysics is used to answer the second question: "Does the layer achieve the full range of insulation values?".

The following steps and settings were used in the software:

- Space Dimension -> 2D
- A 2D model (.dxf) of the design is loaded into COMSOL Multiphysics

Definitions
- boundary probe 1 -> select side facing inside (see figure 38, left)
- boundary probe 2 -> select side facing outside (see figure 38, right)

Materials
- Pibiflex 2560 [solid] (TPC) - > select all solids
  density 1090 kg/m^3
  Thermal conductivity = 0.162 W/(mK)
  Heat capacity at constant pressure 1600 J/(kgK)
- Air [gas] -> select all fluids (gas)

Heat transfer in solids
- Solid -> select all solids
- Fluid -> select all fluids (gas)
- Thermal insulation -> select outer walls (see figure 40)
- Heat Flux 1 = 293.15 K (see figure 38, left)
- Heat Flux 2 = 273.15 K (see figure 38, right)

Surface to surface radiation
-> select all surfaces where radiation can take place except for the outer layers (see

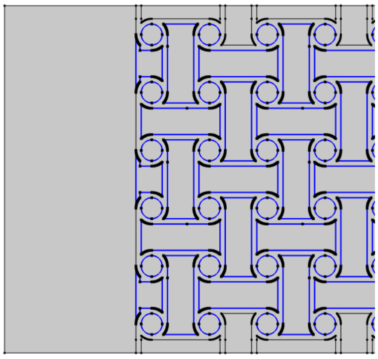


Figure 39. Selection (blue lines) of surface to surface radiation

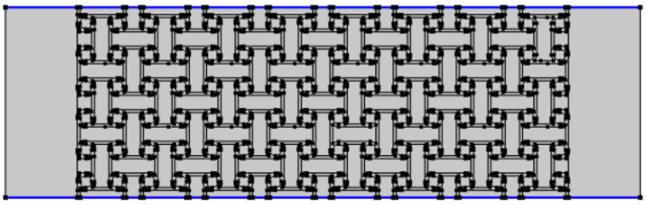


Figure 40. Selection (blue lines) of thermal insulation

figure 39)
- emissivity = 0.8

Laminar Flow (spf)
- incompressible flow

Multiphysics
- Heat transfer with Surface-to-Surface Radiation 1
- Nonisothermal Flow 1
  Include Boussenesq approximation

Study: stationary

For all other settings the default settings were used.

4.2.1 DESIGN 1

Design 1: Auxetic Structure
The first design strategy is based on auxetic structures.

BACKGROUND (LITERATURE REVIEW)
Auxetic structures are structures with a negative Poisson's ratio. Most materials have a positive Poisson's ratio. This means that if you stretch a material from one side, it contracts on the other side. When an auxetic structure is pulled from one side, it expands on the other side (see figure 41) (Sparavigna, 2014). There are many auxetic structures known in the literature (see figure 42) (Dong & Hu, 2023) (Momoh et al., 2024).

PRACTICE
This could be useful for this application because it allows expansion and extraction of cells, resulting in cells that are big enough for convection and small enough for convection to be neglected. Moreover, it collapses the cellular structure into a small(er) object, enabling convective heat transfer around the object.

The design of such a system consists of two elements:
- Auxetic structure
- Puller/pusher

Auxetic structure
A selection of the right auxetic structure will be based on thermal performance in its expanding state. Since there are so many different auxetic structures in the literature, an arbitrary selection is made of an auxetic structure in this phase.

Puller/pusher
The system also needs an element that can push or pull the auxetic structure to the expanding or contracting state. A vacuum tube can be used similar to the one found in literature (see figure 43)

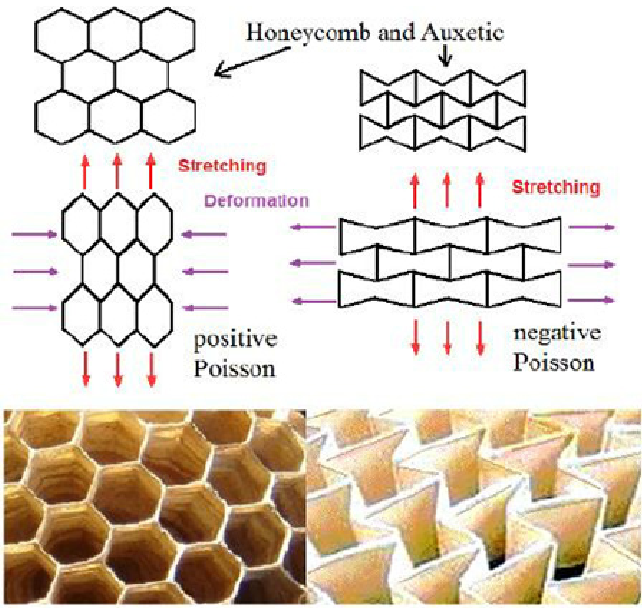


Figure 41. Auxetic structure have a negatice Poisson's ratio, meaning that if they get pulled from one direction they also expand in the other direction (Sparavigna, 2014).

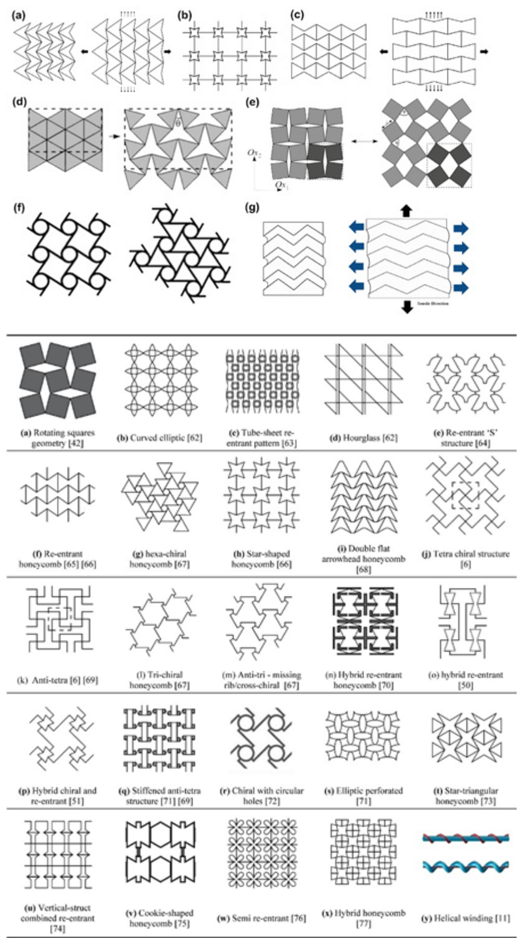


Figure 42. Some examples of auxetic structures (Dong & Hu, 2023), (Momoh et al., 2024).

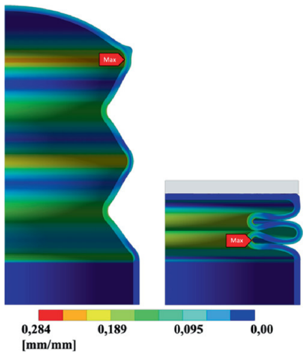


Figure 43. Pusher/puller based on air pressure (Gust et al., 2021).

SKETCH

The initial sketch of the full working principle can be found in figure 45. As discussed earlier, the design consists of an auxetic structure and a pusher/puller. Zooming out this means that a building needs to have multiple connections to an air compressor. From the sketch it was concluded that the design is extrudable. Moreover, the sensitivity to production error is small. After all, if there is a small gap between two chambers the consequences are not so big.

PROTOTYPE

A small prototype of the auxetic structure is made to test the movement of such a structure. At first there were some problems with printing. The quality was low. After a close inspection of the printing path, it was found that there are many printing stops.

This is because at the corner of the circles the program sees it as two separate lines instead of one. A result of this is that there are many stops at that spot (see white spots in figure 46. This was solved by adjusting the thickness of the wall. A lot fewer stops were the result (see figure 47). Although the results were much better, the quality was still not great. This was probably because the distance between the nozzle and the printing bed was too big. This was therefore solved by putting the bed closer to the nozzle.

When the prototype was printed (figure 50)

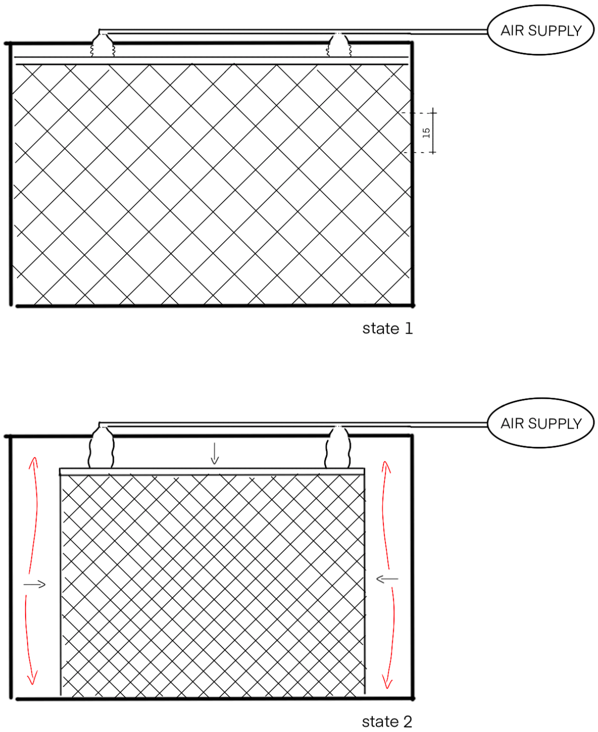


Figure 45. Sketch design

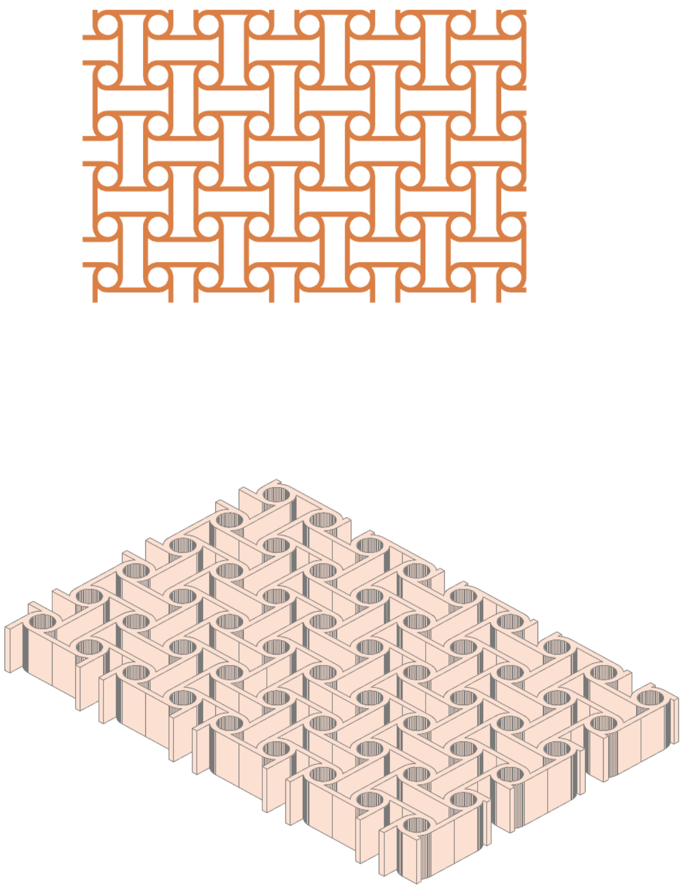


Figure 44. Chosen auxetic structure

the movement worked out well.

INITIAL DESIGN

The initial design was developed using Rhino 8. The size of the cell is 10 mm to prevent heat transfer through convection. The thickness of the wall is 2 mm. Furthermore, at least 30 cells are fitted in the direction of the heat transfer. This number comes from a quick calculation where the assumption is that a single cell has a thermal resistance of 0.17 m^2K/W The first iteration with its measurements can be found in figure 49. This design was used to be further analysed in COMSOL.

COMSOL ANALYSIS

The result of the analysis was a heat flux at one side of 4.7 W/m^2 and the other side of 5.9 W/m^2. The average was taken (5.3 W/m^2) to calculate the Rc value using the following formula:

$R_{tot} = \Delta T / q$

with:
ΔT: temperature difference between outside and inside
q: heat flux
R_{tot}: total thermal resistance ($Rc+R_i+R_e$)

From this calculating the Rc value for this design is 3.8 m^2K/W. The R of the outer and inner layer should be removed to know the R-value of the auxetic structure. The R is calculated using the following forumula:

$R = d / \lambda$

with,
d = thickness [m]
λ = thermal conductivity [W/mK]

The thermal conductivity of TPC is 0.165 W/mK (Ansys, 2023). The thickness of one layer is 0.05 m. Therefore the R-value of one layer is (0.05/0.165=) 0.3 m^2K/W.

The Rc of only the auxetic structure is therefore (3.8 - 2 x 0.3=) 3.2 m^2K/W for a

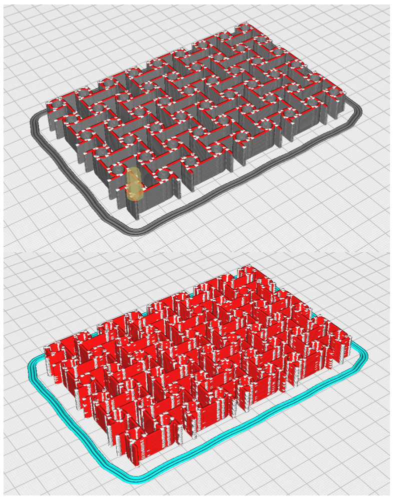


Figure 46. Initial sliced model with many printing stips (white spots)

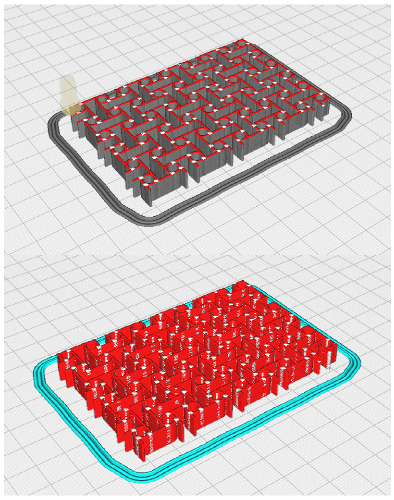


Figure 47. Adjusted sliced model with fewer printing stops (white spots). The thickness of the walls were reduced.

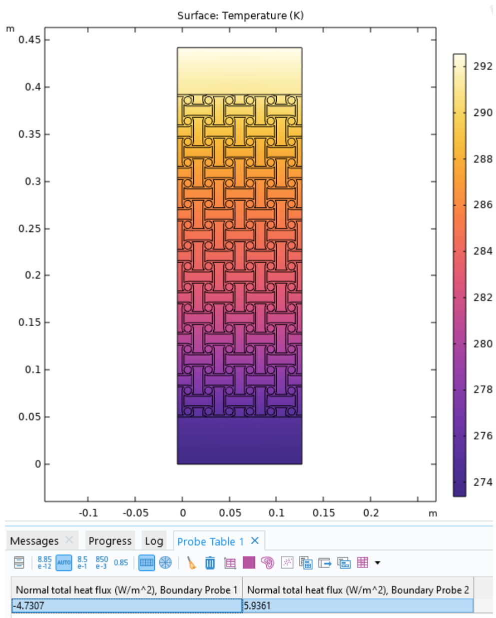


Figure 48. COMSOL result

width of 342 mm. This is about 0.94 m²K/W per 100mm wall thickness.

This is about 0.85 m²K/W per 100mm wall thickness.

LEARNINGS

- making walls thick can introduce more printing stops
- rounded corners help reduce printing time and minimises stops during printing

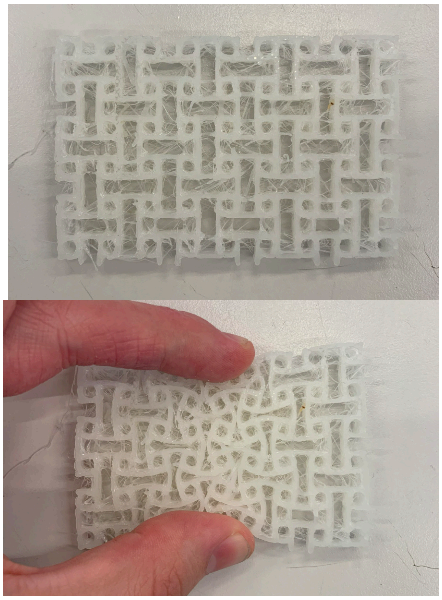


Figure 50. Printed small prototype of auxetix structure to test contraction/expansion

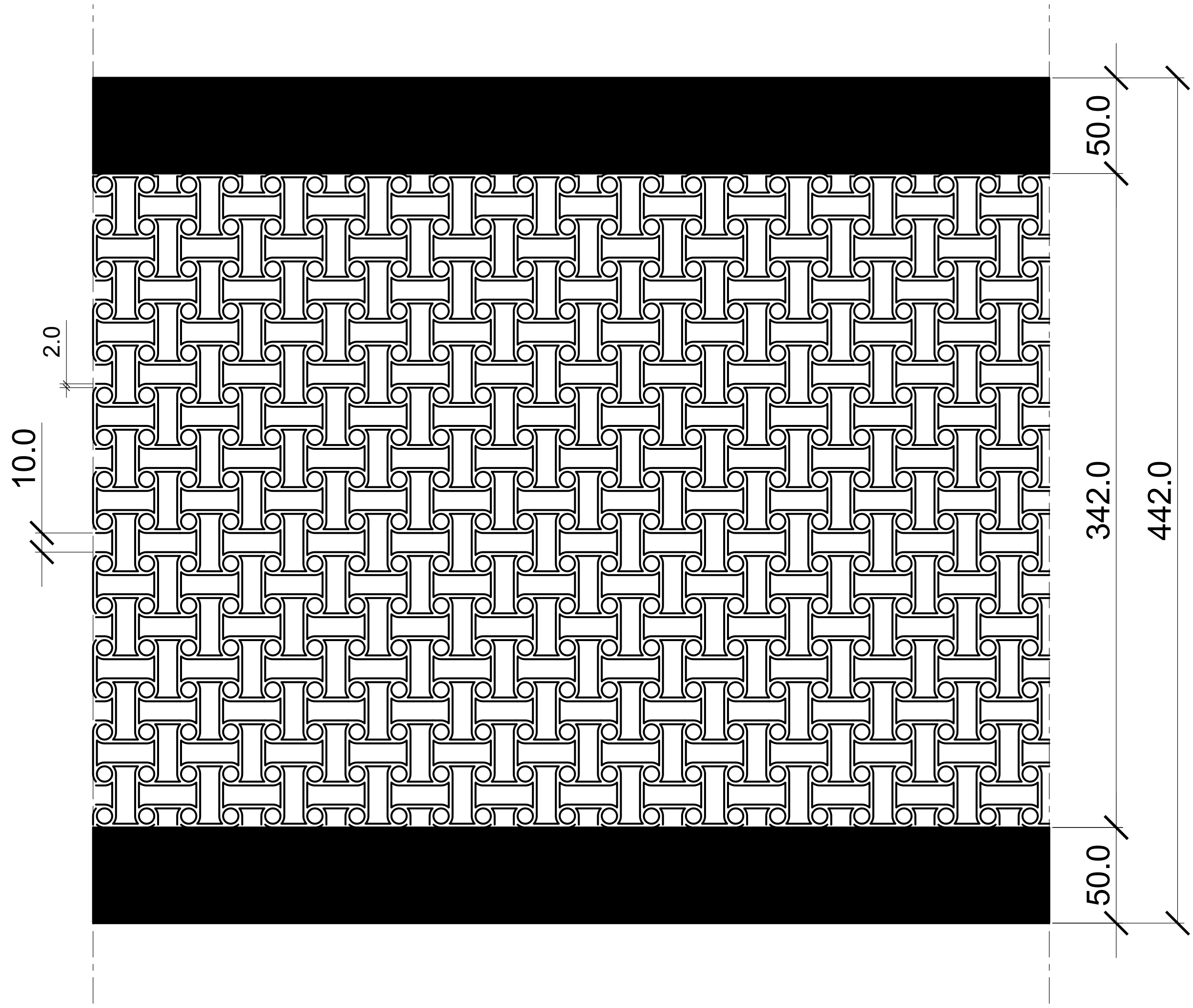


Figure 49. Initial design (top view)

4.2.2 DESIGN 2

Design 2: Soft Robotics
The second design strategy is based on how soft robotics work.

BACKGROUND (LITERATURE REVIEW)
Soft robotics is a subfield of robotics that focuses on designing and constructing robots using flexible and deformable materials, such as silicone, rubber, and other polymers, instead of rigid metal or plastic components. Unlike rigid robots that require complex joints and actuators, soft robots achieve motion using simple inflation, smart materials, or soft actuators, making them more energy-efficient and lightweight.

Soft robotics is applied in healthcare (e.g. soft robotic prosthetics and exoskeletons for rehabilitation), industrial automation (e.g. soft robotic grippers for handling delicate objects like food, electronics, and glassware.), as well as in exploration and search-and-rescue missions (e.g. soft robots capable of navigating confined or hazardous environments), and in wearable technology (e.g. assistive clothing and haptic feedback systems for motion support or communication).

In the literature you can find two ways to make soft robotics (Blanco et al., 2024):

- Through moulding and assembling
- 3D printing

For the latter, FDM is the most commonly used technique due to its accessibility and relatively low price (Hu & Alici, 2019). The types of actuators are bending actuators, helical actuators and vacuum-powered actuators. With the most common materials being thermoplastic elastomer (TPE, TPU and TPS) and thermoset elastomer (agilus, vero, tango, DM-RGD and silicone elastomers) (Blanco et al., 2024).

A lot of research has been done on soft grippers. For example, Dilibal et al. (2018) researched how geometric gradient affects bending response. Dsilva et al. (2025) checked how different parameters like the gap between chambers, chamber height and wall thickness, affect bending response (Dsilva et al., 2025). Peterson & Stano (2021) 3D printed an airtight, assembly free, pneumatically actuated soft gripper using TPU with different shore hardness for each part of the soft gripper.

The principle from soft robotics that is used in this project is how movement is created through pressure (vacuum-powered actuator).
Often the structure of a vacuum-powered actuator consists of multiple fingers (though it can also have a different form as found in some studies, like (Du et al., 2022) or (Gunawardane et al., 2024) and an internal air channel.
When air is pumped through the internal

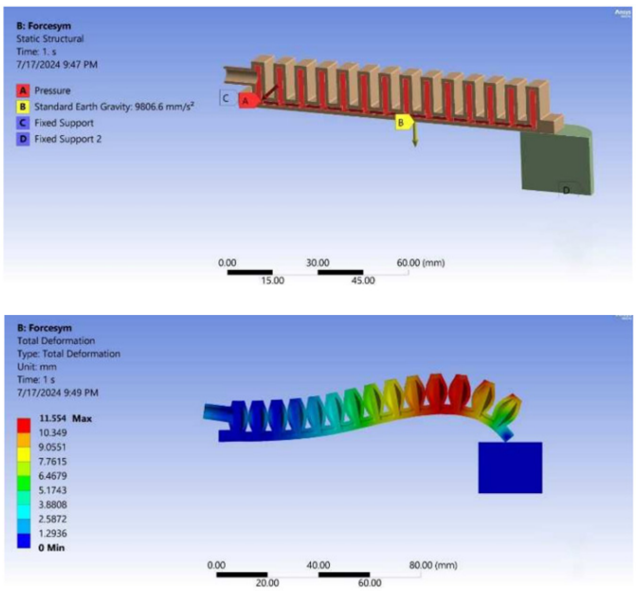


Figure 51. Soft robotics movement (Gaafar et al., 2024).

air channel the chambers inflate, causing the element to bend. When air is released, the element returns to its original shape. (see figure 51) (Gaafar et al., 2024).

PRACTICE
Applying this principle to achieve switchable insulation means that you need multiple soft "robot fingers" that can bend and return to their initial state. The question is how one should design and arrange them and how many are needed. Moreover, the design needs to be airtight. Not doing so would result in a soft finger that can not bend or which needs a lot of constant pressure, and thus energy, to bend.

SKETCH
Three different design directions are proposed:
- Horizontal arms
- Animal fur
- Simple plant

In figure 52 you can find a sketch of horizontal arms. The insulation is based on the first strategy to create thermal resistance, which is reducing the distance between two layers to 15mm. By bending one or multiple layers you change the distance between these layers and therefore you can adjust the thermal resistance of the whole package. This means that there is an ability to create multiple values for thermal resistances as opposed to a simple on/off state. The question is however if this is needed.

In figure 53 you can find a sketch of the animal fur principle. The principle is based on how the fur of mammals works. If mammals have it cold their fur stands up (piloerection) right to trap a layer of air close to the skin, providing an extra layer of thermal resistance. When they have it cold their fur relaxes (pilorelaxation) releasing heat (Mota-Rojas et al., 2021). We can use the same principle to create air cavities. When it is in a cooling state, there is no air pressure in the soft fingers. The distance between two horizontal elements is 30mm resulting in heat convection. However, when it is in a heating state, the fingers curl up and divide the initial two horizontal elements into two spaces with a width of 15mm each (see figure 56).
The air is divided into multiple branches, where each branch goes to a horizontal element that has multiple fingers.
Like the previous principle, this one can have a gradient in its thermal resistance as well, if you give control over which fingers should curl up.
In figure 54 a sketch is made of the simple plant principle. It is similar to the previous

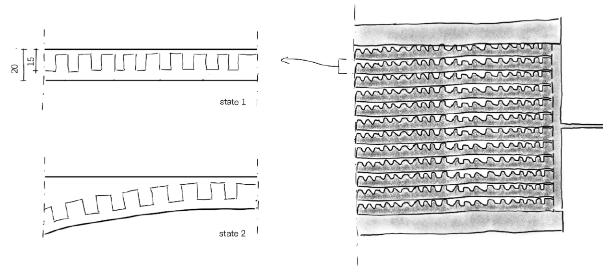


Figure 52. Sketch design 1: Horizontal arms

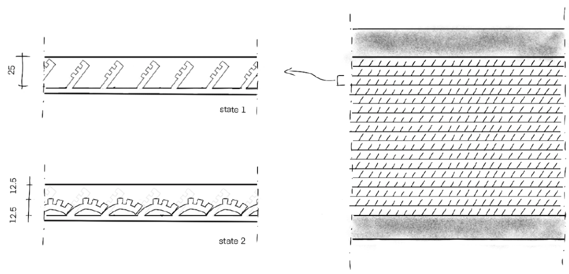


Figure 53. Sketch design 2: Animal fur

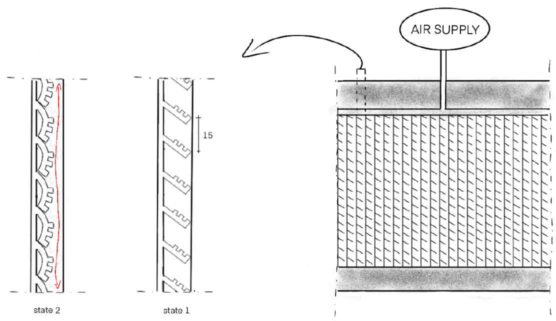


Figure 54. Sketch design 3: Simple plant

principle that it creates air cavities. It consists of vertical elements that have small soft side shoots. At the cooling state, the fingers are straight. At the heating state the fingers curl up creating air cavities of 15mm (see figure 55).

SELECTION
The strategy selected is based on the design criteria set earlier. The following design criteria are relevant for the selection:
- Potential for rapid production (extrudability)
- Durable switching mechanism
- Minimal energy required for the switching mechanism
- Sensitivity to production errors

It is important to note that the values assigned to these criteria are relative to other designs. The results are summarised

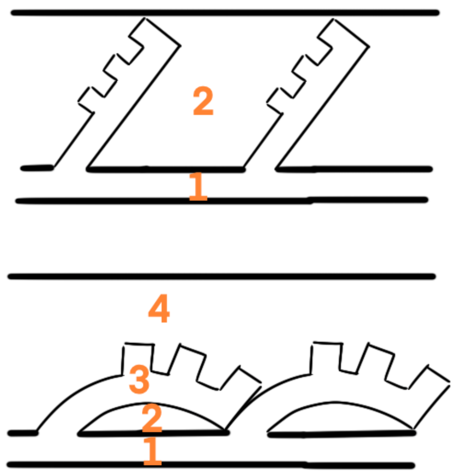


Figure 56. Increased air cavities from 2 to 4 in animal fur design

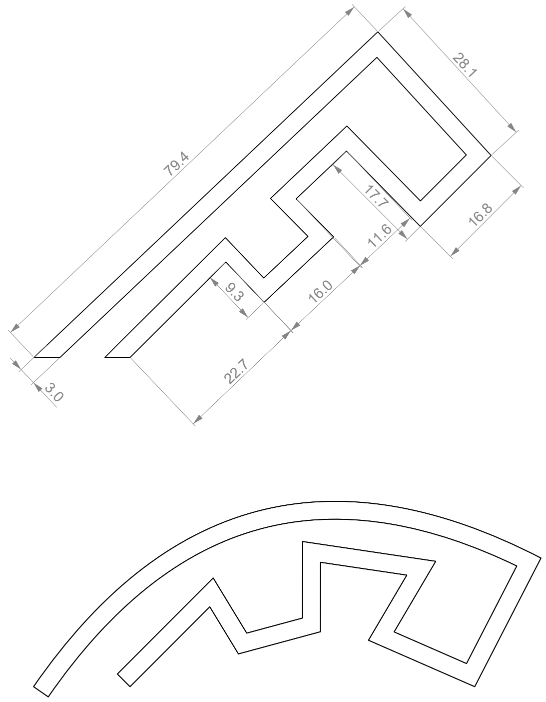


Figure 55. Designed movement

	Extrudable	Durable	Energy to switch	Sensitivity to production errors	Total
Horizontal arms	yes	Medium (2)	Low (3)	High (1)	6
Furry penguin	Yes	High (3)	Medium (2)	Low (3)	8
Simple plant	Yes	High (3)	High (1)	Low/medium (2.5)	6.5

Table 8. Decision matrix for different design directions of soft robotics

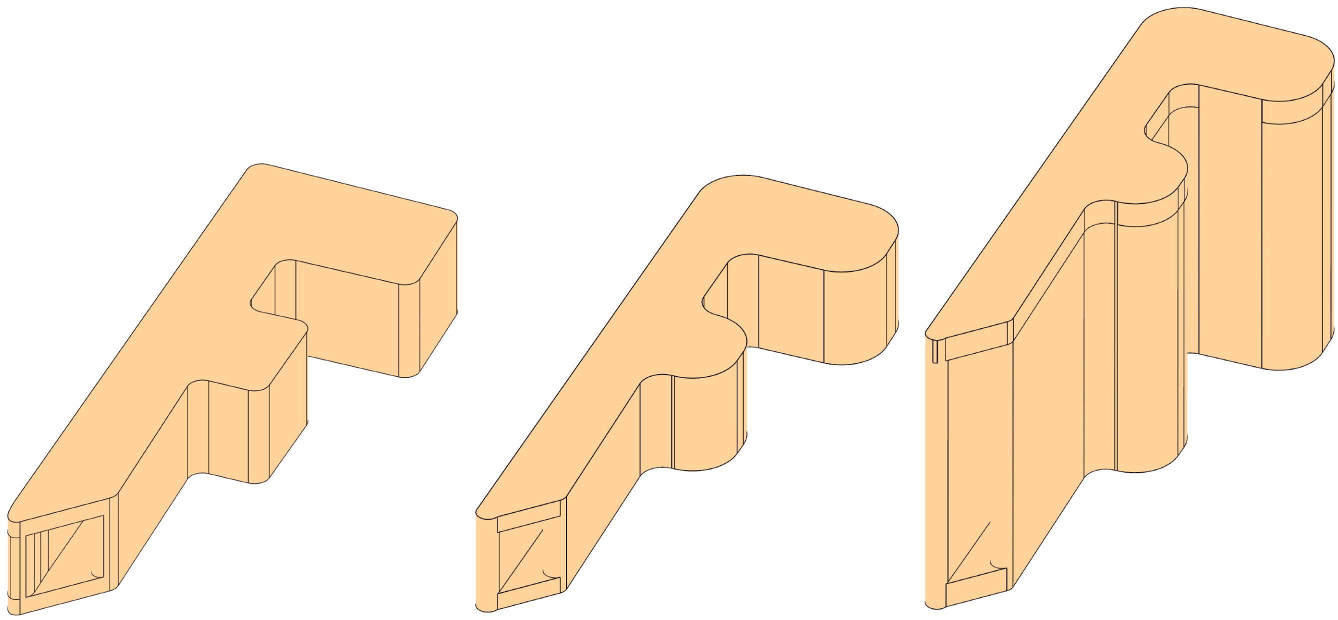


Figure 57. Design development of sample from left to right: second design has a slimmer cavity, third design is the same as second design but extruded in the vertical direction.

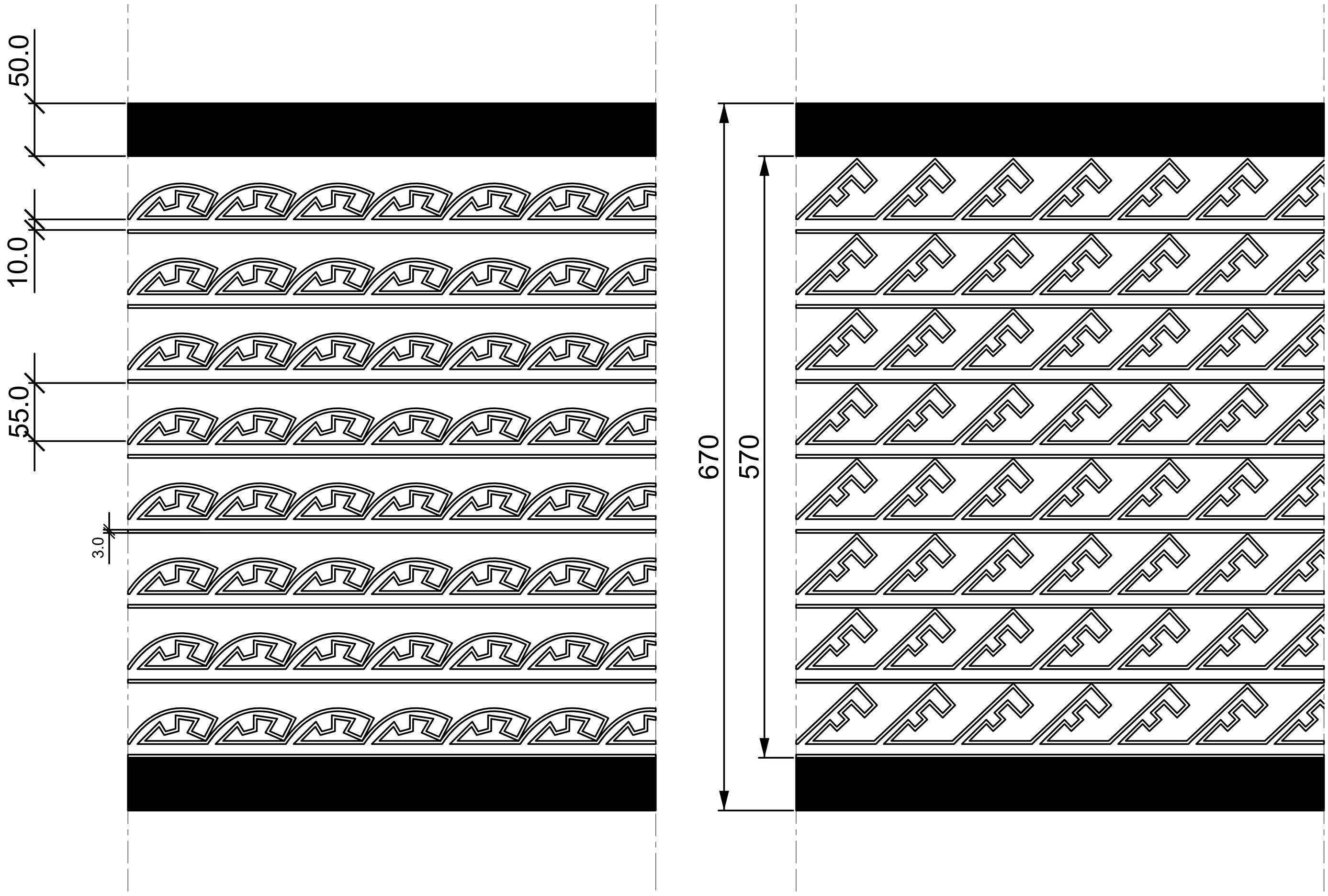


Figure 58. Initial design (top view)

Figure 59. Prototypes

in Table 8, with points allocated for each value. They all carry equal weight. The total points is a summation of all the points allocated for each criterion.

Based on this, it was concluded that the animal fur design would be worth it to look further at.

SMALL PROTOTYPE

A small prototype was made to test the movement of a critical part. The critical part is considered the finger (see figure 59). The thickness was initially set to 3mm because that is the nozzle size when using the large scale printer (Comau NJ60) at LAMA lab. However, the prototype showed little flexibility and did also not move under air pressure.

Since the flexibility of a material depends on the material used, the amount of the material and the design of the material, and the first two parameters are fixed (TPC and thickness of 3mm), the design was altered to achieve the desired flexibility.
In the second iteration the opening was smaller in height. Moreover, the edges were rounded more to give a better printing result. Through this the desired flexibility was still not achieved.
However, the finger would be extruded in its final application. This extrusion would add more flexibility. To test if this would work a third finger was prototyped, with

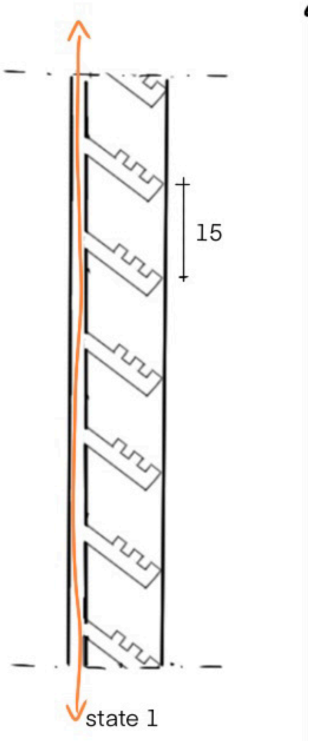


Figure 60. Direct contact with outside through valve

double the height. The flexibility was similar to the second prototype.

INITIAL DESIGN

The initial design was developed using Rhino 8. The shape of the fingers is developed by testing it through prototyping as previously written. These fingers can open and close. There are more cells the heat needs to go through when the fingers are closed, which means that there is a higher thermal resistance when the fingers are closed (see figure 56).

Another idea was to turn the design 90 degrees to increase the effect of the non-insulating state, after all, there is a more direct contact with the outside when the fingers are closed in this orientation (see figure 60). However, this would not be beneficial because in the open state there is also a direct contact to the outside since there are vertical valves where the fingers are connected (see figure 60).

The design from figure 58 was used to be further analysed in COMSOL.

COMSOL ANALYSIS

The result of the analysis was a heat flux at one side of 4.1 W/m^2 and the other side of 5.2 W/m^2. The average was taken (4.65 W/m^2) to calculate the Rc value using the following formula:

$R_{tot} = \Delta T / q$

with:
ΔT: temperature difference between outside and inside
q: heat flux
R_{tot}: total thermal resistance ($Rc+R_i+R_e$)

From this calculating the Rc value for this design is 4.13 m²K/W. The R of the outer and inner layer should be removed to know the R-value of the auxetic structure. The R is calculated using the following forumula:

$R = d/ \lambda$

with,
d = thickness [m]
λ = thermal conductivity [W/mK]

The thermal conductivity of TPC is 0.165 W/mK (Ansys, 2023). The thickness of one layer is 0.05 m. Therefore the R-value of one layer is (0.05/0.165=) 0.3 m²K/W.

The Rc of only the auxetic structure is therefore (4.13 - 2 x 0.3=) 3.53 m²K/W for a width of 570 mm. This is about 0.62 m²K/W per 100mm wall thickness.

LEARNINGS

- flexibility is created in three ways: through material, amount of material and shape. The first two are in this case fixed. Therefore, more flexibility needs to be created through the shape

- adding more curves, and making the cove more circular makes it bend easier

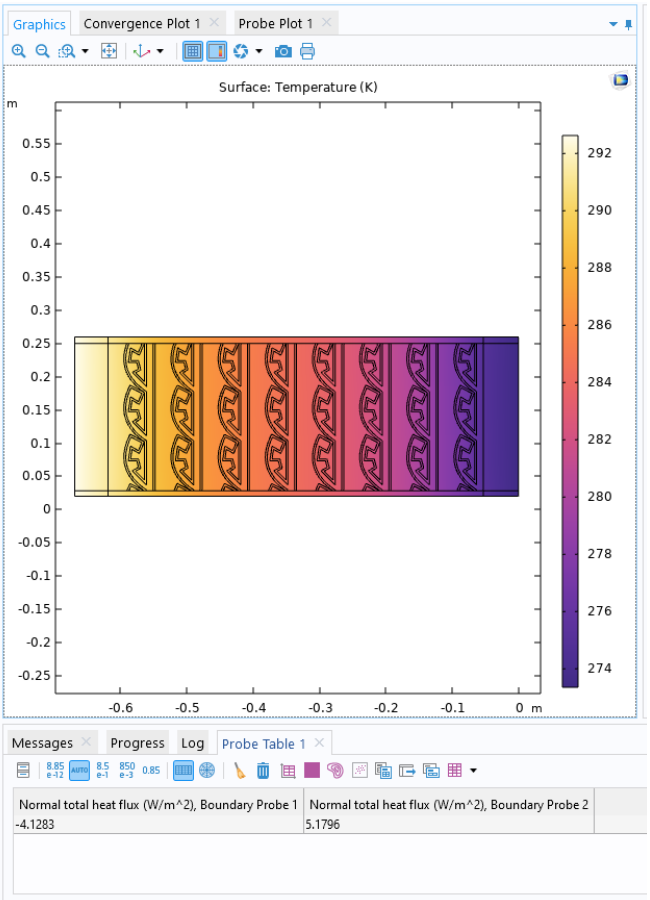


Figure 61. Result COMSOL analysis

- it matters in which direction the object is printed. If the print path is parallel to the bending direction you get a stiffer object whereas if you print it perpendicular to the bending direction it becomes less stiff. However, the latter has a bigger chance to introduce holes in the object if the object gets bend.

4.2.3 DESIGN 3

Design 3: Soft Robotics Doors
The third design strategy is based on soft robotics and the learnings from the previous design.

BACKGROUND (LITERATURE REVIEW)
The background is similar to the previous design. The learnings from the previous design are taken into this design.

PRACTICE
Based on the previous findings it is important to create a design that is not sensitive to errors during productions. Therefore, this design minimises the components needed that need to be airtight.

SKETCH
An initial sketch of the design can be found in figure 62. It minimises the components that need to be airtight to the doors at both end sides of the facade panel. Moreover, the part that is hollow, and therefore that needs to be air tight, is only a part of the door (see white in figure).

SMALL PROTOTYPE
A small prototype of the hollow part of the door is made to test its bending capabilities. When printed, it was found

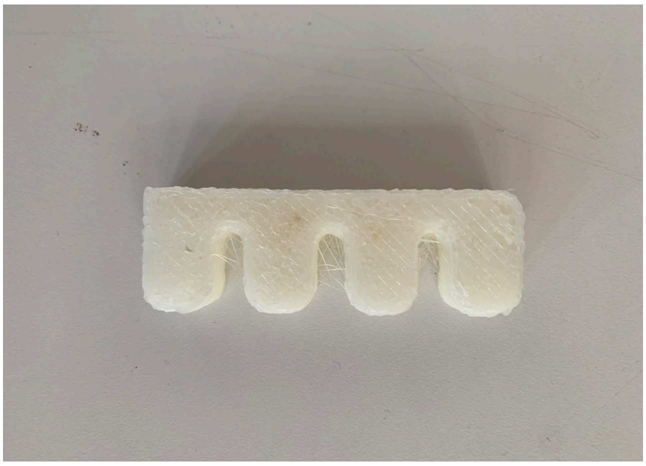


Figure 63. Prototype of hollow element

that the prototype is still too stiff for it to be controllable by air pressure. Since the shape is near optimal for bending, the only solution could be to get a thinner wall (currently it is 3mm) or to change the shore hardness of the material (currently it is 85A).

The wall is set to 3mm because this is the nozzle size of the available equipment for the 3D printer. It would be possible to get a lower nozzle size (2mm). Also, if the design is suitable for other production techniques (which is the case because it is extrudable) more options open up to make the wall thinner. These other production techniques can make it easier to create an airtight

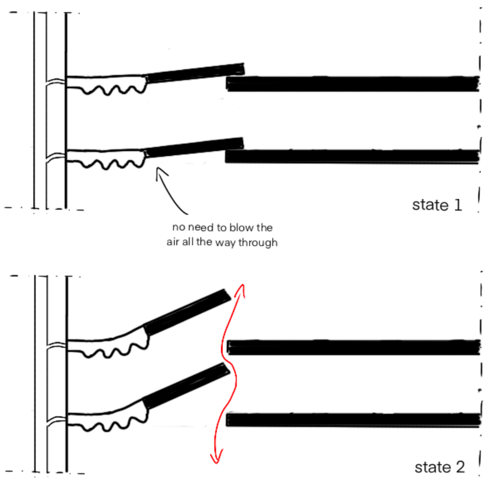
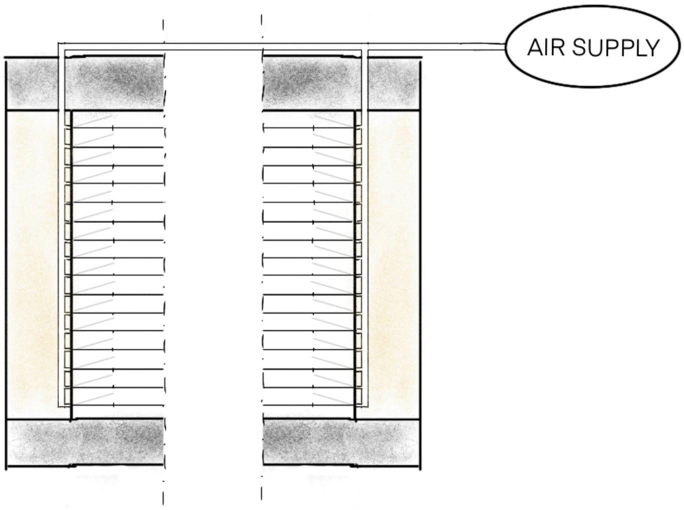


Figure 62. Sketch design



component.

Lowering the shore hardness would not be possible since TPC has a shore hardness between 40D (~85A) and 72D (FacFox, 2023).

INITITIAL DESIGN

A drawing of the initial design can be found in figure 64. It consists of horizontal elements with a distance of 15mm from each other. The thickness of the lines is 3mm. This design is used for the COMSOL analysis.

COMSOL ANALYSIS

The result of the analysis was a heat flux at one side of 3.6 W/m² and the other side of 4.4 W/m² (see figure 65). The average was taken (4 W/m²) to calculate the Rc value using the following formula:

$R_{tot} = \Delta T / q$

with:
ΔT: temperature difference between outside and inside
q: heat flux
R_{tot}: total thermal resistance ($Rc+R_i+R_e$)

From this calculating the Rc value for this design is 4.83 m²K/W. Like in the previous designs the R of the outer and inner layer should be removed to know the R-value of the auxetic structure.

The Rc of only the auxetic structure is therefore (4.83 - 2 x 0.3=) 4.23 m²K/W for a width of 537 mm. This is about 0.79 m²K/W per 100mm wall thickness.

LEARNINGS

Since the shape is optimised the solution for bending needs to be found in the amount of material used (i.e. thickness of the wall).

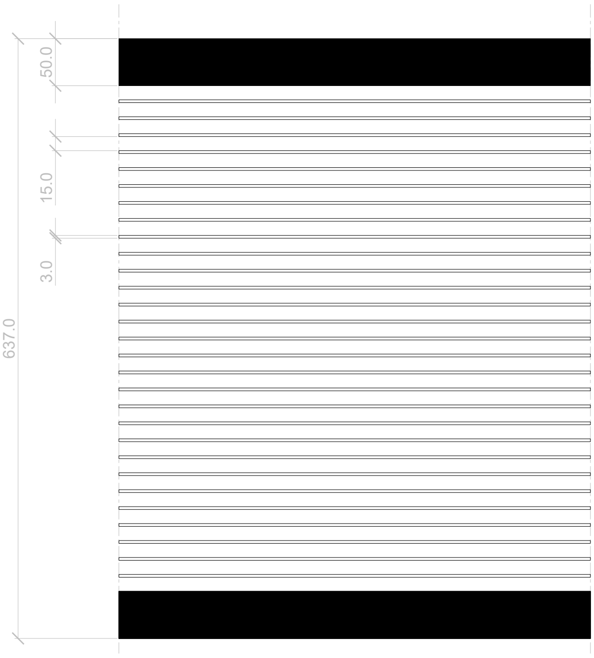


Figure 65. Intial design (top view)

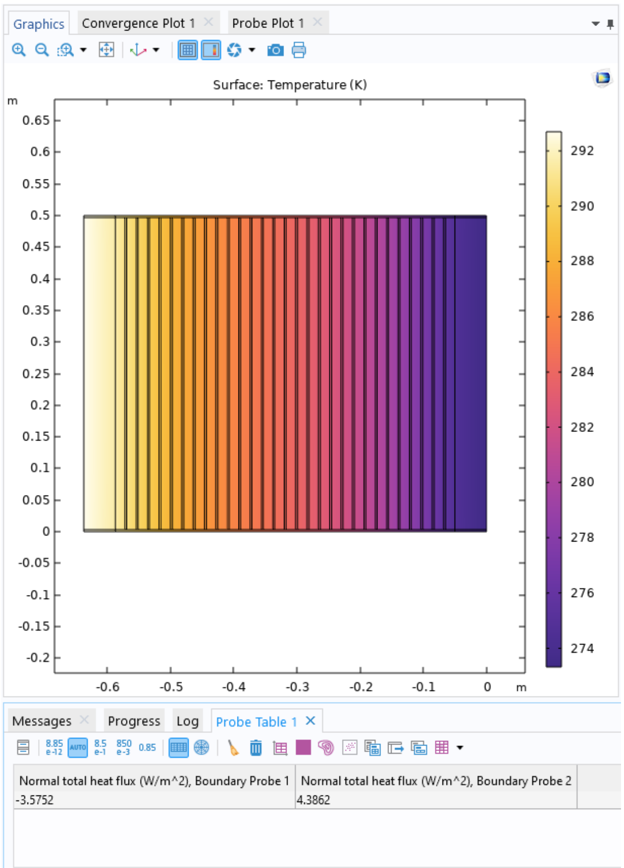


Figure 64. COMSOL analysis

4.2.4 DESIGN 4

Design 4: Organic Tree
The fourth design principle is based on the shape of trees.

BACKGROUND
This design is inspired by the shapes of trees, more specifically fractal trees (see figure 66). Together the branches create small air cavities which are desired to create insulation. The idea is that once pressure is applied, the fractal tree curls up, changing the sizes of the air cavities and creating an easy pathway for heat to go through.

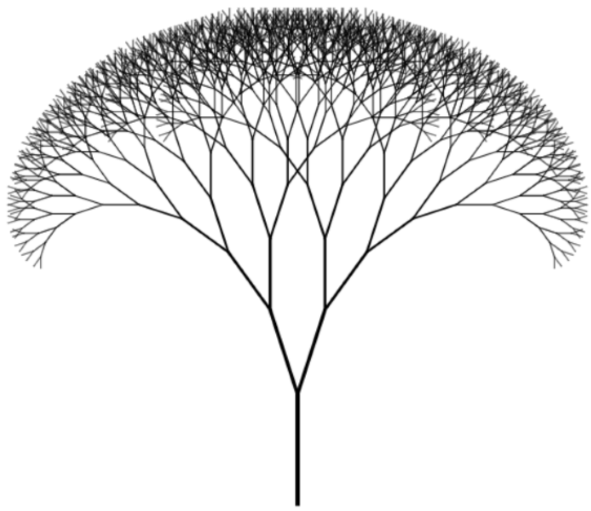


Figure 66. Fractal tree (Seemannn, 2017)

PRACTICE
To bring this idea to practice, knowledge on how to bend sheets from the research by Out et al. (2016) was used. Two thin sheets of a material are needed which are heat-sealed to each other. By heat-sealing two sheets to each other an air channel can be created. This air channel needs to be designed in such a way to get the desired shape change when air is blown in. Out et al. (2016) did this by heat-sealing hinges in the material. These hinges can have a line shape, arc shape or diamond shape (figure 67).

It was found that the diamond shape creates a stiffer hinge than the line shape and it allows for a wider range of bending angles than the arc shape. Depending on the width/height ratio of the diamond, different bending angles can be achieved (figure 68). The sheet bends in the direction towards the side where the sealing is applied.

To create this they used three different manufacturing techniques:
- Manual sealing – manually sealing the two sheets with a commercially available heat sealer
- Heat press sealing – creating a custom metal stencil with a CNC-mill or water jet cutter and using that as a heat press (figure 69)
- Robotic sealing – creating a path for a robot arm to follow which has an attached sealing head (figure 70)

Manual sealing is good for quick rough tests. Heat press sealing is good for making large quantities of the same design. Robotic sealing is good for versatile and precise

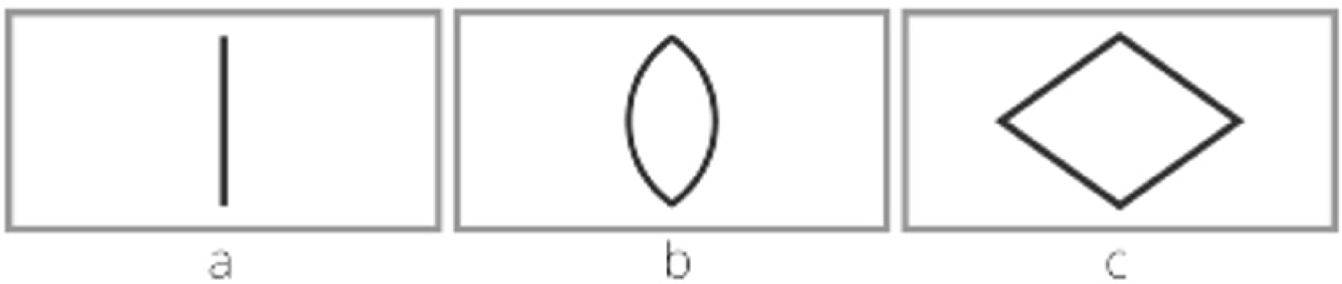


Figure 67. Three different shapes for hinges: a. line, b. arc, c. diamond (Out et al. 2016).

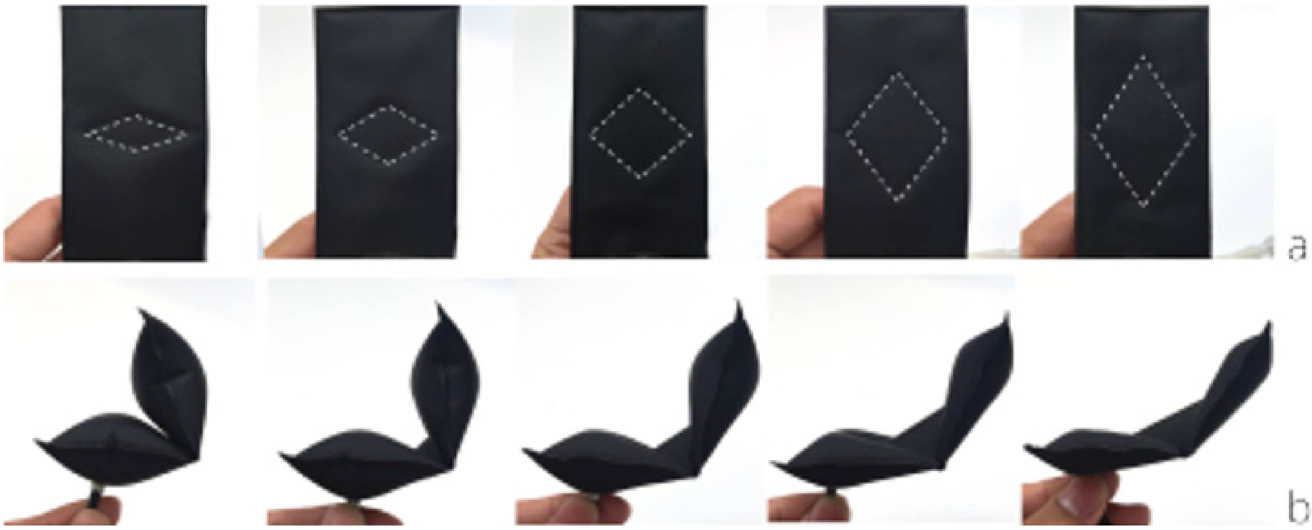


Figure 68. The width/height aspect ratio of the diamond hinge (a) determines the bending angle at full inflation (b) (Out et al. 2016).

sealing capabilities.
Using this approach problems with the design not being airtight is less likely than with 3D printed designs.

SKETCH
An initial sketch of the design can be found in figure 71. In the insulated state there is no pressure inside the air channels, resulting in a random organic structure. When the air pressure is applied, the sheets cramp up into a ball, resulting in a wall with a lower Rc value.

SMALL PROTOTYPE
A small prototype made by students from Hogeschool van Amsterdam can be found in figure 73. This prototype shows the bending ability of the sheets when air pressure is applied. As seen in the figure the prototype has a diamond shaped hinge. This is where the bending happens.

LEARNINGS
- This design approach is a good solution to the previous approach where it was concluded that extra flexibility should be created through amount of material (i.e. thickness)
- Bending can be created by heat sealing hinges in a material – out of the

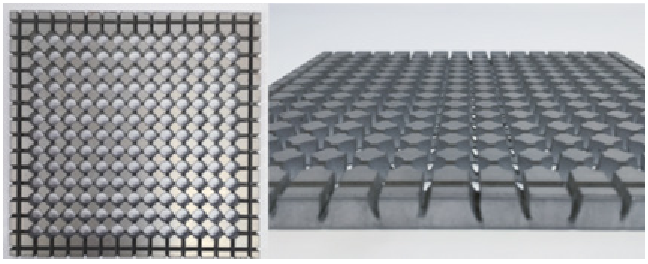


Figure 69. Heat press sealing (Out et al. 2016).

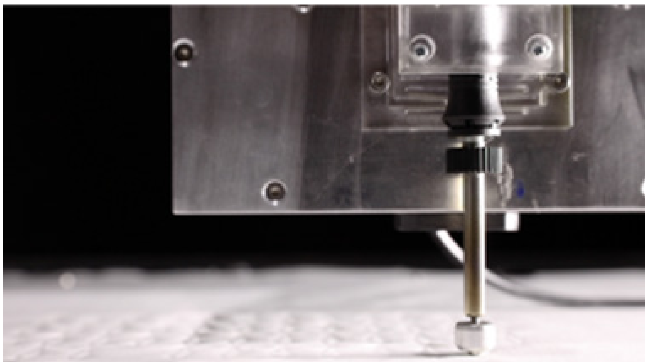


Figure 70. Robotic sealing (Out et al. 2016).

three explored hinges (line, arc and diamond) a hinge in a diamond shape is desired because it allows for better control of the bending angle and it is stiffer than the line hinge.

- 3D printing may not be the only answer for this application.
- although a good possible solution, the whole system needs to be airtight, making it vulnerable to production errors. This is why this idea got rejected and therefore the COMSOL analysis was not done.

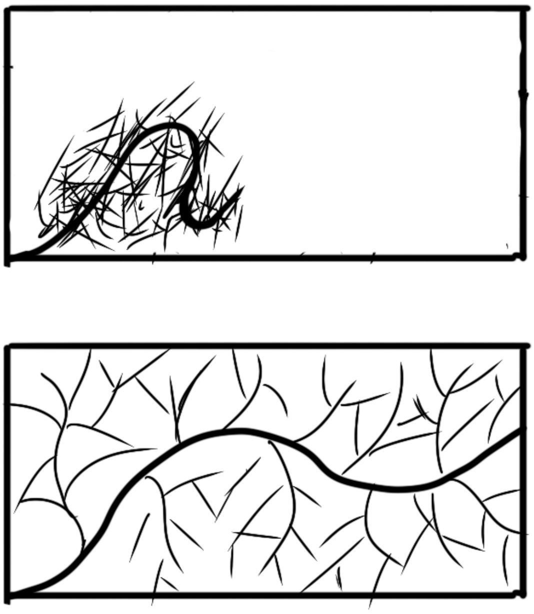


Figure 71. Sketch design. Conducting (top) and insulating (down)

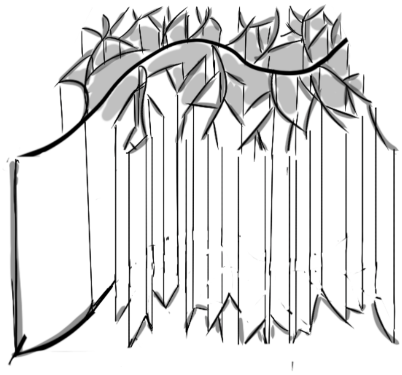


Figure 72. Sketch design.3D view (insulating)

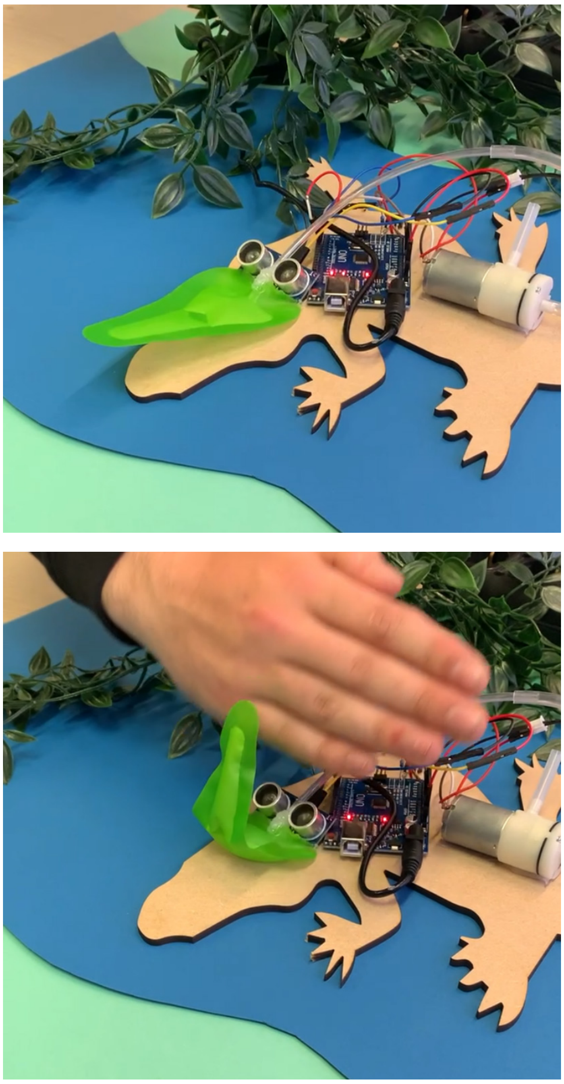


Figure 73. Prototype of working principle developed by students from Hogeschool van Amsterdam

4.3 DESIGN SELECTION

A summary of all answered questions for each design can be found in table 9. Only for the auxetic structure and organic tree this research succeeded to make the prototype work as intended. The soft robotics design and doors design failed because this study did not succeed making the prototype airtight.

When it comes to the Rc-value per 100 mm the auxetic structure design scored the best out of the designs where a simulation was done.

Moreover, the sensitivity to production errors was the lowest for the auxetic structure design. This is because this design did not require an airtight design, whereas the others did.

Since all designs are extrudable in one side, all were considered suitable for rapid production (i.e. extrusion).

When it comes to the energy required during production, it was though that the auxetic structure and doors design use the least energy. This is because switching the state only requires airpressure in a local spot, whereas for the other two designs the whole design needs to be pressurised.

From this overview it is concluded that the auxetic structutre design would be most suitable to develop further. This is mainly because of the low sensitivity to production errors and the high Rc-value per 100 mm.

Summary	Design 1: Auxetic Structure	Design 2: Soft Robotcs	Design 3: Doors	Design 4: Organic tree
Does the prototype move like it was intended?	Yes	No	No	Yes
What is the Rc-value per 100mm?	0.94 m^2K/W	0.62 m^2K/W	0.79 m^2K/W	Not tested
How sensitive is it to production errors?	Low	Very high	Medium	Medium
Is there potential for a rapid production method? (is it extrudable)	Yes	Yes	Yes	Yes, but an extra step is needed to attach the sheets
Does the design require a lot of energy in its application?	Low	Medium	Low	Medium

Table 9. Initial design

5. FINAL DESIGN

This section consists of the following sections:

5.1 Workplan - which introduces the chapter and objective

5.2 Failure mode and effect analysis (FMEA) - which explores different potential failures of the system during application and proposes measurements to mitigate these

5.3 Smart control system - which shows the control system to make the facade responsive

5.4 Final design development - which shows the design process in this stage

5.5 Windload calculation - which looks at the structural stability of the facade element

5.6 Final design - which shows the final drawings of the developed product

5.7 Manufacturing methods - which looks at the possible manufacturing technique for the facade element

5.1 WORKPLAN

Objective
The objective of this section is to further develop the initial design into a final design. The design is considered final once it meets the design criteria from chapter 3.2.1.

This section outlines the development process of the responsive facade element, focusing on the technical and structural aspects required to bring the concept to a feasible and functional design.

Method
In chapter 5.2, a Failure Mode and Effect Analysis (FMEA) is conducted to identify potential failure scenarios during the facade element's life cycle and to propose preventive measures. Chapter 5.3 presents the design of the smart control system that enables the facade to switch between insulating and conducting states in response to external stimuli.

Chapter 5.4 shows the final design development of the facade element, integrating insights from previous analyses. To ensure structural reliability, chapter 5.5 includes a wind load calculation assessing the performance of the system under wind loads.

All the findings from the previous chapters get integrated into the final design in chapter 5.6. The chapter also shows how the facade element gets integrated into a building.

Finally, chapter 5.7 explores potential manufacturing methods for the developed facade element on a scalable level.

5.2 FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Objective
The objective of this chapter is to identify all possible failures during usage of the facade element and to propose measures to address these failures. This is done using a Failure Modes and Effects Analysis (FMEA) (Stamatis, 1995). It starts with listing all the components, followed by identifying possible failure modes for each component; after that, an analysis of the effect of each failure mode is made.

Failure modes and effect analysis
For each component, measurements are taken to reduce the severity and the occurrence of the failure modes. Generally speaking, in case of a failure, the façade element goes to its insulating state:

Pusher, air compressor, pressure pipes: the neutral state of the façade element is the insulating state + oversized pusher + limited amount of parts for pusher

Smart control system: adding watchdog timers, which automatically reboot the system if it is not responsive anymore, or in case of an error (e.g. data cannot be fetched from the API anymore because it ceased to exist), the façade element goes to its insulating state.

Temperature sensor: an extra sensor is added and the data from these two sensors is cross-checked. In case of a big temperature difference between the

Component	Potential Failure Mode	Effect of Failure
Switchable insu-lation	Leaks	Reduced thermal resistance; increased energy use
Pusher	Leaks, material degradation, broken part	No or limited insulation change
Air compressor	Fails to activate / loss of pressure	No or limited insulation change
Pressure pipes	Leaks or rupture	No or limited insulation change
Smart control system	Software bug / no signal / API discontinued	No or inaccurate insulation change
Indoor temper-ature sensor	Incorrect readings / breaks	No or inaccurate insulation change
Outer wall (TPC layer)	Leaks (water air), aging	uncomfortable indoor climate
Inner wall (TPC layer)	Leaks (water air), aging	uncomfortable indoor climate

Table 10. Failure Modes and Effects Analysis (FMEA) (Stamatis, 1995).

two sensors (>5C), the wall automatically switches to its insulating state.

Switchable insulation: made a little bit thicker than needed.

Outer and inner wall: both walls are made a little bit oversized.

A summary of the different interventions can be found in figure 74.

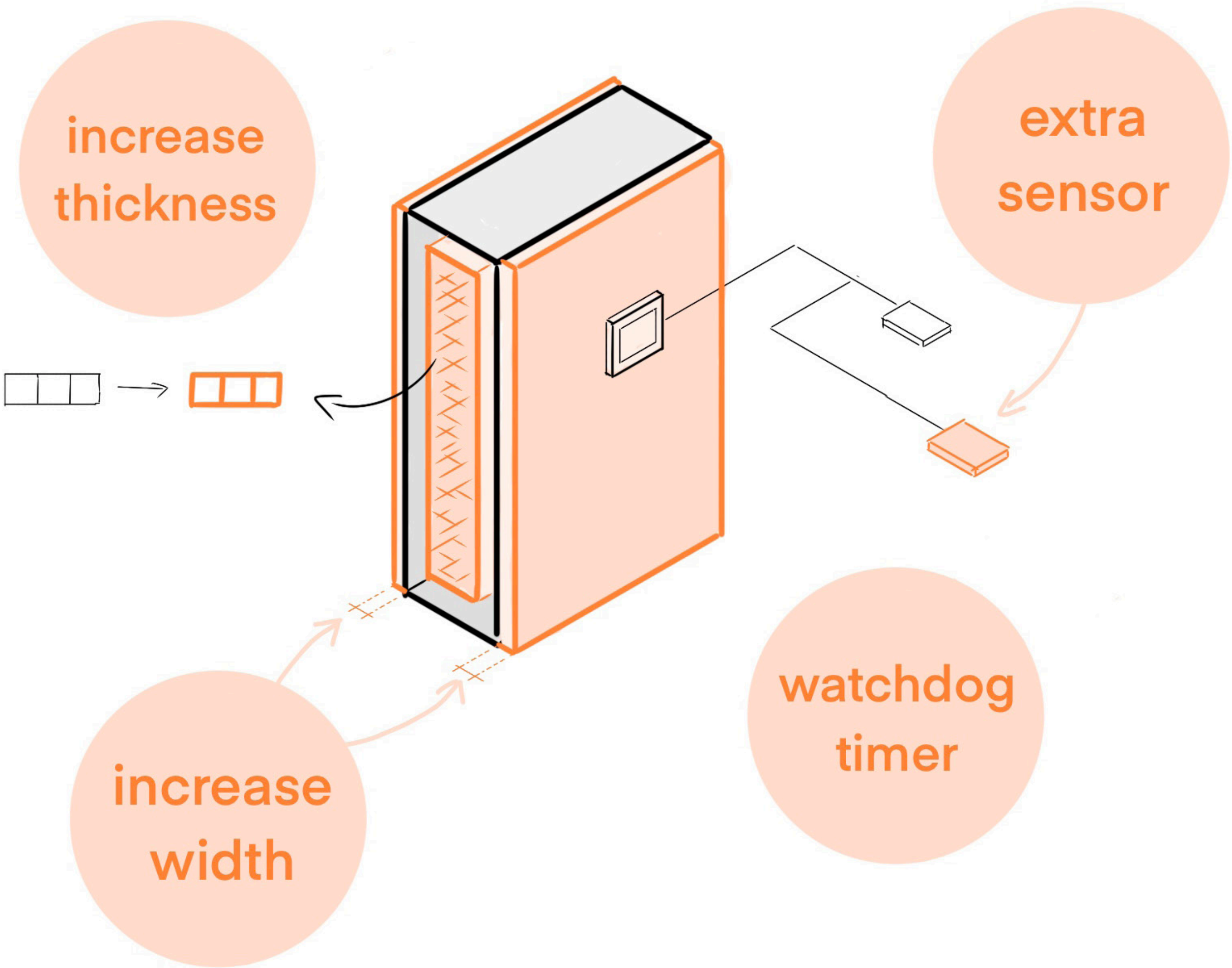


Figure 74. Summary of interventions to mitiage potential failures

5.3 SMART CONTROL SYSTEM

Objective
The objective of this chapter is to identify all possible failures during usage of the facade element and to propose measures to address these failures. This is done using a Failure Modes and Effects Analysis (FMEA) (Stamatis, 1995). It starts with listing all the components, followed by identifying possible failure modes for each component; after that, an analysis of the effect of each failure mode is made.

Smart control system
Literature review
When it comes to the control strategy level, Salah et al. (2024) identified four different strategies to control the insulation layer (see figure 75):

1. Scheduled-based
- Switches according to a preset timetable or seasonal schedule
- No flexibility because it does not respond to real-time climatic data

2. Rule-based
- Switches according to real-time climatic data through predefined logical rules
Two-step control strategies (binary switch)
Multi-step control strategies
E.g. temperature-based, solar-radiation-based and illuminance-based etc.
3. Genetic algorithm
- Finds the most optimal R-value based on one optimisation objective

4. Predictive modelling
- Finds the most optimal R-value based on multiple optimisation objectives
- Achieves better performance compared to other strategies. The result is improved energy efficiency, comfort, and building cost savings.

The thermal insulation automatically changes its state, resulting in a responsive facade. This was achieved by writing a

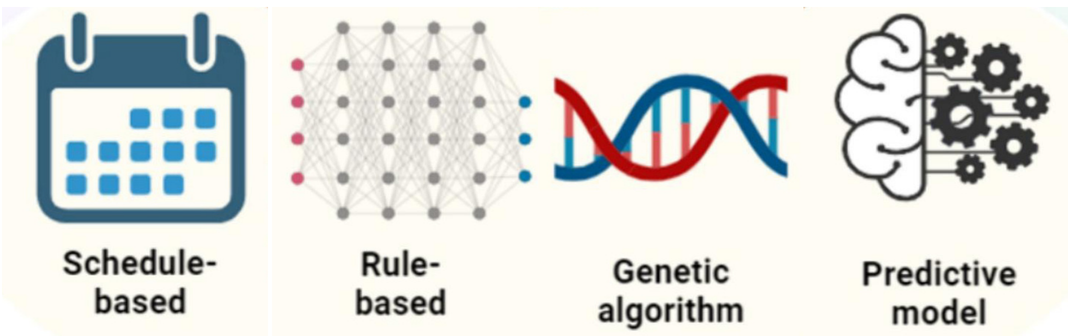


Figure 75. Four different control strategies for controlling the state of the insulation layer (Salah et al., 2024)

script in Python and connecting this to the hardware using a micro controller.

Software
In this Python script current local weather data is being fetched using a weather API by WeatherAPI.com. A desired indoor temperature is set to 21 degrees Celsius, although users can change this according to their desire. At the same time the indoor temperature is measured using a temperature sensor. The desired temperature is constantly compared to the current indoor temperature and the outdoor temperature. If the indoor temperature is higher than the desired temperature and the outdoor temperature is lower than the indoor temperature, then the air compressor turns on/off, changing the cell structure, and the thermal resistance of the building envelope decreases to 0.5 W m^2/K. In all other cases the building envelope is at its highest insulation, 4.7 W m^2 / K (figure 76).

Switching states is prevented for cases where the temperature difference between indoor and outdoor is considered insignificant. This is the case when the temperature difference is 1 degree Celsius or lower. Moreover, a deadband is used to prevent the system from rapidly switching in the case that there is a fluctuation in temperature around the switching condition.

A deadband is a range of input values in a system where no output occurs. This can be necessary to prevent small fluctuations or noise from causing unnecessary reactions. In this case a deadband in the form of time would be useful when the temperature conditions are met. The time delay deadband is set to 5 minutes, meaning that the wall only switches from state when all conditions are met for at least 5 continuous minutes.

The full code is written in python and can be found in the appendix.

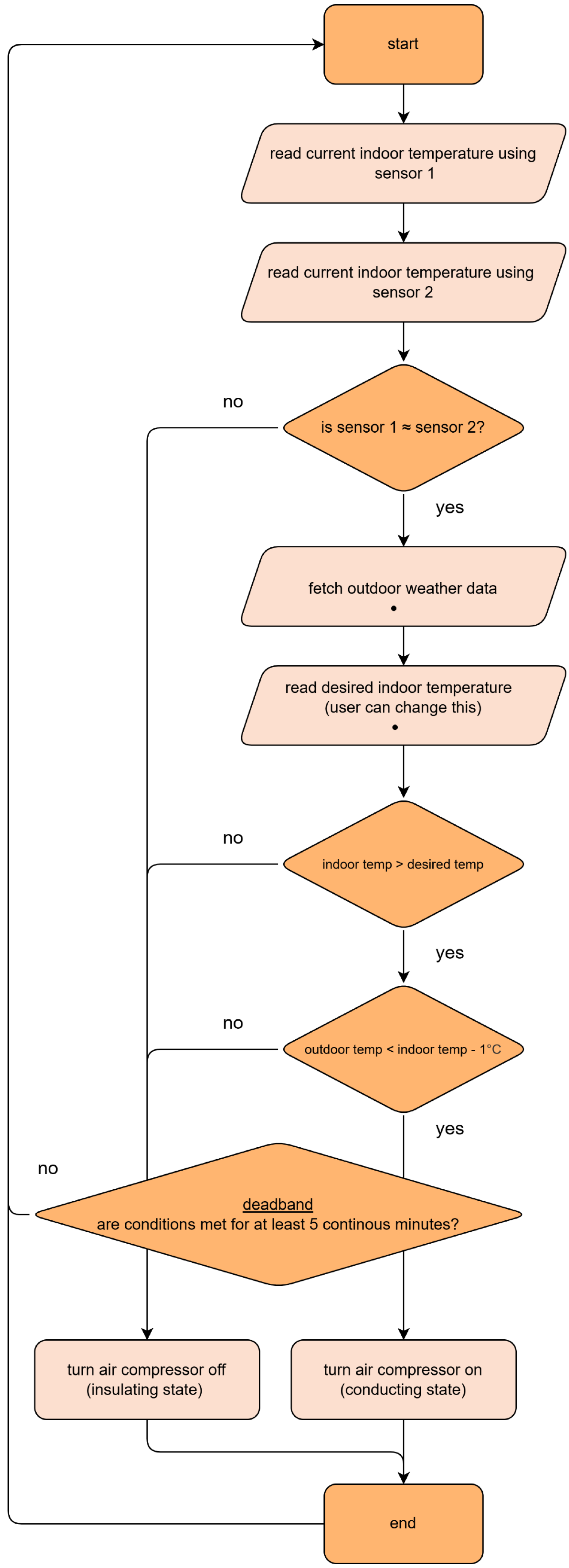


Figure 76. Flowchart smart control system

Hardware

The hardware used are:

- Raspberry Pi 3 (micro controller)
- Air compressor
- DHT22 temperature sensor
- SD card
- Cables
- Heschen Electric Pneumatic Solenoid Valve 4V210-06
- Breadboard

A schematic of the setup can be found in figure 77.

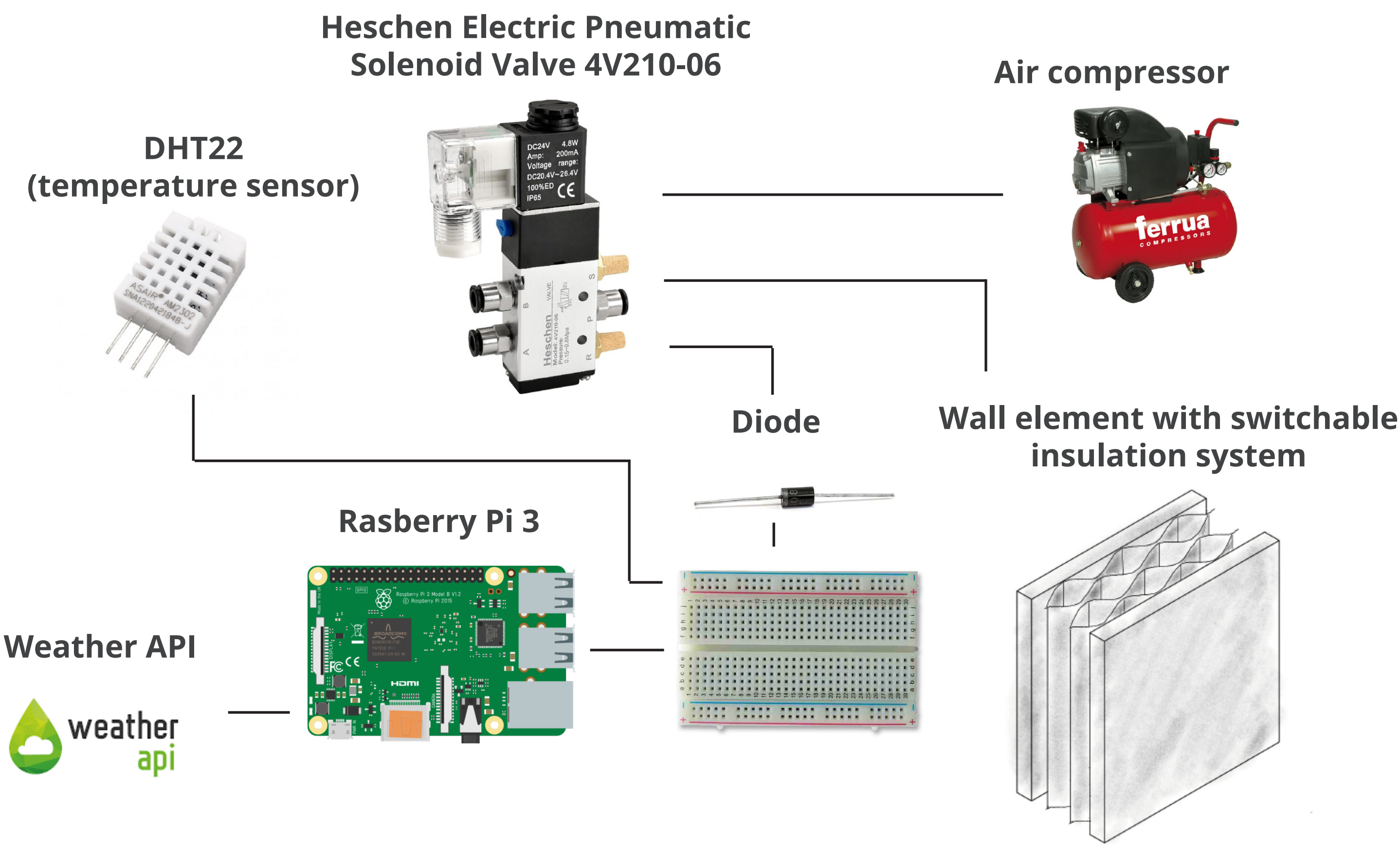


Figure 77. A schematic of the air control system

5.4 FINAL DESIGN DEVELOPMENT

Objective
The objective of this chapter is to further elaborate on the selected design from the preliminary design phase (i.e. the auxetic structure principle). Therefore, a design and selection of the following components will be made:
- auxetic structure
- pusher/puller mechanism

These components are integrated to achieve the mono-material wall element with switchable insulation. Moreover, this chapter shows the practicality of the developed facade and shows the full design expressed in artist impressions and drawings.

Design and Development Process
In 5.3.1 a design and selection of the auxetic structure will be made. In 5.3.2 it is determined how the auxetic structure should be positioned in the wall. In 5.2.3 a design and selection for the pusher/puller mechanism will be made. 5.2.4 integrates the different components into a full functional facade element. 5.2.5 analysis the wind loads on the facade element. 5.2.6 explores different manufacturing methods for the facade element.

Evaluation criteria
Selecting the right components will be based on the developed design criteria from chapter 3.2.1.

For the auxetic structure the following criteria are used:
- movement
- extrudability
- material usage
- durability
- Rc-value

For the pusher/puller mechanism the following criteria are used:
- durability
- recyclability (possibility for mono-material)
- energy usage

5.3.1 Selection and design of auxetic structure
Literature review
To be able to design an auxetic structure it is important to know which auxetic structures are already out there.
The following search terms were used in Scopus:
"Auxetic Structures" AND “review”
This resulted in 63 papers, of which
9 were found to be useful. 8 Of these were accessible via the institution.

The article that was not accessible was from Kazemi & Eghbalpoor (2024): *Types and application of auxetic cells: A review.*

There are a lot of different auxetic structures. However, the literature is not consistent with the classification of auxetic structures. For example some consider an arrowhead geometry under the re-entrant type (Balan P et al., 2023) while others classify it as a topology of its own (Hu et al., 2024).
The classification from Joseph et al. (2021) seemed to be the most complete (see figure 78). Added to this list needs to be the perforated topology.

Selection and design
When selecting the right structure the following criteria were used from most to least important:

Usability (movement + extrudability) > material usage > durability > Rc-value in conducting state

Miura-folded mechanism (figure 79), Helical auxetic yarns (figure 79) and crumpled mechanisms were considered not usable

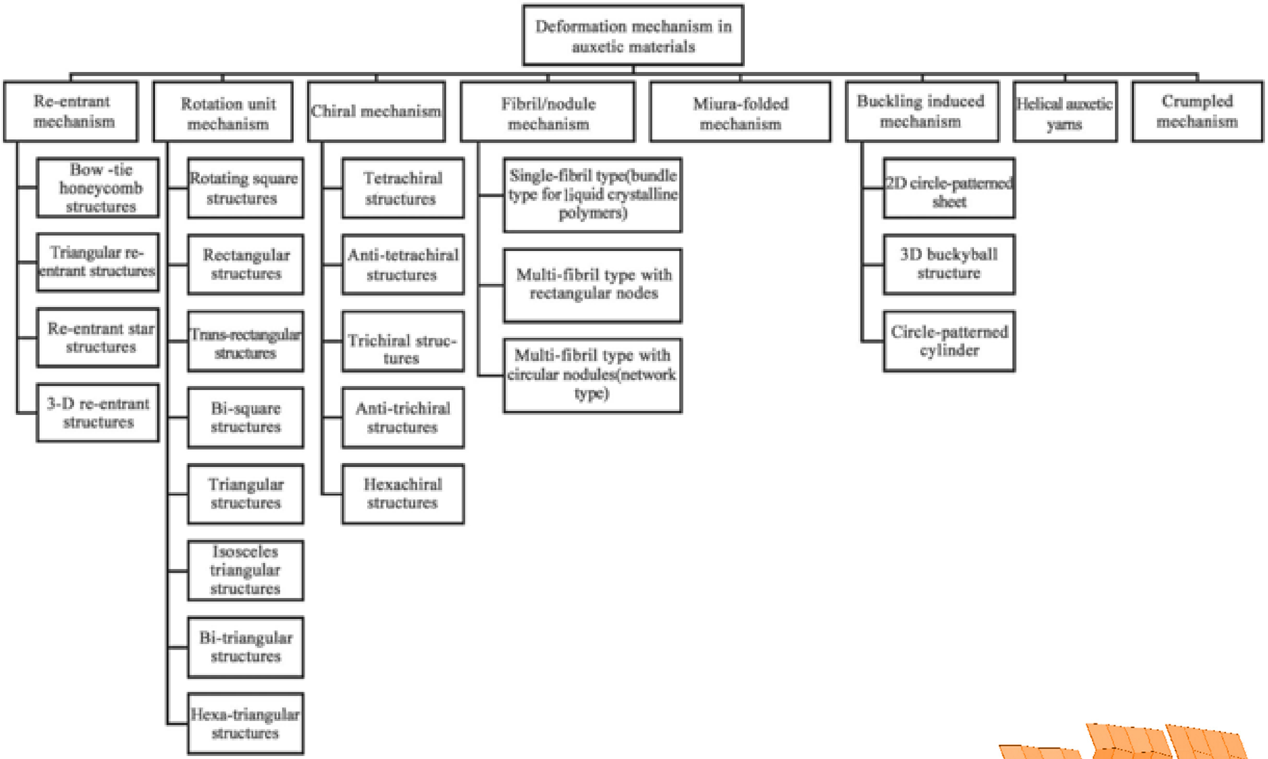
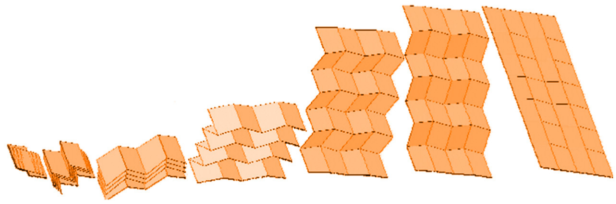


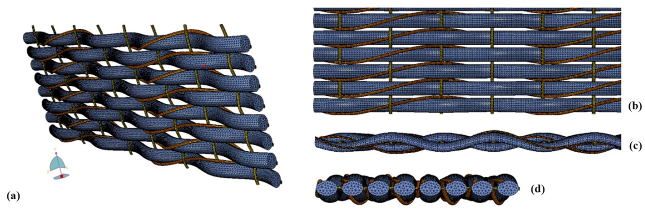
Figure 78. Classification of auxetic structures based on their deformation mechanisms (Joseph et al., 2021).

because of their 2-dimensional nature.

Fibril mechanism (figure 80) rotational unit mechanisms (figure 81), perforated mechanism (figure 82), and buckling induced mechanism (figure 83) seem to use a lot of material because of their planar nature.

Re-entrant and chiral mechanism are





(a) Fabric model **(b)** Top view **(c)** Front view **(d)** Side view

Figure 79. Miura-folded mechanism (top) (Dureisseix, 2012), and Helical auxetic yarns (down) (Gao & Chen, 2022).

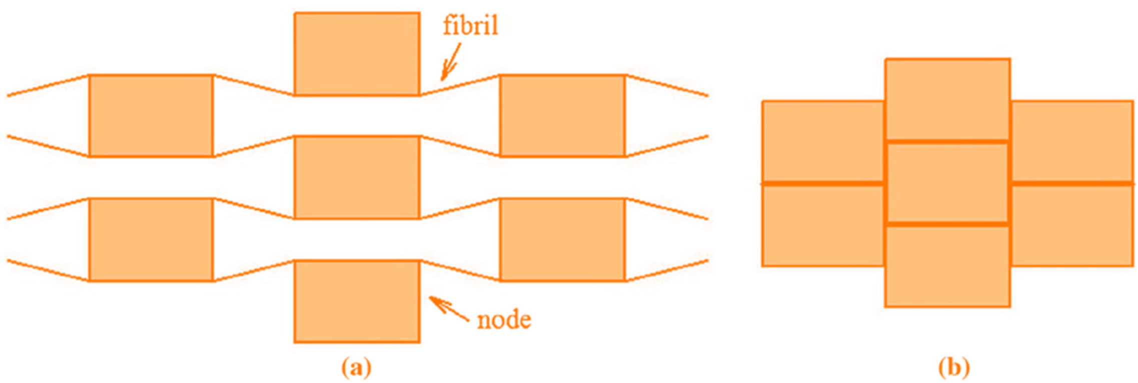


Figure 80. fibril mechanism . Reprinted from (Liu & Hu, 2010)

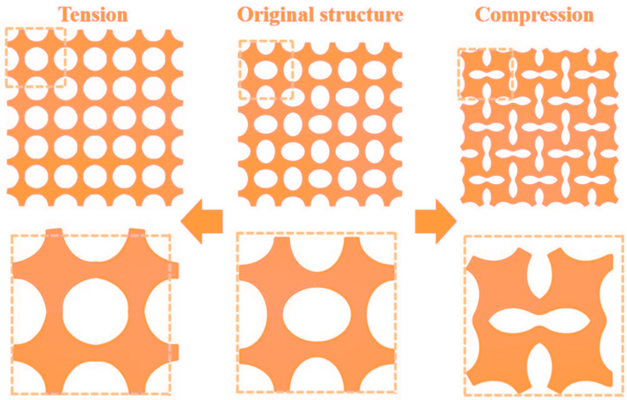


Figure 83. Buckling induced mechanism . Reprinted from (Zhang et al., 2021)

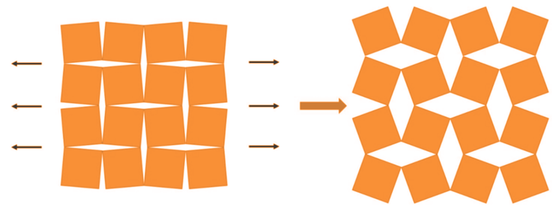


Figure 81. Rotational unit mechanism (Teng et al., 2023).

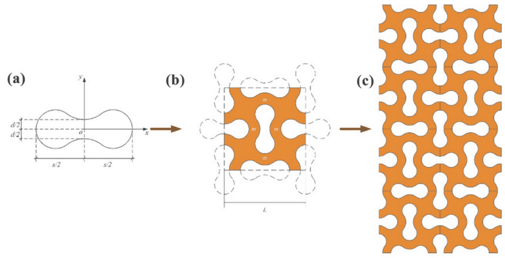


Figure 82. Perforated (Liu et al., 2023).

therefore the most suitable topologies. Figure 82 shows different types of re-entrant and chiral auxetic structures.

The question now arise: which one is the most durable and has the lowest Rc in the conducting state? The following assumption is made: Structures with more curves are more durable. Looking at the figure it is then a logical step to pick one of the chiral structures, since it has more curves.

However, when it comes to the lowest Rc-value in the conducting state it is argued that when the structure is folded it needs to be as close to a solid as possible. This allows for more heat transfer in the conducting state. Moreover, the created air gap when the auxetic structure is collapsed probably needs to be as big as possible in order to achieve the lowest Rc-value.

Since the chiral structures collapsed state always has cavities (after all, the circles cannot close), and because the sharp edges in the re-entrant structure are easy to work around (the same structure can be designed with more rounded curves), the re-entrant structures are selected. Out of the three in figure 84 the triangular auxetic seemed to come the closest to a solid when compressed. To increase durability, the edges are rounded off to get an auxetic structure similarly to that of Wang et al. (2018) (see figure 85).

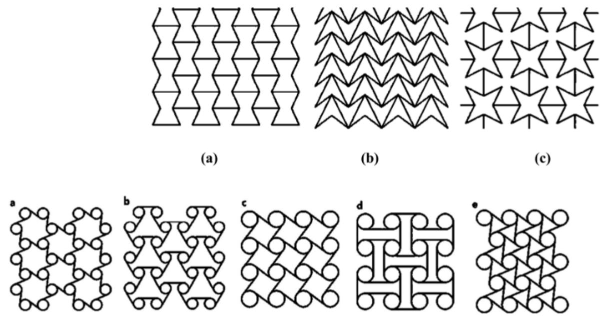


Figure 84. Types of re-entrant and chiral structures (Benke et al., 2025).

Figure 85. Final auxetic design

Determining the width of the auxetic structure.

To determine the width a thermal simulation (using COMSOL Multiphysics) needs to be done to achieve a minimum Rc-value of 4.7 m^2K/W.

According to the COMSOL Analysis (figure 86) the heat flux at one side is -4.07 W/m^2 and the other side 5.04 W/m^2 with a temperature difference of 20 degrees Celsius. Like in the preliminary design phase, an average of the absolute values are taken to find heat flux through the auxetic structure. This is approximately 4.5 W/m^2. The thermal resistance is determined using the following formula:

$R_{tot} = \Delta T / q$

with:

ΔT = temperature difference between outside and inside [°]

q = heat flux [W/m^2]

R_{tot} = total thermal resistance ($Rc+R_i+R_e$) [m^2K/W]

Following this formula, the R_{tot} is about 4.4 m^2K/W for a structure with a thickness of 584 mm. Since the geometry in the COMSOL has an inner and outer solid layer that skewer the results, the R-value of both these layers get removed from the R_{tot}. To calculate the R-value of both these layers the following formula is used:

$R = d / \lambda$

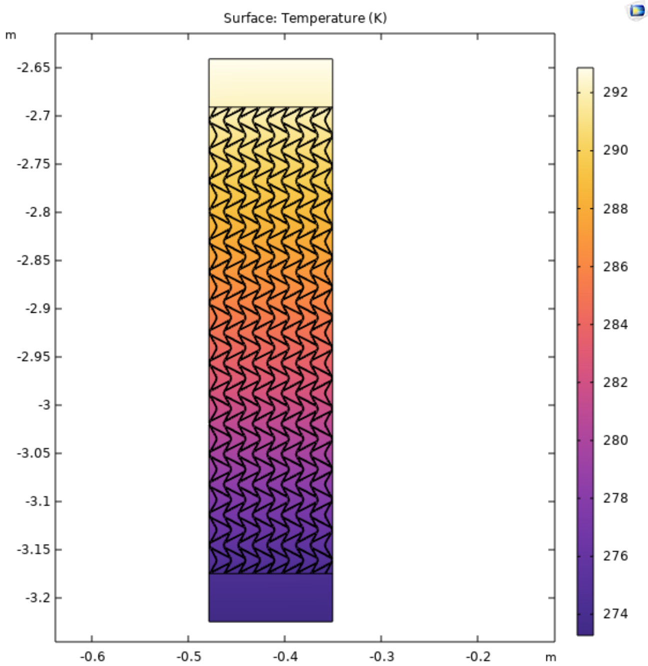


Figure 86. Comsol results with triangular auxetic structure

with,

d = thickness [m]

λ = thermal conductivity [W/mK]

The thermal conductivity of TPC is 0.165 W/mK (Ansys, 2023). The thickness of one layer is 0.05 m. Therefore the R-value of one layer is (0.05/0.165=) 0.3 m^2K/W.

The R_{tot} of only the auxetic structure is therefore (4.4 - 2 x 0.3=) 3.8 m^2K/W for a width of 484 mm.

This results in a thermal resistance of around 0.785 m^2K/W per 100mm. To achieve a R_{tot} of 4.84 m^2K/W (and therefore a Rc of 4.7 m^2K/W), a width of approximately 617 mm is needed (see figure 87).

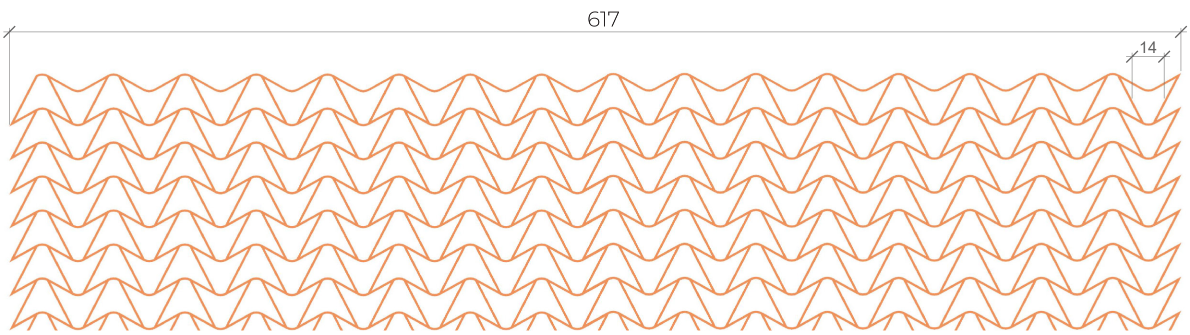


Figure 87. Minimal width required to achieve Rc-value of 4.7 m^2K/W

5.3.2 Position of the auxetic structure

When positioning the auxetic structure inside the wall there are three options (see figure 88):

- Put the auxetic structure on the long side of the wall
- Put the auxetic structure on the short side of the wall
- Put the auxetic structure in the middle of the wall

For each position there are a couple of advantages and disadvantages (figure 89, 90, 91):

Short side of the wall
Advantage: you only need to push it from one side
Disadvantage: no circular flow possible + extra solution needed to prevent a cold bridge

Long side of the wall
Advantage: you only need to push it from one side
Disadvantage: no circular flow possible

Middle of the wall
Advantage: circular flow possible
Disadvantage: you need to push it from two sides

Positioning it at the short side of the wall is the least favourable because of the potential of a cold bridge. A circular flow is desired to further decrease the Rc-value in the conducting state. To get the advantage of both the circular flow and only needing to push from one side, an extra layer is added inside the wall supported by a trusses, which acts as the side wall for the auxetic structure (see figure 92).

The question now arises how big the gaps need to be, in where the air can flow through.

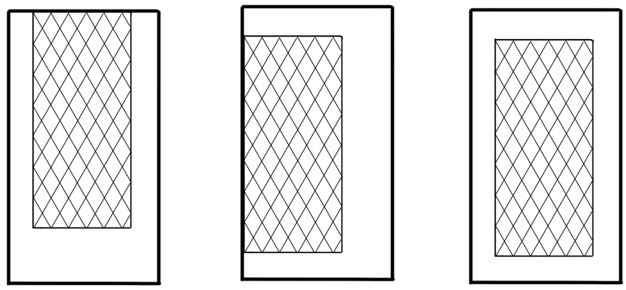


Figure 88. Three possible positions for the auxetic structure from left to right: short side, long side and middle.

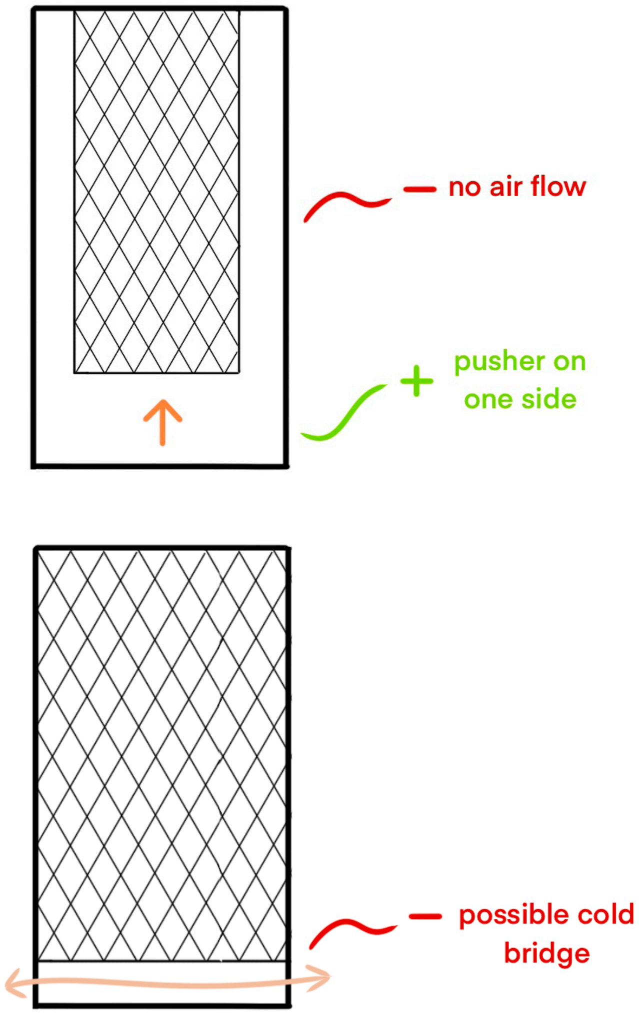


Figure 89. Advantages (green) and disadvantages (red) of positioning the auxetic structure to the short side of the wall

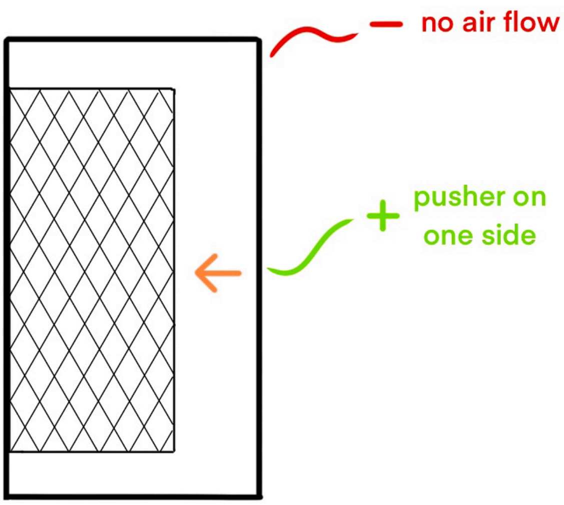


Figure 90. Advantages (green) and disadvantages (red) of positioning the auxetic structure to the long side of the wall

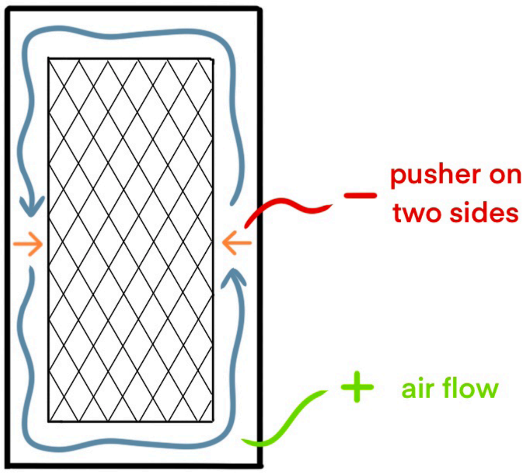
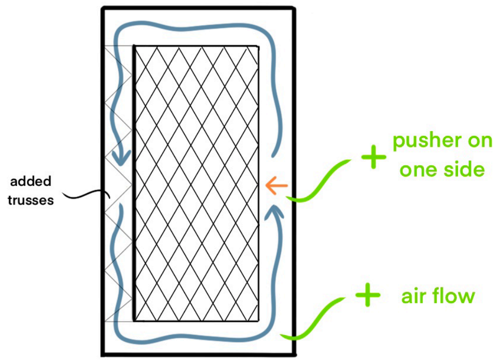


Figure 91. Advantages (green) and disadvantages (red) of positioning the auxetic structure in the middle of the wall



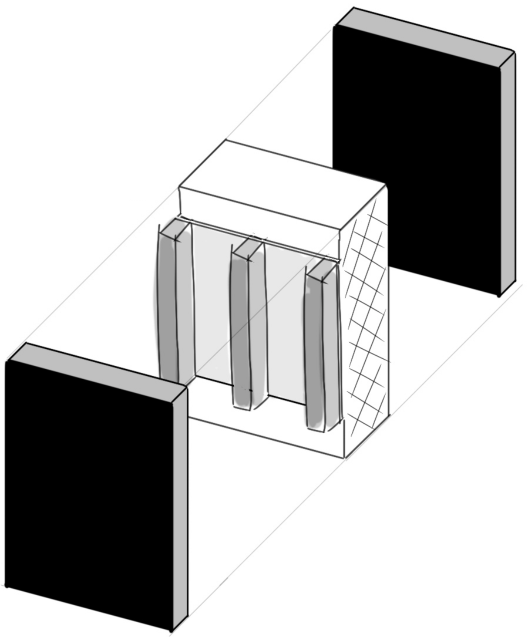


Figure 92. Combining the advantages of positioning the auxetic structure to the side of the wall (only pusher needed from one side) and middle of the wall (air flow)

Air gaps literature review
Pflug et al. (2015) created a translucent façade element with switchable insulation by moving the insulation layer up and down (see figure 93).

In their study they looked at the effects of different air gaps on the U-value (=1/R). The results can be found in figure 94. The goal in the conducting state is to get a U-value which is as high as possible. Contrary to expectations, it was observed that doubling the ratio C/A and D/A resulted in a lower U-value (see 7C and 11C in figure 94). The authors explained that one possible reason for this could be that turbulence zones appear in the vertical gaps, which counteracts the natural convection. Therefore, it is better to have the same air gap for C, A and D.

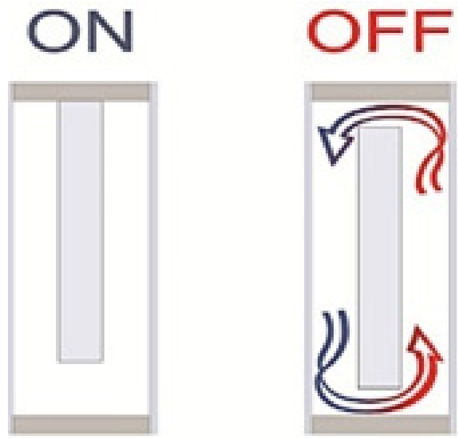
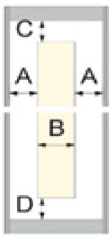


Figure 93. Switchable insulation concept from Pflug et al. (2015)

Table 2
Measurement results of the second measurement campaign. I = insulating state, C = conducting state.



N° (–)	A (mm)	B (mm)	C (mm)	D (mm)	Δθ (°C)	U-value (W/(m² K))
5I	17.5	10.0	0.0	35.0	15	1.33
6I	17.5	10.0	0.0	35.0	29	1.44
7C	17.5	10.0	17.5	17.5	14	1.72
8C	17.5	10.0	17.5	17.5	29	1.86
9C	30.0	10.0	30.0	30.0	14	1.83
10C	30.0	10.0	30.0	30.0	28	2.03
11C	17.5	10.0	35.0	35.0	14	1.58
12C	17.5	10.0	35.0	35.0	29	1.77
13I	17.5	10.0	0.0	0.0	15	1.31
14I	17.5	10.0	0.0	0.0	34	1.41
15I	17.5	10.0	35.0	0.0	15	1.44
16I	17.5	10.0	35.0	0.0	29	1.57

Figure 94. Results study (Pflug et al., 2015)

5.3.4 Displacement and force

When designing with an auxetic structure, it is important to know how much force it takes to compress it and how much it moves in the x and y directions. To find this out a sample is 3D printed with the following dimensions: width = 158.62 mm, length = 202.45 mm, height = 10 mm, thickness = 1mm (see figure 103).

The amount of force needed to collapse the auxetic structure (small scale)
To understand how much force is needed to collapse the auxetic structure an experiment is done. This auxetic structure is placed and pushed on a scale to measure how many grams it takes to collapse the auxetic structure. This amount is then converted to newtons. In figure 95 a photo of the setup can be found. The two objects beside the auxetic structure are there to prevent the auxetic structure from buckling. Before the experimentation, a test was done to see how accurate the used scale was. A 100 gram object was placed on the scale, which the scale measured as 98 grams (see figure 96). This discrepancy needs to be rectified in the final result.

It was measured that it takes 748 grams to collapse the auxetic structure (see figure 98). Taking into account the inaccuracy of the scale, this is equal to around 763 grams. This is around 7.49 newtons. An assumption is that if the auxetic structure gets twice as long in any direction, the amount of force needed to collapse the auxetic structure will also be twice as big.

Displacement

To be able to design with the auxetic structure it is also important to know how it behaves when collapsing. After some experimentation with the structure these are the findings:

- Pressing it from one side goes easier than from the other side (see figure 97)
- Changing length does not have an effect on the compressed width
- If one side gets twice as long the compressed length of that side also gets twice as long
- At a certain compression length, the width is maximally compressed (this thesis calls it the critical number, see figure 101)

Determining the horizontal and vertical air gaps

With this information the vertical air gap can be calculated. Given that the auxetic structure is 2700 mm high, the height of the collapsed auxetic structure can go down to approximately 2360 mm. Meaning that there is an air gap of 170 mm at each side when collapsed.

The horizontal air gap can also be calculated. As argued earlier the width of the auxetic

Figure 95. Setup to test strenght of auxetic structure. The side walls were used to prevent buckling of the auxetic structure when pressed.

Figure 96. Testing the accuracy of the weight.

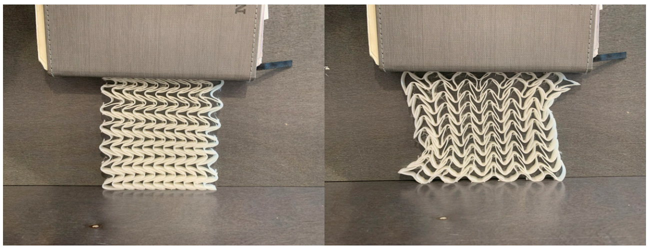


Figure 97. Pushing from both sides. Left one results in cleaner collapse and less force is needed.

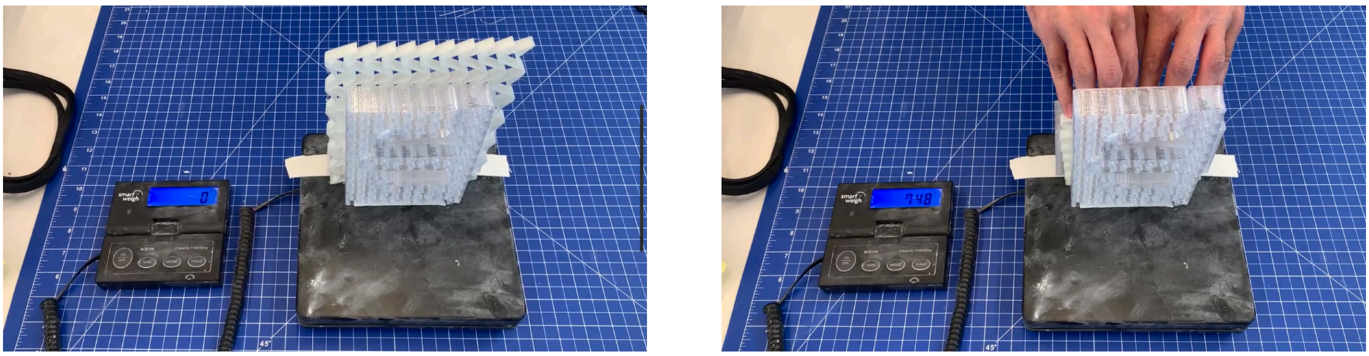


Figure 98. Results of test. 748 gram is needed to collapse the structure.

structure should be at least 617 mm to achieve the desired thermal performance in the insulating state. With this width, the critical number to reach the maximum length compression (i.e. to compress it to a length of 2360 mm) is ((617 x 57) / 202) = 174 mm. The compressed width is then (617 - 174 =) 443 mm (see figure 100).

As discussed in Chapter 5.3.3 to maximise air flow and therefore minimise the Rc-value in the conducting state, the horizontal and vertical gaps need to be of the same size. Coincidentally, with an auxetic structure with a height of 2700 mm and width of 617 mm has a vertical air gap of 170 mm and a horizontal air gap of 174 mm, which is almost equal.

Determining the Rc-value in the conducting state

With these measurements the Rc-value in the conducting state is determined using COMSOL Multiphysics. A heat flux of 14.96 W/m^2 was calculated (see figure 99). The R_{tot} can be determined using the following

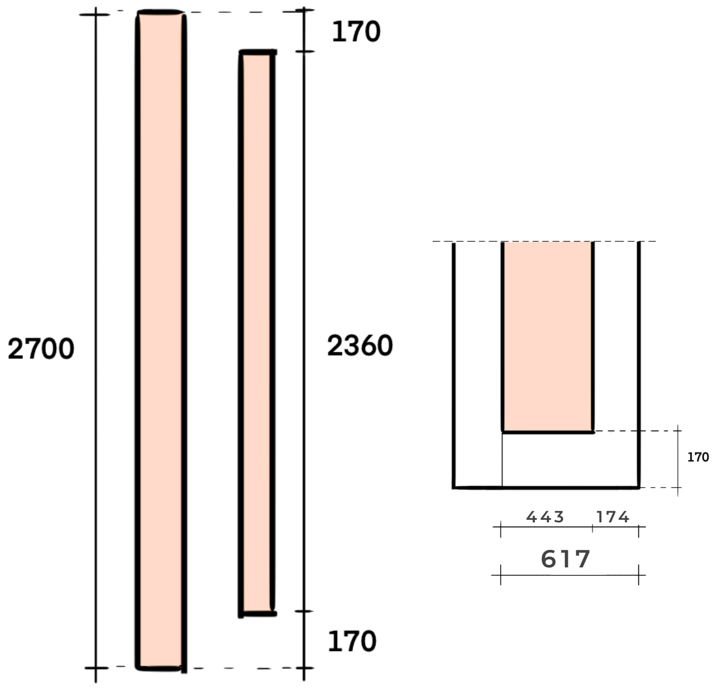


Figure 100. Dimensions of auxetic structure in its application with horizontal and vertical airgaps

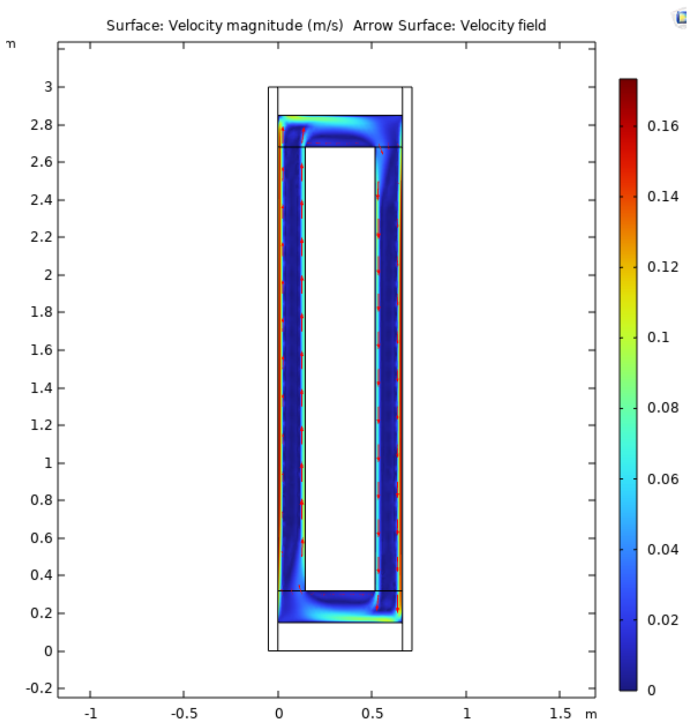


Figure 99. Results COMSOL analysis in conducting state. The heatflux for this design is 14.96 W/m^2

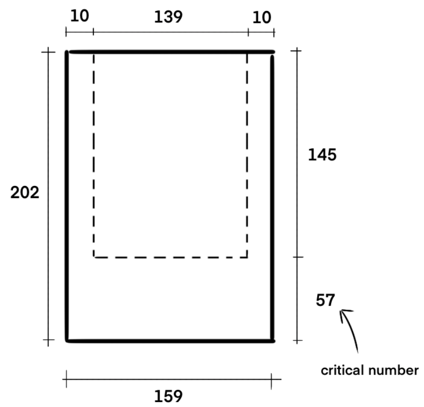


Figure 101. Dimensions of 3D printed auxetic structure normal (line) and collapsed (dotted line). The critial number is 57 mm.

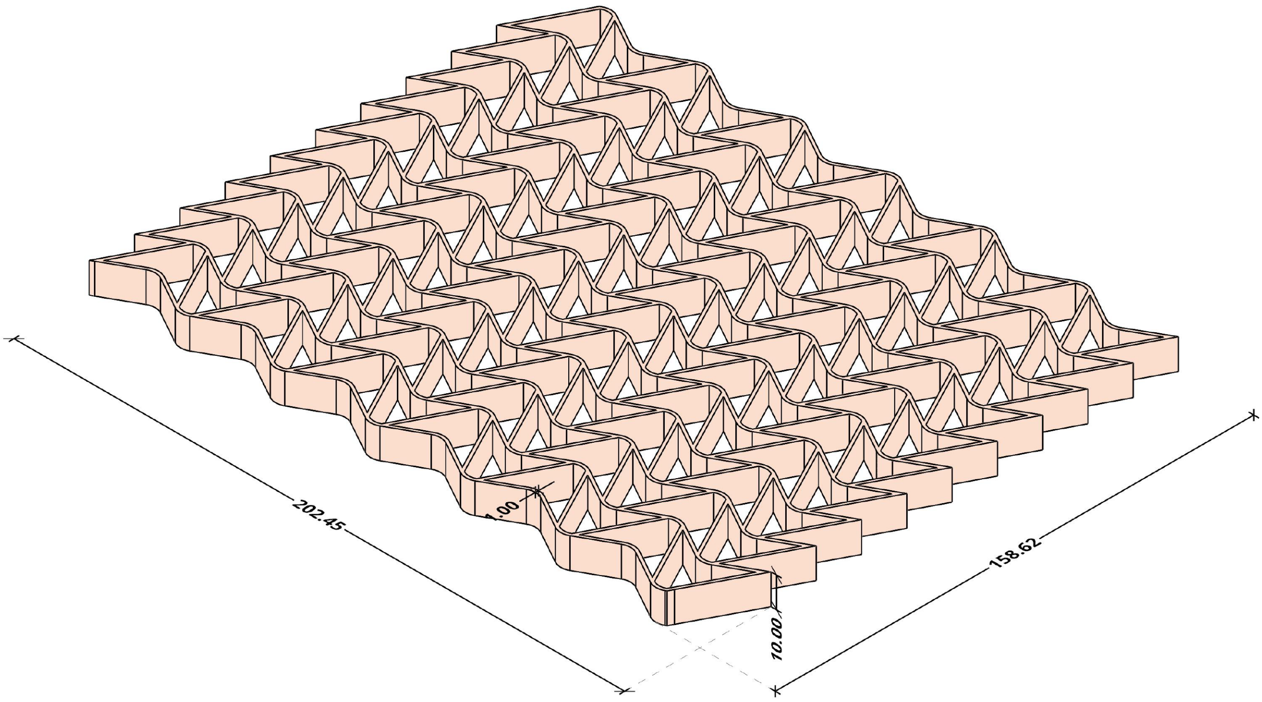


Figure 102. Dimensions of 3D printed sample

formula:

$R_{tot} = \Delta T / q$

with:
ΔT = temperature difference between outside and inside [o]
q = heat flux [W/m^2]
R_{tot} = total thermal resistance ($Rc+R_i+R_e$) [m^2K/W]

It was calculated that the R_{tot} is 1.33 m^2K/W. This means that the Rc-value in the conducting state is (1.33 - 0.17 =) 1.16 m^2K/W.

It was also checked whether splitting the structure up in multiple auxetic structures would have a stronger effect on reducing the Rc-value (see figure 103). The heat flux for this design is 15.22 W/m^2, meaning that there is a 0.25 W/m^2 difference compared to the previous design. This difference in heat flux has a neglectable impact on the Rc-value.

The amount of force needed to collapse the auxetic structure (full scale)
For the real life scenario the auxetic structure in its relaxing state is 617 mm wide, 2700 mm high and 1000 mm deep. Extrapolating from the force needed to collapse the prototype it was found that the auxetic structure in this size needs a force of around 38.8 kN to collapse!

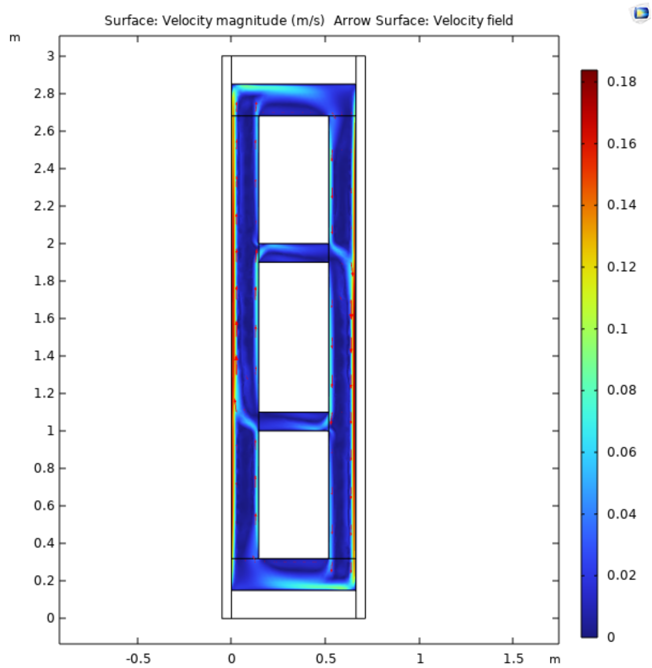


Figure 103. Splitting the auxetic structure in three parts. The effect on the Rc-value is neglectable

Solutions for high force
Obviously the force needed to collapse the structure is too high. Therefore in this section some proposals are made to reduce the force needed to collapse the structure.

As mentioned earlier in the thesis, the three approaches to change the flexibility of a product is through changing the material type, material amount and shape. Therefore decreasing the force needed to collapse the auxetic structure can be done by:

- Changing the shore hardness (material type):
Utilizing a material with a lower Shore hardness can increase flexibility and reduce the force required for deformation. Softer materials tend to offer less resistance to compression and bending, making the auxetic structure easier to collapse.

- Changing the auxetic structure (shape):
All previous calculations were made with the triangular auxetic structure in mind. However, as seen previously, there are a lot of different auxetic structures. Other auxetic structures could be explored on force needed to collapse the structure. Moreover, slight changes to the auxetic structure could be made to improve flexibility. For example, the auxetic structure designed in this thesis had rounded corners to increase durability. However, refinements could be made to balance flexibility and strength more effectively.

- Using a smaller auxetic structure in the façade (amount):
Instead of letting the whole wall collapse to reduce the Rc-value, one can explore what the effects are on the Rc-value are if only a small part of the wall needs to collapse. A smaller auxetic structure means less force is needed to collapse it.

- Decreasing the width of auxetic structure (amount):
Decreasing the width of the auxetic elements reduces the overall material

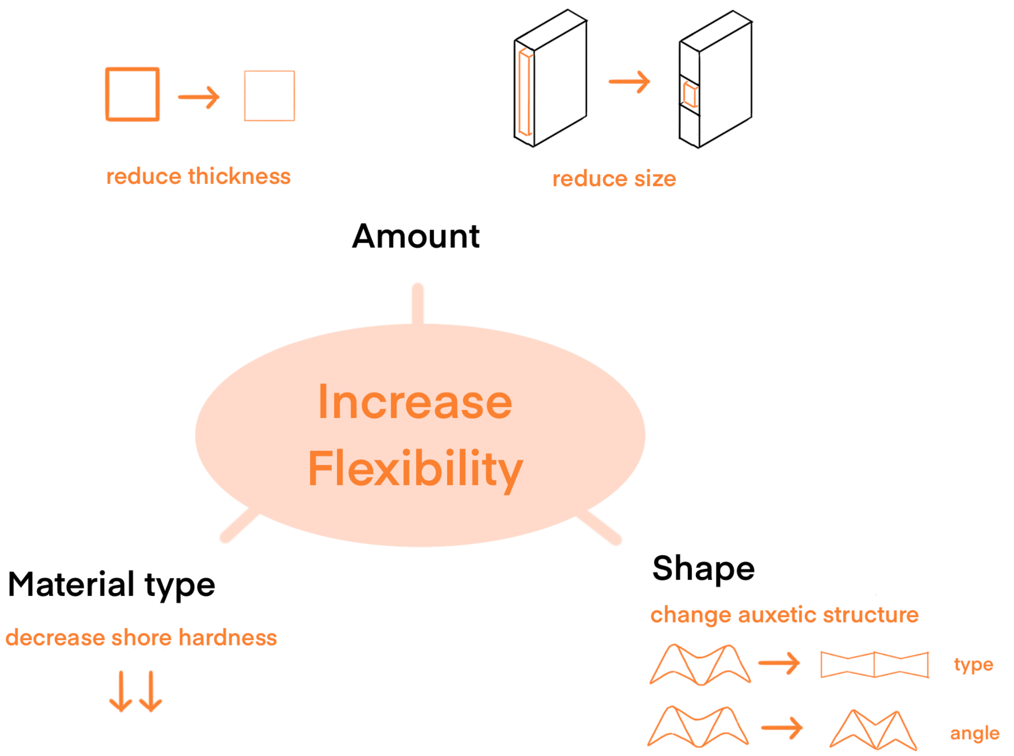


Figure 104. Summary of possible measures to increase flexibility and therefore reduce the force needed to collapse the auxetic structure

volume and structural stiffness, thereby lowering the force needed for deformation.

Overall the most effective solution is likely to come from a combination of these measures. By selecting a softer material, optimizing the auxetic geometry, and strategically reducing material amount - through smaller auxetic units or reducing width - it is possible to improve flexibility while ensuring that the structure retains its (switching) insulating function.

A summary of all measures can be found in figure 104.

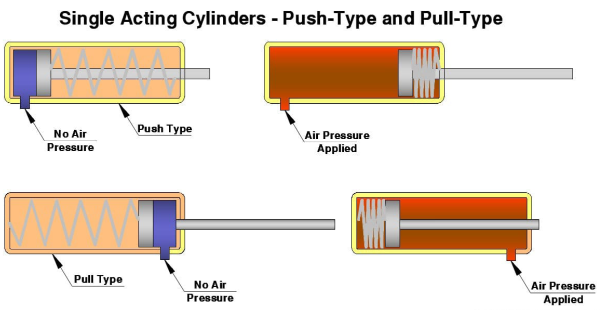


Figure 105. Single-acting pneumatic cylinder (IQSdirectory, 2025)

For now, the thickness of the walls of the auxetic structure is reduced from 1 mm to 0.4 mm. The result is that a force of 15.5 kN is needed to collapse the structure.

5.3.3 Pusher design and selection

The pusher is an important element of the wall, because it is the element that is responsible for switching the insulation state. The selection criteria of the pusher come from the design criteria:

- Recyclable (mono-material)
- Durable switching mechanism
- Energy usage for switching mechanism

To understand durability a bit better it is good to look at the failure modes and analysis of this component from chapter 5.2. This study identified three ways the pusher component can fail to perform its intended function:

- When leakage occurs
- When a part is broken
- When the material degrades

Therefore a pusher is considered durable when there is minimal risk of leakage, a reduced number of components, and can

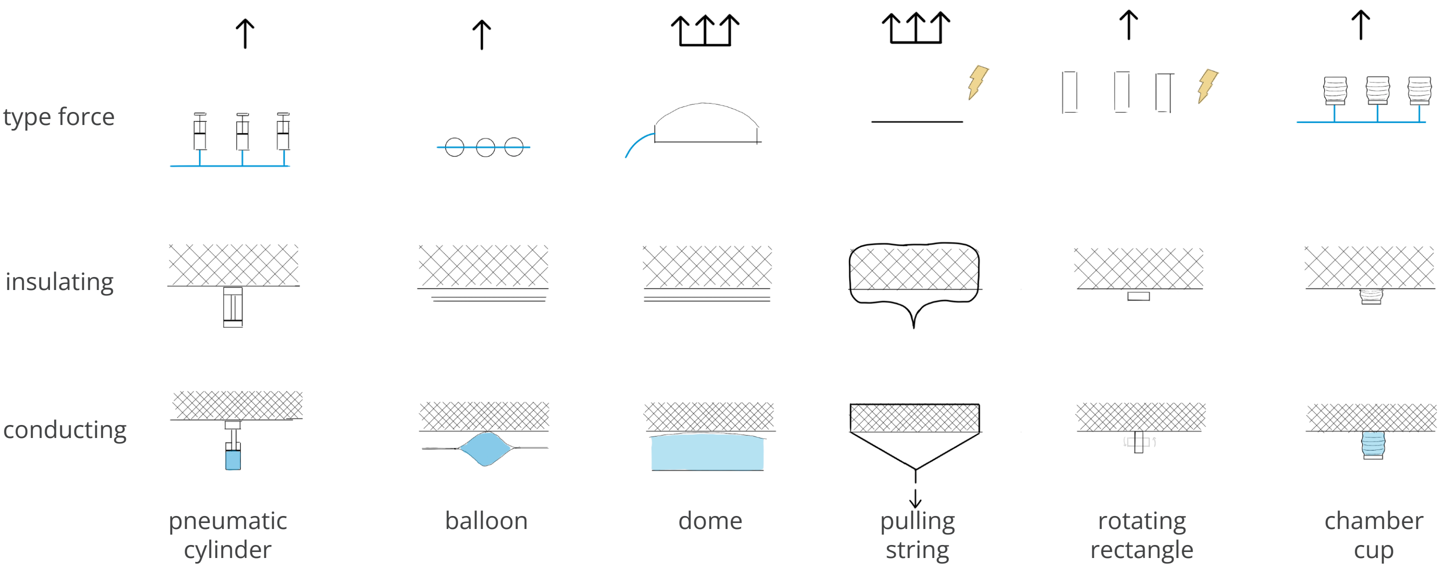
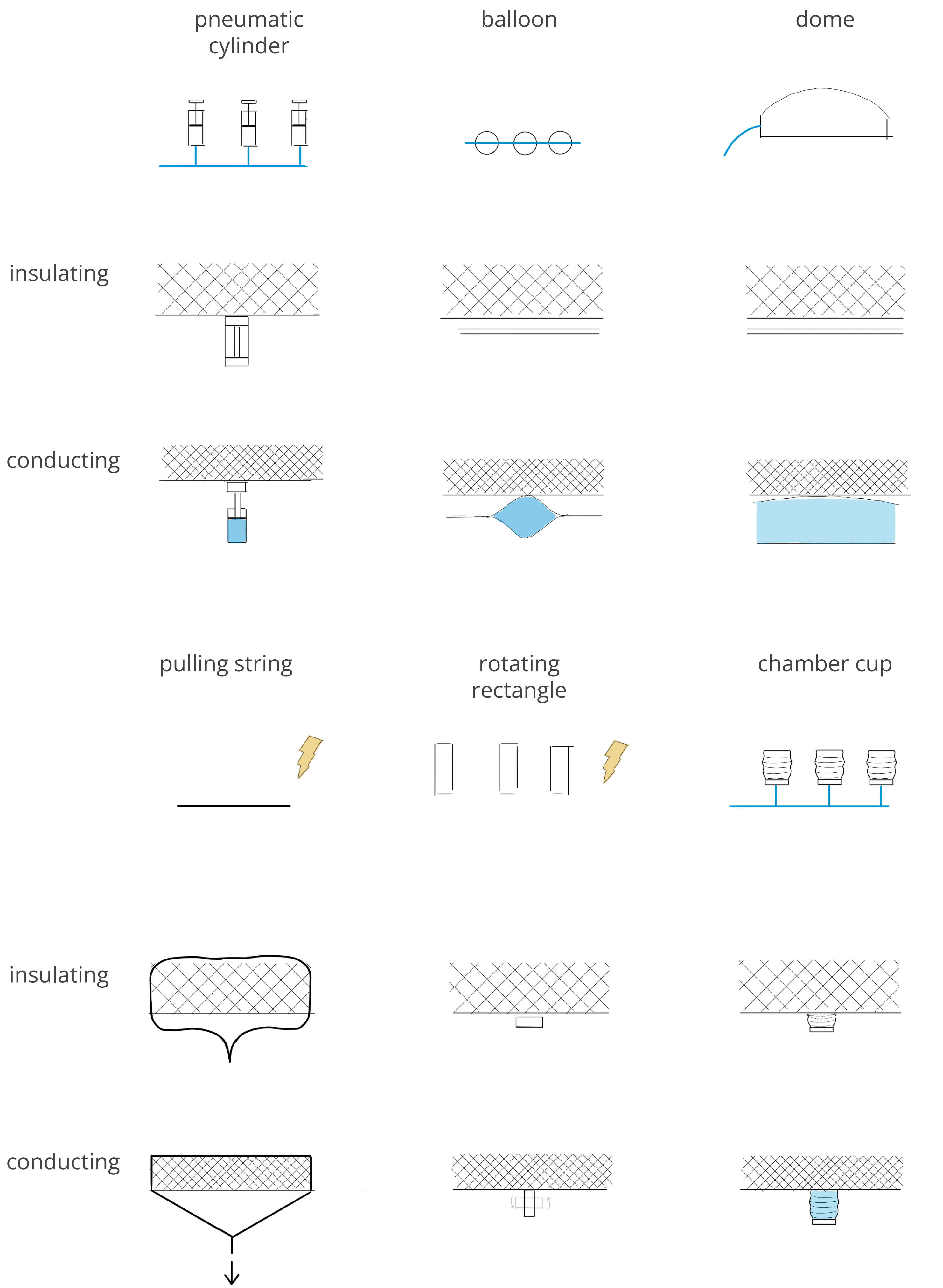


Figure 106. Designed pushers


pneumatic cylinder
balloon
dome
insulating
conducting
pulling string
rotating rectangle
chamber cup
insulating
conducting

be manufactured in an oversized format.

The following designs are made for the pusher (see figure 106) all are either a point force or a uniformly distributed force (see figure 107):
- Chamber cup (air pressure) (point force)
- Pneumatic cylinder (air pressure) (point force)
- Balloon (air pressure) (point or uniformly distributed force)
- Dome (air pressure) (uniformly distributed force)
- Pulling string (uniformly distributed force)
- Rotating rectangle (uniformly distributed force)

Chamber cup
This idea was already proposed in the initial design phase. A chamber gets filled up with air and as a result expands in one direction. When air releases, the chamber gets flat again (see figure 106).

Pneumatic cylinder
A basic pneumatic cylinder consists of three parts: an air chamber, an extender and a spring. The extender naturally goes to one side in the chamber because of the spring. When air pressure is applied, the extender goes to the other side of the chamber until the air is released (see figure 105).

Instead of putting the spring inside the chamber, the auxetic structure acts as the spring.

Balloon
Using the principles of design strategy 4 from chapter 4.2.4, a sheet is inflated to create air pockets. These air pockets act as a force to press the auxetic structure. When air is released, the sheet goes back to 2D (figure 106).

Dome
This design has the same idea as the balloon design by inflating a material. With this design a large air pocket is made (see figure 106). The difference is that this design acts as a spreading force instead of multiple single forces. More air pressure is needed (and therefore a bit more energy), but the resulting force is bigger.

Pulling string
In this design a string is used to create the movement in the auxetic structure. This string is put around the auxetic structure with the two end points of the string facing

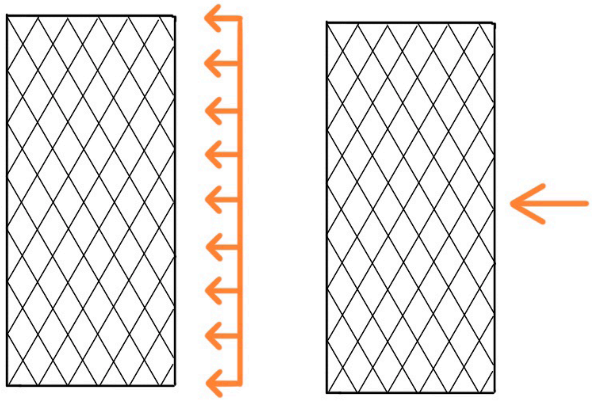


Figure 107. Uniformly distributed force (left) and point force (right)

Figure 108. Pneumatic cylinder

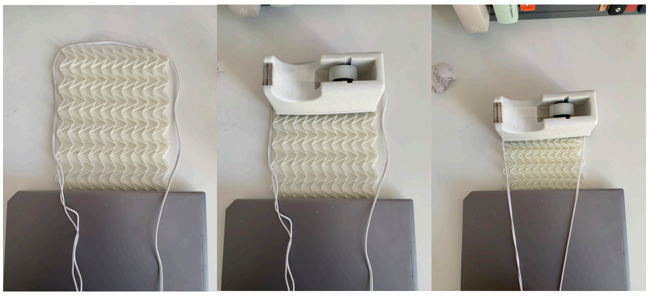


Figure 109. Pulling string. An object was placed on top to prevent buckling when pulled

inside. These two endpoints are pulled or released to create the movement (see figure 106).

Rotating rectangle
In this design a long vertical element shaped as a rectangle is used to create movement in the auxetic structure. When this rectangle rotates 90 degrees it pushes the auxetic structure (see figure 106).

Some of these designs are electrically driven (rotating rectangle and pulling string). In the second phase of this research it was assumed that a pneumatic actuator, was needed to ensure safety and durability. This was before the auxetic structure design was developed, where the movement is not created internally (like was thought) but through an external force. The electrically driven pushers are considered safe and most likely durable, since they do not need

	Sensi-tivity to leakage (durabil-ity) 1-4	Amount of parts per pusher (durabili-ty*) 1-2	Possi-bility to oversize? (durabil-ity) 0-1	Energy usage 1-4	Recycla-ble (mo-no-mate-rial) 0-1	Practical-ity 1-3	Total points
Cham-ber cup	High (1)	2 (1)	No	Medium (2)	Yes	High (3)	8
Pneu-matic cylinder	Medium (2)	2 (1)	Yes (1)	Medium (2)	Yes	High (3)	10
Balloon	High (1)	1 (2)	No	Medium (2)	Yes	Medium (2)	8
Dome	High (1)	1 (2)	No	High (1)	Yes	Medium (2)	7
Pulling string	Low (3)	1 (2)	Limited (0.5)	low (3)	Yes	Low (1) (Pos-sibility for cold bridge)	10.5
Rotating rectan-gle	None/ low (3.5)	2 (1)	Yes (1)	Very low (4)	No (-3)	Medium (2)	8.5

Table 11. Decision matrix pushers
**it is hard to estimate durability without a proper test. A test would involve something like pushing and pulling a lot of times and test the effects of it. Because of the time limit of this research, an estimation based on assumptions are made. The assumption is that the more parts a pusher consist of the less durable it is*

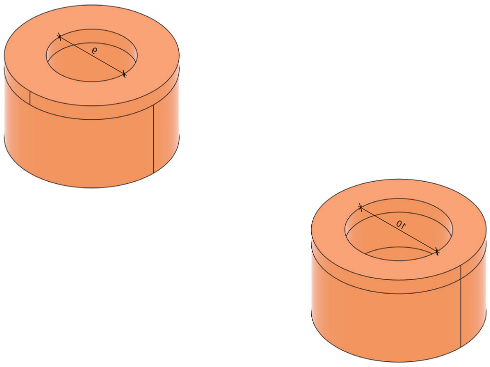


Figure 112. Head designs

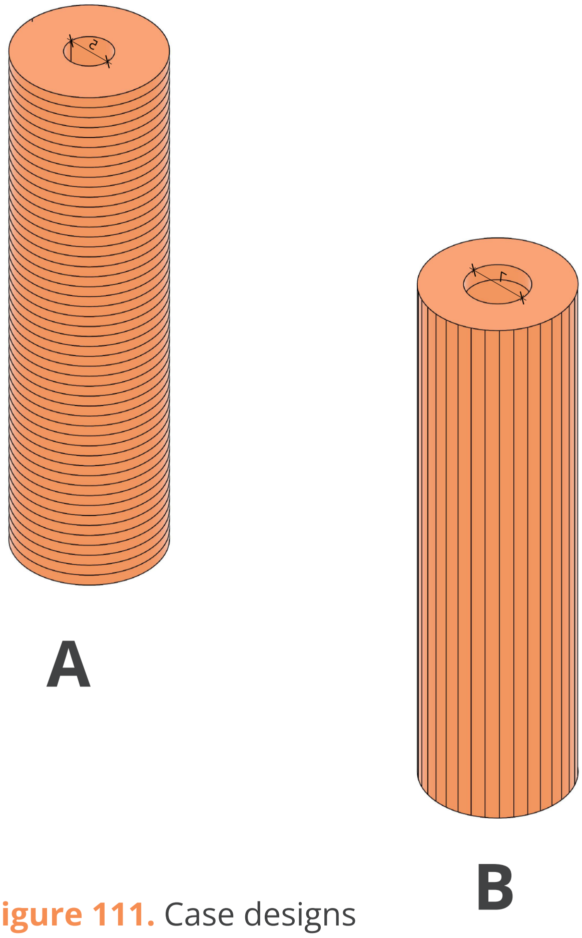


Figure 111. Case designs

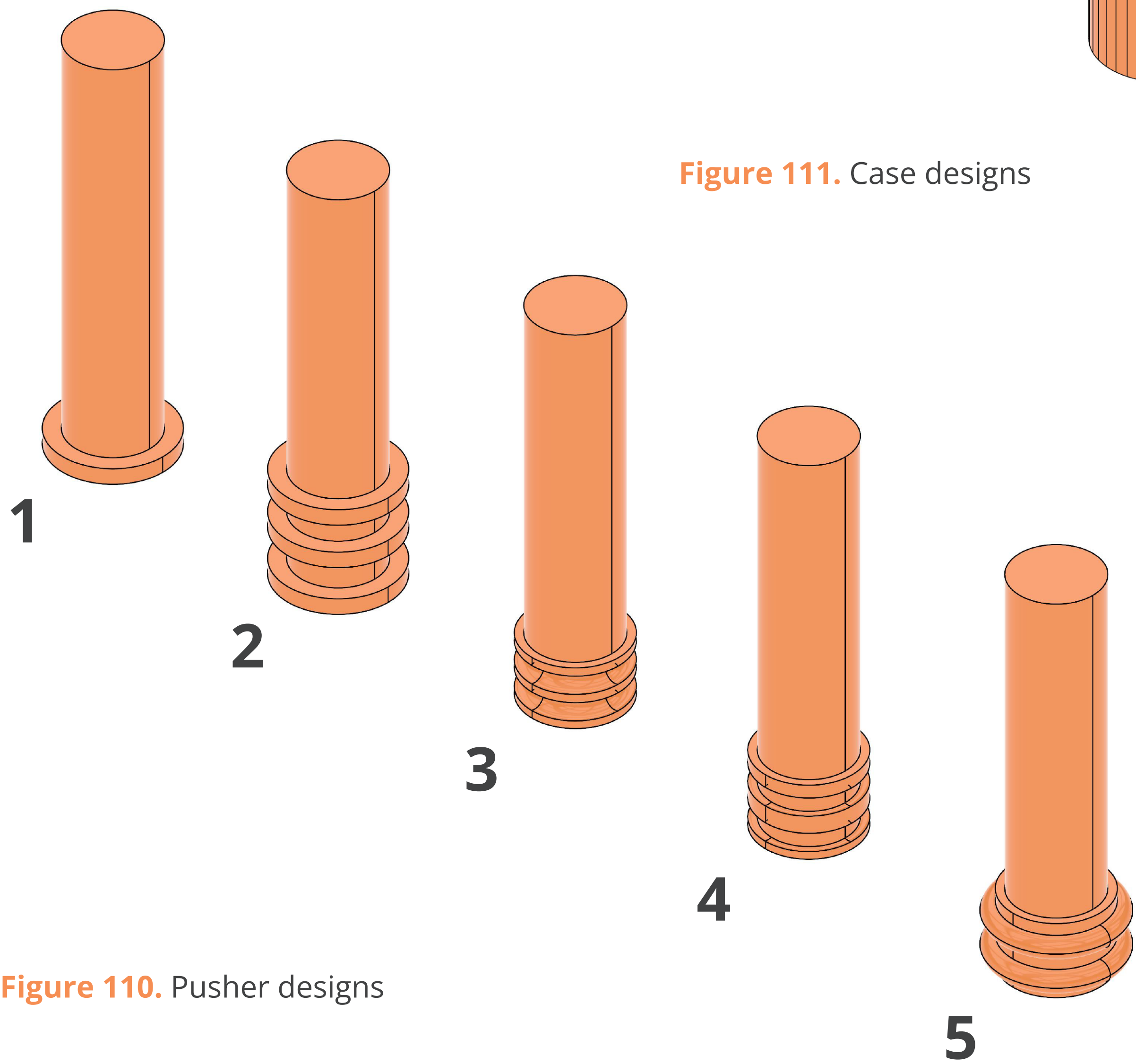


Figure 110. Pusher designs

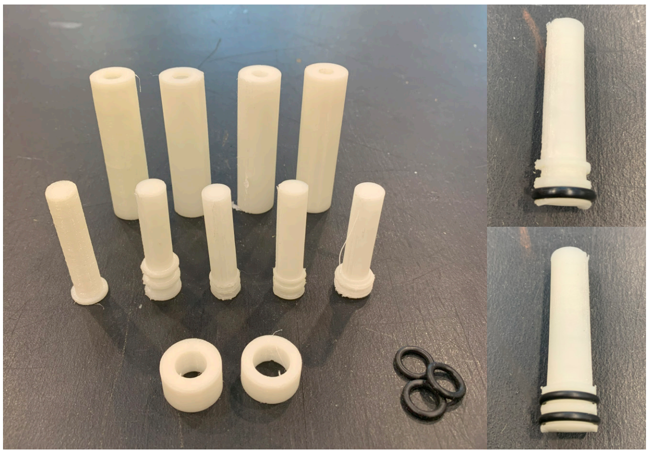


Figure 113. Overview of developed pneumatic cylinder prototypes

many parts to function.

These designs were assessed using the matrix (see table 11). It is concluded that the pneumatic cylinder and pulling string are the most promising ones.

These two designs are further tested in practice. The samples can be found in figure 115. The pneumatic cylinder was 3D printed using a Bambu PS1. This is because additive manufacturing as a full scale production method was out of the picture, and therefore printers with smaller nozzle sizes, like the Bambu PS1, were available. It was discovered that the printing quality is better if the parts are printed separately.

It required a lot of force to move the pneumatic cylinder, because of friction. One of the reasons is because of the many layers which are perpendicular to the movement of the cylinder.

Although the pulling string has more points than the pneumatic cylinder, it is still not selected because of the cold bridge it creates (the string needs to go around the auxetic structure).

Pneumatic cylinder design
The pneumatic cylinder developed here consists of three main components: the pusher, the case, and the head.

- The pusher is the moving part that responds to applied or released air pressure.
- The case houses the pusher, forming an airtight space.
- The head is placed on top of the case to prevent the pusher from being ejected when air pressure is applied (figure 112).

Design 1
For the first iteration case A (figure 111)and pusher 1 (figure 110) were 3D printed. The pusher fit well into the case, but it was hard to move the pusher within the case because of high friction. Additionally, the pusher was unstable and capable of rotating. Next to that, it was found that the pneumatic cylinder was not completely airtight. There was an air leak between the foot of the pusher and the case.

Design 2
To prevent the rotational movement, air leak and reduce the high friction, case B and pusher 2 were developed. Case B is similar to case A, but this time the case was 3D printed parallel to the direction in which the pusher moves. The friction between the pusher and case decreased as a result of this. The rotational movement and air leak was prevented by adding extra base layers to the pusher. Although, moving the pusher inside the case was easier than in the first design, it was still too rough for the application. Moreover, the pneumatic cylinder was still not fully air tight.

Design 3
To improve airtightness, an experimental design incorporating O-rings was created. These O-rings could potentially be made from TPC, supporting the goal of a mono-material design. Pusher 3 and 4 were developed. Both of these pushers had space for two O-rings to snap into. When testing these pushers with case B, it was found that the friction was reduced dramatically. Moreover, the pneumatic cylinder was airtight.

Design 4
Pusher 5 was an attempt to integrate the O-ring directly into the pusher design. However, this led to increased friction. A likely reason is that the integrated O-ring could not roll, as it was fixed to the pusher body

Although a good direction has been made to make the facade mono-material by developing pneumatic cylinder out of the same material as the rest of the facade (i.e. TPC). It was discovered and decided that the pneumatic cylinder needs to be out of a stronger material, because the forces needed to collapse the structure is too high. To ensure the mono-materiality of the facade element it was decided to put pneumatic cylinder needs to be outside of the facade element.

Amount of pushers
As discussed in section 5.2.2 it takes around 7.49 newtons to get this auxetic structure to the other state when pushed in the middle of the structure.

Conclusion
This chapter explored various auxetic structures, evaluating each based on usability, material efficiency, durability, and their thermal resistance (Rc-value) in the conducting state. Ultimately, the triangular auxetic structure was selected and redesigned with curves to enhance its durability.

Moreover, the position of the auxetic structure was determined. The position had an influence on the Rc value and the amount of pushers needed. An additional supporting structure was integrated to facilitate airflow, further reducing the Rc-value in the conducting state, while maintaining the advantage of single-sided actuation for collapsing the auxetic structure. It was also concluded that consistent air gap sizing around the auxetic structure in the conducting state is important for minimizing the Rc-value.

Research into the displacement of the triangular auxetic structure led to the determination of its final dimensions. With these dimensions, an Rc-value of 4.7 m^2K/W in the insulating state and 1.16 m^2K/W in the conducting state was achieved. However, the force required to collapse the entire structure proved to be too high, and several measures have been proposed to mitigate this issue.

In addition to the auxetic structure, various pusher designs were developed, with the pneumatic cylinder identified as the most suitable for the application. An attempt was made to fabricate the pneumatic cylinder from the same material as the rest of the facade to achieve a mono-material design. This was unsuccessful due to the high forces involved in collapsing the structure and the soft nature of TPC. As a result of this, it was decided to construct the pneumatic cylinder from steel and position it outside the facade element to ensure ease of recycling.

5.5 WIND LOAD CALCULATION

Objective
The objective of this chapter is to determine the thickness of the outer layer of the facade in order to prevent extreme deflection as a result of wind loads.

Wind load calculation
The magnitude of the wind load is determined by the wind pressure. For the basic pressure, the formula is:

$q_b = ½ \times \rho \times v^2$

with,
ρ = air density
v = air speed

In the Dutch National Annex to Eurocode 1 Part 1-4, an air density of 1.25 kg/m³ is used. When determining the wind load, the extreme pressure at the reference height z must be used:

$q_p(z) = c_e(z) \times q_b$

with,
$c_e(z)$ = the exposure factor

Determining the magnitude of the extreme pressure is done using the height, location

Figure 114. Three different regions for wind pressure in the Netherlands (Arends, 2020)

Hoogte	Gebied I			Gebied II			Gebied III	
m	kust	onbebouwd	bebouwd	kust	onbebouwd	bebouwd	onbebouwd	bebouwd
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0,49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,53

Figure 115. Table showing the extreme pressure q_p in kN/m² for each height (Arends, 2020)

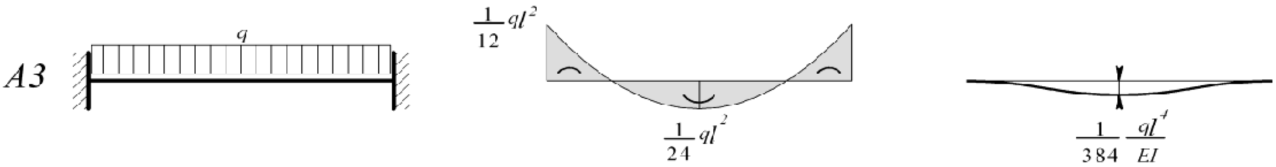


Figure 118. Force diagram for facade panel

of the building and whether there are already buildings around it. There are three regions in the Netherlands with different wind pressure (figure x).

Assuming the facade is located in Delft (region 2) within the city, figure 116 and figure 117 indicates that the extreme pressure is 0.58.

Calculating the wind load on the facade can be done using the following formula:

$F_{w,e} = A_{ref} \times 1.2 \times q_p(z_e)$ [kN]

with,
A_{ref} = area of facade

0.46 x 1.2 x 0.58 = 0.32 kN/m = 0.32 N/mm

Deflection calculation
To calculate the deflection the following formula from figure 118 is used:

$$\frac{1}{384}\frac{ql^4}{EI}$$

with,
q = load per unit area [N/mm]
E = modulus of elasticity [N/mm^2]
L = length between supports [mm]
I = moment of inertia mm^4

The following values are used for the calculation:
q = 0.32 N/mm
E = 0.1 GPa = 100 N/mm^2
L = 2850 mm

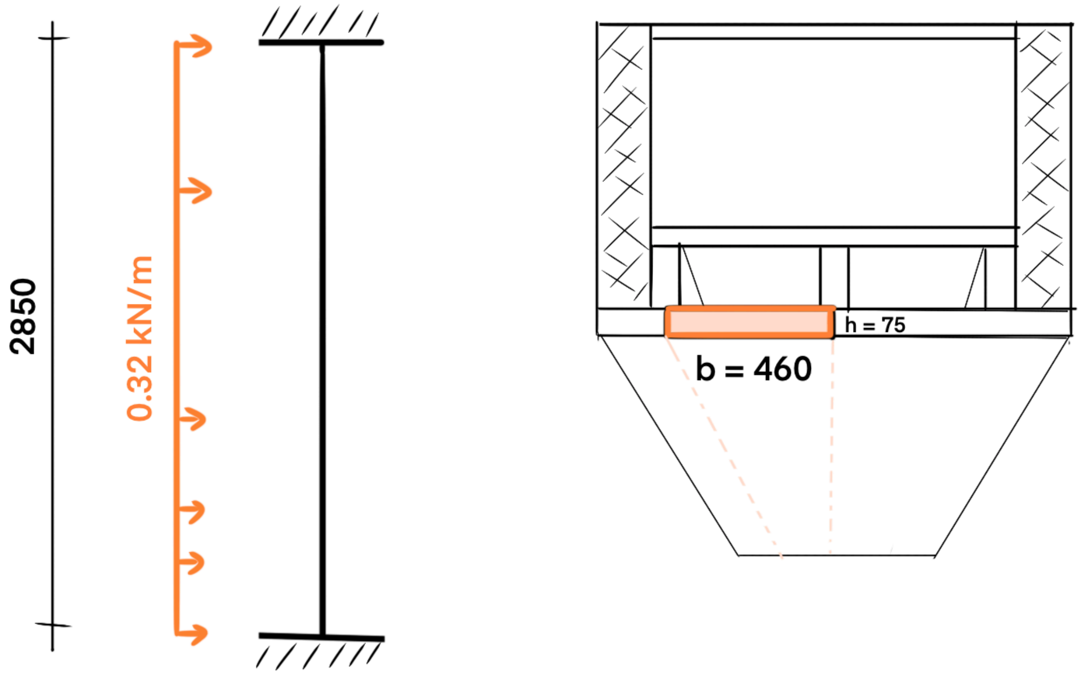


Figure 119. Diagrams of force and and cross section

$I = 1/12\ (b \times h^3) = 1/12\ (460 \times 75^3) =$
$6.1 \times 10^6\ mm^4$ (figure 119)

With this the deflection is calculated:
Deflection = $(1/384) \times ((0.32 \times 3000^4) / (100 \times 16.1 \times 10^6)) = 34$ mm

The allowable deflection = L / 240 = 2850 / 240 = 12 mm

Currently the deflection is higher than the allowable deflection (34mm > 12mm).

To reduce the deflection two logical steps can be taken:
- reduce the L
- increase the h

The L can be reduced by adding a sub beam behind the facade panel, which results in a L half the size. Increasing the h can be done by making the panel thicker. It was decided to make the panel thicker.

To calculate how thick the panel needs to be, the previous formula is rewritten to isolate the h:

$$h = \sqrt[3]{\frac{q \times L^4}{32 \times b \times E \times W_{max}}}$$

Since all the numbers stay the same and the maximum deflection (W_{max}) that is allowed is 12 mm, the thickness of the panel (h) can be calculated. It was calculated that the outer panel needs to be at least 106 mm thick in order to prevent extreme deflection. To have some error margins the outer layer of the facade is set to 110 mm thick.

5.6 FINAL DESIGN

The following pages present drawings of the final design. The auxetic structure is collapsed using an external pneumatic cylinder, which transfers force to the building's main structure. The façade element is attached to the main structure using steel angles.

In the vertical section, the air gap on the right appears curved. This curvature results from the need to distribute the point force exerted by the pneumatic cylinder. An uniform load distribution, on the auxetic structure is the result.

All components are connected using sealed joints. Additionally, the sides of each component are curved to simplify assembly and to prevent relative movement between joined components.

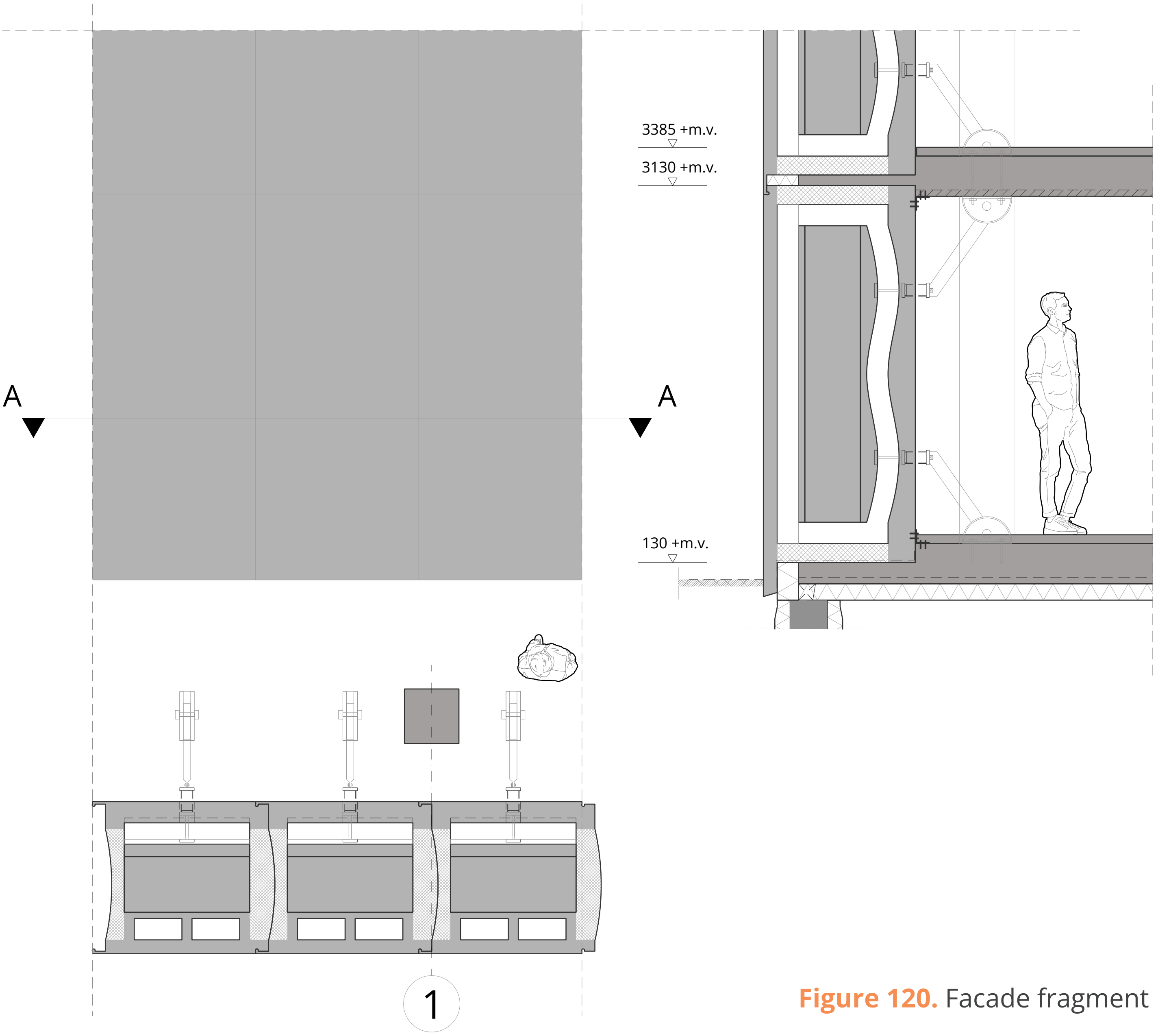


Figure 120. Facade fragment

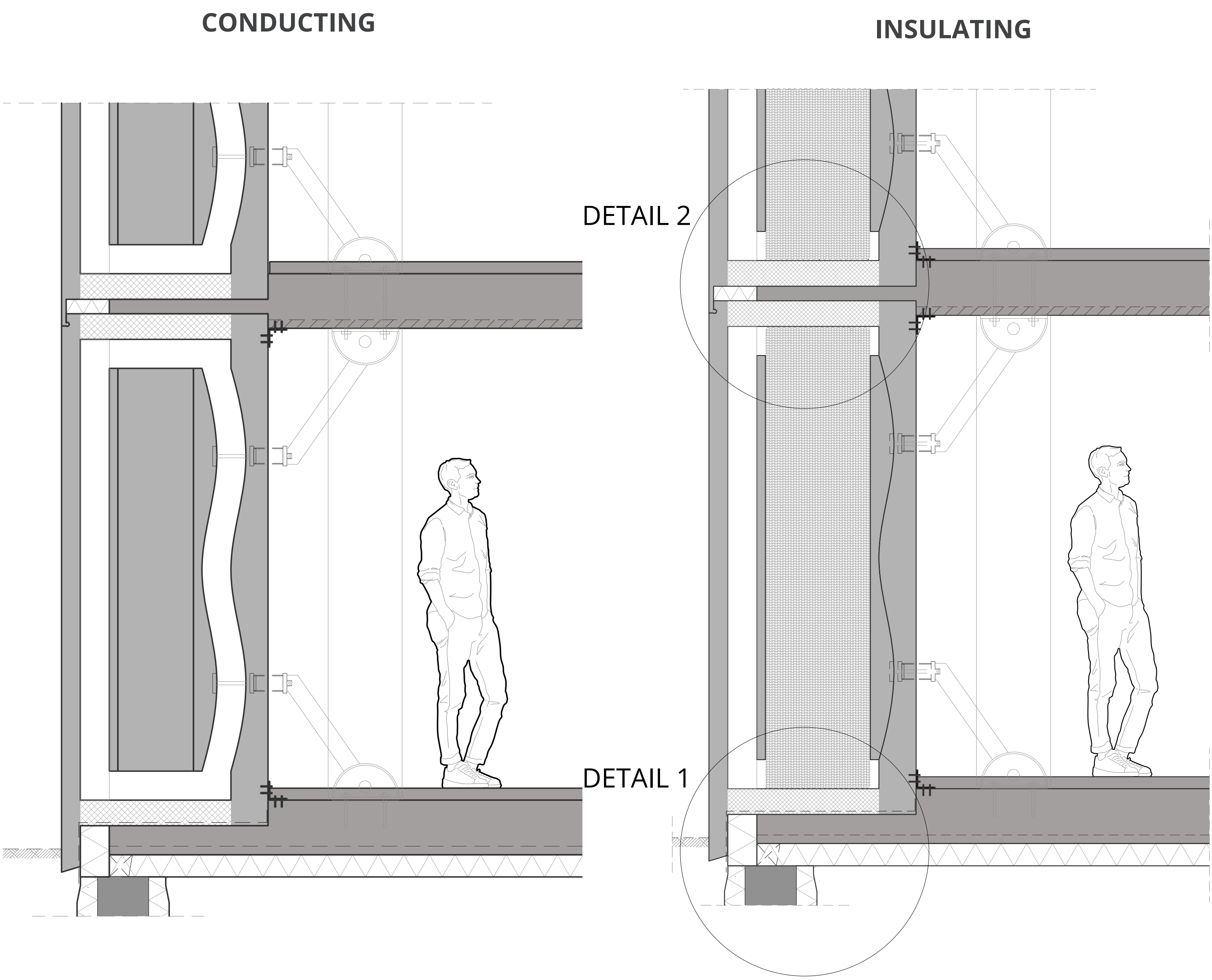


Figure 121. Vertical section with conducting state (left) and insulating state (right). To achieve uniform load distribution on auxetic structure , the plate that receives the force is curved.

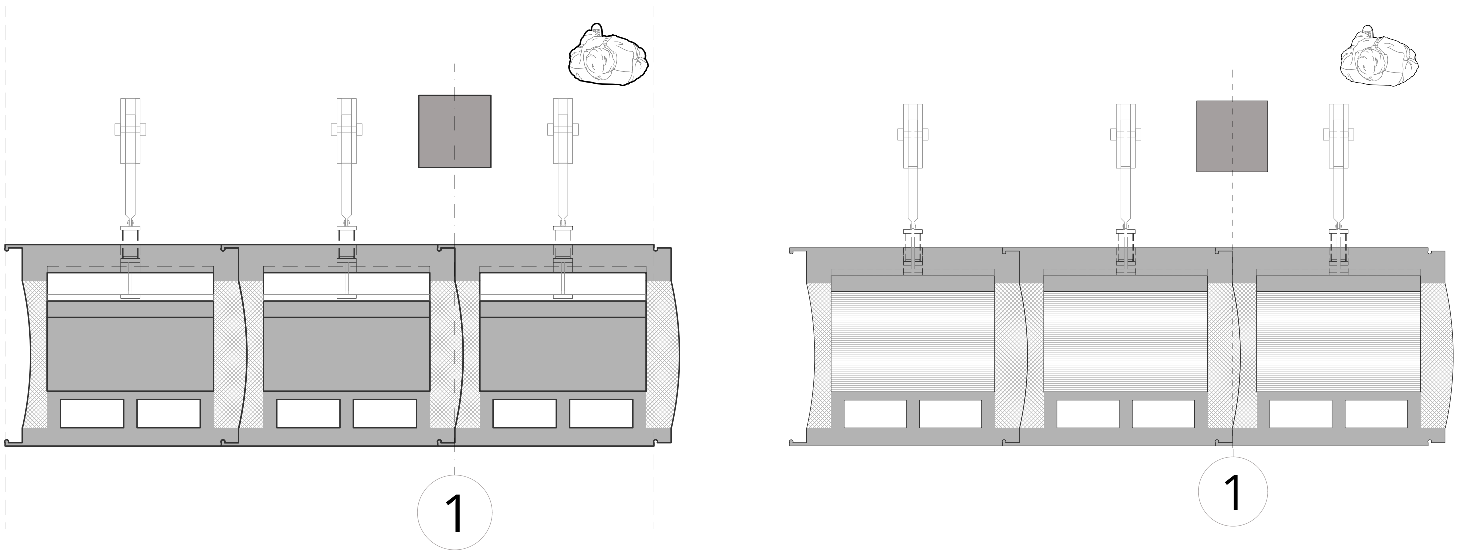


Figure 122. Horizontal section with conducting state (left) and insulating state (right).

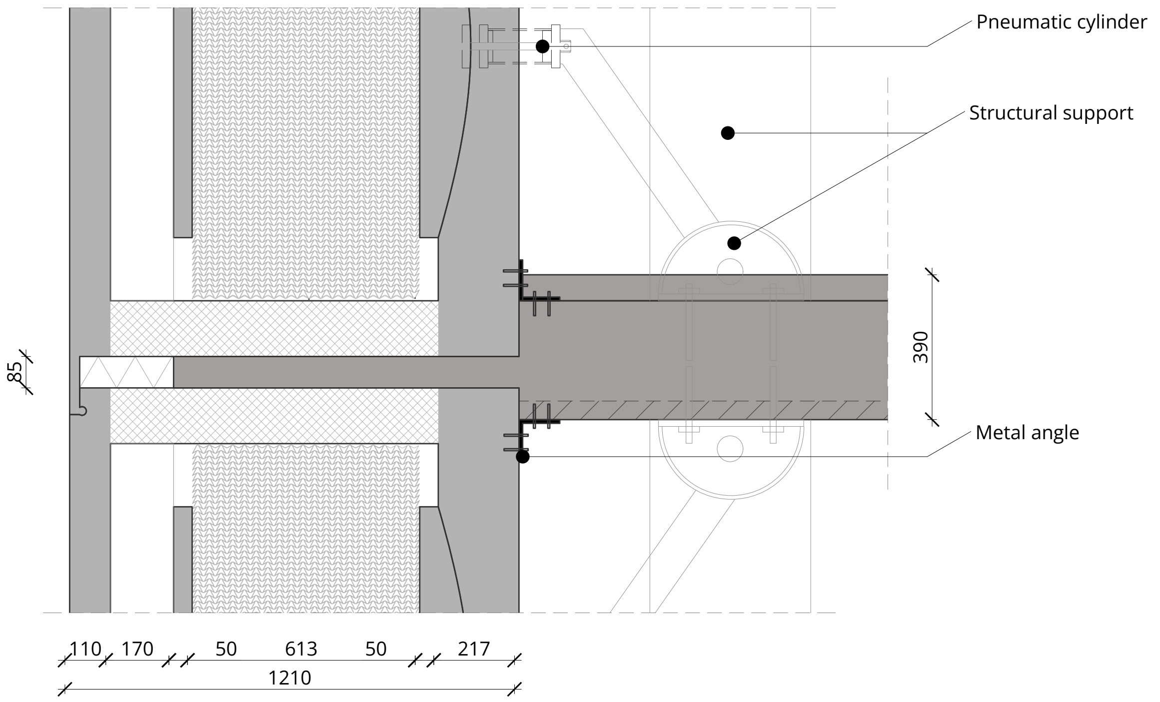


Figure 123. Detail 2. The facade is attached using iron angles.

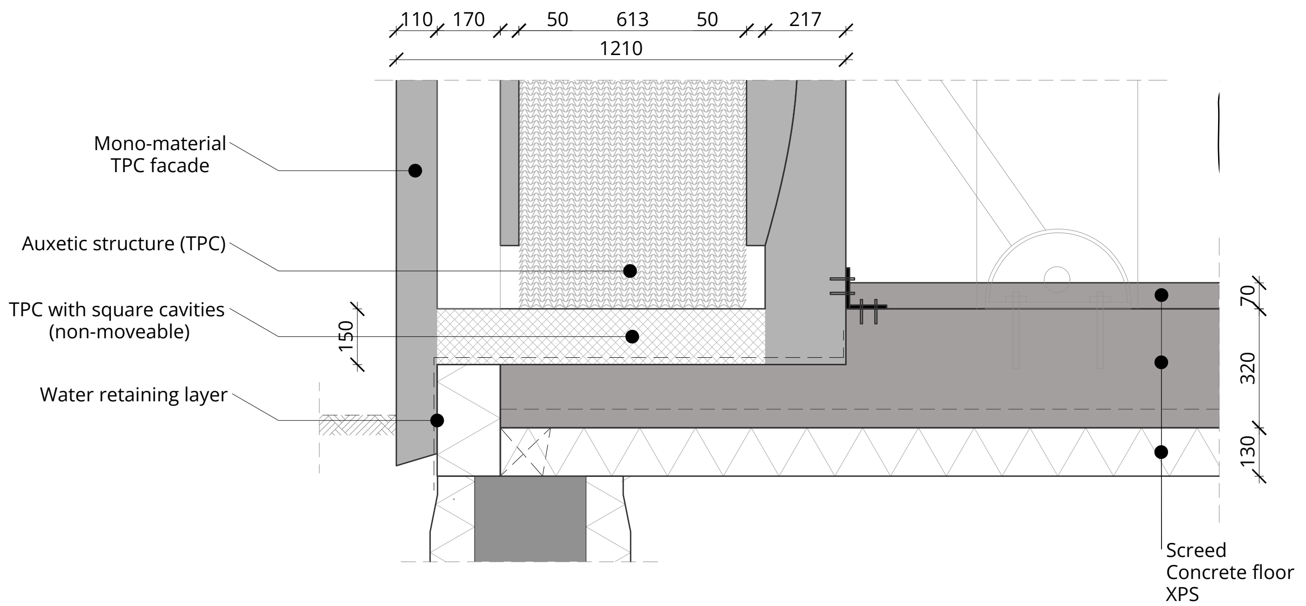


Figure 124. Detail 1. A static pattern is put on at the sides of the panel to prevent cold bridges.

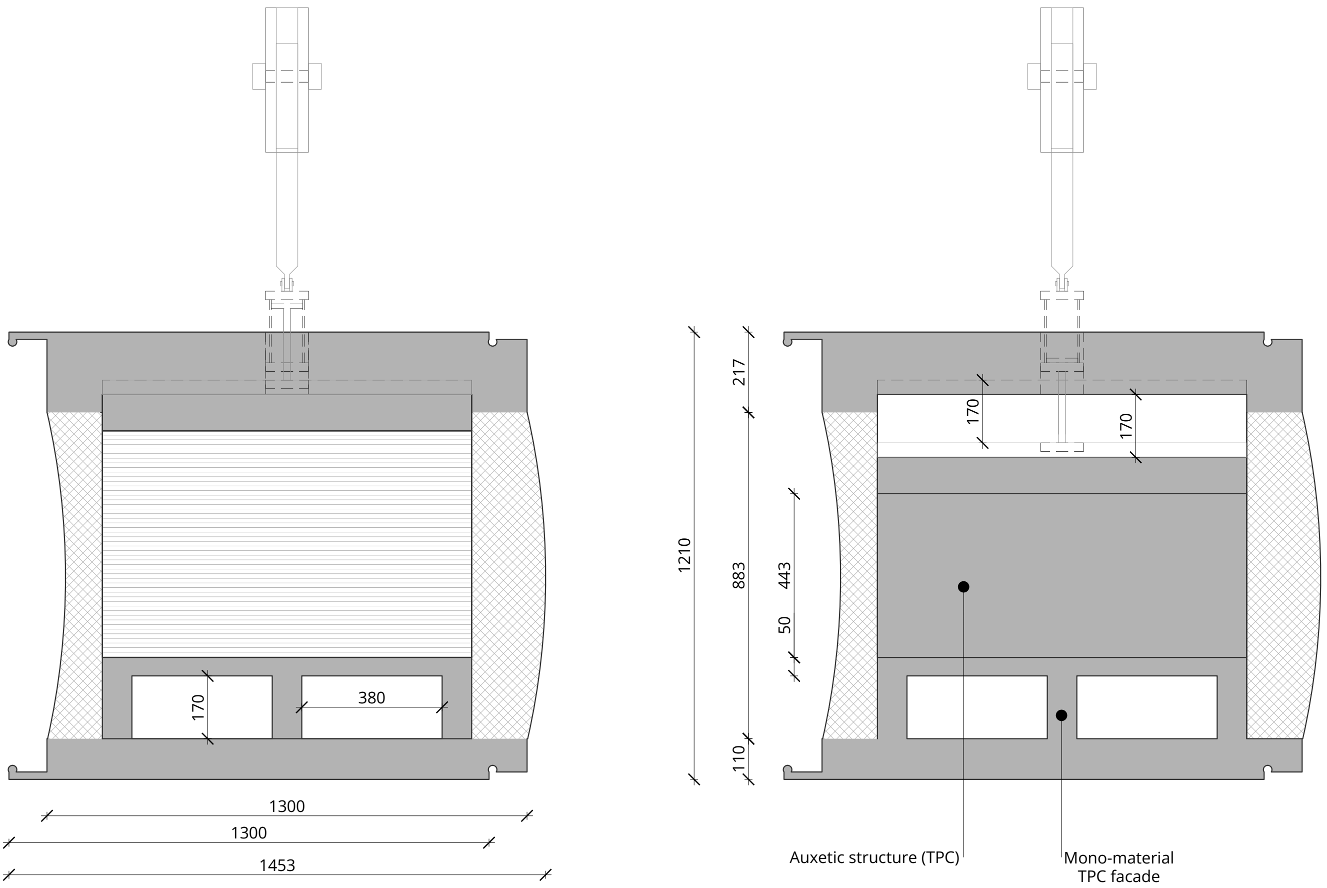


Figure 125. Top view detail. he sides of each component are curved to simplify assembly and to prevent relative movement between joined components.

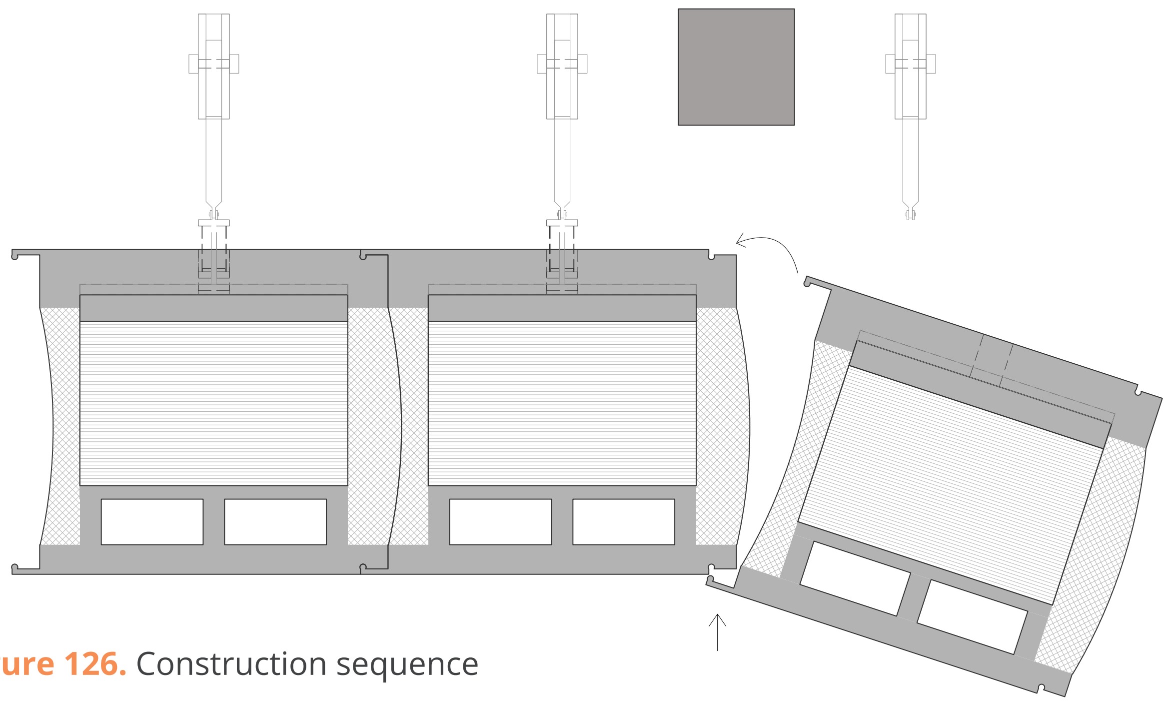
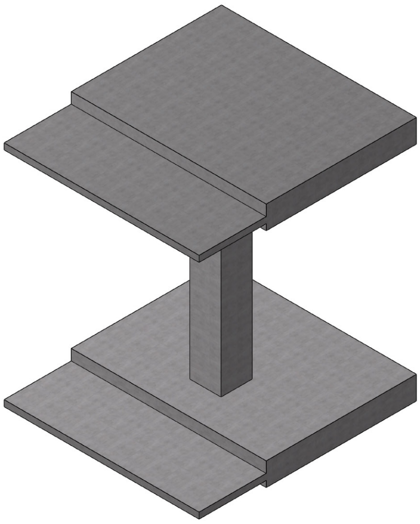
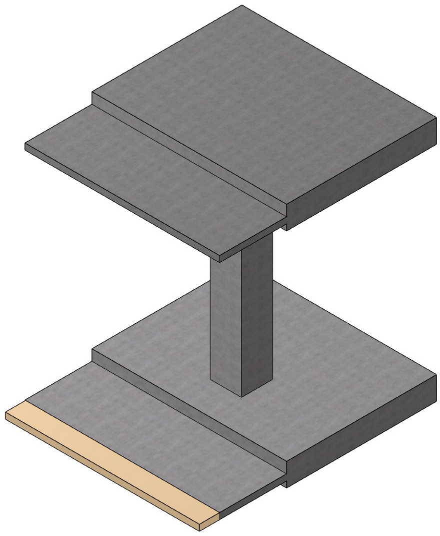


Figure 126. Construction sequence

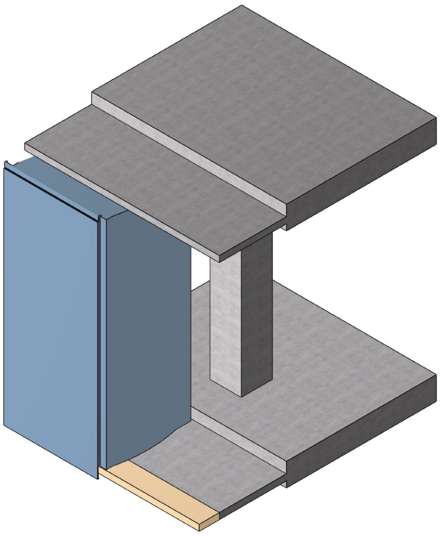
BUILDING SEQUENCE*



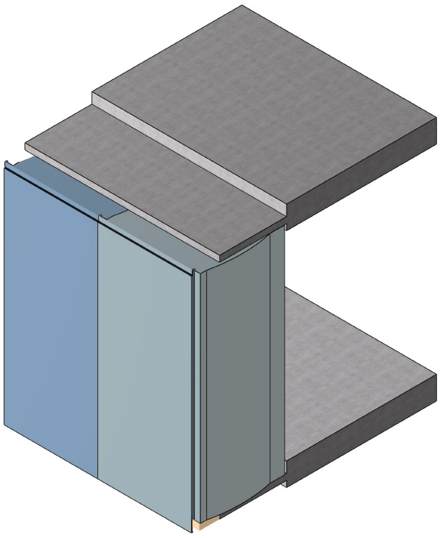
1. structure



2. insulation

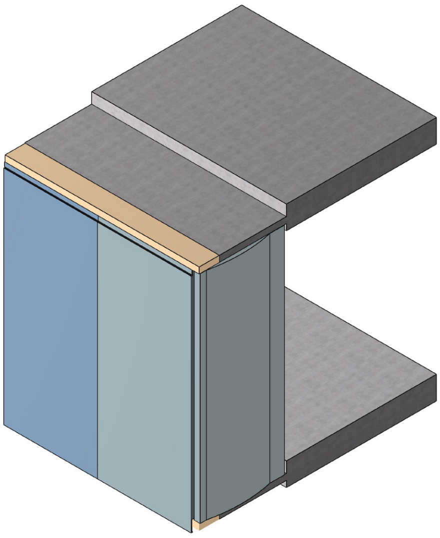


3. first floor facade elements

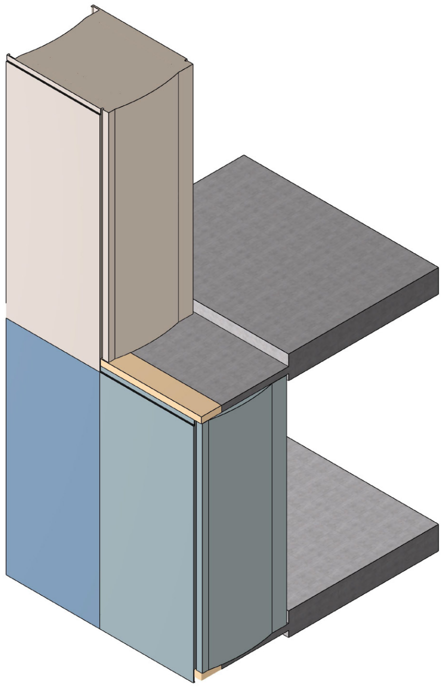


4. first floor facade elements

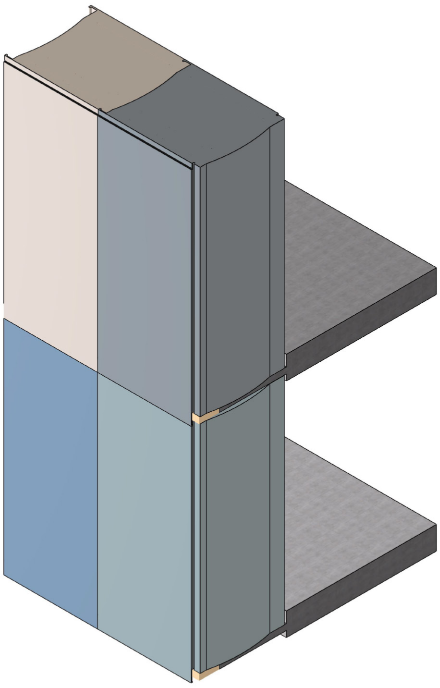
**the water retaining layer and iron angle are not shown in here*



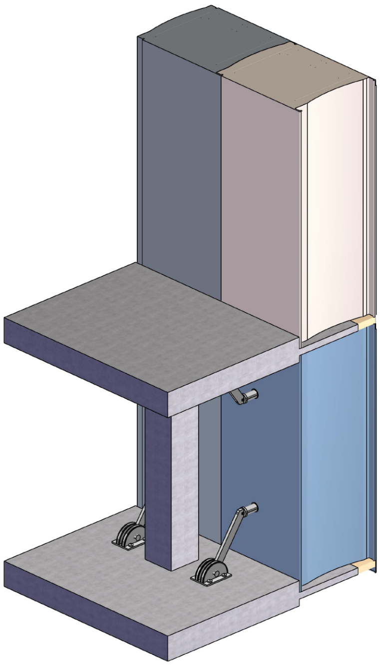
5. insulation



8. second floor facade elements

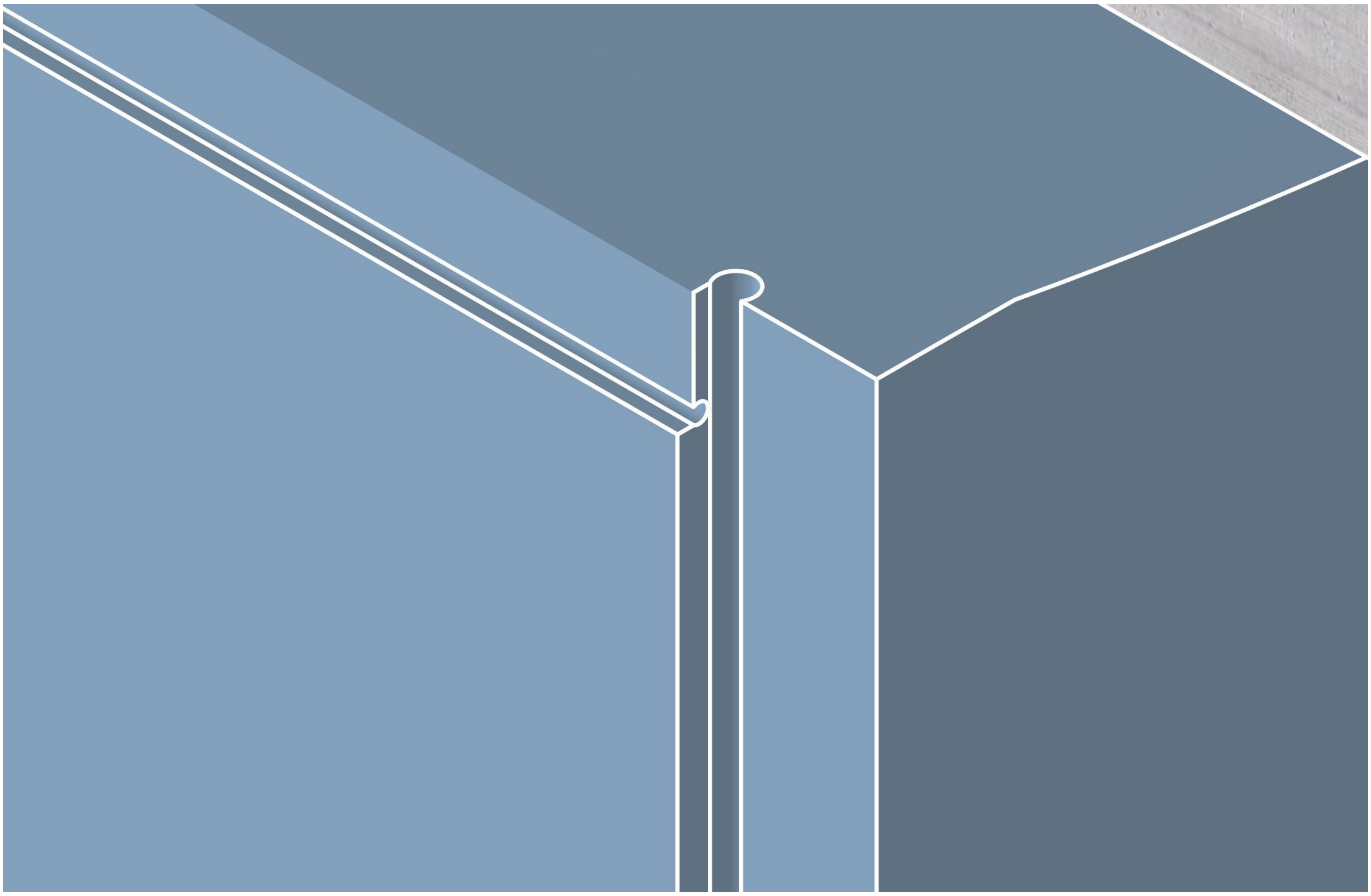


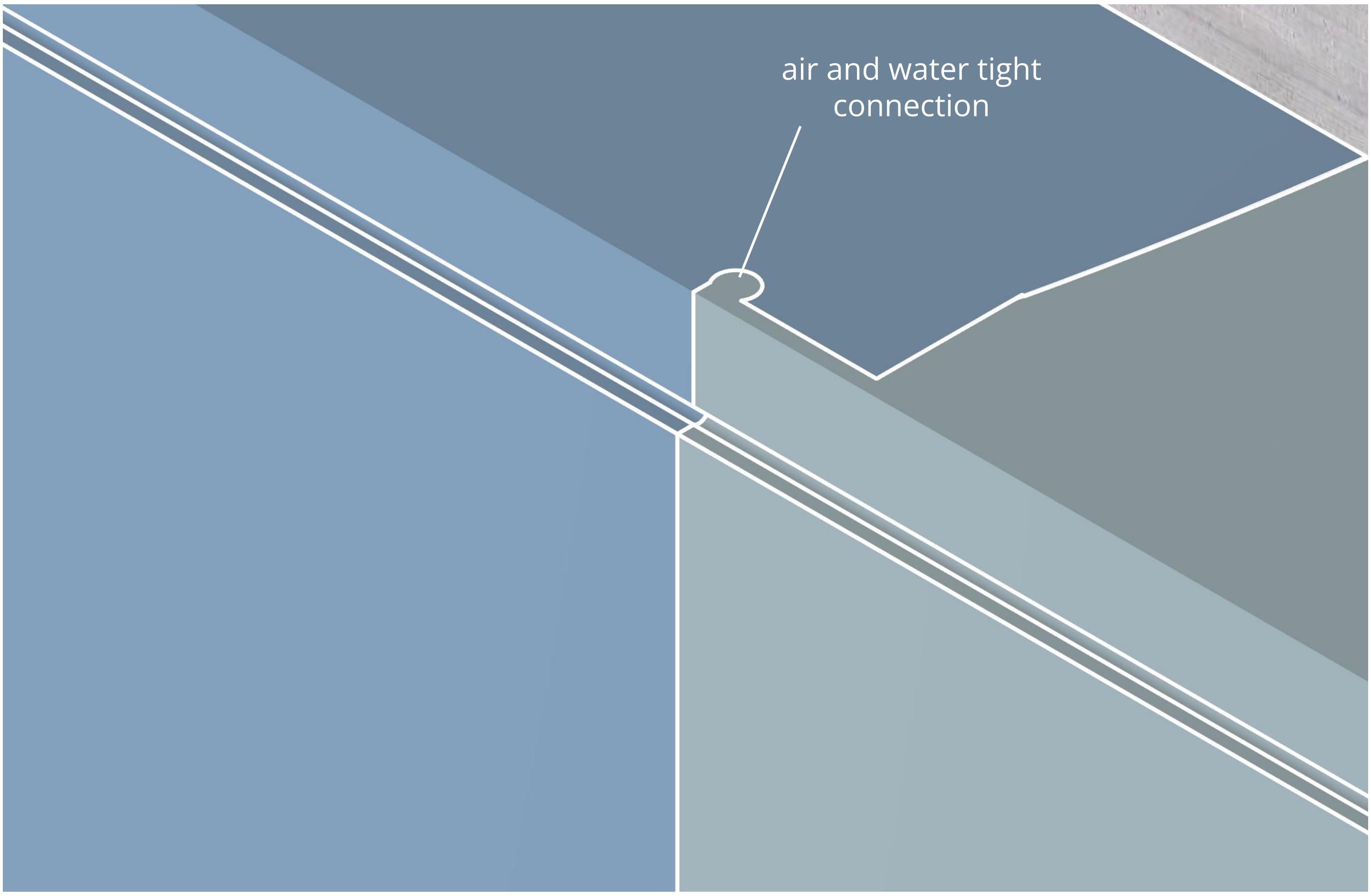
7. second floor facade elements

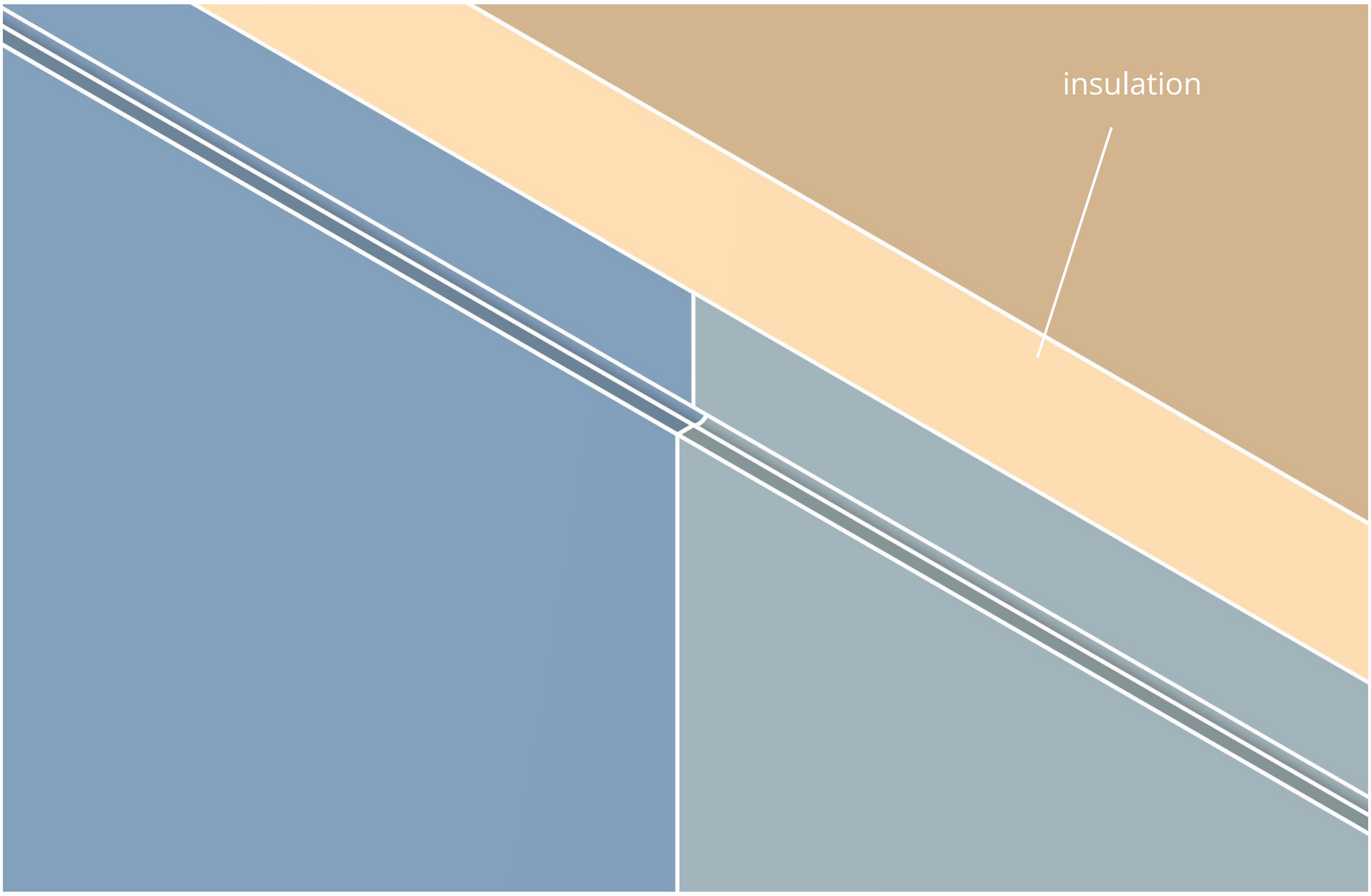


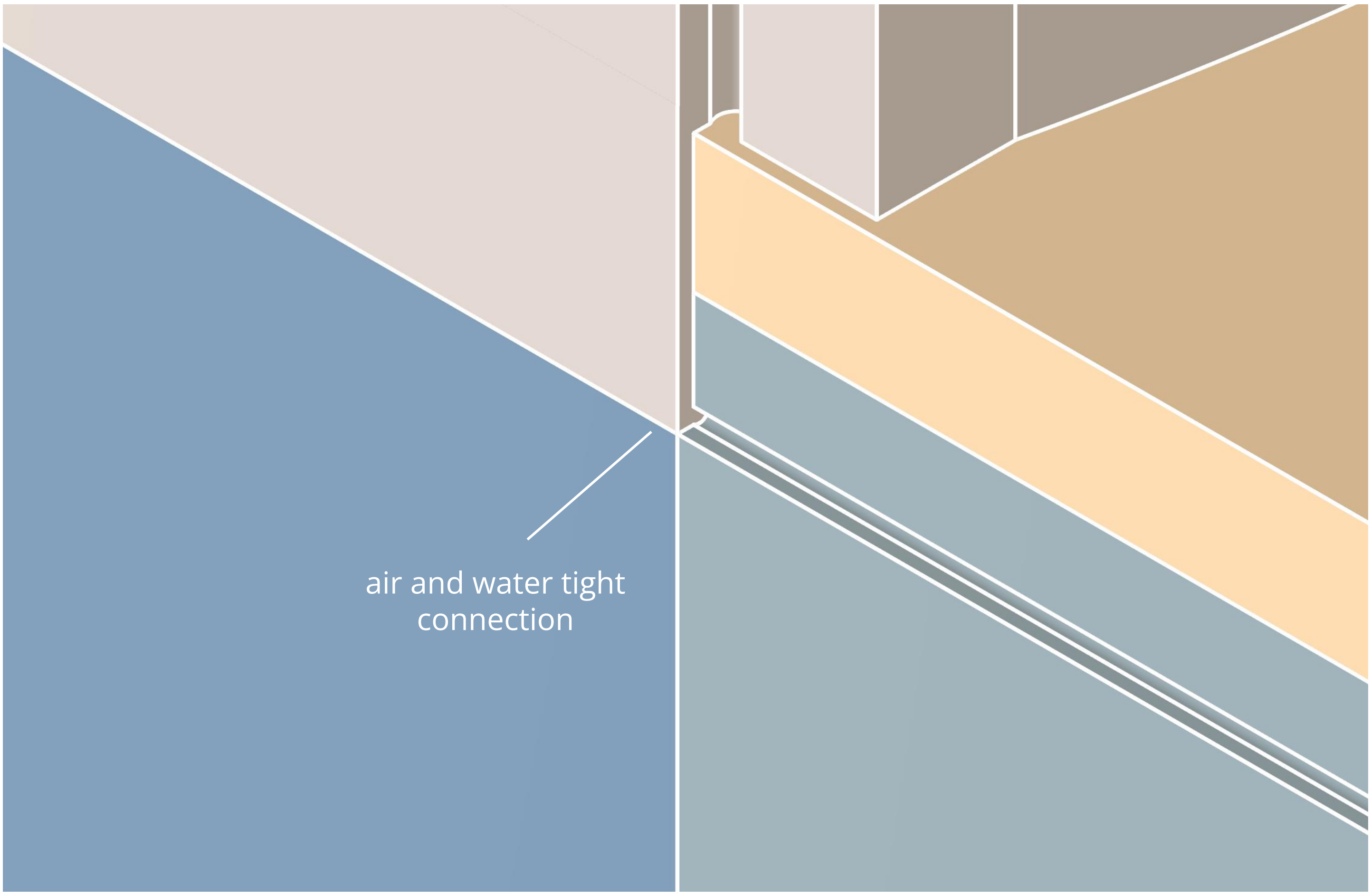
9. pneumatic cylinders

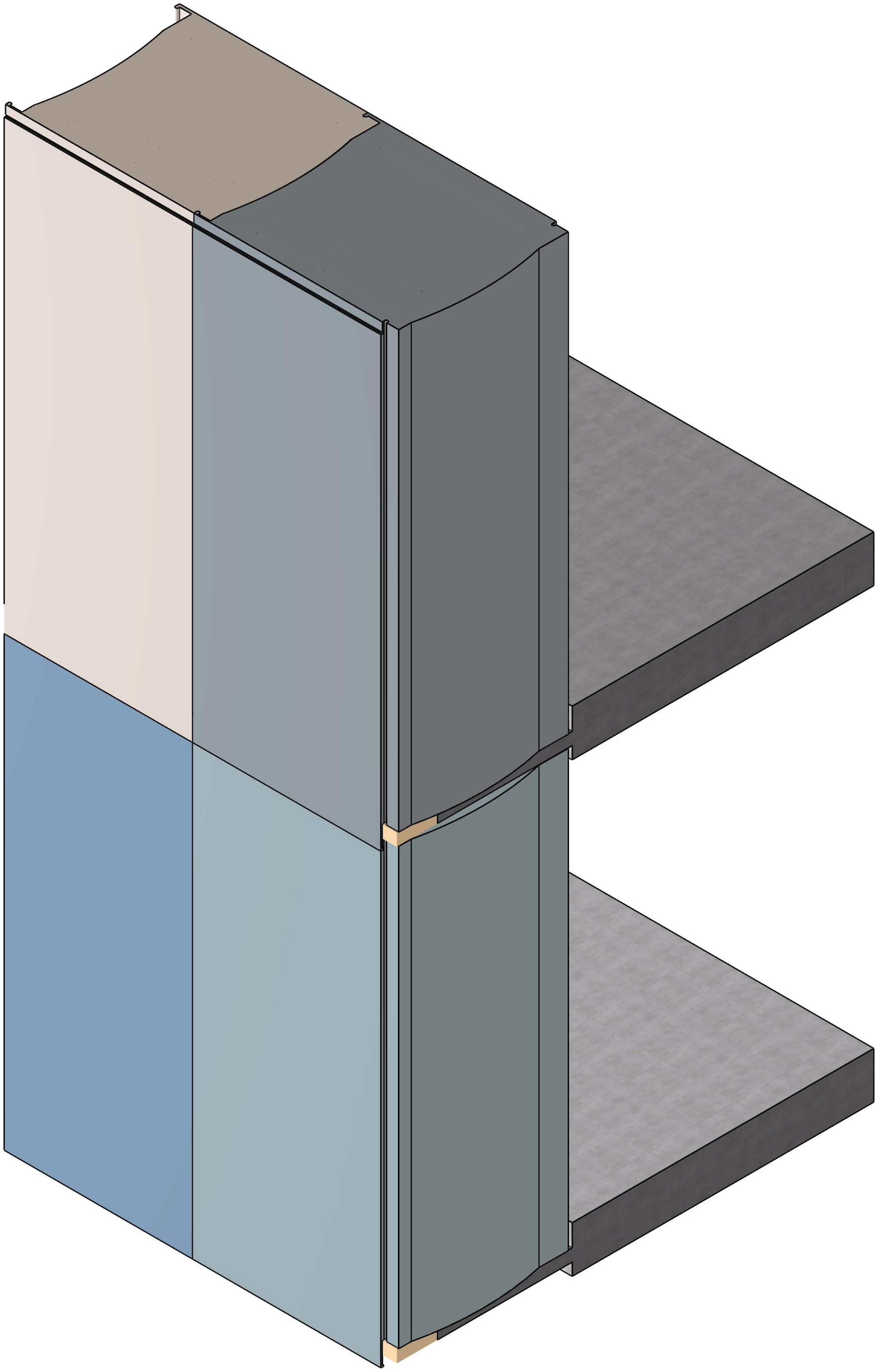
EXTERIOR CONNECTION DETAIL



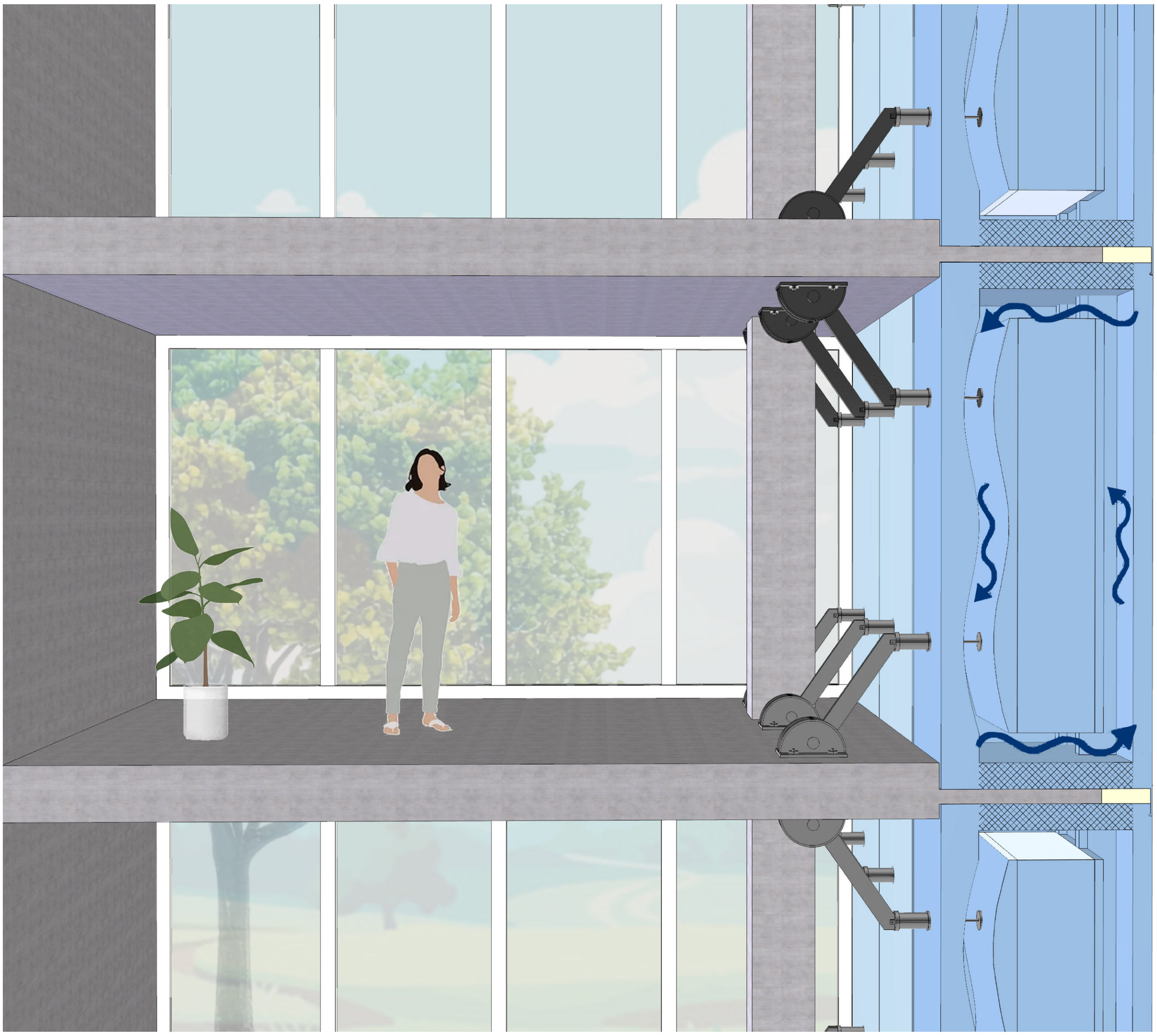



insulation


air and water tight
connection

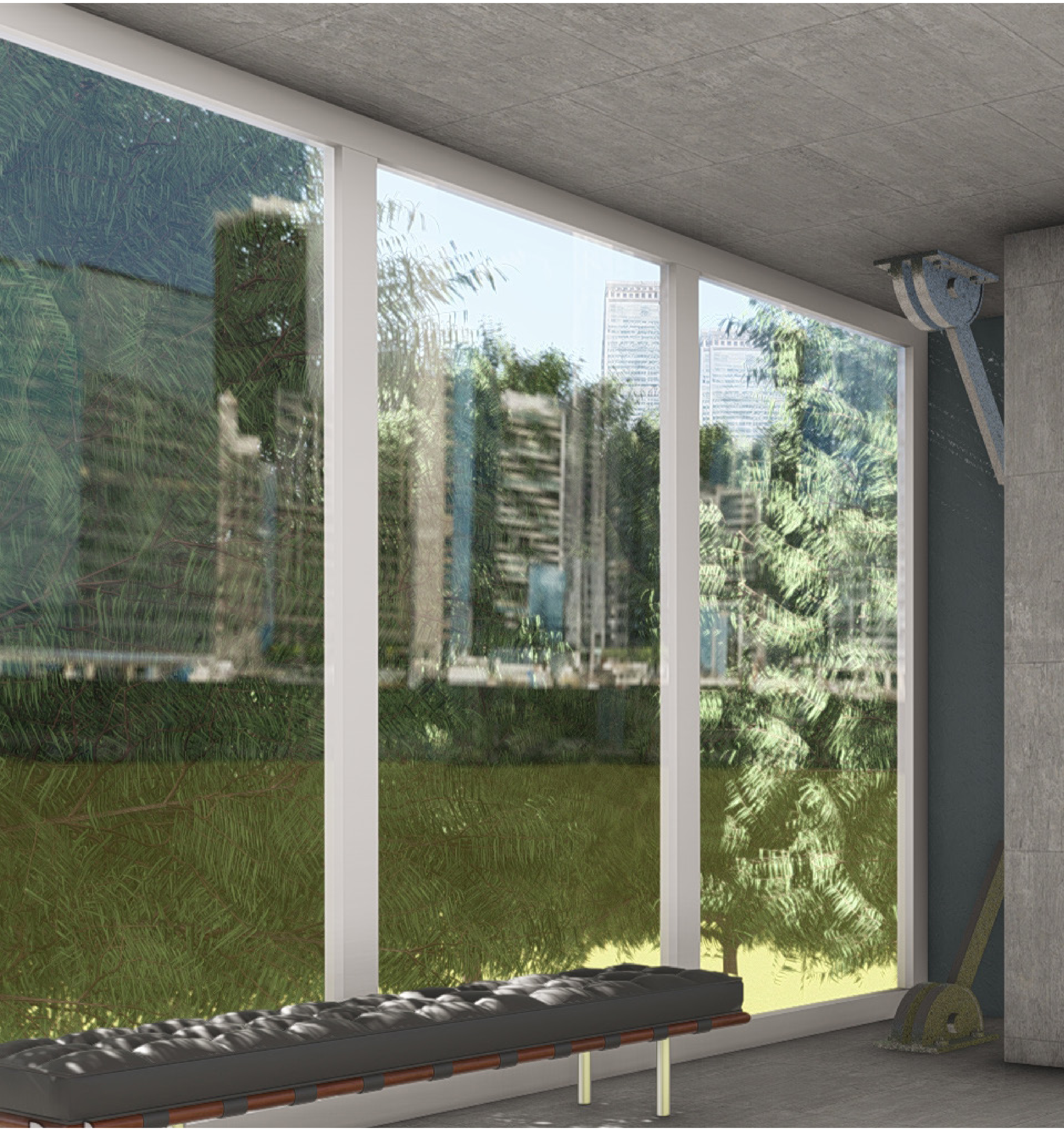


CONDUCTING *Rc = 1.16 m²K/W*



INSULATING

Rc = 4.7 m^2K/W



5.7 MANUFACTURING METHODS

Objective
The objective of this chapter is to explore which manufacturing methods are suitable for the developed facade element. Ultimately the goal is to show the feasibility of the developed product.

Generally, manufacturing methods can be divided into the following categories:

Casting (Primary shaping process)
What: Pouring molten material into a mould where it cools and solidifies into the desired shape.
Examples: Sand casting, die casting, investment casting
Material(s): Mostly used for metals, but also applicable to some plastics and ceramics.

Moulding (Primary shaping process)
What: Shaping a liquid or pliable material by forcing it into a mould cavity.
Examples: Injection moulding, compression moulding, blow moulding
Material(s): Predominantly used for plastics and rubbers; some composites as well.

Forming (Primary shaping process)
What: Reshaping solid material using mechanical force without removing material, often through deformation.
Examples: Rolling, forging, bending, extrusion, deep drawing
Material(s): Mostly used for metals, but also applicable to thermoplastics and sheet materials.

Machining (Typically a secondary shaping process)
What: Removing material from a solid workpiece using cutting tools to achieve desired geometry and finish.
Examples: Drilling, turning, milling, grinding, reaming
Material(s): Metals, plastics, wood, composites

Joining (Secondary process)
What: Assembling multiple components into a single structure. Can be permanent or reversible.
Examples: Welding, soldering, brazing, riveting, adhesive bonding, mechanical fastening (e.g. bolts, screws)
Material(s): Metals, plastics, composites

Additive Manufacturing (Primary shaping process)
What: Building up components layer by layer from a digital model, typically using material deposition.
Examples: Fused deposition modelling (FDM), stereolithography (SLA), selective laser sintering (SLS), direct metal laser sintering (DMLS)
Material(s): Plastics, metals, ceramics, composites

The selection of a manufacturing process can be based on:

- Material
- Object geometry
- Number of parts
- Tool and material costs
- Required levels of automation

Moulding could be interesting to look at for this application. This is because thermoplastics are used and because of the object geometry. Ultimately this results in a cheaper version.

Some widely used options for mouldings are:
- Injection moulding – Plastic pellets are melted and injected into a mould to form complex shapes.
- Compression moulding – Heated thermoplastic material is placed into a heated mould and compressed into shape.
- Extrusion – Molten thermoplastic is pushed through a shaped die.
- Blow moulding – Used for making hollow items (like bottles). Air is blown into molten

plastic inside a mould.
- Rotational moulding – Powdered plastic is placed in a mould that rotates and heats up, coating the mould interior to form hollow parts – great for big, thick-walled items like tanks.
- Thermoforming – A sheet of thermoplastic is heated until soft and then shaped over a mould.

Based on these and the shape of the auxetic structure, the extrusion mould was thought to be the most suitable and economical manufacturing method for the developed facade element.

According to Ansys, the production rate of polymer extrusion can be from 0.01 m/s to 2 m/s (Ansys, 2023).
Moreover, it is proven that an extrusion can be at a large scale. In figure 129 the opening of the large-diameter pipe plant for the extrusion of XXL pipes can be seen. The outside diameter is up to 3,500 mm, and the length is up to 600 m (Agru, 2017).

Figure 129. Extrusion at large scale (Agru, 2017)

6. CONCLUSION

CONCLUSION

This thesis looked at how to develop a responsive façade element with a switchable insulation that is easy to recycle. The main question was:

How to engineer a mono-material façade element that can adapt its thermal insulation value?

This question will be answered by answering the sub-questions:

1. What is the required insulation range for the switchable system?
This thesis concluded that the insulation range needs to go from around 4.7 m^2K/W in the insulating state to as low as possible in the conducting state. During the time of writing this thesis, 4.7 m^2K/W is in line with Dutch regulations for new built buildings. The aim was to minimise the Rc-value in the conducting state to speed up the heat loss process. The developed design has a Rc-value of 1.16 m^2K/W in the conducting state.

2. What are the design requirements for the façade element?
This thesis developed multiple requirements for the facade element. These requirements and reasons can be found in table 12.

3. What switching mechanism is suitable for changing the thermal resistance?
It was found that there are two strategies to switch the thermal resistance:
- Increasing/decreasing natural convection through cell height
- Changing relative density by adding/removing material or expanding the material

This thesis developed designs only using the first strategy and argued that a flexible material should be used to achieve this. Moreover, to move this material – and therefore change the cell height – an

Design criteria	Why?
Minimal energy required for the switching mechanism	Goal of facade element is to reduce energy usage of a building
Minimal energy required during production	Goal of facade element is to reduce energy usage of a building
Durable switching mechanism	There is a high frequency of movement over its lifetime
Recyclable	This is one of the ambitions of this thesis project
Fire retardant	Requirement for facades
UV resistant	Material faces outside
(rain) water proof	Material faces outside
Fast production	Reduce printing time to reduce costs (+ energy)
Insulating	Requirement for buildings in the Netherlands
Switchable insulation	To improve energy efficiancy of the building envelope

Table 12. Design criteria and reasons

actuator is needed. This thesis discovered that a pneumatically driven actuator was most suitable for this application mainly because of its durability and suitability for the built environment.

Using this, the thesis developed four different design directions of which one was selected because of its potential for fast production, high thermal insulating properties and low sensitivity to production errors. This was the design based on auxetic structure which is a structure with a negative Poisson's ratio. When pushed the auxetic structure collapses, closing the cells and creating an air flow inside the façade, which increases the thermal conductivity.

4. What material supports both functionality and recyclability?
TPC was found to be suitable. TPC is a flexible and strong material that is partly made from biobased sources. It is fire retardant, UV-resistant, and waterproof. It also works well for 3D printing, can be recycled, and does not need a heat chamber during production. On top of that, it is non-toxic - passing ISO irritation, ISO cytotoxicity, and USP VI tests - and it has the EU Ecolabel, showing it's safe and environmentally friendly.

This thesis limited itself to only materials that are 3D printable. This was before the design phase where the discovery was made that a mono-material façade element with a switchable insulation can also be achieved through other manufacturing techniques. This was discovered during the design phase after the development of the auxetic structure which is extrudable. Therefore a mono-material façade with switchable insulation does not require complex irregular changing shapes as was first thought.

5. How should the infill pattern be designed to achieve the insulation range?
The infill pattern is an auxetic structure which can collapse in all sides if pushed from two parallel sides. The façade was designed with a triangular auxetic structure since it seems to use little material compared to some other auxetic structures. Moreover, it was assumed that this structure comes relatively close to a solid when collapsed (which is desired), compared to other potential structures. To increase the durability of this structure, rounded corners were added.

6. Has the desired performance been achieved?
According to a simulation in COMSOL Multiphysics, the thermal performance of 4.7 m^2K/W in the insulating state has been achieved. This goes down to 1.16 m^2K/W in the conducting state.

Future research
This study showed the potential of mono-material façade elements with a switchable insulation.

Limitations
The limitations of this study are that the developed product has not been manufactured on full scale. As a result of this it was hard to test the viabilty of the final design. Moreover, force required to collapse the auxetic structure was not taken into consideration when selecting the auxetic structure type for the final design. In this study it was clear that the force to collapse the full scale structure was too high. Another auxetic structure type could have lowered the required force.

Further research could be on:
- Optimising the auxetic structure to reduce the force needed to collapse it
- Developing connections for this façade
- Optimising the auxetic structure, by taking into account material usage, strength and thermal resistance
- Exploring different (biobased) flexible materials with this developed principle

7. REFLECTION

REFLECTION

It has been a great educational journey. There are a couple of things I want to reflect on. First, I will reflect on the gradiation process, than on the societal impact of the project.

GRADUATION PROCESS
General reflection
A big thing that struck me is the change of course throughout the thesis. Initially I aimed to create a switchable facade using 4D printing techniques. As I gather more information on smart materials and became more practical it did not seem to be the most effective way.

3D printing in combination with pressure driven actuator was than thought to be the best suited. However, when I started to design I realised that there are simpler and cheaper production methods for some of the designs I made. This realisation came after I already made a choice in material. I limited myself to materials which are easy to 3D print. During the process I could have never know that other production techniques could achieve a mono-material switchable insulation. This makes me realise the importance of designing to gather knowledge.

Because 3D printing is not really needed, there is a potential to use other materials which are not suitable for 3D printing. However, 3D printing was necessary to answer some of the questions I had during the design process (mainly to test the movement and sensitivity to production errors of a design). It would have been very hard to test this without a 3D printer.

Another thing I want to reflect on is the order of things I did. In hindsight I would have done the Failure mode and effects analysis earlier as this shaped the final design (I currently did it halfway P3 and P4, but doing this right after P3 would have been better). Moreover, I would have first tested the force to collapse different auxetic structures as this seem to be a bottle neck of the design. I should have done this when selecting an auxetic structure.

How is your graduation topic positioned in the studio?
My graduation topic is about developing a mono-material façade element with a switchable insulation. This topic is an intersection of façade/product design, building physics and computational design. The latter because 3D printing techniques were used to develop the design.

How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)
The objective of the research is developing a responsive façade element with switchable insulation that is easy to recycle

The research approach was research by design. This was generally effective in addressing the research objectives. This was because it allowed me identify problems and find solutions. Identifying problems was done by sketching. While sketching some questions occurred to me: like how thick should this panel be? Where should the auxetic structure be placed inside the wall? How big should my wall element be?

Finding the solutions was done by a combination of research and design. The research approach forced me to explore multiple solutions. This is useful, because usually the first solution is not the best solution. By developing multiple solutions to a problem you can select the best one based on some criteria.

Strengths:
- Multiple solutions can be explored
- Encourages innovation: Open-ended, exploratory nature allows for creative and non-linear thinking

Weaknesses:
- It takes a lot of time

Opportunities:
- Real-world impact: Prototypes or proposals can influence policy or convince investors

Threats:
- Risk of aesthetic bias: Visually compelling outputs may overshadow critical analysis or flaws in reasoning

How are research and design related?
In this research, design and research are closely connected. Research informs the design criteria and builds understanding of core concepts, while the designed solutions reflect and refine that understanding and design criteria:

Design criteria (research) + (need for) understanding of core concepts (research) <-> designed solution(s)

This is best showed using an example:

The design criteria were derived from research and my vision for a mono-material switchable façade element. Some criteria, like fire retardant, UV resistance and water proof were derived from research on criteria for facades in the Netherlands. All the design criteria shaped the design. But before a design could have been made the core concepts of heat transfer through cavities needed to be researched in order to develop the design strategies. Using these design strategies, four different designs were made for the switchable insulation. During designing, research needed to be done on other core concepts like soft robotics and auxetic structures. Moreover, the design process also shaped the criteria - for example, during the process it was discovered that a mono-material façade element with switchable insulation does not have to be 3D printed which used to be a design criterium.

SOCIETAL IMPACT
To what extent are the results applicable in practice?
The developed façade element is a proof of concept. However, when it comes to the applicability of the façade element more research needs to be done. As of now, the force needed to collapse the structure, and therefore switch the insulating state, is regarded to be too high. Moreover, some proper force testing needs to be done on the façade in a relevant environment.

To what extent has the projected innovation been achieved?
The goal of this thesis was to develop a mono-material façade element with a switchable insulation. Both of these elements can be found in the final product. Therefore the projected innovation has been achieved.

Does the project contribute to sustainable development?
Yes, this is because the switchable insulation saves operational energy of a building. Moreover, the façade element is designed to be easy to recycle by since it is mono-material.

What is the impact of your project on sustainability (people, planet, profit/ prosperity)?
The façade element ensures a comfortable indoor climate by cooling the building when it is needed. Moreover, it can save operational energy and it is easy to recycle, which is good for the planet. These savings in energy are also indirectly cost savings, increasing profits for building owners.

What is the socio-cultural and ethical impact?

The developed façade in this thesis is made out of soft plastic (although a recommendation is to research other materials for the developed concept). This is a relatively rare material for the outer layer of a façade in the Netherlands where brick is the dominant material. Moreover, one can question if we should really design for recycling when you can also design for reuse?

What is the relation between the project and the wider social context?

The project is a unique façade solution for buildings. What is making it unique is that it is easy to recycle and that it can save more operational energy than most façades. This is because it is mono-material and because it can switch its insulation value between low and high, allowing to passively cool the building when it is needed.

How does the project affects architecture / the built environment?

The project promotes the circular economy in the building sector since it is designed for recycle. Moreover, the use of plastic as material allows the architect for a wide range of colours to be used for a design. Next to the esthetical value of the product, the product also allows for energy savings in the built environment because of its switchable insulation. This is important since the built environment has a large share on (operational) energy usage in the worldwide energy consumption.

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APPENDIX

Python code for the control system

```python
import requests
import time
import board
import adafruit_dht

def isEqual(sensor1, sensor2, margin=1.0):
    return abs(sensor1 - sensor2) <= margin

def fetch_outdoor_temperature(API_KEY, CITY):
    BASE_URL = "http://api.weatherapi.com/v1/current.json"
    params = {
        "key": API_KEY,
        "q": CITY,
        "aqi": "no"
    }
    try:
        response = requests.get(BASE_URL, params=params)
        if response.status_code == 200:
            data = response.json()
            return data["current"]["temp_c"]
        else:
            print("Error fetching data:", response.status_code)
            return None
    except Exception as e:
        print("Exception fetching outdoor temperature:", e)
        return None
```

```python
def main():
    #desired indoor temperature
    desired_indoor_temp = 23

    API_KEY = [redacted]
    CITY = "Delft"

    #DHT22 connected to a GPIO pin
    dht_device = adafruit_dht.DHT22(board.D4)
    dht_device2 = adafruit_dht.DHT22(board.D17)

    #deadband control
    last_switch_time = None
    DEADBAND_SECONDS = 5 * 60  # 5 minutes
    compressor_state = None  # 'on' or 'off'
    last_weather_fetch = 0
    weather_refresh_interval = 5 * 60  # 5 minutes
    outdoor_temp = None

    while True:
        try:
            #fetch sensor data (indoor temperature)
            sensorData = dht_device.temperature
            sensorData2 = dht_device2.temperature

            #check if sensor data is reliable, if not turn or keep compressor off (insulating state)
            if sensorData is None or sensorData2 is None:
                if compressor_state != "off":
                    compressor_state = "off"
                time.sleep(10)
                continue

            if not isEqual(sensorData, sensorData2):
                if compressor_state != "off":
                    compressor_state = "off"
                time.sleep(10)
                continue

            indoor_temp = (sensorData + sensorData2) / 2

            #refresh outdoor temp every 5 minutes
            current_time = time.time()
            if current_time - last_weather_fetch > weather_refresh_interval or outdoor_temp is None:
                outdoor_temp = fetch_outdoor_temperature(API_KEY, CITY)
                last_weather_fetch = current_time

            #control thermal resistance
            if indoor_temp > desired_indoor_temp and outdoor_temp < indoor_temp - 1:
                #CONDUCTING STATE
                if compressor_state != "on" and (last_switch_time is None or (current_time - last_switch_time) >= DEADBAND_SECONDS):
                    #turn compressor on
                    compressor_state = "on"
                    last_switch_time = current_time
                else:
                    #keep compressor on
                    continue
            else:
                #INSULATING STATE
                if compressor_state != "off" and (last_switch_time is None or (current_time - last_switch_time) >= DEADBAND_SECONDS):
                    #turn compressor off
                    compressor_state = "off"
                    last_switch_time = current_time
                else:
                    #keep compressor off
                    continue


        except RuntimeError as error:
        # Reading may fail occasionally; retry

            compressor_state = "off"

        #delay of 10 seconds between fetching temperature data from sensors
        time.sleep(10)

if __name__ == "__main__":
    main()
```