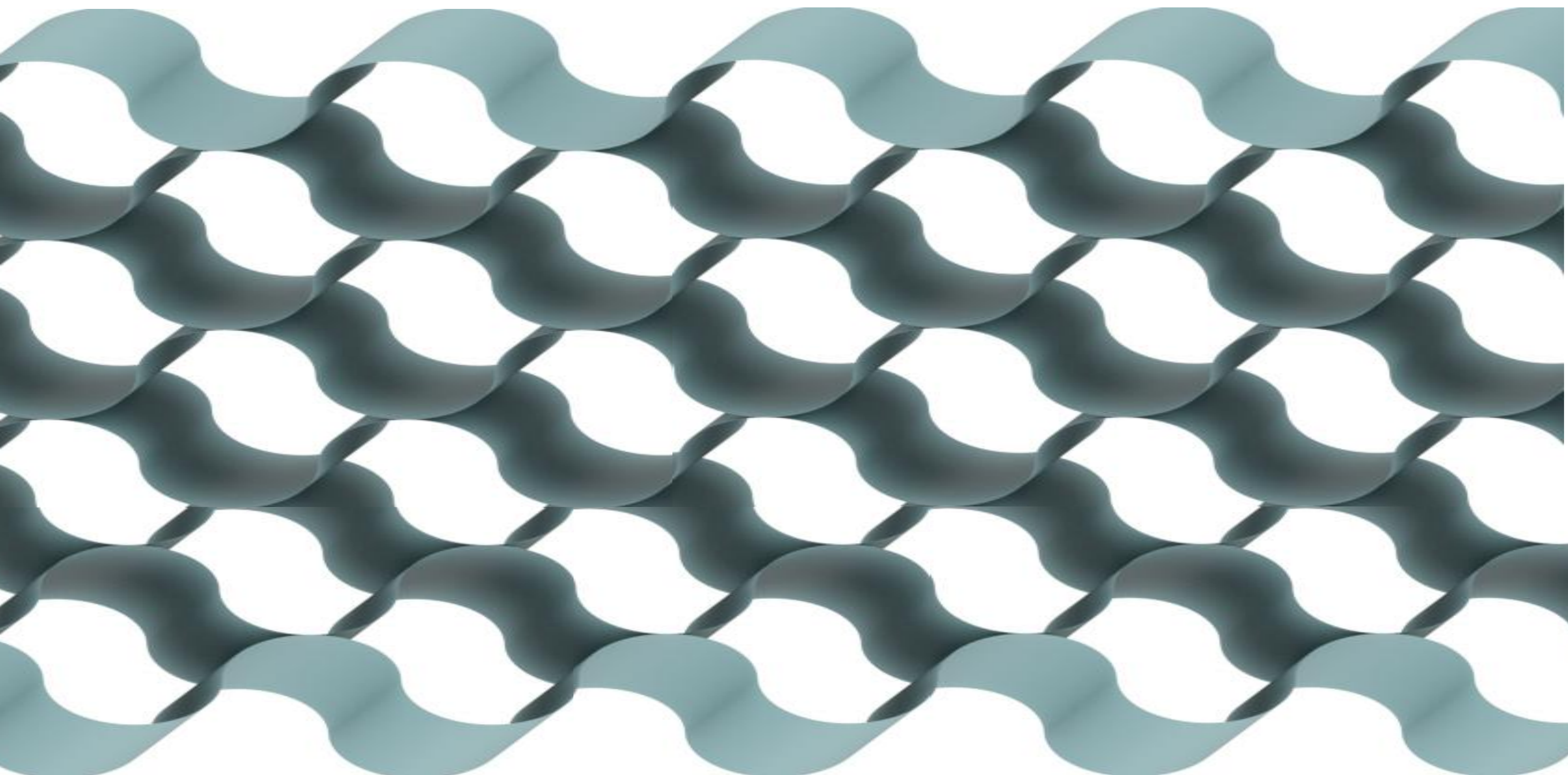
Development of a novel thermal insulation system for building envelope application

Elena Katsoula



TU Delft

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Development of a novel thermal insulation system for building envelope application

by

Elena Katsoula

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Nomenclature

α thermal diffusivity [$m^2\ s^-1$]

β thermal expansion coefficient

δ thickness of a single air layer [m]

λ Thermal conductivity [W/mK]

λ_{bubble} Thermal conductivity of air inside the bubble [W/mK]

λ_{cav} Thermal conductivity of air cavity [W/mK]

λ_{cond} Effective thermal conductivity due to conduction [W/mK]

λ_{conv} Effective thermal conductivity due to convection [W/mK]

λ_{con} Thermal conductivity of concrete [W/mK]

λ_{eff} Effective thermal conductivity of porous structures [W/mK]

λ_{foil} Thermal conductivity of aluminum foil [W/mK]

λ_{PET} Thermal conductivity of PET [W/mK]

λ_{rad} Effective thermal conductivity due to radiation [W/mK]

ν dynamic viscosity [Pa s]

ε_1 Hemispherical emissivity of the surface on the warm face of the airspace

ε_2 Hemispherical emissivity of the surface on the cold face of the airspace

A Cross sectional area [m^2]

b Width of the airspace [m]

d Thickness of the airspace[m]

g gravitational acceleration constant 9.81 [m/s^2]

h Height of a layer of material [m]

h_a Conduction/Convection coefficient [W/m^2K]

h_c Convection coefficient [W/m^2K]

h_r Radiative coefficient [W/m^2K]

k Thermal conductivity [W/mK]

k Thermal conductivity of air 0.025 [W/mK]

L Internal thickness of wall

l Lenght of a layer of material [m]

N Number of air layers for insulation configuration

Nu_{L} Nusselt number for single layer of air

Q Heat flow [W]

q_c Convective heat flow [W]

q_k Conductive heat flow [W]

q_{in} Internal heat flow [W]

q_{out} External heat flow [W]

R Total thermal resistance of a building element [m^2K/W]

R_m Thermal resistance of a layer of a material [m^2K/W]

R_{se} External surface thermal resistance of air [m^2K/W]

R_{si} Internal surface thermal resistance of air [m^2K/W]

R_{tot} Thermal resistance of the airspace [m^2K/W]

$R\alpha_{\delta}$ Rayleigh number

T_i Internal temperature [°C]

U Thermal Transmittance [W/m^2K]

w Width of a layer of material [m]

ΔT Temperature difference [Kelvin or Celsius]

ΔT_o External temperature [°C]

α_{se} Heat transfer coefficients of air for the outer surface of the construction [W/mK]

α_{si} Heat transfer coefficients of air for the outer surface of the construction [W/mK]

∇T Temperature gradient

Preface

The current report marks the completion of my Master's degree in Building Engineering at Delft University of Technology. The research was conducted in collaboration with ABT B.V. The topic of this research arose from my interest in façade design with the incorporation of new technologies aiming to contribute to a more sustainable future. At this point, I would like to express my gratitude to all the people who supported me.

First, I would like to express my sincere gratitude to the members of my committee, for their valuable help and guidance throughout this process. I would like to thank the chair of my committee, Prof. Mauro Overend for his valuable inputs and and guidance. Special thanks to Dr. ing. Marcel Bilow, who shared his experience on prototyping and his knowledge on façade design with me and for his guidance through each stage of this project. Sincere thanks to Ass. Prof. dr. Mariana Popescu, for her valuable advises on the design exploration stage, her encouraging words and support. Special thanks to Ing. Rowan van Wely, my supervisor at ABT for his continuous support, guidance and input in formulating the research topic.

Furthermore, I would like to thank Ing. Gertjan Peters from ABT for giving me the opportunity to perform this thesis. I would like to express my sincere gratitude to Dr. Han Xiao Cui for sharing his knowledge in the field of building physics and switching technologies and helping me understand this new research field for me. Thank you for your patience and help at every stage of this thesis. Special thanks to Dr. ir. Martin Tenpierik,for his great assistance on providing me technical support for the needs of thermal simulations.

Finally, I would like to express my deep gratitude to my family for their support, endless love and continues encouragement to pursue my aspirations. Last but not least, I will forever be grateful to my friends, the old ones and the new ones. You have been my fellow travelers on this unforgettable educational journey and I thank you for always being by my side and especially for supporting and encouraging me through this difficult year.

Elena Katsoula
Rotterdam, February 2023

Abstract

The building sector is responsible for 38% of global energy and process-related greenhouse gas emissions. In recent decades, a rapid increase in energy consumption in buildings has been witnessed, making energy reduction a pressing issue. Thermal insulation systems, that can operate dynamically in response to changing transient conditions, by alternating between thermally conductive and insulated states, are gaining attention in their architectural applications, since they constitute an effective mean for reducing energy consumption while simultaneously improving occupants comfort levels.

Despite the pioneering work that has been conducted by researchers to develop adaptive insulation technologies in different engineering fields, currently none of the adaptive insulation technologies are embedded in real-world buildings for a number of reasons. The aim of this thesis, therefore is to identify these reasons and on this basis, to explore, the different ways in which an adaptive insulation system can be created.

There are no established standards or requirements for the development of adaptive thermal insulation technologies. Consequently, this research initially focuses on the creation of design criteria that address aspects related to thermal performance, design feasibility, and technological complexity of the examined systems.

Subsequently, the exploration of different design concepts was initiated by first creating a scheme of aspects, concerning the geometry of the core, the mobility of the outer layer, the number of cavity compartments, the type of actuation and the types of mechanisms that facilitate the transition between thermal insulation states. From the combination of these aspects, six design alternatives emerged, the principle of operation of which is based on the idea of a structure that can inflate and deflate during the transition of the system from the insulated to the conductive state. The core geometry of the concepts was modeled within TRISCO steady-state 3D software tool, where various parameters were tested in order to obtain the final topology. The aim was to achieve a thermal resistance comparable to that of state-of-the-art insulating materials in their insulated state and furthermore, to achieve a large range of shift in order to acquire a significantly low thermal resistance in the conductive state comparable to the case of an uninsulated concrete block.

Simultaneously, the thermal transmittance (U-value) for the insulated and conductive states of each concept was estimated through numerical simulations in TRISCO and validated using analytical models for comparison. The results of the analysis indicated that, the thickness of the air cavity and the emissivity of the membrane material greatly affect the examined thermal resistance. Additionally, the range of shift depends significantly on the degree of evacuation of the air cavity. It has been found that technologies whose structure and working principle allow full compression of the core in the conductive state, can lead to a lower thermal resistance which is governed by solid conduction. The results of the simulations showed that one of the examined concepts satisfied the initial goal, achieving thermal transmission which ranged from 0.13 W/m^2K to 2.79 W/m^2K in the insulated and conductive states respectively. Whereas, the thermal resistance ranged from 7.5 m^2/KW to 0.4 m^2/KW in the insulated and conductive states respectively. The obtained values of thermal transmittance from TRISCO, were compared with the thermal transmittance from analytical formulas. In this way, the accuracy of the numerical simulations was validated.

The final stage of the design exploration phase led to the selection of the final design through a multi-criteria analysis that is aligned with the aforementioned initial design criteria. The final design is a 1.5 m by 0.75 m opaque panel of low emissivity honeycomb core made up of 10 mm cells. In the insulated state the panel has a thickness of 0.18 m while after being compressed the thickness is reduced to 1/3. Actuation of the system is achieved using a dual-function pump that supplies air to a system of channels that access the core. An approximation of the sizes of the pump and pipes were given for the design of the air-supply system. In this way, the system can be reversibly switched between an inflated state governed by gaseous conduction and a deflated state, where the solid conduction of

adjacent surfaces governs. The architectural application of the adaptive insulation system, considers the element as an infill component in which the outer skin is integrated into the system, implying that the transition between thermal states is visible from the façade.

To conclude, this research explores the potentials of using the parameters influencing heat transfer capability for the development of an adaptive insulation system intended to be used in the building envelope. The research through design resulted in a promising design based on the resulting thermal performance indicators. However, to realise the proposed technology, tests on physical model need to be conducted. The thermal performance of the system should be validated experimentally in order to derive statistical data for its safe application and the actual dimensions of the air-supply system need to be determined.

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Research framework

1.1. Introduction

Sustainability strategies is an ongoing topic of conversation. For several decades there is an increasing awareness towards the anthropogenic influence in the greenhouse effect, which has resulted to global warming and climate change. Both phenomena have caused by the increasing levels of greenhouse gases in the atmosphere which are highly related to the human activities. This has led to an increase of the average temperature on the planet by nearly 1°C in the past century as well as to an alteration of the climate patterns in regional and global scale. As a consequence, extreme and unpredictable weather conditions have already become common across the world. This is mostly noticeable in the big cities because of the great amount of buildings, the limited existence of green areas and the high population density. Therefore, measures must be taken to reduce greenhouse gases.

Building and construction sector impose a great threat to the environment since they account for 37% of energy-related CO2 emissions (*IEA – International Energy Agency* 2022). In this regard, building sector has a key role in the reduction of the greenhouse gases emissions. Among the most influential factors that will impact the way of designing buildings for the present and the future will be the need for decarbonization and supply of energy from clean and renewable sources. This can be succeeded by the triple strategy of reducing energy demand, decarbonizing the power supply and addressing building materials' carbon footprint. In recent years, building regulations for high-performance buildings have become stricter and more complex, due to the demand of reduction of the CO2 emissions. The latter points out the need of creating new materials and developing intelligent technologies and products which can ensure that new buildings are sustainable and energy-efficient in order to meet the present and future demands imperative.

The building envelope is one of the most important elements of the overall design of the structure, given that it defines its unique architectural character and it has a substantial effect on users' interaction with their indoor and outdoor environment due to its intrinsic design and location. Therefore, the building envelope can regulate the energy consumption and it can affect the indoor environmental quality of a building. The development of adaptive façade technologies which are capable of adjusting to alterations and can have a profound effect on achieving occupants' comfort and energy-saving. This improvement can be achieved by considering the building envelope as an active and dynamic element which can automatically respond to the changing conditions. This means that, a selective approach needs to be adopted, where the static building envelope is replaced by a dynamic one, capable of adjusting, in terms of function and form, in order to respond to the climate shift.

Despite the great technological improvements in the field of façade design there is still place for new approaches keeping in mind the future demands. The design of new and future structures is challenging because on the one hand it has to satisfy the occupants in term of aesthetics and indoor comfort and on the other hand should aim to contribute to the reduction of the anthropogenic impact to the global warming. This can be achieved, among others, with strategies and technologies which can improve the energy efficiency of the buildings. The focus on this thesis will be the development of an adaptive insulation system which can respond in a dynamic way to the environmental changes.

1.2. Problem statement

1.2.1. Paris agreement

The negative effects of global warming and climate change are more than ever visible in everyday life, imposing drastic measures to reduce the greenhouse gases responsible for these phenomena. Therefore, all possible measures must be taken to ensure a sustainable future for present and future generations.

Paris Agreement establishes a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C (*Paris Agreement* n.d.). The building sector have a significantly high contribution to the greenhouse gases emissions. More specifically, a building's entire lifecycle is responsible directly and indirectly for 38% of global energy- and process-related CO_2 emissions, while the industry and transport are count for 32% and 23% respectively. The direct carbon dioxin emissions are accounted for about 9% of global energy and process-related CO_2 emissions resulted from the burn of fossil fuels in buildings (both residential and no-residential), another 19% comes from the generation of electricity and heat used in buildings (both residential and no-residential), and the remaining 10% is related to the manufacturing of construction materials (*IEA – International Energy Agency* 2022). Embodied carbon emissions related to the building sector can be addressed, inter alia, by implementing plans for efficient use of materials taking into account their entire life cycle and through strategies to reduce energy demand in order to meet net-zero emissions objectives of 2050. The latter can be achieved on the one hand by improving the efficiency of appliances and on the other hand by reducing the heating and cooling demand.

1.2.2. Adaptive insulation technologies as a strategy to achieve energy efficiency in buildings

Although the key role of the building envelope towards highly energy efficient building has been established for a long time, until recently, all efforts and attention have mainly been focused on increasing and optimizing the thermal insulation of the envelope components. However, a highly insulated façade may not be always the most favorable in terms of indoor comfort and energy savings, imposing that this is not a feasible approach anymore. This is indeed the case, in a temperate climate during mid-seasons and summer months when a façade with a lower R-value is more beneficial since it facilitates the transfer of the indoor heat air towards the outdoor space during the night, while a highly insulated façade could contribute to retain undesirable heat, causing overheating discomfort. This phenomenon is often observed in office buildings experiencing high internal loads. In this regard, new and more pioneering ideas and technologies need to be developed at material and technology level, considering the fact that the façade can play a crucial role in regulating the energy and mass flows from outdoors to indoors and vice versa. In this regard, adaptive insulation can be considered as an effective alternative to static insulation for the building envelope. Previous researches have proven that adaptive insulation technologies can have a positive impact on the energy savings, compared to a conventional insulation system. This is indeed the case of an office room in Shanghai, which was examined in order to evaluate the effect of an adaptive insulation panel, consisting of two external layers capable of modulating their thermal properties and an internal layer used as a static thermal storage, on energy consumption and thermal comfort compared to a static insulation system (Favoino, Jin, and Overend 2014). The investigation showed that the adaptive insulation could substantially outperform static insulation solution both in terms of energy consumption and indoor thermal environmental quality. More specifically, thermal comfort could be improved by 40% to 60%. The largest improvement was achieved in the mid-season in which outdoor climatic conditions are closer to human comfort range. The opposite trend followed in the case of cooling and heating demand, where a decrease of 40% to 80% and 30% to 40% respectively was observed, depending on the season. Generally, the yearly potential in energy saving was estimated to be 25-35%. The benefits of the adaptive insulation are also evident when a parametric study was performed in the same reference office room in Shanghai, for the estimation energy reduction and thermal comfort enhancement. In this case, except from the thermal conductivity, the position and the thickness of the insulation varying (Jin, Favoino, and Overend 2017). The results of the investigation indicated that adopting this adaptive insulation system a reduction of 10 to 50% in energy demand can be achieved compared to the performance of the static insulation. It is therefore clear that, a certain level of climate response and adaptability in the changing environmental conditions can be proven beneficial in terms of reduction of the energy consumption. Despite the benefits, the use of adaptive insulation technologies is limited due to a number of reasons. The ultimate goal of this research, is to develop an adaptive insulation system, with an emphasis on the control of the parameters influencing the heat transfer capability as well as its incorporation into the building envelope. Producing estimates of its effect on energy consumption is beyond the scope of this thesis.

1.3. Research objective

From the scientific community, existing research on adaptive insulation has proven to be very promising in terms of energy savings and thermal comfort improvement compared to a static insulation. Consequently, the main objective of the research is to contribute towards the research of novel insulation technology by identifying first the parameters that limit the use and then developing an adaptive insulation system for façade application that is able of alternating between high insulated and low insulated states.

1.4. Research questions

The main research question is:

> **To what extent can parameters affecting heat transfer capability be used to create an adaptive insulation system that can be applied to a building envelope?**

Sub-questions:

- What are the main parameters influencing heat transfer capability of a system?
- What are the main design criteria for the development of an adaptive insulation system?
- What is the relationship between core geometry and thermal efficiency?
- How can adaptive insulation system be integrated into a building envelope?

1.5. Research methodology

The methodology to be followed for the thesis is a combination of a research through design and a multi-criteria analysis. The development of the thesis can be divided into five phases:

Literature review
After the scope of the research is defined, a literature study is carried out. During this phase, emphasis is given on understanding topics related to the research framework. At the core of this study is the theoretical framework to explore the main aspects of the problem statement and the research question. Therefore, the literature study includes:

- The study of the basic facade systems
- The exploration of the concept of adaptability
- The investigation of the heat transfer mechanisms
- An analysis of adaptive insulation technologies for thermal control
- A sensitivity analysis of the tools for the estimation of thermal performance.

Design guidelines
The next phase involves the set of design boundaries. According to the conclusions of the literature research, the boundary conditions for the design are defined which are linked with the targeted thermal performance, the design feasibility and technological complexity of the system.

Research through design
Once the boundary conditions are set, the goal of this phase is to explore different design concepts. The research through design is achieved through sketching, 3D modelling, numerical simulations and materiality research. During this phase, design solutions for the adaptive thermal insulation are explored. Various alternatives of different core structure, and technological features are developed and

analyzed on a preliminary level in this phase. During this phase a further research was conducted on existing and novel mechanisms in the fields of car technology, robotics and bio-engineering for inspiration. Once the preliminary concepts are established, the definition of their core geometry follows along with the exploration of their thermal performance, through thermal analysis simulations. This phase can be characterised as a feedback loop process, where the preliminary concepts are used as starting point for the thermal analysis simulations and then the information gained from the numerical simulations is utilised as the new inputs for the update of the concepts. The final stage of this phase is a multi-criteria analysis, where the different design alternatives are compared with each other based on the design criteria set in phase 2. The highest scoring concept will define the final design.

Application in the building envelope
This phase involves the finalisation of the prevailed design and its application into the building envelope. In this regard, the materials for the construction of the adaptive insulation panel are described and then a methodology of integrating into the building envelope is suggested.

Discussion, Conclusions and Reflections
In the final phase, all the findings of this research are summarized and suggestions for further research are proposed.

2

Theoretical background

2.1. Introduction

In this chapter, the basic knowledge of the heat transfer mechanisms will be presented. The aim of the research is to gain an understanding on the parameters that influence the heat transfer capability and their contribution to the design of an insulation system that can operate in a dynamic way.

First, in Sections 2.2 and 2.3, an overview of the evolution of the design of building envelopes and an introduction to the concept of adaptability will be given, respectively. In Section 2.4, the definition of heat transfer mechanisms and the description of the characteristic thermal properties of materials will follow. In Section 2.5 The strategies to improve the thermal performance of a material will be discussed on the basis of heat transfer mechanisms and in Section 2.6 a review of adaptive insulation technologies applied in sectors other than the building environment will be carried out. Finally in section 2.7 a comparison will be made between the available thermal simulation software.

2.2. Building envelope evolution

2.2.1. Existing façade systems

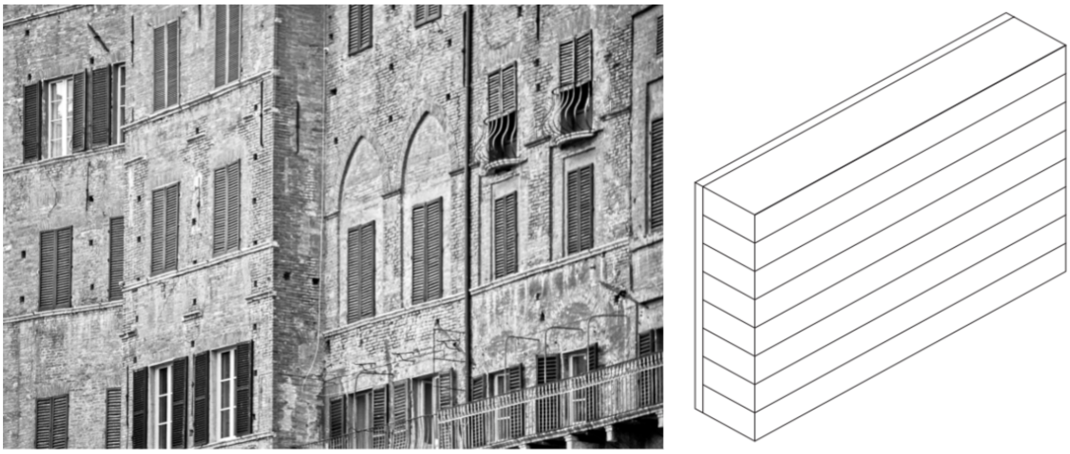
The form and function of present-time wall and building envelope are closely related to the history of human evolution. The design, the building materials and the construction techniques evolved at a pace dictated by matching need and available resources.

Initially, the building requirements were limited in the fulfillment of the primary need of creation of a shelter for the protection against the weather conditions. As a result, the first houses were characterized by a particularly simple form, where the existence of large openings was absent. As the society evolved, the needs and the building requirements increased and thus the desire for better shelter grew. New materials and new construction skills were developed, resulting in more advance forms of structures. Influencing factors for the further development of the façades were the climate conditions of each region, the various life styles and dwelling styles which constitute the base for the development of the two basic principles for the construction of the outer envelope of a dwelling: fixed solid walls designed for permanent use, and more flexible, less permanent façades which are typically represented by tents for mobile use. Depending on the location of the insulation layer two different types of solid wall construction may be distinguished (see Fig 2.1): warm façades, where the thermal insulation layer is applied directly to the surface of the building either on the outer or the inner surface and cold façades, where a ventilated cavity in introduced between the outer weather protection layer and the thermal insulation layer (Klein, Bilow, and Auer 2007).

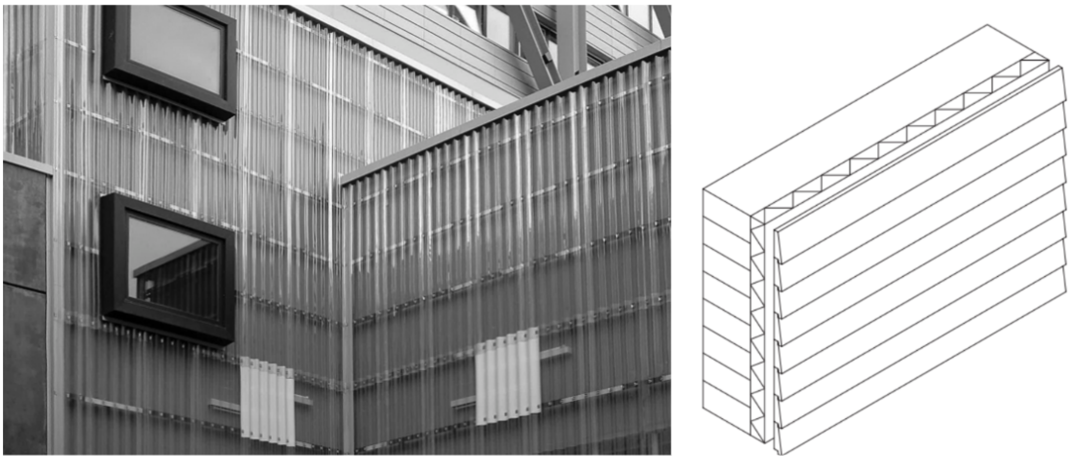
Gradually, large openings filled with translucent materials, gained more space into the solid wall and at the same time, a separation of supporting system and enclosure was realised. These two parallel developments resulted in the transformation of the solid wall into the relatively lightweight modern façade structure. Nowadays, there is a large variety of ways that a building envelope can be constructed. On a first level a distinction can be based on their load or non load-bearing capacity and then on a second level a distinction can be based on their on-site or off-site fabrication method and their functions. In the book of Klein, Bilow, and Auer 2007, several facade types along with their characteristics are presented:

Curtain wall

Structurally speaking, curtain walls (see Fig 2.2) are non-load bearing systems that separate the building's exterior from the interior, while supporting its own weight and the imposed seismic load and/or wind load. Since this type of façade system constitutes a non structural element, it is lightweight and can be constructed from a variety of different materials (cladding or glazing) to meet the various aesthetic or functional requirements. Curtain walls are hung from the top of a building and supported laterally at different floor levels. The edge beams are responsible for holding most of these supports. The vertical and lateral loads are generally led to ground floor by floor, but special load-bearing elements may be added to bridge longer spans. From a building physics point of view, the main function of a curtain wall is to eliminate the water penetration, to resist to wind and thermal loads and to add soundproofing.



(a) Solid masonry wall of Market place in Sienna, 13th century



(b) Cold façade of Port Event Center, in Düsseldorf, Norbert Wansleben, 2002

Figure 2.1: An example of the solid construction (a) and cold façade (b) system (Klein, Bilow, and Auer 2007).

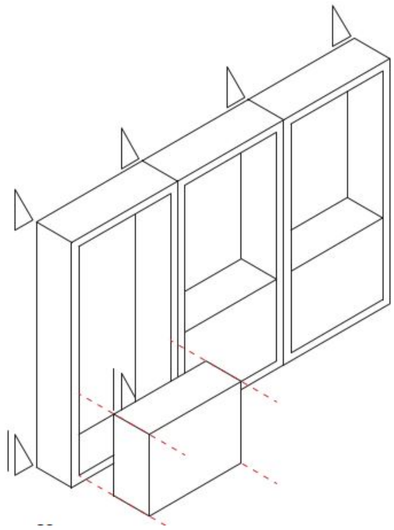
Double façade

Another type of façade is the Double façade system (see Fig 2.3). As its self-explanatory name indicates, is a system consisting of two layers of glazing. In Double façade system the façade is separated in two glazed layers (the 'skins'), enclosing an air cavity, generally used for hosting and protecting the shading system and for airflow control. In this way, the building can be provided with ventilation, additional soundproofing and protection against high wind loads. The ventilation properties of a double-skin facade are also crucial, as they have a great influence in its thermal performance, with the height of the cavity influencing the most the air extraction (Alberto, Ramos, and Almeida 2017). Commonly it can be classified according to three parameters: type of ventilation, geometry of the cavity, and airflow path inside the cavity (Loncour et al. 2004). Based on the geometry of the cavity, four main variations of Double façade may be distinguished: Second-skin façade (see Fig 2.4b), Box-window façade (see Fig 2.4a), Corridor façade (see Fig 2.5) and Shaft-box façade (see Fig 2.6).

Second-skin façade

A variant of the Double façade is the Second-skin façade (see Fig 2.4b), which is obtained by mounting a layer of glass on the entire inner façade. It is characterized by its simple structure and the absence of a large number of moving parts. The ventilation mechanisms are provided at the top and bottom zones of the façade. One disadvantage of this system is the fact that is difficult to have control on the interior environment conditions, thus there is the risk of overheating. In terms of energy consumption, second skin façade is the most energy-efficient compared to the other double façade subcategories (Alberto, Ramos, and Almeida 2017).

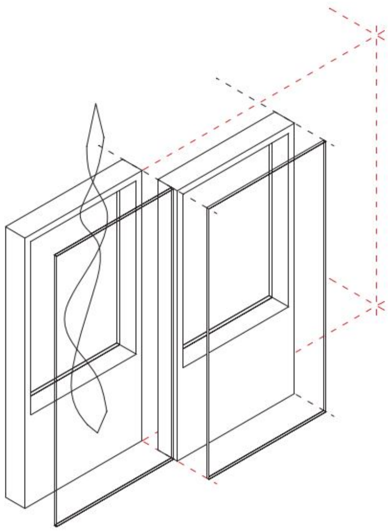
(a) Mies van der Rohe's Federal Center in Chicago, 1964



(b) Curtain wall

Figure 2.2: An example of the curtain wall system of Mies van der Rohe's Federal Center in Chicago, 1964 (Klein, Bilow, and Auer 2007).

(a) Triangle Building, Cologne, Gatermann + Schossig, 2006

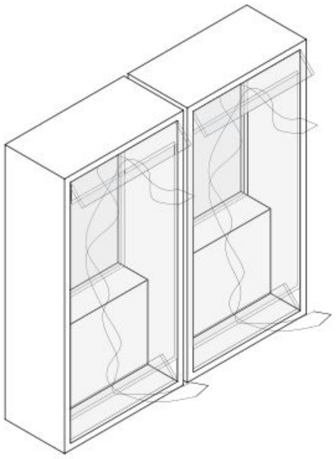


(b) Double façade

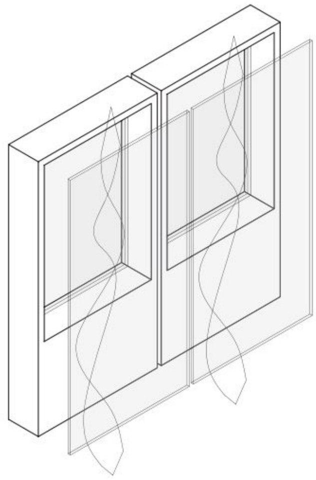
Figure 2.3: Figure on the right (b) shows a representation of the double wall system and figure on the left (a) shows the Triangle Building in Cologne which is consists of both single and double façade (Klein, Bilow, and Auer 2007).

Box-window façade

A Box-window façade is comprised of one-storey height façade modules, in which the air cavity is divided by horizontal and vertical means at the level of each façade module. This type of window is common in areas with high external sound levels and special requirements (Oesterle 2001). In contrast with the Second-skin façade, this model allows to the users to have and active control over their own internal environment conditions, since they can change the internal temperature by opening or closing the ventilation claps. The disadvantage is that this freedom may have an opposite effect on the conditions experienced by another user.



(a) Box-window façade



(b) Second-skin façade

(c) Box and Second-skin façade

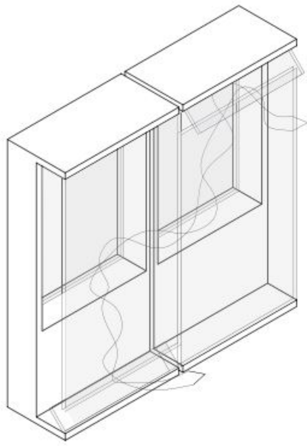
Figure 2.4: A scheme of the the box construction principles of the second-skin (a) and box-window façade (b) are indicated in this figure.The bottom sub-figure (c) shows an example of the box-window on the left and the second-skin on the right (Klein, Bilow, and Auer 2007).

Corridor façade
Corridor façades (see Fig 2.5) are characterized by a wide air cavity horizontally partitioned at the level of each storey or over several rooms along each floor. The intermediate air cavity located between the two glass layers composes a corridor over a whole storey. The air flow along the horizontal length of the floor is blocked by vertical baffles, thus preventing noise and air interference between adjacent rooms. Furthermore, corridor façades connect neighbouring double-façade elements in order to permit staggered ventilation of the space between the two skins.

Shaft-box façade
the last variant of the double façades is the shaft-box (see Fig 2.6). A set of box-window elements are placed in the facade with continuous vertical shafts that go along a number of stories to create a stack effect. On every story, the vertical shafts are linked with the adjoining box windows by an opening. The stack effect draws the air from the box window into the vertical shafts (Oesterle 2001). This system requires complex installation but is highly effective in terms of thermal performance.

Alternating façade
This façade type emerged from the need of variable ventilation requirements of a building. Alternating façades (see Fig 2.7), are a single-skin construction that can be locally transformed to double-skin. Depending on the outside and inside climate conditions, ventilation can be provided through the single

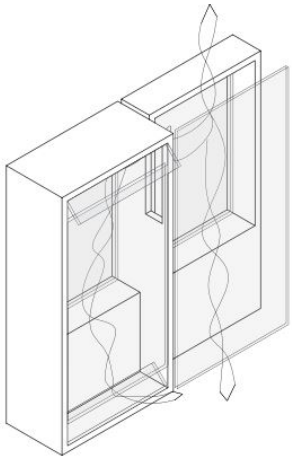
(a) Stadttor Building, Düsseldorf, Petzinka Pink und Partner, 1998



(b) Corridor façade

Figure 2.5: Figure on the right (b) shows a representation of the corridor façade and figure on the left (a) shows the Stadttor Building in Düsseldorf, where the storey-high façade elements have rotary timber baffles on the inside and a continuous glass skin on the outside (Klein, Bilow, and Auer 2007).

(a) Photonics Centre, Berlin, Sauerbruch Hutton Architects, 1998

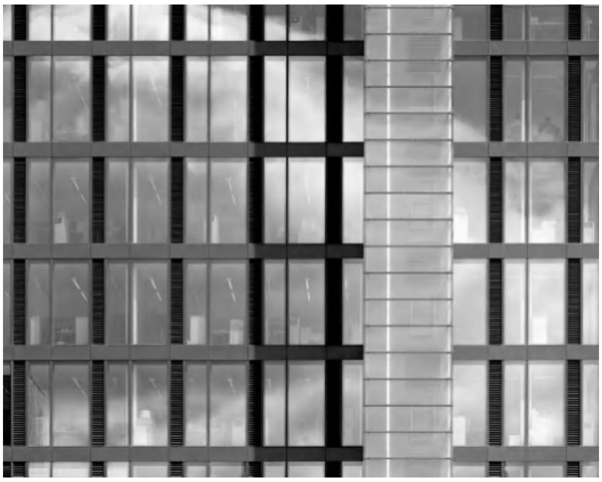


(b) shaft-box

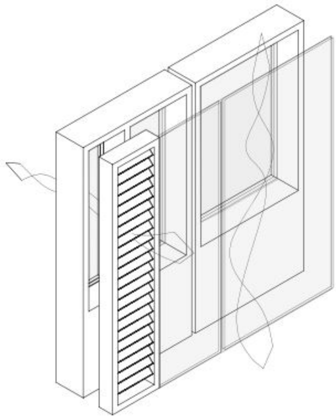
Figure 2.6: Figure on the right (b) shows a representation of the shaft-box façade and figure on the left (a) shows the Photonics Centre in Berlin, where the shaft-box façade, consisting of vertically separated ventilation shafts in the plane of the façade which merge at the top for effective ventilation of the space enclosed by the double façade (Klein, Bilow, and Auer 2007).

or double skinned façade to ensure comfortable conditions in the room almost any time of year. This system, combines the benefits of the buffering effect of the double façade and the simplicity of the single-skin.

Integrated façade
By integrating in the concept of the double façade more functions rather that ventilation, a new façade system arise. The integrated façade (see Fig 2.8) or generally called a “modular façade” or “hybrid façade”, integrates functions related to the environment and building physics like active environmental-control or lighting components.



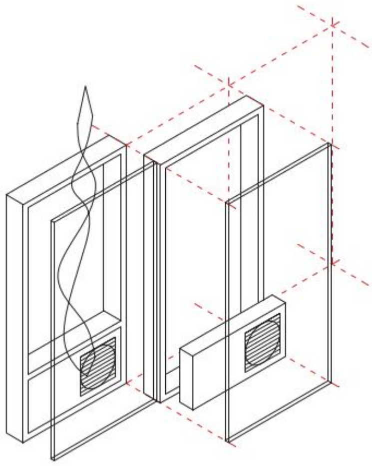
(a) Debitel Headquarters, Stuttgart, RKW Architektur + Städtebau, 2002



(b) alternatingfacade

Figure 2.7: Figure on the right (b) shows a representation of the alternating façade and figure on the left (a) shows the Debitel Headquarters in Stuttgart, where Different parts of the façade in this building were built as single-skin façade with a permanent louvre layer, single-skin façade with a louvre layer behind it and double façade (Klein, Bilow, and Auer 2007).

(a) Post Tower, Bonn, Helmut Jahn, 2003



(b) integratedfacade

Figure 2.8: Figure on the right (b) shows a representation of the integrated façade and figure on the left (a) shows the Post Tower in Bonn, which constitutes one of the first hybrid façades where environmental-control modules built into the top part of the façade could be controlled locally as individual units (Klein, Bilow, and Auer 2007).

2.3. Adaptivity and the building envelope

2.3.1. Definition of adaptive façade

Over time, the interest shifted towards the interrelationship and interaction between the building and its surrounded environment, which resulted to the development of the adaptive façade. The term 'adaptive' is often synonym to 'responsive', 'dynamic', 'switchable', 'smart' and 'active'. What distinguishes this type of façade technologies is its ability to reversibly adjust physical properties in response to transient boundary conditions in order to meet the changing preferences of building users (R. . Loonen et al. 2013). In recent years, architects and building engineers have taken an important step towards these kind of responsive solutions. This is facilitated with the elaboration of new materials, more advanced

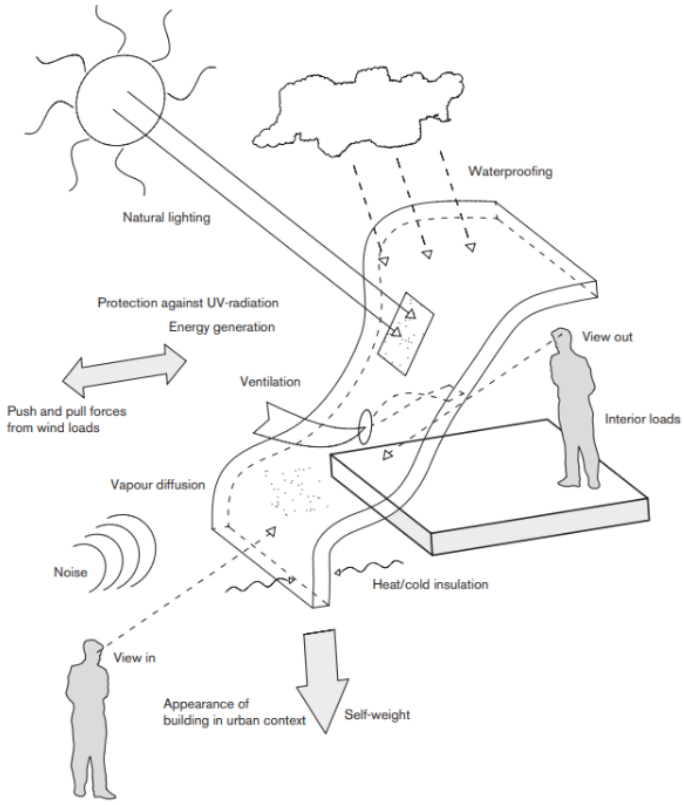


Figure 2.9: Figure indicates the several functions of a facade (Klein, Bilow, and Auer 2007).

building construction techniques and equipment. In this regard, instead of shutting the environment out, adaptive façades makes use of it, in a manner that can have a positive impact on the indoor comfort level of the occupants as well as on the energy consumption.

In the literature, different descriptions can be found for adaptive skins based on how the envelope responds to user requirements and external environmental conditions. R. . Loonen et al. 2013 defines in his paper the “Climate Adaptive Building Shell (CABS)” as a façade system which is able to adapt as a function of the buildings’ users’ needs and the variable climatic conditions to which the building envelope is exposed. By definition, a climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time, either passively or actively, in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building energy performance and/or interior comfort. An envelope with the capacity to adapt itself through changes in reversible, incremental and mobile ways is defined as “Acclimated Kinetic Envelope (AKE)” according to Wang 2016. A different definition of climate adaptive building skin is given by Wigginton and Harris 2002, namely “Intelligent Building Skins (IBS)”, where they identify responsiveness, not only to environmental changes, while the identification of an envelope that changes in response to a acclimate change is given by Hasselaar 2006 as “Climate Adaptive Skin (CAS)”, which can adjust and adapt itself to changing situation.

2.3.2. Adaptive façade classification

There are several ways that adaptive façade can be classified. The characterisation can be made based on different factors, namely the purpose of the façade, the responsive function, the type of function, the components, the response time, the spacial scale, the visibility level and the degree of adaptability. This characterization in terms of technologies and purpose is indicated in Fig 2.10. In addition, an alternative way of classifying the adaptive façade can be done in terms of system, component and material level, based on the scope of interest and scale of the dynamic mechanism. This can be seen in the Figure 2.11.

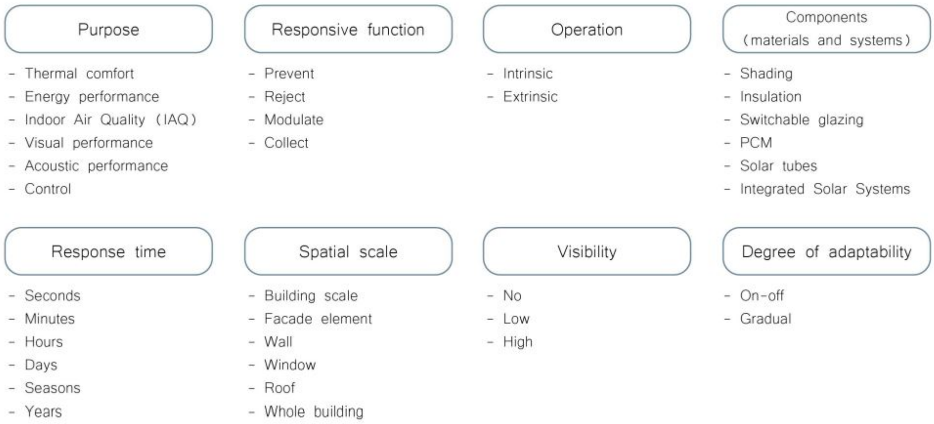


Figure 2.10: Adaptive façade classification (adapted from Knaack et al. 2015).

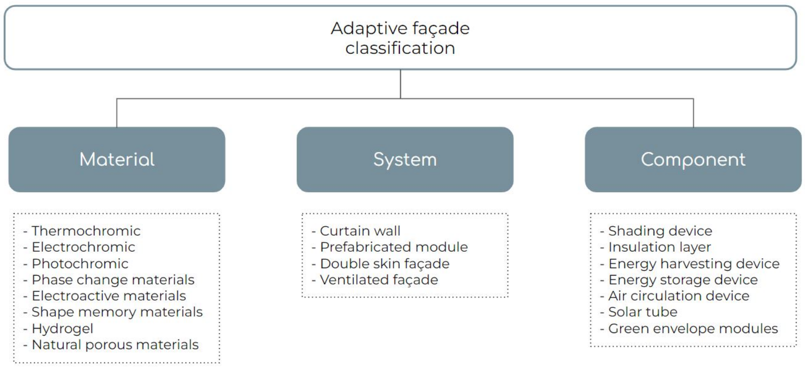


Figure 2.11: Adaptive facades classification based on material, component and system scale (adapted from Knaack et al. 2015).

From the above-mentioned classifications it becomes clear that the adaptive façade technologies cover a broad spectrum of aspects and depending on the area of interest, different aspects can be exploited to achieve the desired building performance and environmental response.

2.3.3. Bio-inspired design approach

Biomimetics

During the literature study of the adaptive façade technologies, a relevance is found to nature's mechanisms for environmental adaptiveness. The latter, led to the further exploration of the working principles of the natural mechanisms and systems and its possible correlation with the building environment. All these are subject of study of the field of biomimetics, which is the science that studies the replication in humans' design of natural methods and processes. In other words, biomimetics aims on the exploration and the execution of designs based on strategies found in the natural environment that can be converted to sustainable solutions for shaping the buildings. According to Knippers and Speck 2012, the applications of biomimetics in research follow two different approaches: "bottom-up" and "top-down" (see Fig 2.12). In the bottom-up approach, the knowledge starts from the observation and analysis of natural role models and then the information is transferred to other disciplines like engineering where it will be translated and applied as a solution to a problem, while the opposite process is followed in the top-down process. More specifically, in the top-down process, research begins from the engineering field, where technical problems are precisely defined prior to determining a solution, and nature is regarded as a source of inspiration for possible solutions to be interpreted in order to obtain the technical solution (Knippers and Speck 2012).

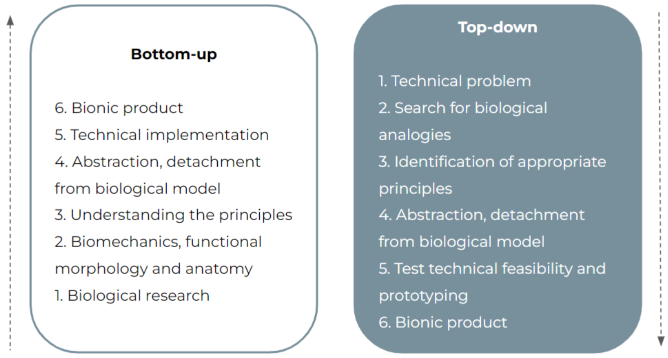


Figure 2.12: Bottom-Up and Top-Down approaches of biomimetics (adapted from Knippers and Speck 2012).

Adaptive thermal regulation mechanisms in nature

Nature is often considered as a source of information when designing temperature control and energy management systems in buildings. Thermoregulation is the thermal adaptive mechanism that birds and mammals have evolved which helps them survive by maintaining a constant body temperature in response to changing environmental conditions. The latter can be achieved through a combination of conscious and subconscious processes. The first refers to tactics that occur automatically and unconsciously in the body of animals while the second refers to strategies that animals deliberately follow to help regulate their body temperature. Among both of them are, the production of heat through metabolism, the development of a well-insulated structure, the regulation of their temperature within defined limits, the modification of the microclimate and their ability to adapt heat exchange with their environment. These biological adaptations are quite flexible, since they allow animals to modify their body temperatures to the hourly, daily, or annual demands for energy. In this regard, animals have developed an insulation mechanism, which changes dynamically, responding to variation in the environment and seasonal climate patterns. An example of conscious tactic of birds is the feather fluffing. Birds tend to elevate their feathers instantaneously to regulate heat exchange in response to the variations of air temperature. This is controlled by their feathers' muscles, which act as actuators, and results in fluffing or flattening of the plumage. In the event of fluffing, birds create air pockets for additional insulation in cold temperatures which can lead to an increase in depth of feather and of insulation of 50% (McCafferty et al. 2017). While a subconscious process is the phenomenon of vasoconstriction and vasodilation of mammals. In the case of vasoconstriction, the blood vessels located underneath the skin constrict, reducing blood flow to the skin, which prevents warm blood from cooling down. When mammals exhibit the opposite phenomenon, and want to exhale the excess heat, they use the vasodilation mechanism, where the blood vessels underneath an animal's skin becomes wider allowing more blood to flow. Therefore, by selectively changing the thickness of their blood vessels in response to changing environmental conditions, they can adjust their body temperature to the preferred temperature range.

A schematic diagram of the way nature can be interpreted for architectural purposes can be seen in Fig 2.13, where the structure and the working mechanism of the penguin's feathers can be source of information for the development of an adaptive thermal insulation system. In this paradigm, the interplay of biology and architecture is achieved through the parallelism of the penguins' feathers and the façade of the building. More specifically, the tightly packed structure of penguins' feathers that allows air to be trapped for thermal regulation could be a reference point for the design of a building's insulation system that can operate based on the same mechanism.

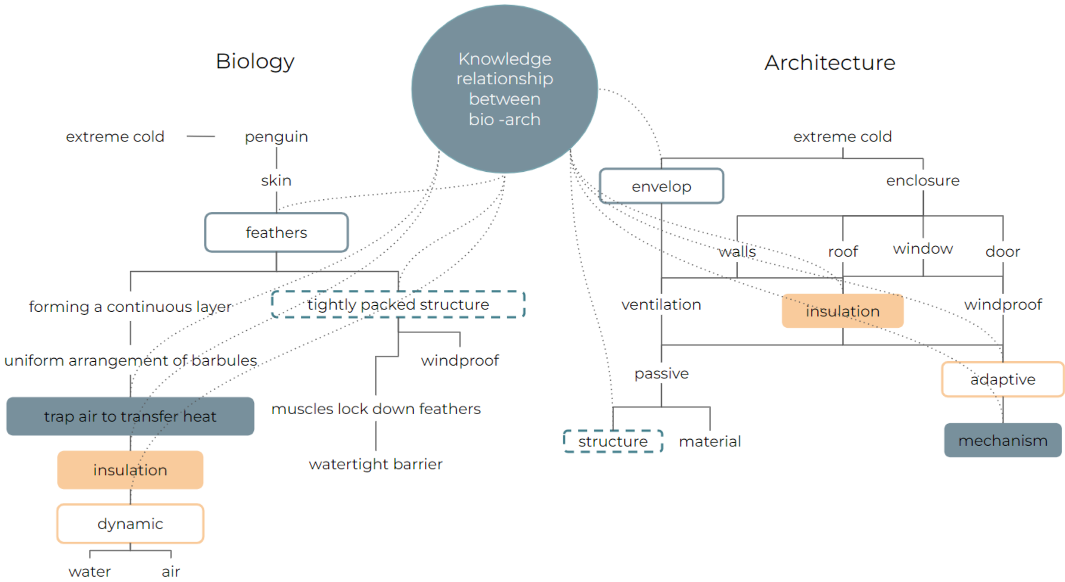


Figure 2.13: Relationship between biology and architecture (adapted from Chayaamor-Heil and Hannachi-Belkadi 2017).

2.4. Building envelope and thermal performance

2.4.1. Heat transfer mechanisms

Building elements can exchange energy, in the form of heat, when there is a temperature difference between the indoor and outdoor space. The heat always flows from the object of high-temperature to the object with low-temperature. In this way, buildings can gain or lose heat. The transport of heat is realized in three ways: conductive heat transfer, caused by the random motion of particles in the substance, convective heat transfer, which involves the combined processes of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow) when thermal energy transports from one location to another, and radiative heat transfer, resulting by the vibrational and rotational movement of the molecules and atoms of a substance.

Conduction

Heat conduction is the transfer of energy from particles of higher energy to particles of lower energy due to interaction between the particles. It occurs within a body or between two bodies in contact without bulk motion of matter. Conduction takes place in all phases of solids, liquids and gases. Conductive heat transfer can be described by the First Law of Thermodynamics the well-known Fourier's Law. The three-dimensional form of which can be described with the following equation:

$$q_k = -k \cdot \nabla T \qquad (2.1)$$

The formula indicates that the conductive heat flow density q_k is a function of the thermal conductivity k (or λ) and temperature gradient ∇T at (x, y, z dimension), where the thermal conductivity is considered as an inherent material property which depends on the nature and dimensions of the heat transfer medium [1], while the temperature gradient depends on the boundary conditions. The thermal conductivity k (or λ), can be described as, the amount of heat flow transfer through a medium of one meter thick, over an area of one square metre with a temperature difference of 1 Kelvin. The lower this value, the higher the thermal resistance, since it is more difficult for conductive heat to pass through the material (Kuijpers-Van Gaalen, Zeegers, and van der Linden 2018).

[1] In microscopic level the thermal conductivity is not considered as an inherent material property but is attributed to free electron flow from higher to lower energy levels, lattice vibration of photons and molecular collision of fluid particles in gases or liquids.

Convection

Heat transfer through convection can be the result of energy transfer due to random motion of molecules of fluid (diffusion) or due to the bulk motion of fluid (advection) on the inner and outer surface of a material or inside a cavity. Two types of convective heat transfer may be distinguished: natural convection and forced convection. The former occurs as a consequence of the temperature-dependent density of a fluid, resulting in buoyancy-driven flow, while the latter occurs when a fluid is forced to flow over the surface by an internal source such as fans and pumps, creating an artificially induced convection current (Hall and Allinson 2010). Convective heat transfer can be introduced by the following equation:

$$q_c = h_c \cdot (T_2 - T_1) \tag{2.2}$$

The formula indicates that the convective heat flow is a function of the convection coefficient h_c and the temperature. The convection coefficient depends on geometry (shape and orientation of surface), material properties (surface roughness) and the thermophysical properties of the interstitial fluid. These parameters will determine whether the flow over the surface is buoyancy driven or forced, laminar or turbulent. In terms of thermal performance, laminar flows, are characterized by well-ordered patterns along the velocity direction, leading to a constant heat transfer rate across the streamlines, which is independent of fluid velocity, while the turbulent flow, is characterized by irregular fluctuations of fluid velocity. For the description of natural convection, Rayleigh number $R\alpha_\delta$ and Nusselt number Nu_L are commonly used, which can be described with the following formulas:

$$R\alpha_\delta = G_r \cdot P_r = \frac{g \cdot \beta \cdot \Delta\mathrm{T} \cdot \delta^3}{\nu \cdot \alpha} \tag{2.3}$$

$$Nu_L = \frac{\delta \cdot h_c}{k} \tag{2.4}$$

In fluid mechanics, the Rayleigh number is a dimensionless number associated with natural convection. It can be defined as the product of the Grashof number G_r, which expresses the relationship between buoyancy and viscosity within a fluid, and the Prandtl number P_r, which expresses the relationship between momentum and thermal diffusivity. As the Rayleigh number increases, the convective heat transfer coefficient will follow the same trend while below a critical value there is no fluid motion and heat transfer is only via conduction. Nusselt number is correlated with the Rayleigh number and is defined as the ratio of convective to conductive heat transfer at a boundary in a fluid (Kimber, Clark, and Schaefer 2014).

Radiation

The third mode of heat transfer is radiation. Every object or body with a temperature higher than 0 K (-273 °C) can emit heat through radiation in the form of electromagnetic waves. When an electromagnetic wave encounters a surface, the photons can either be absorbed, reflected, or transmitted. In the case of opaque materials, transmission does not occur and the majority of photons are absorbed. As a result of this process, the energy carried by the photons is converted into thermal energy and the surface radiates a certain amount of heat back into its environment at a rate that depends on the emissivity coefficient of the material. The latter is a function of wavelength and temperature and ranges from 0 to 1. When the emissivity coefficient equals 1 the maximum amount of radiation is emitted from the surface, which is the case of a black body radiator (Kuijpers-Van Gaalen, Zeegers, and van der Linden 2018). The radiative heat flow can be expressed with Stefan-Boltzmann Law as follows:

$$q_r = \sigma \cdot \mathrm{T}^4 \cdot \mathrm{A} \tag{2.5}$$

Where σ is the Stefan-Boltzmann Constant (5.6703 10-8 (W/m^2K^4), T is the absolute temperature (K) and A is the area of the emitting body (m^2).

2.4.2. Thermal properties of materials

Thermal resistance

An important thermal property which is related to the thermal conductivity and can indicate the thermal performance of a material is the thermal resistance. Thermal resistance can be defined as a measurement of a temperature difference by which an object or material resists a heat flow. The thermal resistance for conduction in a plane surface of a material is expressed with the following formula:

$$R_m = \frac{d}{\lambda} \tag{2.6}$$

The formula indicates that the thermal resistance of a layer of a material is the quotient of the division of the thickness of the layer with the thermal conductivity of the material. Therefore, increasing the thickness of the layer increases the thermal resistance of the material.

Thermal Transmittance (U-value)

Thermal transmittance can be defined as the rate of transfer of heat through matter. The thermal transmittance of a material or an assembly is expressed by the U-value. The thermal resistance of a structure is the reciprocal of its thermal transmittance. Therefore, the lower the U-value of a structure or a material the less the amount of heat that can pass through it. The U-value of a structure can be calculated as the following formula indicates:

$$U = \frac{1}{R_{si} + R_{se} + \Delta T \cdot \frac{A}{Q}} \tag{2.7}$$

2.5. Thermal insulation technology

2.5.1. Classification of thermal insulation materials

Thermal insulation materials are used to insulate the interior space from the exterior environment by means of effectively reducing the transfer of heat between objects in thermal contact or in range of radiative influence.

In the paper of Papadopoulos 2005, a classification of the thermal insulation materials is given, based on their chemical and physical properties (see Figure 2.14). From this classification four main categories emerge; organic, inorganic, combined and new technology materials:

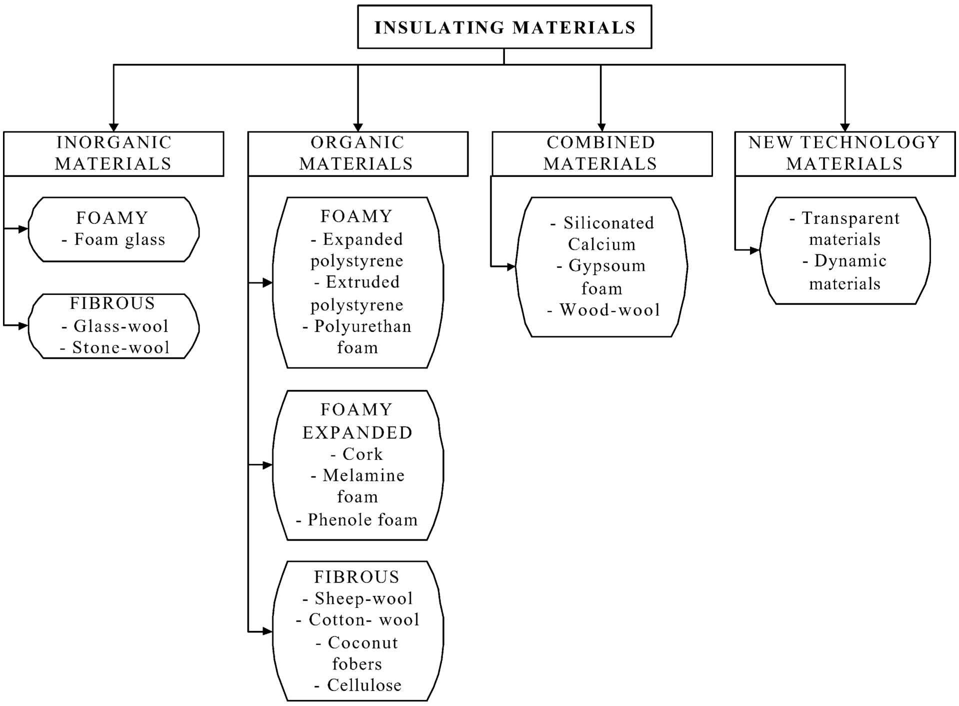


Figure 2.14: Classification of the insulating materials based on their chemical and physical properties (Papadopoulos 2005).

Additionally, a distinction between traditional/convective and state-of-the art insulation materials can be achieved based on their performance in regard to their physical properties, health and environmental issues, their applicability in the building environment and finally their cost. The products that can achieve a higher performance compared to traditional insulation materials can be characterised as state-of-the art. According to Papadopoulos 2005, the indicators for the evaluation of the performance are:

- the ability of the material or product to achieve a lower U-value as compared to conventional insulating products.
- the improvement in the material, either in contrast to their existing state of the art or in comparison to similar energy-performing materials.
- their cost compared to the other insulation products.

Material	Thermal conductivity (mW/mK)	Cutting to adapt for construction	Resistance – fire, water and chemicals	Resistance – physical damage	Performance if perforated	Cost per thermal resistance	Environmental impact of production and use
Vacuum insulation panel	4–8	No	Low	Low	Worse	High	Moderate
Traditional materials							
Cellulose	40–50	Yes	Low	Low	Same	Low	Low
Fibreglass	30–40	Yes	High	High	Same	Low	Moderate
Expanded polystyrene	30–40	Yes	Low	Moderate	Same	Low	High
Extruded polystyrene	30–32	Yes	Moderate	Moderate	Same	High	High
Polyurethane	20–30	Yes	Moderate	High	Same	High	High
State-of-the-art materials							
Gas-filled panel	10–40	No	Low	Low	Worse	High	Moderate
Aerogels	13–14	Yes	Moderate	Low	Same	High	Moderate

Figure 2.15: Comparison of traditional and state-of-the art insulation materials (Alotaibi and Riffat 2013).

2.5.2. Strategies to improve thermal performance

Three main strategies for reducing heat transfer can be found, each focusing on reducing conductive, convective, and radiative heat transfer.

Porosity affects a material's thermal conductivity greatly since air has a lower thermal conductivity than solids. As a result, lowering the proportion of solid material to void can reduce the heat transfer by conduction. The same effect has the incorporation of thin connecting walls, or discontinuous fibers into the material's structure. On the other hand, convective heat transfer is facilitated through the movement of fluid. Therefore, the second method aims to reduce convective heat transfer, by creating small voids or air pockets. In this way, air movement can be minimized which can lead to a substantial reduction of convection. Finally, as a third strategy radiative heat transfer can be minimized by using low emissivity materials.

Porosity

Heat transfer through a solid material is primarily controlled by the thermal conductivity of the material. Gases, have a much lower thermal conductivity compared to liquids and solids, due to their larger intermolecular distance. Thus, a straightforward method to reduce conductive heat flux is by replacing a portion of a solid with a gas through the incorporation of small pores into its solid structure. Depending on the shape of the pores, two different pore structures can be observed. Open pore structures that are complexly interconnected such as pores in granular or fibrous materials and closed pore structures such as pores in extruded polystyrene foams.

As far as it concerns, the heat transfer inside the pores, all three modes are present. In this regard, when a porous nonmetallic solid is subjected to a thermal gradient, heat transfer includes in the solid phase, vibrational conduction, conduction by clashing gas molecules in the pore phase, and radiation either through a semi-transparent solid phase or across large pores. Thus, the effective thermal conductivity of a porous structure can be estimated according to the following formula:

$$\lambda_{eff} = \lambda_{cond} + \lambda_{conv} + \lambda_{rad} \tag{2.8}$$

Previous research conducted by Smith (2013) provided usefull insight in the relation of porosity level and thermal performance. This paper examines the effective thermal conductivity of porous materials with pore volume fractions ranging from 4 to 95%. The results of the study showed that for pore volume fractions less than 15%, variation in the size of the pore affects the effective thermal conductivity, while variations in the porosity level have less significant effects on it. On the other hand, for pore volume fractions greater than 15%, the porosity becomes significant and an increase in the porosity level leads to lower thermal conductivity values. The relation between effective thermal conductivity and porosity is indicated in Figure 2.16 according to which, the thermal conductivity increases with relative density, with nearly linear relationship (Smith et al. 2013).

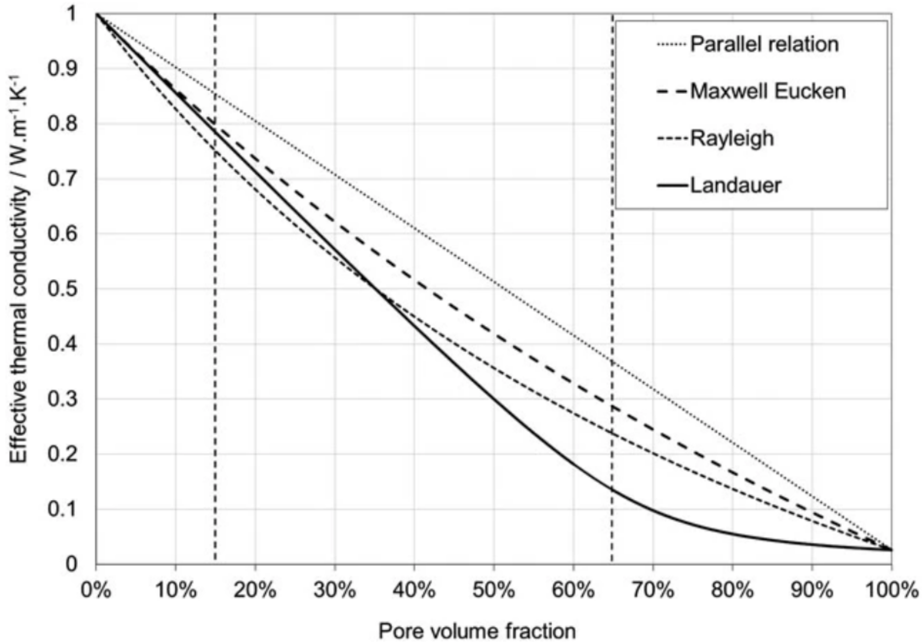


Figure 2.16: Effective thermal conductivity as a function of pore volume fraction according to analytical models (Smith et al. 2013).

In terms of manufacturing, different methods can be used to generate porosity in the solid phase of a non-metallic material, which are related to the controlling the firing cycle of a powder compact obtained by uniaxial forces. With this method a pore volume fraction ranging from 10 to 45% can be achieved. For a higher pore volume fraction, more complex methods including freeze casting, replica, sacrificial, or direct foaming techniques are commonly used (Smith et al. 2013).

Additional cavities
Within a wall cavity, temperature-dependent heat transfer can occur in all three modes; conduction, convection and radiation. Among them, conduction and convection are greatly affected by the width of the cavity. More specifically, in the case of a vertical cavity, an increase in width enhances heat transfer due to convection while decreasing the cavity width has the opposite effect. On the other hand, conductive heat flux and cavity size have an inverse proportional relationship. Consequently, in very narrow cavities, where the air layer is very thin, the resistance to convective heat transfer of air will be significantly small since there not enough molecules of air for convection to take place. The opposite phenomenon will occur in wider cavities. On the other hand, the radiation is independent of the cavity width and is affected by the surface temperatures at the cavity surfaces (Kuijpers-Van Gaalen, Zeegers, and van der Linden 2018). The relation between the width of the cavity and the three modes of heat transfer is presented in Fig 2.17.

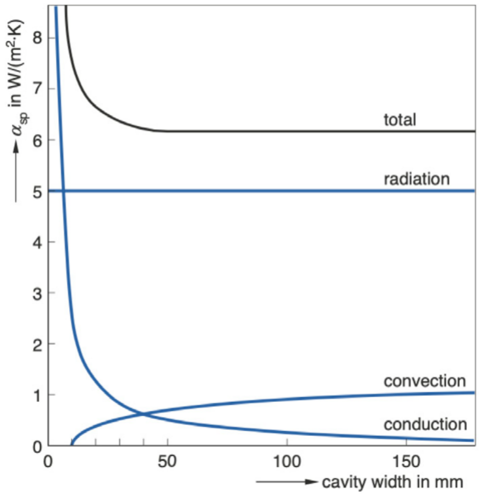


Figure 2.17: Heat transfer through vertical air cavities through conduction, convection and radiation as a function of the width of the cavity (Kuijpers-Van Gaalen, Zeegers, and van der Linden 2018).

The thermal conductivity of still standing air is approximately 0.025 W/mK at room temperature and standard pressure, but its resistance reduces by the flow of air within the cavity. Based on that, another strategy to enhance the thermal performance of a system considers the incorporation of a number of cavities within the same thickness, which may resemble the case of a multi-pane window. According to the work of Kimber (2014), an increase in thermal resistance can be achieved by incorporating thin polymer membranes placed inside a cavity wall with the aim of reducing natural convection to such an extent that it can be considered negligible. The outcome of this research showed that changes in natural convection patterns are affected by changes in the number of internal cavities. As Figure 2.18 indicates, for internal thickness of wall of 10, 15 and 20 cm when the number of cavities is increased, the Rayleigh number is decreased in a linear way which leads to the minimisation of the effects of natural convection. However, Nusselt number approaches a value of unity for large cavity number (N), which approximately occurs near N = 4, 5 and 6 for L = 10, 15, and 20 cm, respectively. Therefore, introducing more partitions would no longer significantly reduce the effects of natural convection (Kimber, Clark, and Schaefer 2014).

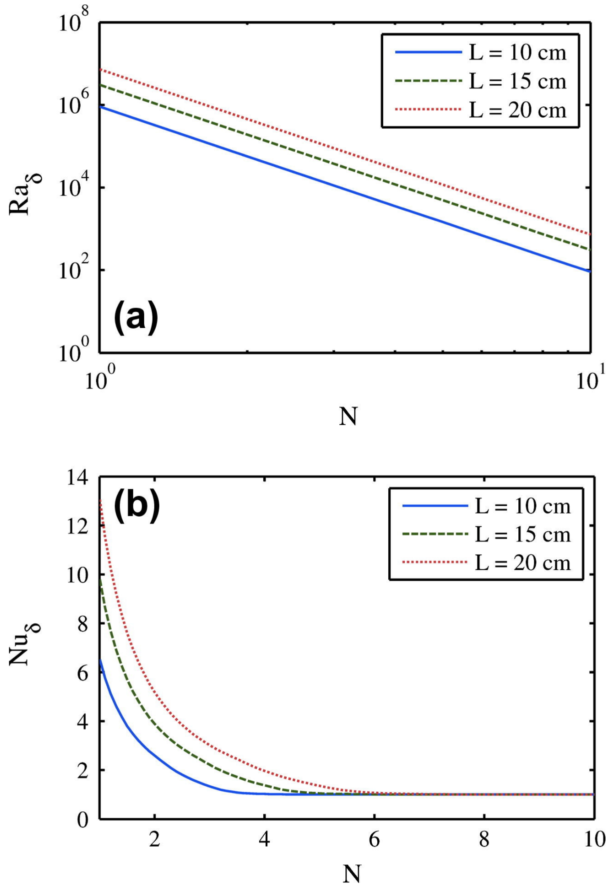


Figure 2.18: Partition natural convection and its dependence on the total number of partitions: (a) local Rayleigh and (b) local Nusselt numbers. (Kimber, Clark, and Schaefer 2014).

2.5.3. Parameters influencing heat transfer capability

Approaching the insulation material from the heat transfer principle level there are three possible directions to follow in order to change the thermal transfer capability. This can be accomplished through alterations to the carriers' density, mobility, and energy capacity (Cui and Overend 2019).

Heat carrier density

Changes on the physical properties of the thermal conductivity can be realized by modifying the number of available heat carriers in the medium which will alter the carriers' density. For conduction in dense gases, the thermal conductivity is determined by the interactions between fluid molecules, so shifts of the thermal conductivity can be achieved by regulating the airflow inside the wall cavity. When the pressure inside the cavity is close to the atmospheric pressure, then the heat transfer falls into the viscous regime (Knudsen number Kn < 0.01). Under these circumstances, the gaseous thermal conductivity is independent of pressure, because the reduction of available gas particles will simultaneously increase their mobility and the mean free path, and thereby neutralize its effect on the thermal conductivity. On the other hand, when the pressure inside the cavity is very low then the heat transfer falls under the molecular regime and the thermal conductivity becomes very sensitive to the pressure level and its proportional to the pressure. This means that for an adaptive thermal insulation, a high level of vacuum (very low pressure) should be ensured in order to be able to reversibly control its thermal conductivity. A method to achieve this is to artificially create small pores or gaps in the vacuum volume to reduce the local Knudsen number and thus make it easier to achieve the pressure-sensitive molecular regime. Such microstructures can be achieved by either using porous filling materials, or fabricating microscale narrow gaps between two bounding surfaces.

Heat carrier mobility
A different approach to shift the heat transfer capability is to improve or obstruct the mobility of heat carriers. This, involves methods to change the geometry of the insulation material. For thermal conduction a method of manipulating carriers' mobility is by creating or removing thermally conductive paths, which can be achieved by structurally rearrange the internal structure of the insulation material. A straightforward strategy for this is by bringing into contact or by separating two solid surfaces, which leads to an alternation between a solid conduction when the surfaces are in contact to gaseous conduction when the surfaces are separated. The gaseous conduction is characterized by a higher thermal resistance than solid thermal conduction. In the case of thermal convection the manipulation of the fluid motion can be by accelerating the fluid circulation, utilizing a pump or fan, in a pipe, embedded in the envelope or by interrupting the buoyancy-driven circulation in the cavity.

Heat carrier energy capacity
The third strategy for the control of the heat transfer capability is to change the energy density of heat carriers. This normally, includes energy conversion from one form to another form of energy. This can be achieved for instance by the interruption of the evaporation-condensation cycle resulting to a shift in heat transfer between a conductive state, which releases or absorbs a significant amount of latent heat by evaporation or condensation, and an insulated state, dominated by gaseous conduction.

2.6. Adaptive insulation technologies for thermal control

2.6.1. Adaptive insulation technologies

Despite the advances on adaptive insulation technologies in the field of aerospace, vehicles, and biomedicine, the application in the building environment is still limited due to the lack of effective products on the market that are applicable to the building environment. In the paper of Cui and Overend 2019 a detailed review is given on the available adaptive insulation technologies derived from the field of aerospace, batteries and vehicles design in order to investigate the possible applications of them and the challenges of their integration into the built environment.

Active Vacuum
Working mechanism
The working principle of this technology is based on the collision between fluid particles and solid surfaces that creates heat transfer through conductivity. Three different regimes can be distinguished: the viscosity regime, where heat transfer is dominated by collisions between fluid particles, the molecular regime, where heat transfer is governed by direct collision between fluid particles and solid surfaces, and the transition regime first two.

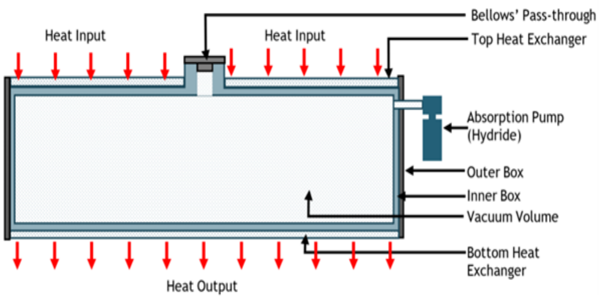


Figure 2.19: Structure of vacuum-based thermal switch (Cui and Overend 2019).

Structure
The main idea of a vacuum-switchable active insulation is to alternate the heat transfer regime between the conductive viscosity regime and the insulated molecular regime. This is achieved by means of reversibly pressurize or discharge the filling materials or narrow the gaps in the insulation layer with a

thermally conductive gas. A typical schematic diagram of a vacuum-based insulation is shown in Figure 2.19. The system consists of a vacuum volume enclosed in a box-shaped envelope and a pump which controls the pressure inside the box. In order to create small pores or gaps inside the vacuum two methods can be followed, namely; use a porous filling material, or fabricate microscale narrow gaps between two bounding surfaces.

In order to achieve good switching efficiency it must be ensured that the influence of heat transfer through the static enclosure structure is minimized, and that an sorption (absorption or getter) pumps that drive the evacuation–pressurization cycle is used rather than a conventional pump. The former can be achieved by having thermally conductive frontal walls and insulating side walls and supports.

Building Integration issues

An advantage of this technology is its high switching ratio. On the other hand, some pitfalls of this technology make it difficult to integrate it into an adaptive building envelope. These are related to the rather large response time and energy consumption of evacuation as well as the requirements for evacuation pumps in terms of permeability, long-term durability and structural robustness.

Mechanical Contact

Working mechanism

The working principle of this technology involves the bringing of two panels into mechanical contact or separation. The presence/absence of mechanical contact causes a change in the dominant thermal transfer mechanism from gaseous convection (or conduction) to solid thermal conduction, resulting in a rapid alternation in overall heat transfer rate by orders of magnitude.

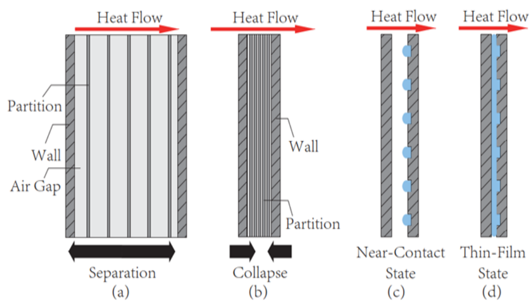


Figure 2.20: Structure of mechanical contact based insulation (Cui and Overend 2019).

Structure

Normally, a mechanical thermal switch comprises three basic elements namely; two polished solid surfaces, an actuator which separates two surfaces or brings two surfaces into contact, and an enclosed cavity as Figure 2.20 indicates. The actuation can be achieved by the employ of several mechanisms, such as: phase change material (para□n wax), electrostatic actuator to activate the mechanical contact between solid surface, shaped memory alloy to move the two surfaces into contact, and a helical return spring to separate them. The performance of mechanical contact switchable insulation can be improved by minimizing the contact thermal resistance at the conductive (contact) state, and by reducing convective heat transfer between bounding surface at the insulated (separated) state. The conductive state can be enhanced by the application of a soft metallic coating or elastomeric layer while the convective heat transfer can be decreased additional partitions in between the wall which will reduce the gap thickness of the cavity (Kimber, Clark, and Schaefer 2014).

In order to achieve good switching efficiency it must be ensured that the influence of heat transfer through the static enclosure structure is minimized, and that an sorption (absorption or getter) pumps that drive the evacuation–pressurization cycle is used rather than a conventional pump. This could be achieved by having thermally conductive frontal walls and insulating side walls and supports.

Building Integration issues

A strength of this system is its relatively simple structure and its high switch ratio. However, the dependence of this system to the cyclic movement of bounding surfaces may pose a challenge of integrating into the building envelope where long term operation is required.

Suspended Particles

Working mechanism

Suspended-particle-based adaptive insulation technologies make use of external electric and/or magnetic fields to break or form microstructures. This technology is based on the principle of heat transport in fluid which can be modified by introducing thermally conductive insoluble (solid) particles. Thermal transport can be achieved by modulating the connectivity and spatial distribution of clustered nanoparticles in the base fluid, leading to a step change in effective thermal conductivity. The formation of such clustering processes is influenced by external fields, such as gravity, magnetism and temperature.

Building Integration issues

A drawback of this technology is the fact that it has a small switching ratio and that requires the presence of electrical or magnetic fields which increases its complexity for integrated into an adaptive building envelope.

Pipe-Embedded Insulation

Working mechanism

Pipe-embedded adaptive insulation controls the convective heat transfer across the embedded pipes, by accelerating or impeding the motion of fluid particles or disturb thermal boundary layers. In the insulated state, the fluid in the pipe is motionless, while once switched to the conductive state the fluid is activated to move by the actuators. The latter leads to a more efficient convection-dominated heat transfer mode.

Structure

Usually, a pipe-embedded adaptive insulation consists of three main elements: actuators that drive the movement of fluids or deform the bounding surfaces, sensors that detect flow patterns and temperature profiles and control strategies which process signals from sensors and operate actuators to modulate the fluid flow. A cross section of this type of system is shown in Figure 2.21.An hypothetical structure of this system can be closed-loop forced convective dynamic insulation. This insulation system utilizes ducts and fans to induce air flows along the back and front sides of the insulation panels and in this way the heat exchange between indoors and outdoors is enhanced.

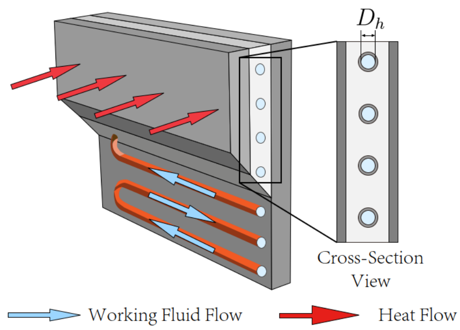


Figure 2.21: Structure of pipe-embedded insulation (Cui and Overend 2019).

Building Integration issues

Generally, this technology can reach a high switch ratio and it has some potentials to be integrated into existing technologies whenever convection takes place. However, a likely weakness of this system is the energy required for the pump or fan to drive the fluid flow might outweigh the benefit of this system. In addition, actuators and fans / pumps should largely meet certain requirements in order to be used in a building shell.

Phase-Change

Working mechanism

Phase-change switchable insulation can undergo transitions between solid, liquid and gaseous states, as response to the change in boundary conditions, such as temperature and pressure. The main working principle is the interruption of the evaporation/condensation cycle which leads to an alternation in heat transfer between a conductive state, where heat is mostly transported by evaporation and condensation processes, and an insulated state, where the gaseous conduction or single-phase natural convection is dominant.

Structure

One of the most effective phase-change switchable insulations is the variable conductance heat pipe (VCHP), a typical configuration of which is shown in Figure 2.22. Four basic elements constitutes an VCHP: a working fluid which undergoes phase transition during heat transfer, a sealed container, consisting of evaporator, condenser and transport (adiabatic) section, a wick structure, pumping condensates back to the evaporator by capillary pressure and a control unit which purposefully and reversibly interrupts the evaporation-condensation cycle. The evaporated fluid creates a pressure gradient that drives vapor to the condenser. During the condensation of vapor, latent heat is released and the capillary pressure resulting from the wick structure pumps the condensate back to the evaporator.

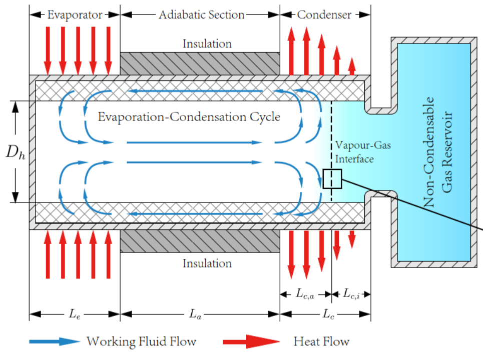


Figure 2.22: Heat and mass transfer in a gas-loaded heat pipe (Cui and Overend 2019).

Building Integration issues

The strongest point of this technology is the significantly high switch ratio and its range. Improvement opportunities lie in the interruptions of the evaporation-condensation cycle leading to a change in heat transfer. Due to the limited space of a building envelope the development of micro flat-plate heat pipes may make this technology suitable for building applications. Nevertheless, flat-plate systems have not literature reviewed because interruption techniques such as non-condensable gas control, vapor flow control, liquid control that are successfully applied in conventional heat pipes, cannot be easily fitted into a flat-plate system.

SPONG3D

The development of an adaptive insulation façade system is described in the paper of M. V. Sarakinioti et al. 2018 where a 3D-printed façade element is developed known as SPONG3D by employing complex geometries in order to succeed an active temperature control. The aim of this project was to integrate multiple functions into a single adaptive façade system emphasizing first on the to optimization of the thermal performance.

Structure

This façade system incorporates two sub-systems (Figure 2.23). The first system consists of a porous inner core with air cavities to provide thermal insulation. A relatively low solid to gas ratio characterizes the core's cellular structure. The system's inside houses the air cavities, which come in a variety of sizes. The thermal characteristics of the cellular structure and the complexity of the manufacturing process governed the system's ultimate geometry. The second subsystem is composed of a number of external tubes that assist liquid flow. As an adaptable heat storage medium, the liquid serves as a moving thermal mass. Based on necessity, the liquid can be transferred from one side of the façade to the other to absorb and release the heat. Each façade panel is comprised of two external layers, two pumps for water circulation, and two inside layers to manage the flow of liquid through the entire system. A tank that is located in the center of the façade panel can be used to store the liquid. During cooling season, the liquid is initially pumped to the outside layer to discharge the heat to the cool night sky after being deposited on the interior to absorb internal heat gain. On the other hand , water is placed outside during the heating season to retrieve the solar heat gain during the day and is then pumped inside to release this heat inside the building. In order to store the water, the pumps are also connected to the water tank. (V. Sarakinioti et al. 2018).

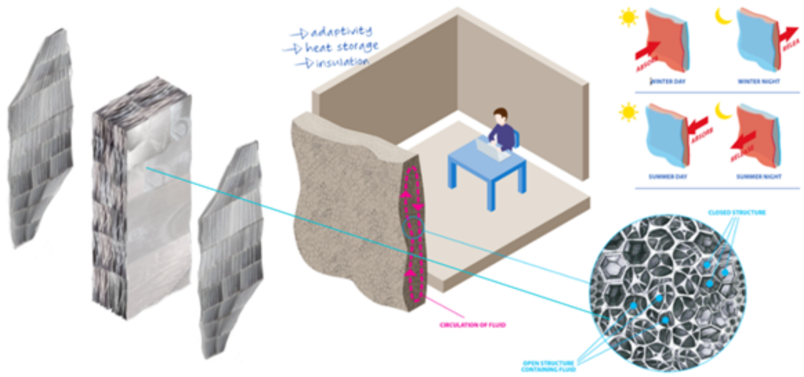


Figure 2.23: Representation of the adaptive mechanism of the 3D-printed façade panel SPONG3D during a whole year (M. V. Sarakinioti et al. 2018).

In terms of energy performance, the potential for energy saving was investigated for different climates. The potential in the heating season was assessed by evaluating correlations between solar irradiance and ambient temperature. Similarly, the potential in the cooling season was examined by comparing the difference between daytime air temperature and night-time sky temperature. The outcome of this study showed that Spong3D has more potential for cooling. Energy simulations performed in an office room showed that a cooling rate of 25 W/m2 could be obtained during typical summer conditions. This roughly translates to 50% of the internal heat gains in a typical office scenario. On a sunny winter day, 4.8 kWh of thermal energy may be produced for a typical 12 m2 office. In composite climates with at least a considerable need for both heating and cooling, Spong3D's added value is most noticeable. (*SPONG3D* n.d.).

Building Integration issues

However, this adaptive façade system requires further developments to lead it towards a marketable façade product. In terms of manufacturing process a weakness of this system is related to the water circulation. The design of the channels should be improved for better water circulation, water tightness and heat storage. Another weakness is the time required for the 3D printing of the panel. In regard to the performance the structural behavior of the 3D printed material need to be examined, especially under extreme thermal conditions. Finally, its durability need to be examined long terms.

2.7. Estimation of thermal performance

2.7.1. Thermal simulation tools

Numerical simulations aim to capture multiphysics aspects of the behavior of a product. A wide range of heat transfer solvers are available in the market, which are broadly classified into two categories:

- FEM Solvers
- Computational Fluid Dynamics Solvers

The size of the model and the computation time are the main drawbacks of FEM thermal analysis. While steady-state solutions are quick, transient solutions can take several hours, even for simple problems (Tudor - George et al. 2016). A handful of software are available in the market for thermal simulation. Table 2.1 gives an overview of these tools along with their calculation method.

Table 2.1: Overview of the software tools used in research for the investigation of the thermal performance

Software tool	Solver
COMSOL multiphysics	FEM
TRISCO	CFD
ANSYS	FEM
THERM	FEM
SimScale	CFD

Among them COMSOL multiphysics and TRISCO are compared in order to determine which is the most suitable for the estimation of U-value.

COMSOL multiphysics
COMSOL multiphysics is a cross-platform finite element analysis (FEA), simulation software tool that stands out for its versatility. The coupling of different physics is possible in this tool in order to observe multiple effects in the same context. Moreover, it accepts a variety of user-defined inputs, allowing it to predict any desired situation.

Steady-state and transient analysis is possible with COMSOL. Steady-state assumes a constant input and boundary conditions which can continue with no time dependency. While in transient simulations the loading conditions can vary over time. So, with COMSOL is possible to simulate realistic scenarios. Finally, any kind of complex geometry can be imported as 3D model from CAD environments in different formats such as breps, meshes and solids. However, with this variety of features that this tool offers comes a degree of complexity. As a result, getting acquainted with the software's interface and system requires some time (*COMSOL Multiphysics® Software* n.d.).

TRISCO
TRISCO is a steady-state finite-difference method (FDM) solver and thermal simulation software tool of 2D & 3D orthogonal building components that is commonly used for building engineering purposes. Linear equations can be solved based on the energy balance technique, and the solution is derived using a fast iterative method. In TRISCO all three modes of heat transfer, namely conduction, convection and radiation can be simulated.

TRISCO is based on the FDM method, a numerical technique for solving differential equations by approximating derivatives with finite differences. The FDM is based on discretizing ordinary differential equations (ODEs) or partial differential equations (PDEs), which can be non-linear and solved employing matrix algebra techniques. Because this method incorporates a topologically square network of lines, TRISCO is unsuitable for the study of complex or irregular geometries and is limited to work only with orthogonal building components. Therefore, the user should model the geometry as rectangular blocks with vertices lying on grid point (*TRISCO: steady-state 3D* n.d.).

Each of the software tools mentioned above has different features and gives different results. The calculation method, the meshing, the way to insert the geometry and the duration of the calculation time are some of the parameters that must be taken into account to choose the most appropriate one. Therefore, an important step is to develop a list of requirements for the software tools that will determine the selection of the most suitable. Thus, the selection criteria are listed as follows:

- Heat transfer mode: The software tool should be able to simulated the three modes of heat transfer; conduction, convection and radiation
- Computational time: The duration of computational time is important. Faster computation is preferred.

Table 2.2: Comparison of different software tools for thermal analysis

	Advantages	Disadvantages
COMSOL	Possibility of working with complex geometries	High computational time
multiphysics	Multiple user-defined inputs are accepted	Complex interface
	Possibility of coupling multiple physical effects	
	Steady and unsteady state calculations	
TRISCO	Simple interface	Not transient calculations
	Possibility of simulating	Geometry has to be simplified
	all three modes of heat transfer	and rebuilt within the software
	Low computational time	

- Steady state and unsteady state simulations: Unsteady state simulations give better representation of the reality but for U-value estimations they are not necessary.
- Availability: The availability of software tool is the most important selection criterion.

Regardless of the fact that transient simulation constitutes a more accurate representation of reality, for U-value estimations, steady-state analysis is more straightforward, it requires less computational time compared to transient and it can give accurate results. So, even thought COMSOL multophysics is a power full software tool for the above-mentioned reasons in combination with the lack of availability of a software licence, TRISCO is chosen as the tool to be used for the numerical analysis.

2.8. Conclusion

In this chapter, the basic knowledge about the concept of adaptability and the heat transfer mechanisms was introduced. Adaptability ensures a systematic flexibility, allowing a façade to compensate for climatic variations in order to meet occupants' comfort requirements. The adaptation can account for seasonal variability, daily weather variations, or even future climate shift. In this way, the optimal performance of the building could be achieved. Nature could be considered as a source of information for the design of adaptive insulation technologies which could provide an opportunity to reduce building energy consumption while simultaneously improving indoor thermal quality.

Building regulations have imposed increased levels of insulation resulting in a reduction in heating demand but at the same time an increase in cooling demand, which underlines the importance of developing insulation technologies that can shift between a high insulated and a low insulated state. For high insulated state the main strategies to enhance the thermal performance of the insulation system are the incorporation of porosity and the creation of thin vertical cavities within the insulation system. Increasing the porosity level has a positive effect on the reduction of the solid conduction while the introduction of inner cavities can reduce the convective heat flow. Radiant heat flux can be minimized by using reflective material.

Then, the mechanisms that can alter the thermal transfer capability of a system were studied. This could be achieved through interventions on carrier density, carrier mobility and carrier energy capacity. Interventions in carrier density can be achieved by artificially creating small pores or voids, with the aim of creating a high level of vacuum so that the thermal conductivity can be controlled and changed in a reversible manner. Carrier mobility modifications include methods that rearrange the internal structure of the insulation system whereby a shift between a low insulating solid conductivity to a high insulating gas conductivity can be achieved. The third strategy includes energy conversion from one form to another form of energy aiming to switch from solid conductivity to gaseous conductivity.

In addition, this chapter presented the review of previous research on adaptive insulation technologies from various fields of engineering, discussing their working mechanism, structure, advantages and disadvantages of each technology as well as their applicability to the building envelope.

Finally, this chapter compared the available thermal simulation software tools. TRISCO was chosen for the numerical analysis due to its accuracy in results, fast computation time, and availability.

3

Design guidelines

3.1. Introduction

The following chapter provides an overview of the design boundaries and design criteria that are important for the development of the adaptive insulation system based on the findings of the literature review.

3.2. Design Boundaries

3.2.1. Climate zone

The Köppen world map climate classification, developed by German-Russian climatologist Wladimir Köppen in 1884, is one of the most widely used climate classification maps. According to Köppen climate classification map, five main climate zones can be identified, based on criteria like temperature, precipitation level and vegetation growth:

- Zone A: tropical or equatorial zone (represented by blue colors). This type of climate is characterised with an all-year-round monthly average temperature of at least 18°C.
- Zone B: arid or dry zone (represented by red, pink, and orange colors). This zone is characterised by large temperature swings between day and night.
- Zone C: warm/mild temperate zone (represented by green colors). The coldest month has on average a temperature between 0 °C and 18 °C, but at least one month averages above 10 °C.
- Zone D: continental zone (represented by purple, violet, and light blue colors). The coldest month has an average temperature below 0 °C, and at least one month has an average temperature above 10 °C.
- Zone E: polar zone (represented by gray colors). The all-year-round monthly average temperature is below 10 °C.

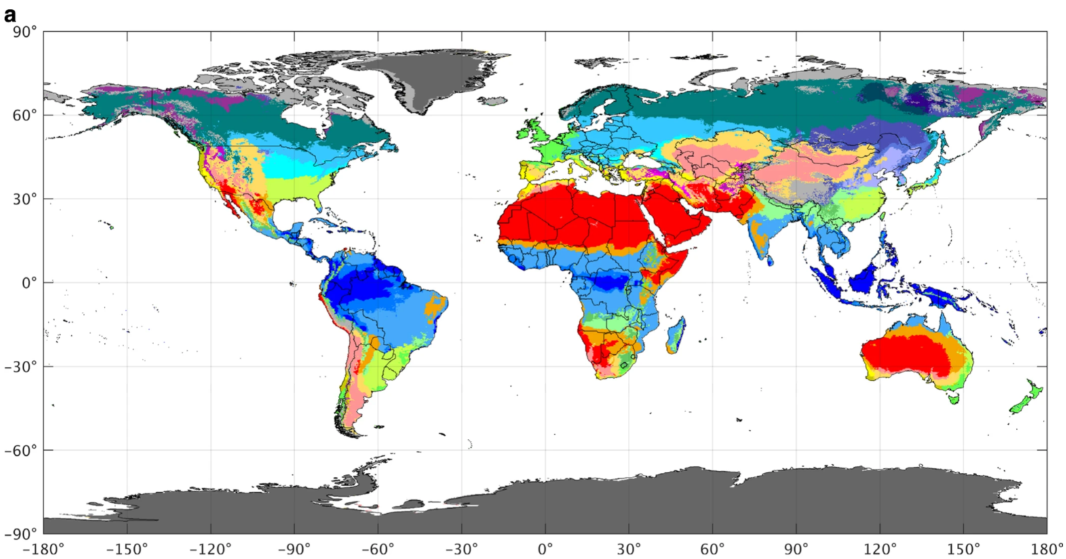


Figure 3.1: Koppen-Geiger climate classification map (Schamm et al. 2014).

A crucial step before the start of the design phase towards the development of the adaptive insulation system, is the definition of the geographical region, because different requirements apply depending on the climate zone. Thus for this project the temperate climate is chosen and the geographic region of the Netherlands.

3.2.2. Working mechanism

The main function of the insulation system is to be able to operate in a dynamic way by means of switching its thermal resistance between a high and a low value. In this regard, the state of the adaptive insulation is influenced by two main parameters; the season (heating [1] or cooling) and the direction of the heat flow. For the present thesis, it is assumed that the direction of the heat flow depends on the temperature deference of the outside and the inside air. Therefore, the function of adaptive insulation is based on the following principle:

The insulation is on the insulated state:

- During the heating season and when the heat flow is towards the outer space (To < Ti)
- During the cooling season and when the heat flow is towards the inner space (Ti < To). For instance during a hot summer day.

The insulation is on the conductive state:

- During the heating season and when the heat flow is towards the room (To > Ti)
- During the cooling season and when the direction of the heat flow is towards the outer space (Ti > To). This could represent the case of room that has gained heat during the day and during the night when the temperature outside is drop, the building can release the heat through night cooling.

[1] Heating period, can be defined as the time of the year when the heating load is higher than the cooling load (the rest of the time can be considered as the cooling period).

3.3. Design criteria

The design of the building envelope is accompanied by a multitude of requirements and needs to be satisfied, which are closely related to the various functions of the building. For the development of adaptive insulation the following design criteria and sub-criteria are derived from the literature review.

The first criteria is related to the thermal properties of the system. The first sub-criteria that fall into this category is the response time required to shift between two thermal states. Following this, is the thermal resistance of the system. The aim here is to reach a higher thermal resistance than the minimum required defined by Building Degree. Finally, one of the most fundamental function that the system should be able to do is, to be able to switch. This can be interpreted as a change in the R-value between a low value for the conductive state and a high value for the insulated state. Therefore, the third sub-criteria of the thermal performance is range of shift. The second criteria is related to the use of the system. The design of the system should fulfil certain requirements which are related to the constructability, the durability and the maintenance of the system.

Another important category that can indicate the efficiency of this system in terms of production is simplicity in design. Currently, insulating materials applied to building envelopes have a simple structure consisting of a single layer of material that makes it relatively easy to apply to the building envelope. With this in mind, ease of construction will be the third and final criterion for the adaptive insulation system.

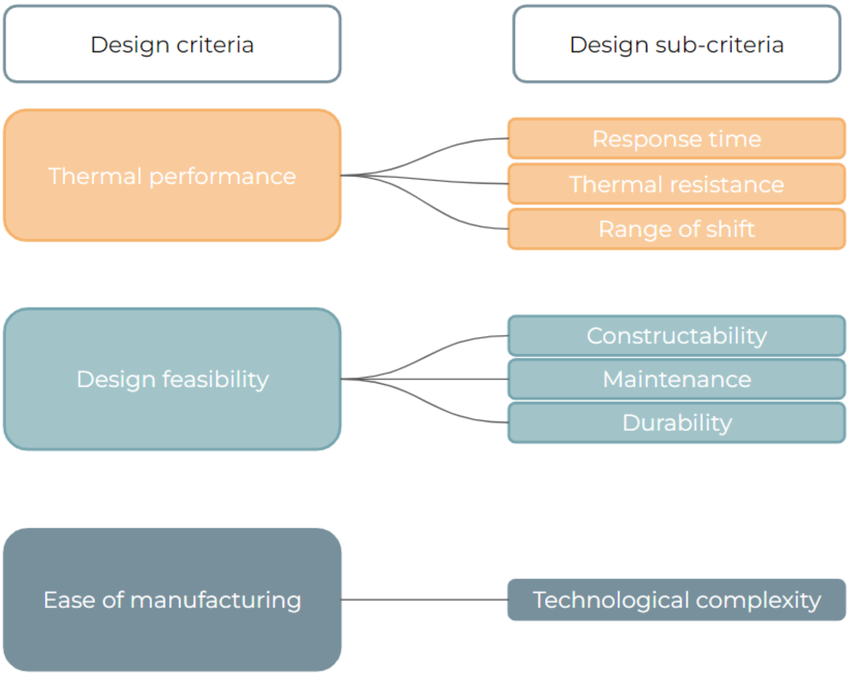


Figure 3.2: The figure represents a summary of the design criteria and the sub-criteria of the adaptive insulation.

Design criteria	Design sub-criteria	Description
Thermal Performance	Response time	Response time refers to the time required for the system to change between the insulated and conductive states. Depending on the type of actuation, and the working mechanism the time may vary.
	Thermal resistance	Thermal resistance is the reciprocal of the thermal transmittance, which can be described as, the heat transfer through a solid object, which is located between two fluids of different temperature. The different building codes suggests different minimum R-values for opaque parts of façades. Based the the Dutch Bouwbesluit, the minimum value for thermal resistance is 4.5 m^2K/W. Therefore, the façades systems should be able to achieve a higher value of the minimum required for the insulated state.
	Range of shift	The capability to switch between different levels of insulation. Systems that can experience a reversible shift within a wide range of U-values (high and low values) are preferred.
Design feasibility	Constructability	Constructability concerns the level of compatibility that the system can reach with the rest of the components of the building as well as the accommodation of movements due to thermal expansion during the life time of the structure. In other words, the ability of the system to be used in different circumstances, details, geometries, interfaces. Systems with high constructability are preferred.
	Maintenance	Maintenance is related to the work that is required in order to keep the product on its good initial level, the regularity and how difficult is to do it. Designs that allow easy access to components for maintenance, restoration and replacement are preferred.
	Durability	Durability is the length of time the product can carry out its function with no damage arising. It can be evaluated on material and system level. The assessment is based on parameters related to the water and air tightness. For instance, concepts that ensure a level of resistance against water penetration are preferred.
Ease of manufacturing	Technological complexity	The level of complexity that the system requires for its assembly. The complexity can be measured in terms of energy that is required to be produced and overall cost. Simple designs facilitate the construction process, which is carried out in an easy and efficient way, which is desirable for the new insulation model.

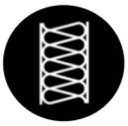
4

Concept generation

4.1. Introduction

In this chapter, the various design alternatives towards the development of an adaptive insulation system will be explored based on a scheme of aspects. In this regard, in Section 4.2, the different aspects will be explained and in Section 4.3 the working mechanism of the deriving concepts will be described.

4.2. Design aspects

Aspects	Description
 Core geometry	The geometry of the core can vary depending on the level of porosity and cell structure of the material. For the current insulation three variations of the core material geometry will be investigated. This aspect has a great influence on the thermal performance of the system.
 External layer	A distinction can be made between two different types of outer layer, based on its mobility. In the case that the outer layer can move together with the insulating layer, it can be considered as part of it, while in the opposite case that it remains fixed in its position during the change of thermal conditions, it is considered as an independent element of the building envelope. This aspect affects more or less all the design criteria.
 Insulation layer	This aspect concerns the number of the insulation layers. It can be one single layer or it can be comprised of several thin membranes. This aspect is important for the thermal performance of the system as well as the design feasibility
 Moving mechanism	Reversible shifting between two thermal states can be realized through rearrangement of the structure of the insulating layer. The latter can be expressed as a change in the thickness of the insulation layer. To achieve this, different mechanisms can be used that will result in an expanded and a compressed version of the system. This aspect affects the technological complexity, the speed of switch as well as the feasibility of the design, since it is highly related to the building system integration issues.
 Actuator	This aspect shows the principle in which the adaptive insulation system is actuated to move from the insulated to the conducted state and vice versa. The choice of the actuator type has a high influence on the technological complexity of the final system.

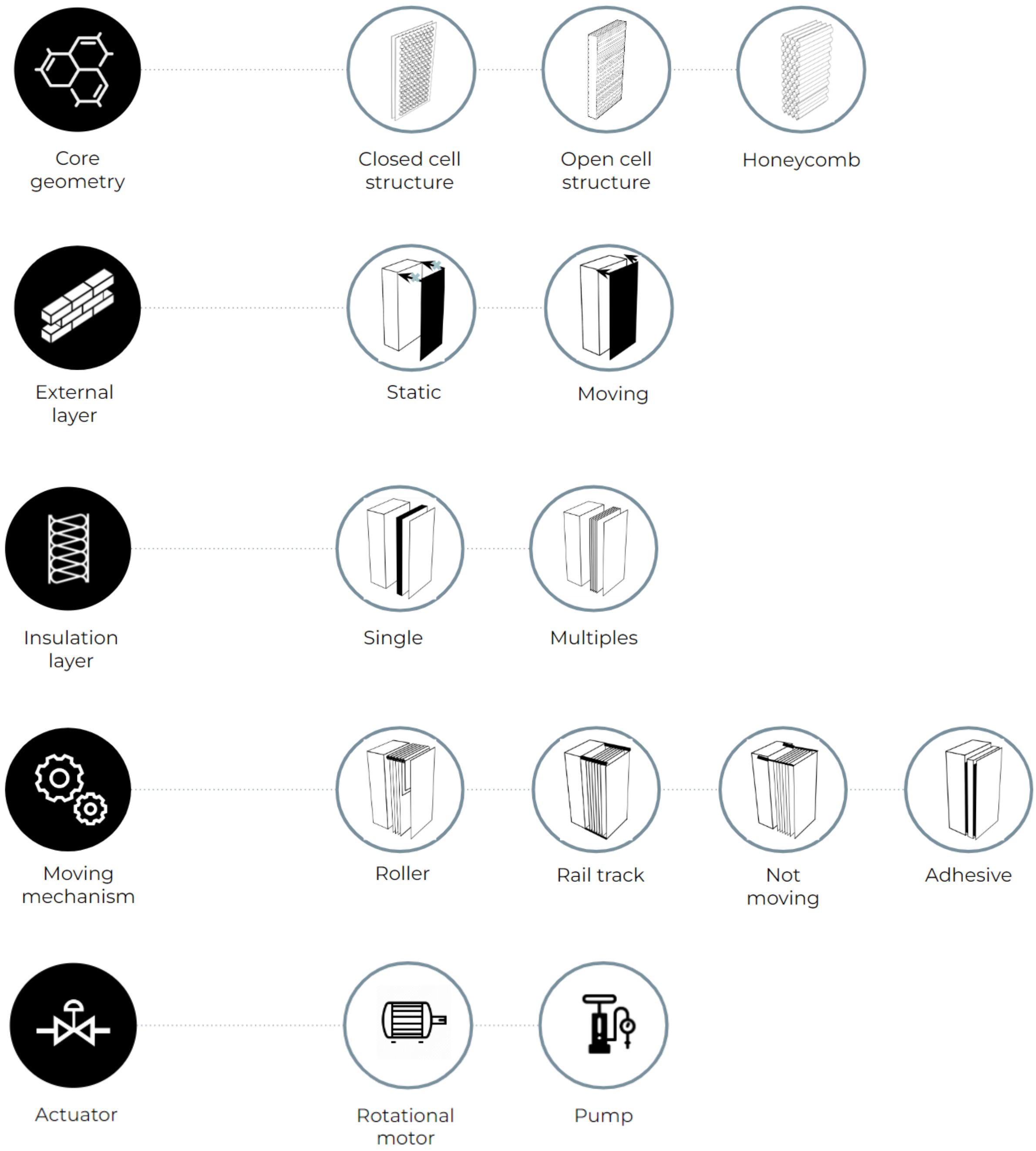
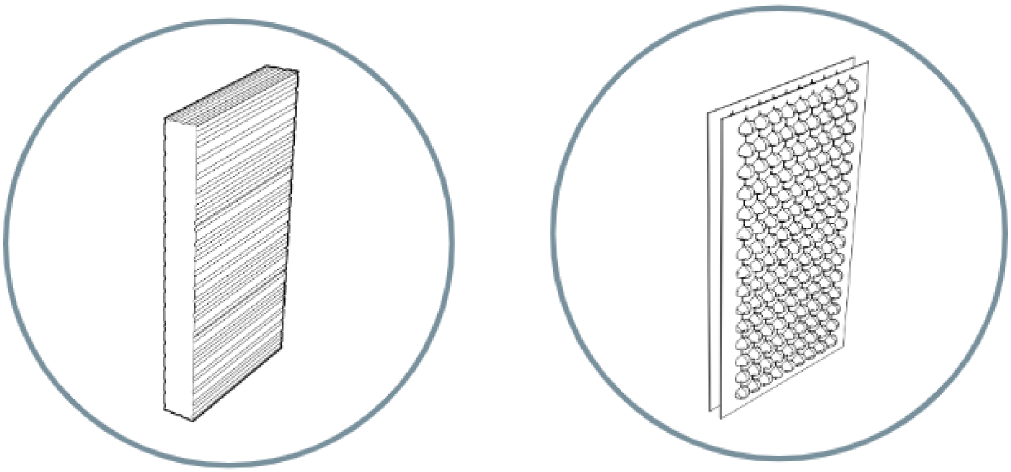


Figure 4.1: Overview of the aspects

4.2.1. Core geometry

The relation between geometry at meso-scale and thermal performance has been extensively investigated for the design of insulation materials. The design principle that governs the insulation technology is based in the manipulation of porous structures and the creation of cavities. For the core material three different geometries will be considered namely; a closed-cell, an open-cell and a honeycomb structure. The influence of them on the thermal performance of the system will be investigated in Chapter 5.



(a) Open cell structure (b) Closed cell structure

Figure 4.2: Representation of the open- and closed-cell variations of core geometry

Open cell structure

The first variation of the core geometry concerns the case of an open cell structure, similar to the filler material of a self-inflatable camping mattress. Typically, open cell materials consist of air pockets created by air pressure inside the fibers and then secured in place by activating a binder. These holes enable them to interlock and interconnect, which results to a spring like loading allowing the insulation material to retain its shape and thickness after compression. Due to its production technique, the open cell structure have a lightweight, soft and cushioning appearance. In terms of manufacturing cost, open cell structures have low production cost.

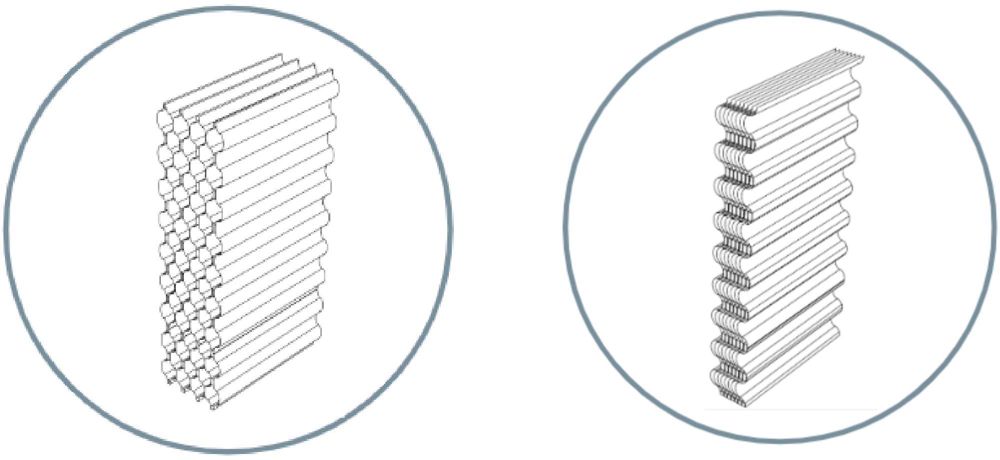
- Good thermal insulation properties
- Low manufacturing cost
- Lightweight
- Cannot resist to water vapor

Closed cell structure

The topology of closed-cell materials is characterized by a network of individual cells which are formed as bubbles inflated with air or other type of gas. The denser cellular composition as compared to the open cell structure further limits the potential for gas movement, as it may only move within the boundaries of its containing cell, and not between cells as in the case of open cell materials. Similarly to open cell materials, the process of heat transfer from warm to cool sides is affected by a combination of all the three modes of heat transfer. Specifically, when a porous nonmetallic solid is subjected to a thermal gradient, heat transfer involves vibrational conduction in the solid phase, conduction by colliding gas molecules in the pore phase, and radiation either through a semi-transparent solid phase or across large pores. However, for pore sizes less than 20 mm convection heat transfer can be neglected. In terms of water permeability, closed-cell structures perform better than open-cell structures, since their topology makes harder for water vapor to penetrate into their cells. However a durability issue is the fact that their R-value decreases with time. Finally, the production process is relatively easy (Koru 2016).

- Good thermal insulation properties
- High resistance to water penetration
- Easy production process
- Heavier than open cell structure

Honeycomb structure



(a) Honeycomb structure (b) Honeycomb structure compressed

Figure 4.3: Representation of the honeycomb variation of core geometry for the extended and the compressed version of the system

The third and last variant of core material geometry is the honeycomb structure. This aspect is based on the design and the working mechanism of gas-filled panels (GFPs). Typically, GFPs consist of a barrier envelope and a gas between layers (a baffle). The enclosed gas can either be air or a heavier gas to decrease thermal advection and conduction. To improve their thermal performance, GFPs are usually made of two types of polymer films: the first type is a metallized film which is used to form a tied assembly called 'the baffle' which produces a honeycomb structure in the panel whereby convection and radiation is suppressed, while a low-diffusive gas-barrier foil is used in a hermetic envelope that maintains the panels inner gas-fill (see Fig 4.4). A stiff or a flexible panel can be produced depending on the the type of foils used for its manufacture. Determining factors for the effective thermal conductivity of the GFPs are, the number of cavities, the baffle thickness, the thermal conductivity of the foil material which will be investigated in detail at the following chapter.

- Excellent thermal insulation properties
- Low water resistance
- High production cost

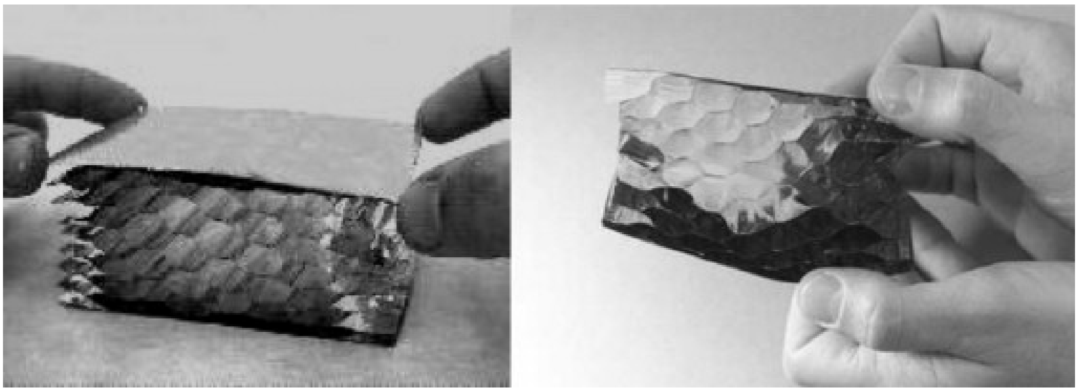
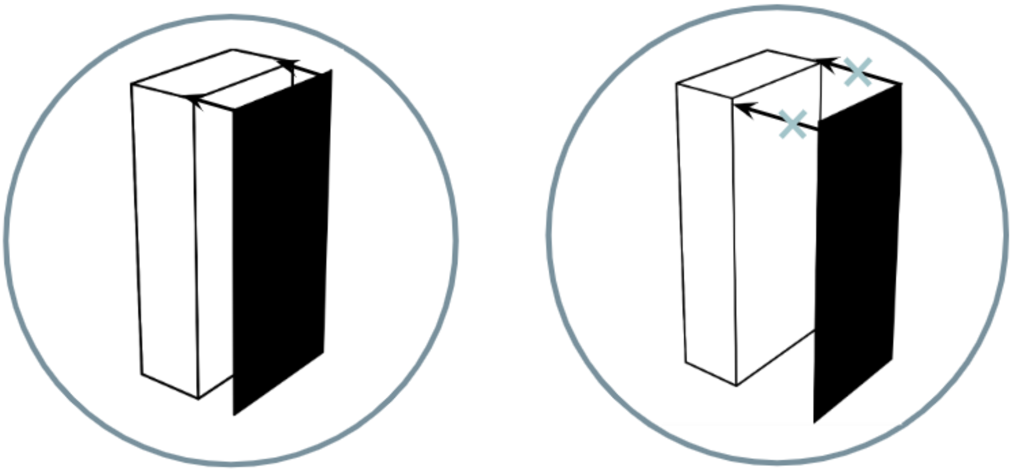


Figure 4.4: The figure gives a view of the internal structure of a gas-filled panel (Baetens et al. 2010)

4.2.2. External layer



(a) Moving external wall

(b) Static external wall

Figure 4.5: Representation of the moving and static variations of external layer

Moving

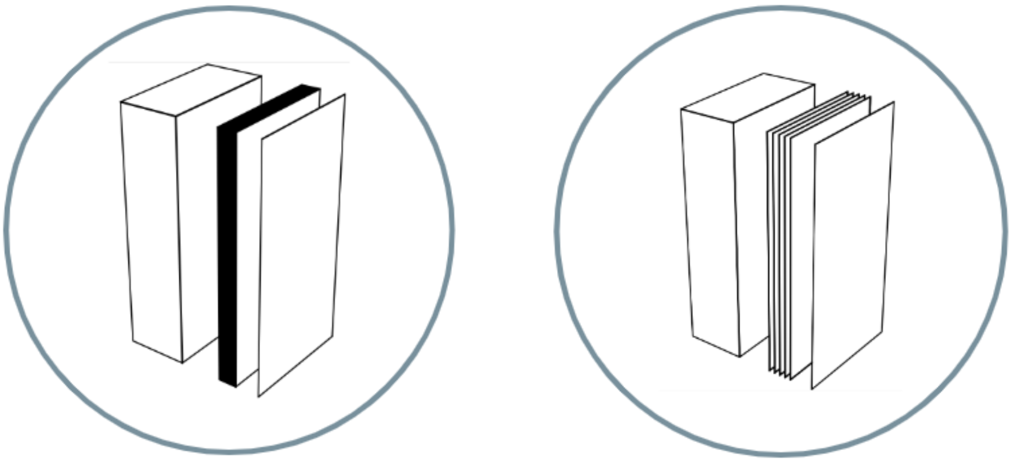
The first variant considers the case of a moving outer layer. In this shape-shifting façade, the outer layer of the wall is considered to be part of the insulation layer and thus can dynamically move with the rest of the system during the transition between the insulated and the conductive states. Thus, an expanded and a compressed version of the adaptive system can be achieved and simultaneously changing the thickness of the whole façade system. During the heating period, when the outdoor temperature is lower than the indoor temperature, the adaptive insulation will operate in the insulated state to ensure minimum heat losses though the façade. For this purpose, the system will be in its extended version. The same applies during the cooling season and when the external temperature is higher than the internal temperature. Also in this case, it should be guaranteed that the system is well insulated so that the insulation layer resists the unwanted heat load to pass thought the walls and to lead to the increase of the internal temperature. During cooling season and in the case that the internal temperature is higher that the external temperature, which can happen mostly during the night, a way to reduce the heating load increased during the day, is by shifting the system to the conductive state. In this way, the external layer can move towards the internal side of the building compressing at the same time the insulation layer. As a result, a higher U-value can be achieved. However, promising this moving façade might be, it increases the level of complexity for its connection with the rest of the building components. Furthermore, this type of system requires the incorporation of a mechanism to facilitate the move which increase the maintenance costs.

- Promising idea that could lead to high range of of U-values
- Constructability challenges
- High maintenance costs

Static
In contrast with the previous case, here the change between the states is not noticeable from the façade but is an internal process. In particular, the outer layer of the façade remains fixed in place throughout this process and only the insulation layer can move towards the wall and vice versa. In this way, an air cavity is created between the outer layer of the façade and the compressed insulation layer upon shifting to the conductive state. However, the transition between two different thermal states is questionable with this system.

- Simpler design compared to the moving
- Maybe not possible to achieve two thermal states

4.2.3. Insulation layer



(a) Single layer (b) Multiple layers

Figure 4.6: Representation of the two variations of the insulation layer

Single
This aspect considers the case of a single layer of insulating material, which is tangential to the inner and outer wall. The transition from the high U-value to the low U-value state is achieved by the compression and decompression of the system respectively, which leads to the varying thickness of the insulation layer. After depressurizing the system, the material used should be able to return to its original shape.

- Conventional solution/Simple design

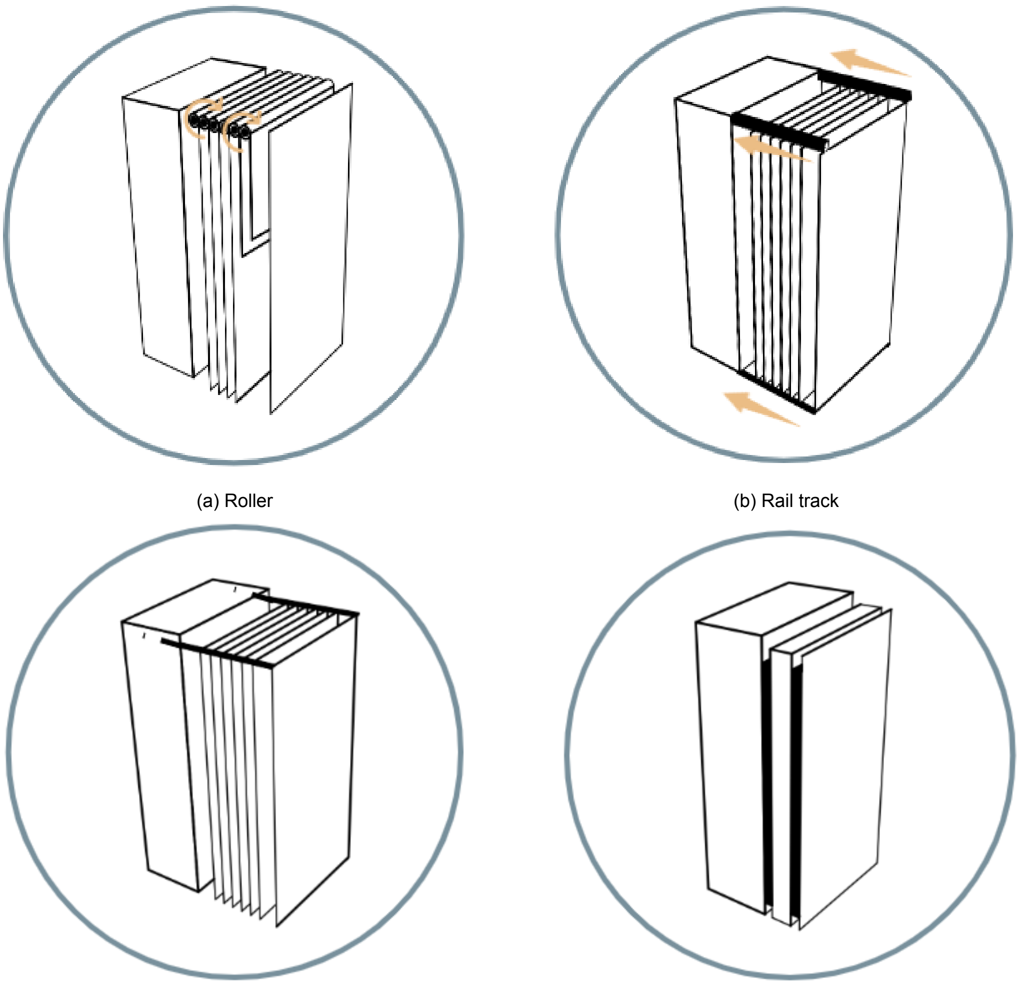
Multiple
The principle of this structure is based on the idea of sectioning off the air into an arbitrary number of layers. In this regard, the structure of the insulating layer, instead of being a single layer of material, consists of separate layers of material alternating with layers of air. The distance between the membranes can vary depending on the target heating state, decreasing and increasing it, for the conductive and insulated state respectively. Within the cavity, the internal membranes can either be fixed in place

or move by folding or by linear displacement parallel to the plane of the façade towards or away from the internal wall.

The ability to achieve both insulated and conductive states with this conceptual system can be achieved by physically collapsing the wall and removing the air entrapped between the inner membranes. Through this practice, the membranes formerly isolating the internal layers of air from one another are now compressed into a single layer of material. Thus, the radiation and convective resistances can be significantly decreased and at the same time the total thickness of the insulation follows the same trend. The number of the compartments as well as the position of the position of the membranes are influencing factors for the ability of the system to achieve a high U-value and a low U-value.

- Modular design
- Higher level of complexity in regard to constructability

4.2.4. Movement mechanism



(a) Roller

(b) Rail track

(c) Anchored

(d) Adhesive

Figure 4.7: Representation of the variations of the moving mechanism

Roller
The transition between the states can be realized through the change in the thickness of the insulating layer. The first mechanism that can be used for this purpose is a blinds-roller-like system. This con-

cept can be combined with the aspect of multi-layer insulation where the inner membranes are hung separately from cylinders. By rolling up and down the films, the desired sizes of façade cavities can be created. A major issue of this aspect is the fact that it increased the panels depth.

- Simple design
- Requires a high panel's depth
- High maintenance costs because motors are used to operate the system

Rail track
The second alternative of the movement mechanism explores the possibilities of using a rail track system. As in the case of the blinds-roller-like system, the rail track can be combined with the aspect of multi-layer insulation, where the membranes can move along the rail and towards the inner wall. In this way, the membranes can move closer and further apart, thereby alternating between conductive and insulated states.

- Simple design
- Regular maintenance costs

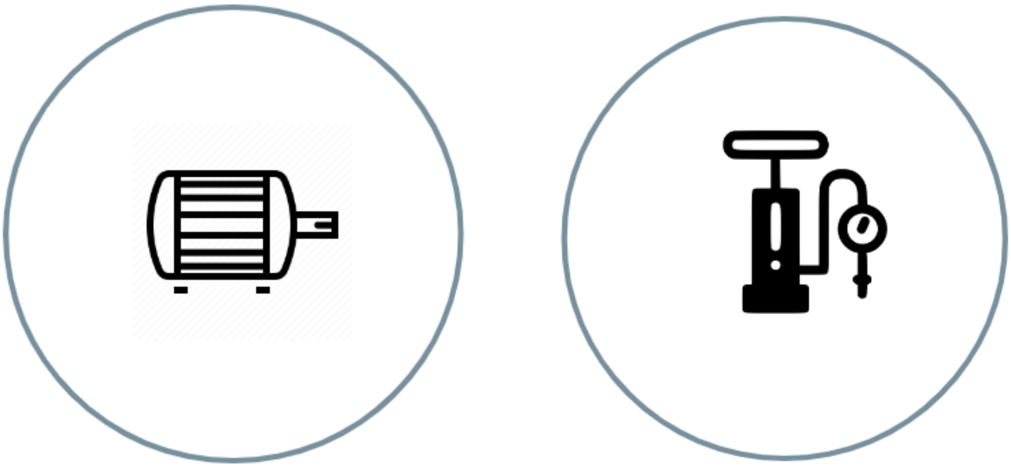
Not moving
In the third alternative, the insulation layer is fixed in place, in the cavity created between the inner and outer wall. This concept can be combined with both aspects of single and multi-layer insulation. In the first, the insulating layer can expand and compress by introducing and removing air or another type of gas, pulling at the same time, the outer wall along with it. Whereas in the case of multi-layer insulation, the internal membranes are suspended from the top of each façade element and fixed in place. In the aforementioned structure, the change of insulation thickness is realised at element level, by filling and extracting air in its micro structure.

- Simple design
- Low maintenance costs

Adhesive
The fourth and last variant of this aspect considers the case of a single insulation layer which is attached to the inner wall with the use of an adhesive.

- Strong connection type
- Regular maintenance costs
- Cannot be recycled

4.2.5. Actuator



(a) Rotational motor (b) Pump

Figure 4.8: Representation of the two variations of the actuator system

Rotational motor
The final aspect to investigate is the type of actuator system. The first alternative considers the case of a rotary motor which can be operated to bring into contact and separate the inner and outer insulation surfaces. However this option requires additional energy input and it might increase the complexity of the system.

- Increased complexity
- High operational costs

Pump
The difficulty of actuating the transition from insulated to conductive states could be resolved by directing ductwork from the building's HVAC system to inflate the wall for insulation and deflate it for conduction.

- Regular maintenance costs

4.3. Development of preliminary design concepts

4.3.1. Folding multi-layer insulation

This first idea is the result of the combination of multi-layer insulation and the movement mechanism achieved by the use of rollers, which is inspired by the shading system that uses roller blinds. Taking the latter as a point of reference, the basic idea behind this design is to create a system in which the inner layers of insulation are placed parallel to each other and each hangs from a cylinder. Consequently, by winding the rolls up and down, the desired insulation thickness can be achieved.

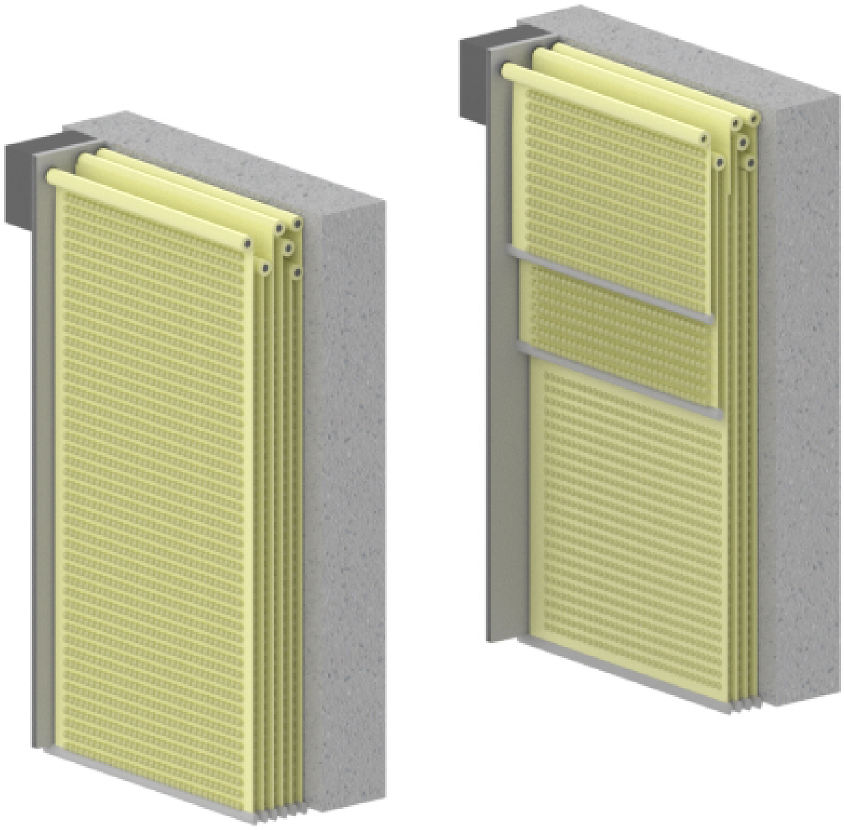


Figure 4.9: Impression of concept 1 of Folding multi-layer insulation

In this concept, the exterior cladding is an independent part of the structure and remains fixed in place. Thin films, made of a polymer bubble-like closed-cell material, which are filled with air, consist the core in order to provide with thermal insulation. The initial position of the system is assumed to be that in which the all membranes are down to achieve maximum insulation. The transition from the insulated to the conductive state is achieved by means of upward rotation of the outer rollers, which pull the films with them, just as in the case of a sun shading system that uses roller blinds. In order to achieve a small distance between the inner layers and at the same time to avoid an excessive increase in the thickness of the insulating layer, some of the cylinders are placed on top of each other, in a way that ensures the creation of sufficient space to accommodate the inflated membranes when they are up. As a result of this rearrangement, in the conductive state, the thickness of the core is reduced by half and wider air cavity is created between the external cladding and the core. Small rotary motors can be used to operate the rollers, one for each of the rollers. To facilitate the process of pulling up and down, and keep the membranes in place, a bar is integrated in the bottom of each membrane.

An advantage of this concept, is its relatively simple structure and operation, which is based on the working principle of a sun shading system, which is a widely used technology. Therefore, from a technological point of view this system has low complexity. On the other hand, a weakness of this concept is that using rollers will greatly increase the depth and the height of the panel. In addition, a rotary motor is required for each cylinder. Regular maintenance is therefore needed to ensure that the system works properly. Finally, an increase in the operational energy is also expected. If this concept is chosen, its operation in the event of a power outage should be examined.

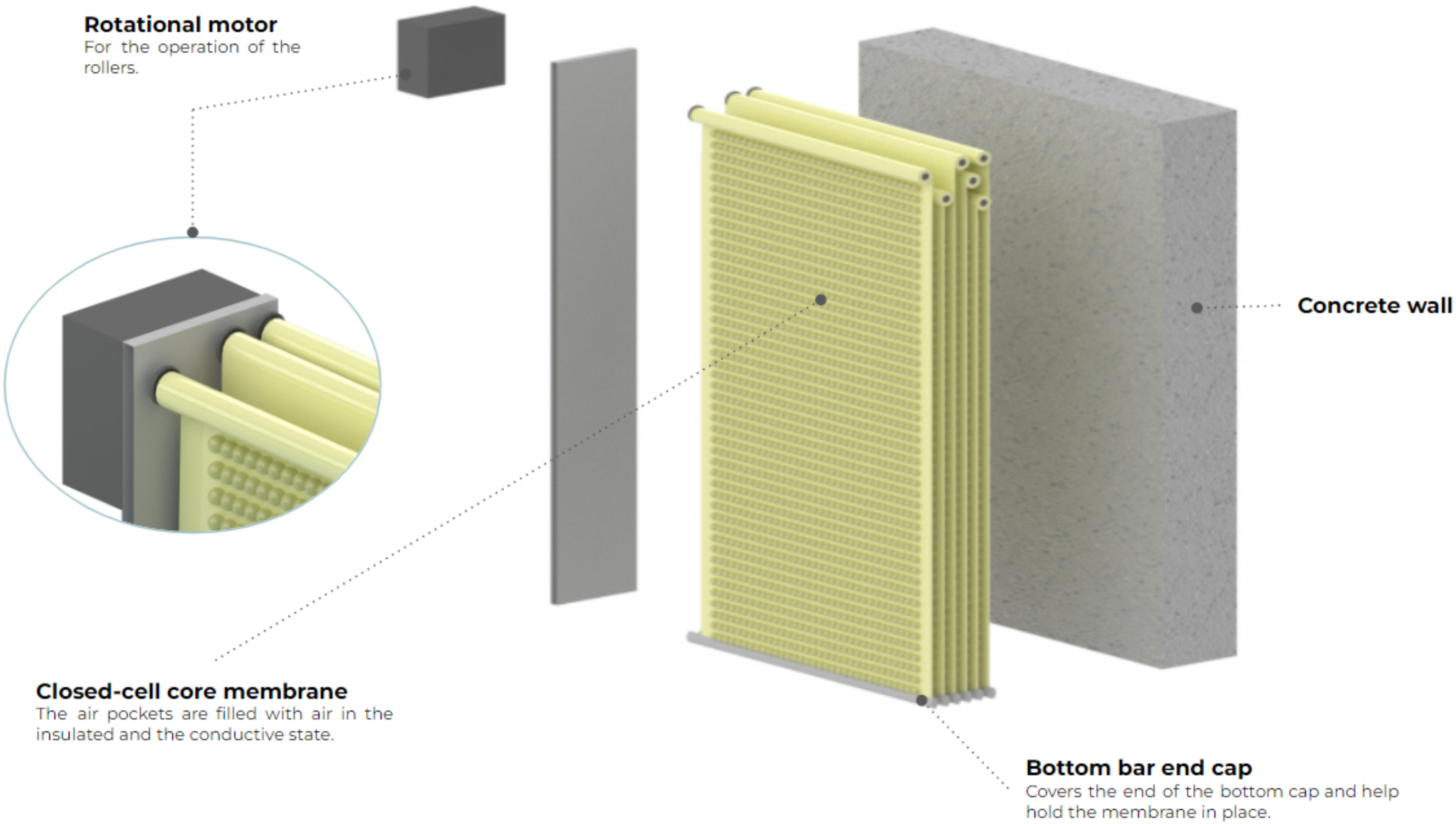


Figure 4.10: Exploded view of concept 1 of Folding multi-layer insulation.

4.3.2. Sliding partition multi-layer insulation

The second design concept, derives from the combination of multi-layer insulation and the movement mechanism achieved by the use of rail track. It is based on the operating mechanism of movable partition walls. An approach of converting this working mechanism into an adaptive insulation product could be achieved through the expansion and compression of the membranes of a multi-layer insulation that uses a rail track.

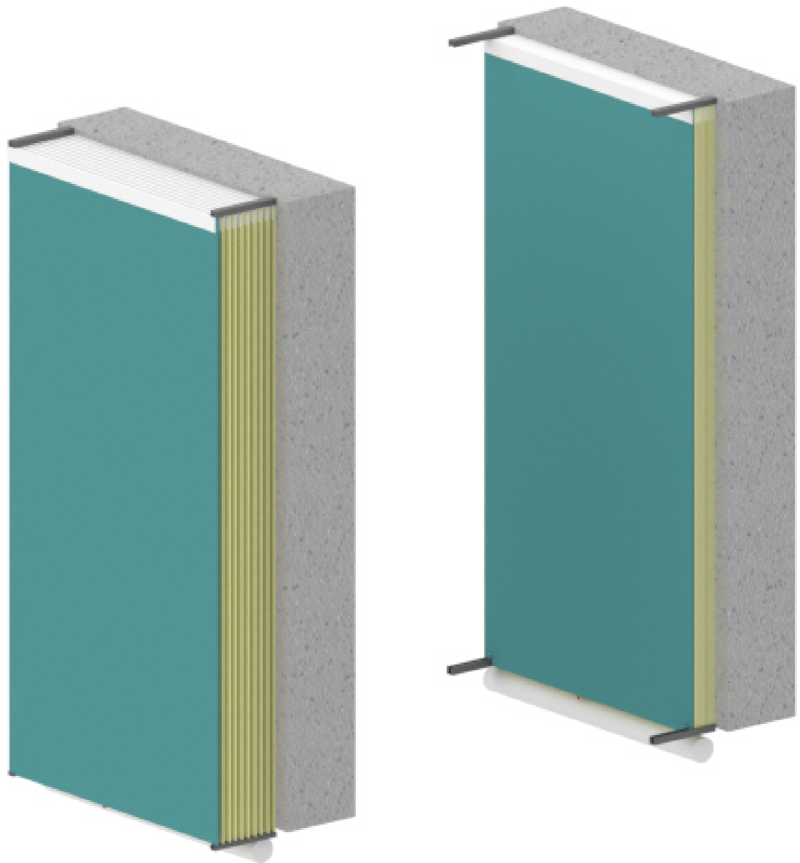


Figure 4.11: Impression of concept 2 of Sliding partition multi-layer insulation.

This façade system incorporates two sub-systems. The first sub-system consists of a multi-layered core to provide thermal insulation. The core is a bubble-like polymer closed-cell structure with a relatively low ratio of solid to gas. The second sub-system encompasses a lightweight outer layer which is attached to the core thus they can move together as one, when the system shift between the two thermal states. Furthermore, this modular insulation element includes an anodized aluminum track which is fixed to the top and the bottom of each façade unit to guide the sliding insulating panels. The initial position of the system is assumed to be the extended. To control the movement of the air through the system, each floor incorporates air pipes that are connected with a dual-function pump for air intake and suction. Based on the necessity, the bubbles can be inflated and deflated with air in order to increase and decrease the R-value of the system respectively. In this concept, the membranes can inflate and deflate autonomously through a series of channels located at the bottom of them which are connected to the central air supply tube.

During the cooling season and when the temperature outside is lower than the temperature inside, which happens mainly during the night, the system is shift to its high U-value. In this case, the inner membranes are deflated through air suction and in this the façade system is forced to slide towards the inner wall. The same compressed version is adopted during the heating season and when the external temperature is higher than the internal. On the other hand, during the heating season and while the temperature outside is lower than the temperature inside, the system is shift to its low U-value in order to minimise the transmission loses through the opaque parts of the façade. To achieve this, the bubbles are now filled with air via the same pump, thus increasing the thickness of the core and at the same time pushing the façade system outwards, resulting in an extended version.

An advantage of this system arises from the fact that it is based on simple and modular design. This is beneficial for two main reasons. The first concerns the reduction of manufacturing costs and the second concerns the ease of maintenance since the system consists of similar elements that can be easily replaced. However, one of the elements that needs further investigation if this concept is developed concerns its constructability related issues and more specifically, the connection of this movable façade system to the openings.

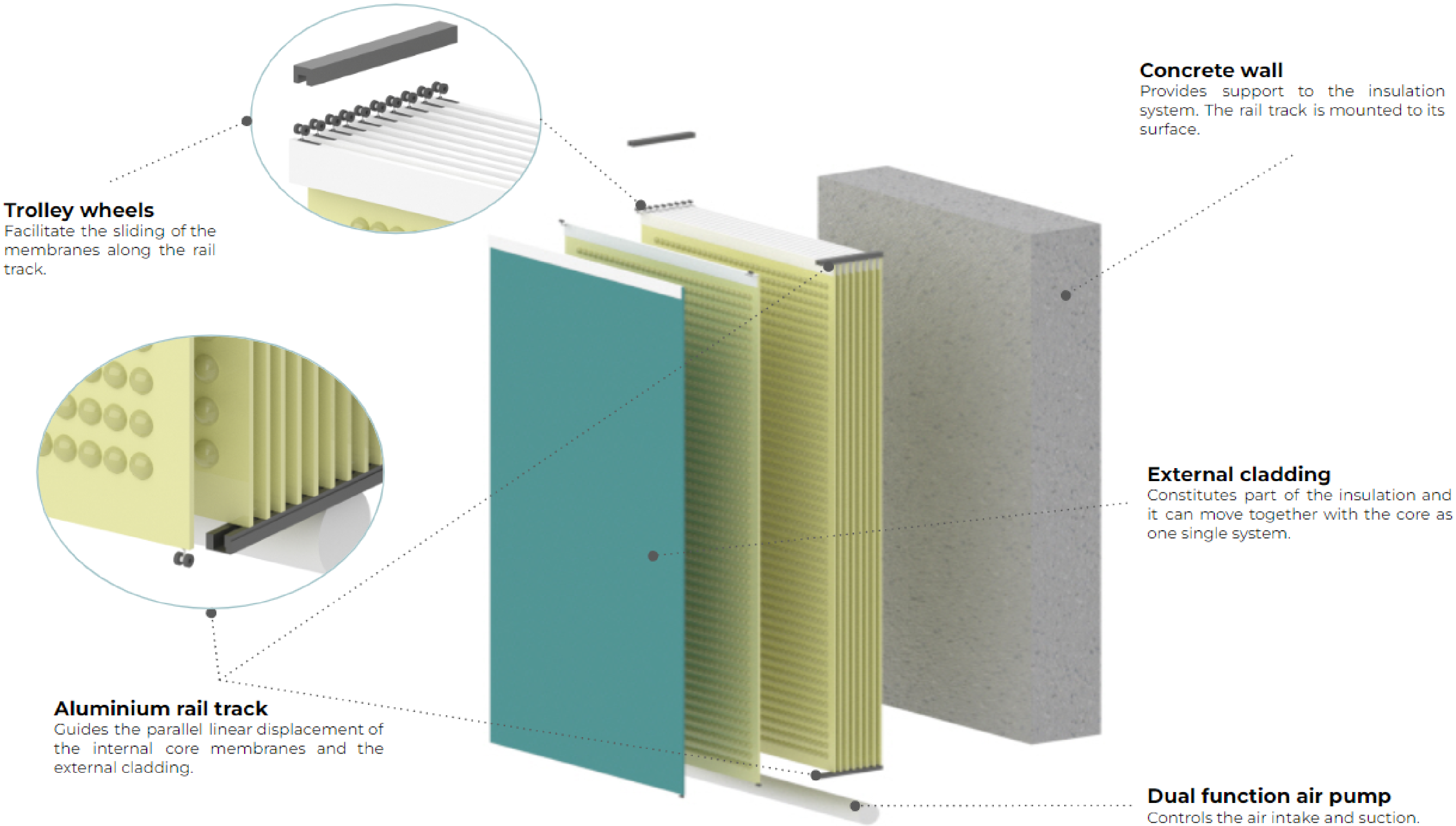


Figure 4.12: Exploded view of concept 2 of Sliding partition multi-layer insulation.

4.3.3. Anchored insulation

The third design concept, is a multi-layer core which can be fixed on the ceiling of each floor. In this idea, the core is a bubble-like polymer closed-cell structure with a relatively low ratio of solid to gas. The external layer for this concept is an independent element and is fixed to its initial position. The core membranes are suspended from a steel profile fixed to the concrete wall behind and remain in place during the transition from the insulated to the conductive state.

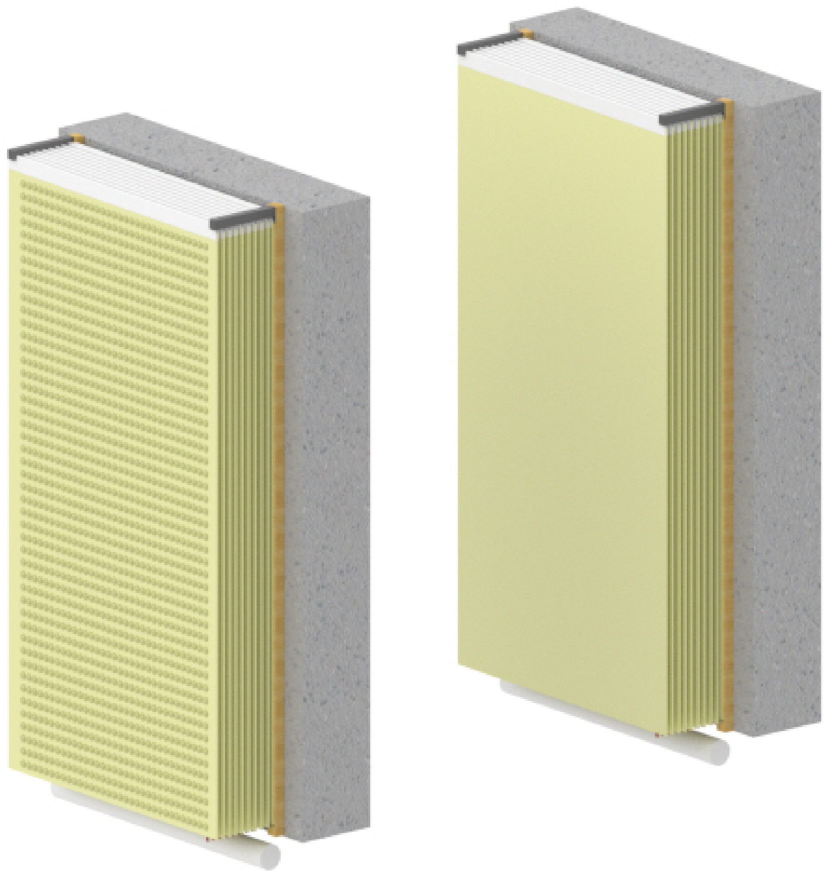


Figure 4.13: Impression of concept 3 of Anchored insulation.

As in the second design concept, each floor incorporates dual-function pumps for air intake and suction. In this concept, the thickness of the core remains constant. In the insulated state, air enters through the channels and fills the bubbles, causing the inner membranes to inflate and approach their neighboring membranes. While in the conductive state, air is removed through the channels causing the internal membranes to flatten.

The advantage of this system is the fact that it is based on a simple design which is easy to be integrated into a façade component and it requires less maintenance compared to the previous concepts. However, the way the system works raises questions about the extent to which a significant difference between a high and a low insulated state could be achieved.

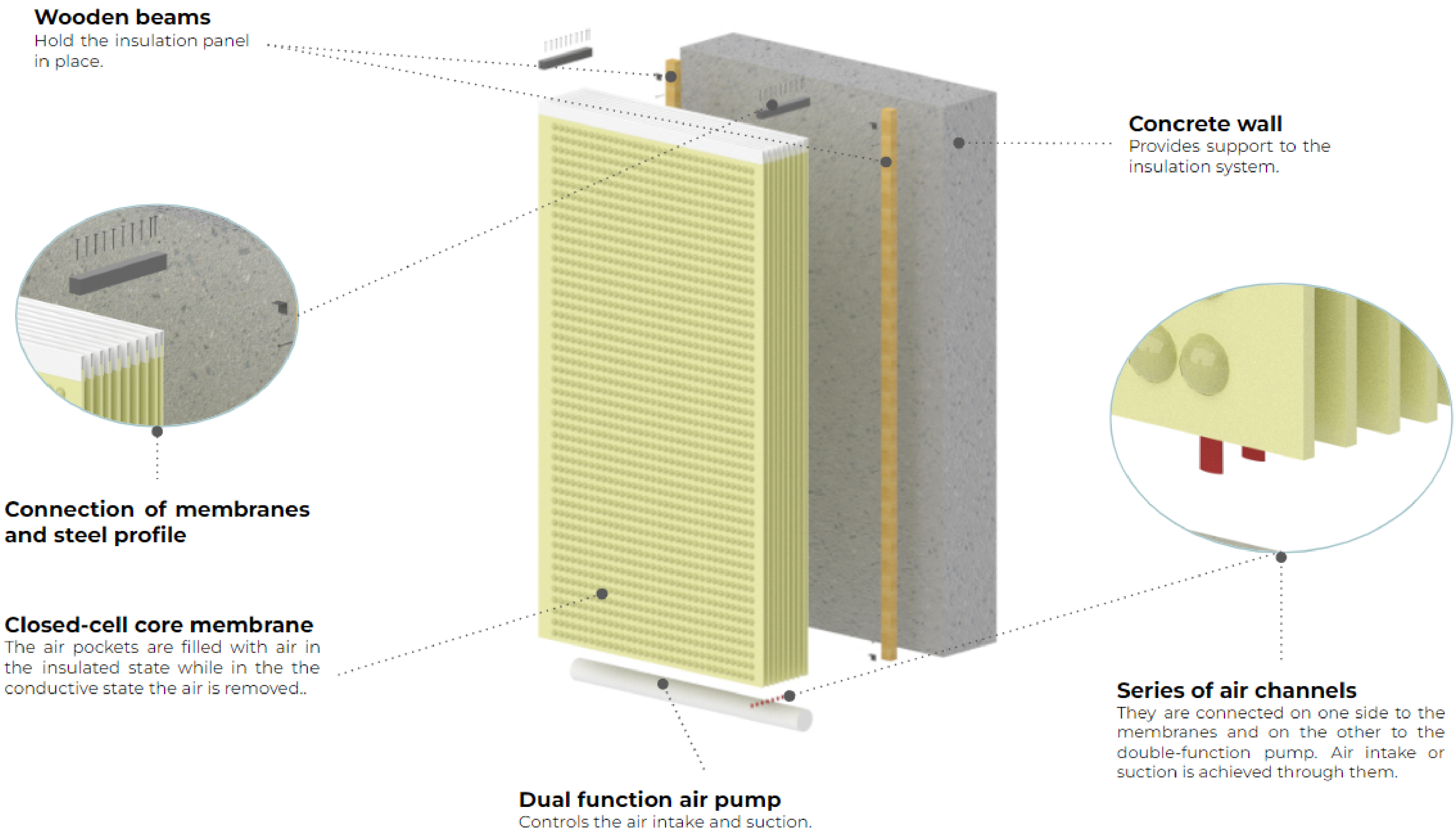


Figure 4.14: Exploded view of concept 3 of Anchored insulation.

4.3.4. "Self-puffing" insulation

The fourth idea is inspired by the thermoregulatory mechanisms of birds, which by inflating and flattening their feathers can adapt to changing environmental conditions. To translate this bio-mechanism into a façade system, the honeycomb aspect is used and the ways in which it can extend and compressed are explored in this concept. This concept comes in two variations.

Alternative A

The façade system includes two sub-systems. In the first variant of this concept the first sub-system consists of a single layer honeycomb core to provide thermal insulation and the second sub-structure is a light-weight external cladding which is attached to the core, thus they can move together as one. The transition from the conductive state to the insulating state can be actuated with a parallel push to open outwards by incorporating metal scissors on the perimeter of the insulating panel. According to the size of the panel, each projected panel can be equipped with at least three frictions in the edge of the panel. The closing and the opening can be achieved manually, using a lever handle. The initial position of the system is assumed to be the extended.

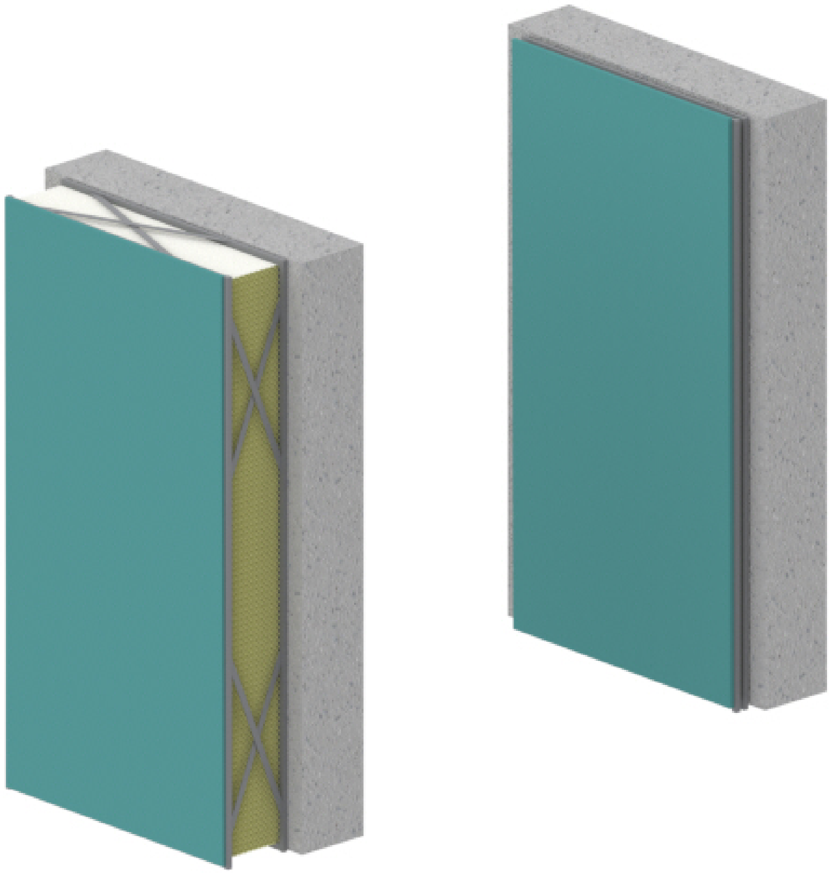


Figure 4.15: Impression of concept 4 of "Self-puffing" insulation, alternative A.

An advantage of this concept is that the the frictions is easily accessible, which facilitates maintenance procedure. In addition, operating costs are expected to be low. However, since the resting position of the system is the extended one, the frictions will need regular maintenance as they will be exposed to the weather.

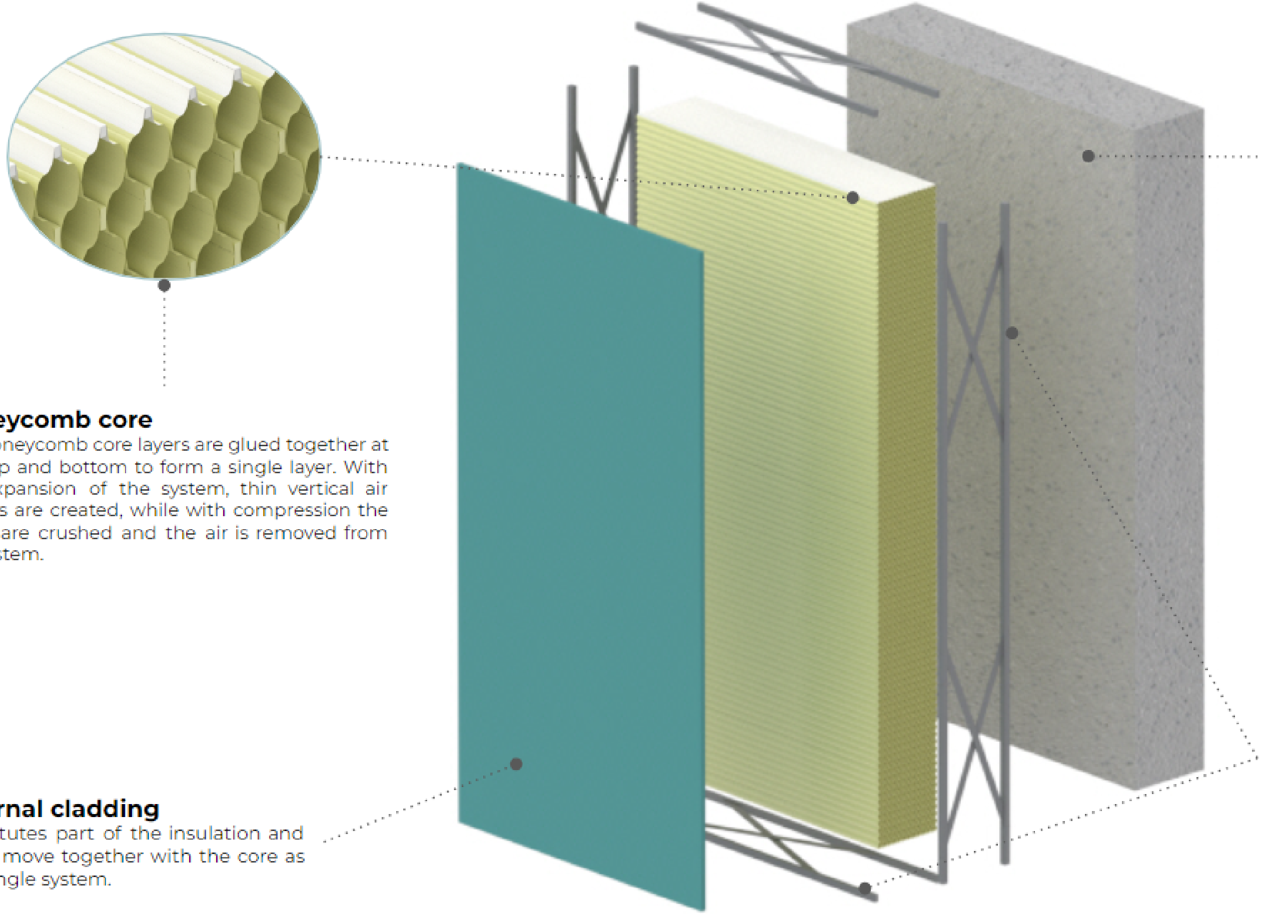


Figure 4.16: Exploded view of concept 4, variant A of Self-puffing insulation.

Alternative B
Similar to the first variant, the façade system incorporates two sub-systems where the first sub-system consists of a single layer honeycomb core the second sub-structure is a light-weight external cladding which is attached to the core. The core is glued to the concrete wall. As required, the system can be inflated and deflated through air channels running through the core. Each unit has holes in the bottom of the panel to facilitate the passage of air. Each floor or unit is connected to an air tube. The initial position of the system is assumed to be the extended one. The transition from high to low insulation can be achieved by introducing air and pressurizing the façade system respectively.

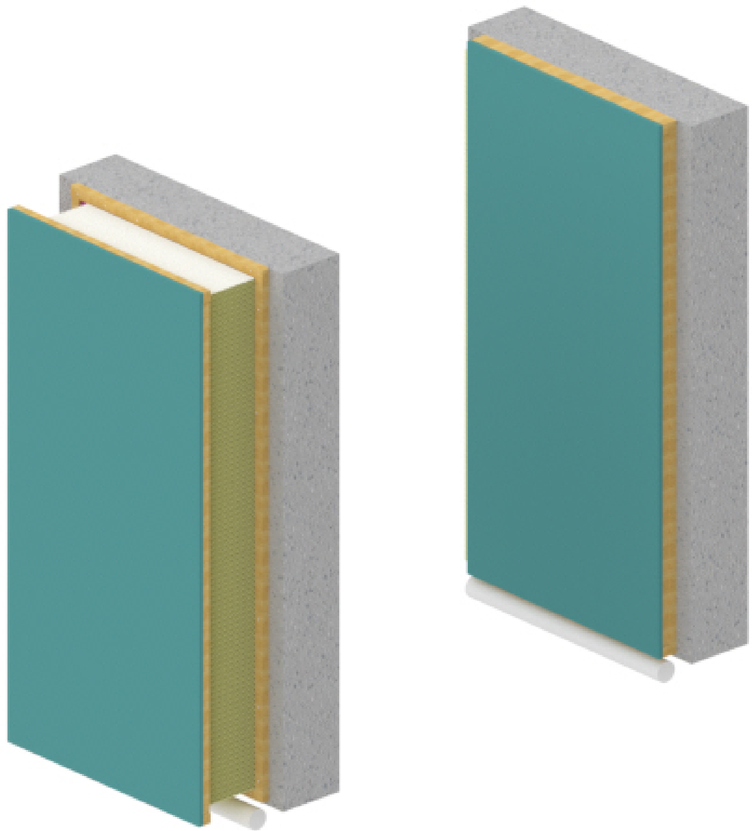


Figure 4.17: Impression of concept 4 of “Self-puffing” insulation, alternative B.

During the cooling season and when the temperature outside is lower than the temperature inside, the system is shift to its conductive state. In this case, The pump can take the air out of the system leading to a deflated core. In this state, the whole façade system is pulled towards the inner wall. The same configuration is adopted during heating season and when the external temperature is higher than the internal. While, when the façade system switches to its insulated state, is filled with air and it expands in the horizontal direction.

One aspect of this alternative that needs further investigation is the way that the system can be held in place and well as the connection of this mobile façade system to the façade openings.

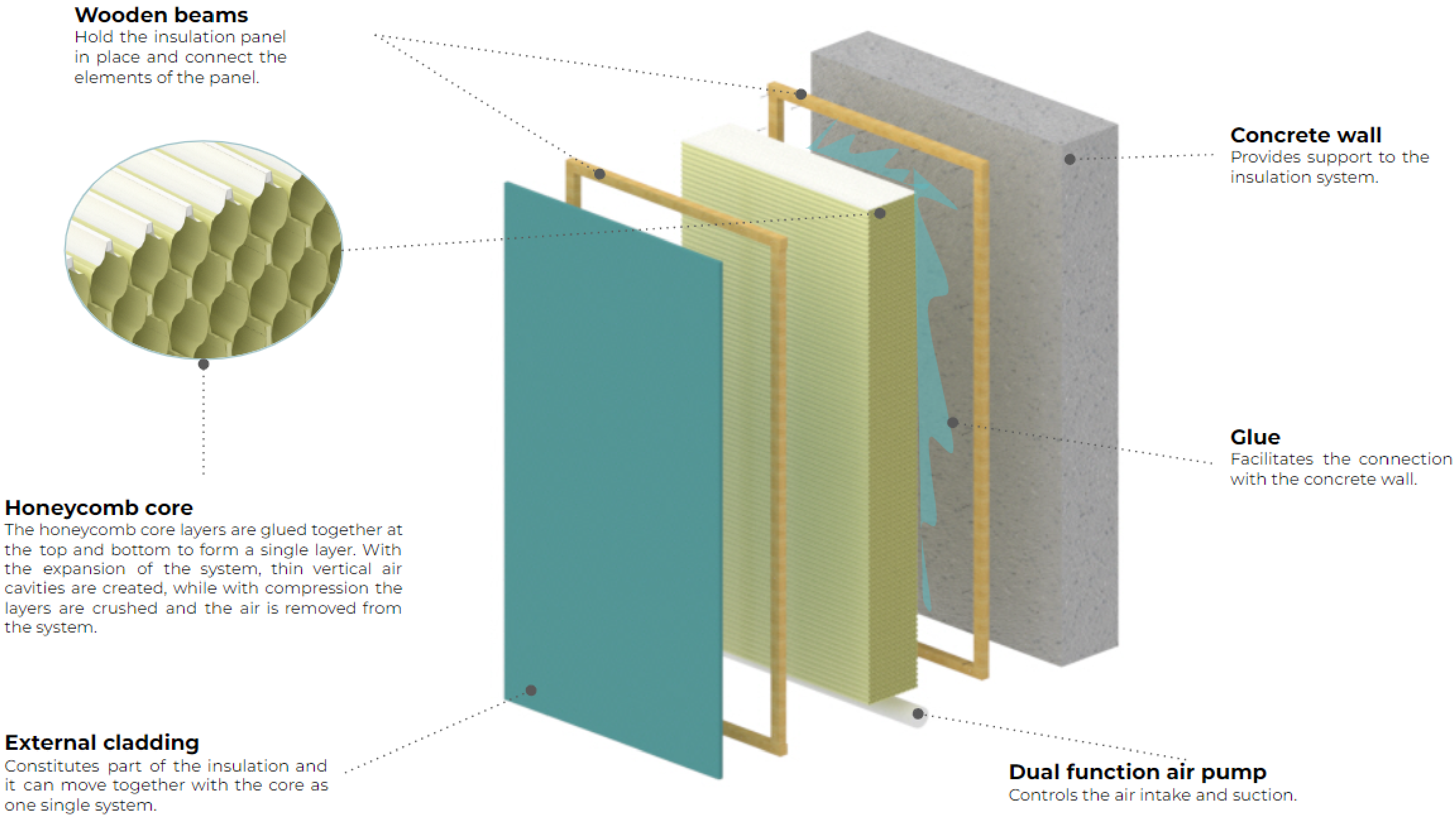


Figure 4.18: Exploded view of concept 4, variant B of Self-puffing insulation.

4.3.5. “Cushion” insulation

The last of the six design concepts concerns the “Cushion” insulation. This concept is inspired by the working principle of the self-inflating mat. The latter consists of a layer of compressible open-cell foam covered by an airtight fabric and a sealable valve. When the valve is open, air enters the system and the open cell foam can expand.

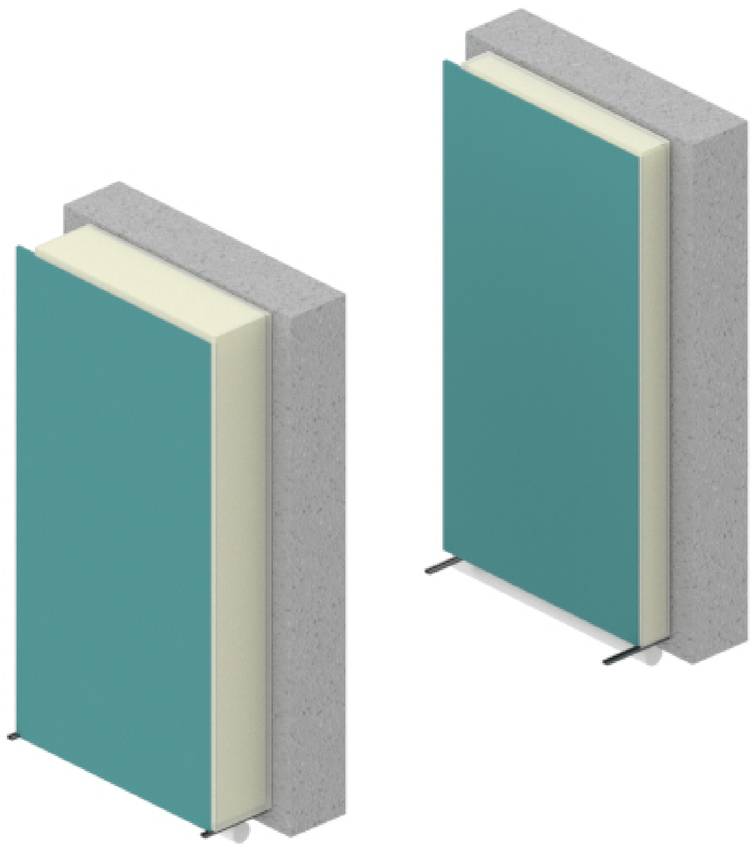


Figure 4.19: Impression of concept 5 of “Cushion” insulation.

This system is composed of three sub-structures. The first sub-structure is the core of the façade system which is a single layer of open-cell foam material. The second sub-structure is an airtight layer of fabric wrapped around the foam to completely cover it and a valve. The third sub-structure is the outer façade layer which is lightweight and is attached to the core. The system is attached to the internal concrete wall, suspended from the top, and an aluminum profile is integrated at the bottom to provide guidance.

The initial system position is extended when the system is in high insulation mode and the foam cells are filled with air. Transition to the low insulation state can be achieved by using a suction pump that can remove air from the system. In this way the foam is compressed and the entire façade is pulled towards the inner concrete wall. To maintain this configuration, the valve should be closed.

A difficult point for the implementation of this idea is the stability of the system. as it must be able to carry a lot of loads to ensure that the system remains in place, combined with the fact that the aluminum profiles used for the facilitation of horizontal movement can create thermal bridges. Another issue is the fact that in the open cell the foam already has good thermal properties which are beneficial for the insulated state, although this can be a problem for increasing its U-value for the conductive state.

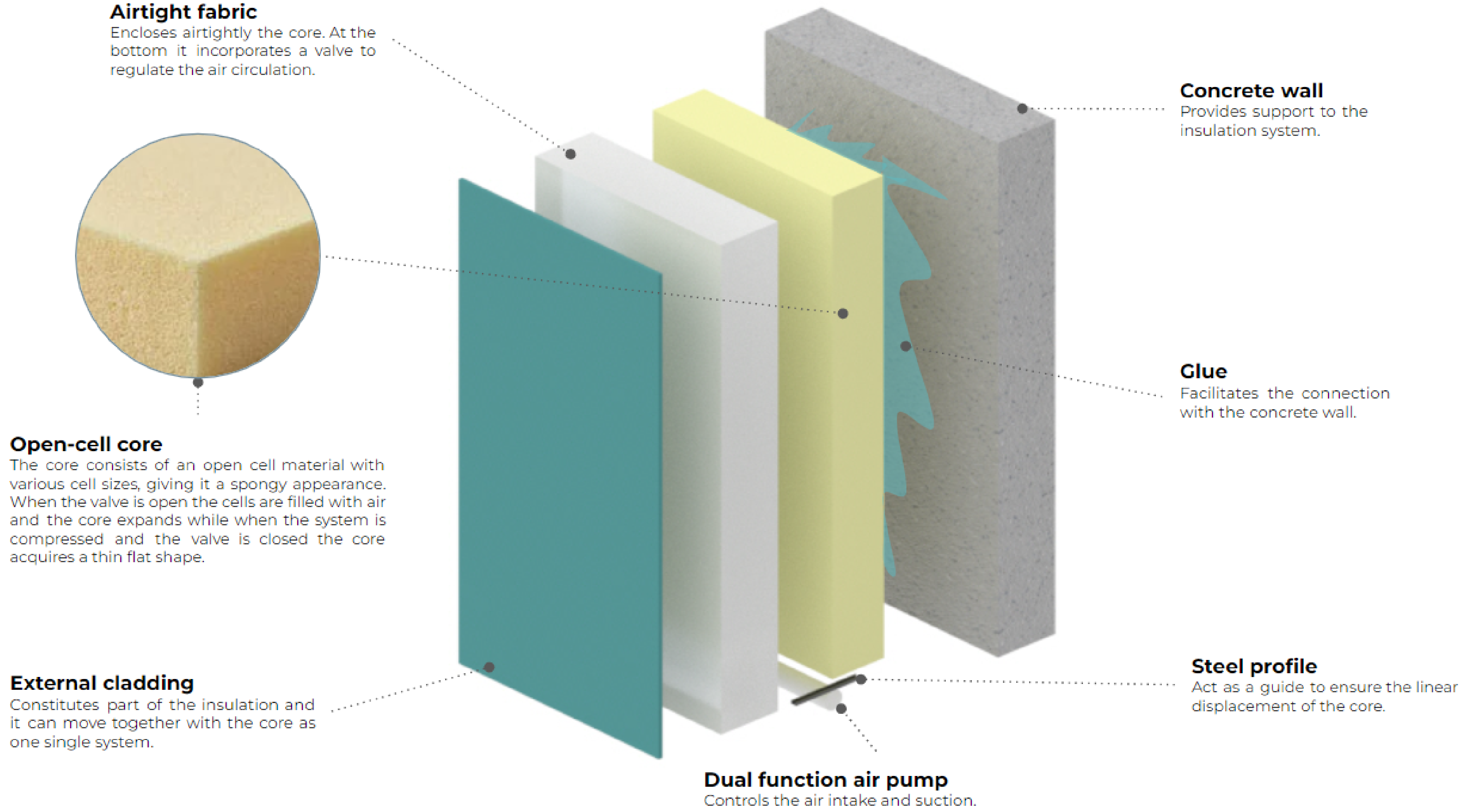


Figure 4.20: Exploded view of concept 5, “Cushion” insulation.

4.4. Conclusion

In this chapter, the preliminary design concepts were presented and analysed. Starting point for the conception of the design alternative was the creation of a scheme of aspects. The scheme included all the characteristic elements that constitute the adaptive insulation system which were categorized into aspects. This resulted to the creation of five aspects concerning the type of core geometry, mobility of the external layer, number of inner membranes, moving mechanism and type of actuation. Then, each aspect was divided into two or more sub-aspects.

The idea behind this practice was to create a system that could offer flexibility to the designer to combine different sub-aspects together, potentially resulting in a multitude of design ideas. In this way, the first concepts developed by combining one sub-aspect of the five categories of aspects with the remaining sub-aspect . Thus, the following six concepts emerged:

- Folding multi-layer insulation
- Sliding partition multi-layer insulation
- Anchored insulation
- “Self-puffing” insulation Alternative A
- “Self-puffing” insulation Alternative B
- “Cushion” insulation

A description of attributes, potentials and limitations of each design alternative was given in line with the design guidelines defined in Chapter 3. Folding multi-layer insulation relies on a simple design but it increases the panel’s depth. In addition, an equal number of rotary motors are required to operate the rollers of each panel, which increases the regularity of maintenance and costs. Sliding partition multi-layer insulation is expected to have lower operational costs however the external moving wall increases the construction complexity of this idea. Although the simple design incorporating non-moving parts enhances the design feasibility and ease of manufacture of Anchored insulation, this configuration raises concerns about the range of U-values the system could achieve.Both variations of the ”Self-puffing” insulation are based on a structure that seems more promising in terms of technological and thermal performance compared to the other types of movable façade, as they combine the benefits of multi-layered and single layer insulation. Finally, the weak points of “Cushion” insulation is the fact that is already an insulation product so it might not be able to achieve a high U-value as well as its low resistance to penetration of water which decreases the durability showing the less potential compared to the other five concepts.

It should be noted that, the development of the aforementioned design concepts, was limited on a preliminary stage. Therefore, aspects concerning the detailed design of the core as well as the façade application were not resolved at this point. However, the “Cushion” insulation had the most of weaknesses and the least control potential so this concept will not be further investigated.

5

Investigation of thermal performance

5.1. Introduction

One of the influencing factors and criteria for the selection of the final design concept is the thermal performance of the system. The previous chapter, laid the foundations for the first development of design ideas. In this chapter, the emphasis will be on determining the final core geometry of the façade system. In this regard, an estimation of the thermal transmittance (U-value) of the preliminary design concepts will be done using TRISCO steady-state thermal analysis software tool.

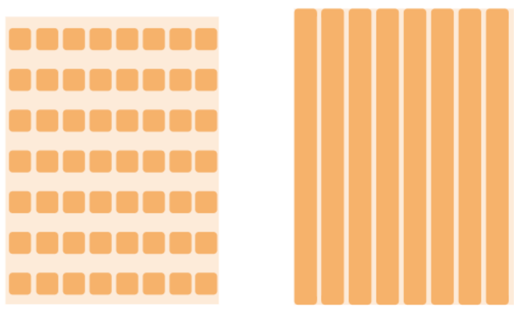
5.2. Simulation set-up

5.2.1. Geometry

The geometry can be described with a list of rectangular blocks, which vertices lie on grid points of a rectangular grid. The geometry was discretized along the x-axis, y-axis and z-axis. For this reason the core geometry for each concept was simplified and reshaped within the software along with the rest of the elements of each proposed system. Due to the homogeneity of the core material, a 60x30x40 cm (length x width x height) element was considered for the simulations for the estimation of the U-value instead of an entire façade unit. Two different core geometry patterns were studied for the thermal analysis:

- closed-cell structure
- honeycomb structure

The closed-cell core is comprised of small cells which were placed next to each other leading to elongated cells with their long dimension perpendicular to the direction of heat flow. On the other hand, the honeycomb core was designed as vertical thin blocks of varying thicknesses that span the height of the core element. The vertical section of these two patterns is illustrated in Figure 5.1.



(a) Vertical Section of Closed-cell core

(b) Vertical Section of Honeycomb core

Figure 5.1: Vertical section of the 3D core geometry illustrating the two different core patterns.

5.2.2. Mesh

To improve the quality of the obtained results, after the core geometry was determined, the number of nodes was increased by, splitting the grid meshes into smaller meshes of width = 5 mm.

5.2.3. Boundary conditions

For the simulation of the heat transfer between the inner and the outer side of the façade, an ambient temperature of 20°C and an outdoor temperature of 0°C were considered. The inner and outer surfaces were considered as adiabatic. Furthermore, the heat transfer coefficients were specified for the adiabatic surfaces as 7.7 W/m^2K for the inner and 25 W/m^2K for the outer surfaces.

5.2.4. Materials

Materials can either be defined by the user, by assigning them the appropriate value for thermal conductivity (λ) or selected from the material library. TRISCO is equipped with a database of several building materials. Materials in this software tool are referred to as colours. Thus, materials and surface boundary conditions with different thermal properties are identified using different colors.

5.2.5. Mode of heat transfer

In cavities, the heat transfer is realised through conduction, convection and radiation. However, according to findings of the literature review in small cavities (up to 20 mm) convection is minimised and it can be disregarded. To take into account both conduction and radiation on the performing simulations, an adjusted effected thermal conductivity value was assigned to air.

The estimation of the effective thermal conductivity in cellular structures, was studied according to NEN EN ISO6946 standard, which provides a calculation method for the thermal resistance and transmittance of building components, depending on the topology and dimensions of the body to be studied. In particular, the standard presents a method for calculating the thermal transmittance of components composed of multiple layers, and Annex B presents a method for calculating the resistance of small unventilated airspaces with a width less than 10 times their thickness.

The calculation of the effective thermal conductivity for high and low emissivity surfaces is therefore realised according to the following procedure:

The thermal resistance of the airspace, Rg, is given by:

$$R_g = \frac{1}{h_a + h_r} \tag{5.1}$$

Where,

$$h_r = \frac{h_{r0}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 2 + \frac{2}{1+\sqrt{1+d^2/b^2}-d/b}} \tag{5.2}$$

$$h_a = 0.73 \cdot \Delta\mathrm{T}^{1/3} \tag{5.3}$$

The formula takes into account the geometry of the airspace, with d representing the thickness and b representing the width of the airspace, ε_1 and ε_2 are the hemispherical emissivities of the warm and cold faces of the airspace, respectively and h_{r0} is the radiative coefficient for a black-body which depends on the temperature and it can be derived according to Table 5.1.

Table 5.1: Values black body radiation coefficient according to mean temperature (*NEN-EN-ISO 6946:2017* 2022).

Mean temperature [°C]	$\mathbf{h_{r0}}$ [W/m^2K]
-10	4.1
0	4.6
10	5.1
20	5.7
30	6.3

The design values of effective thermal conductivity of air for low emissivity surfaces were calculated based on the above mentioned procedure which are depicted in Table 5.2. While for high emissivity surfaces, the design values of effective thermal conductivity (Table 5.4) were calculated based on the design values of thermal resistances obtained from Table 5.3.

Table 5.2: Calculated effective thermal conductivity of unventilated air layers with low emissivity surfaces according to (*NEN-EN-ISO 6946:2017* 2022)

Thickness of air layer [mm]	**Thermal resistance** [m^2/KW]	**Effective thermal conductivity** [W/mK]
5	0.48	0.0104
10	0.48	0.0209
15	0.48	0.0313
20	0.48	0.0417

Table 5.3: Thermal resistance of unventilated air layers with high emissivity surfaces (*NEN-EN-ISO 6946:2017* 2022)

Thickness of air layer [mm]	**Thermal resistance** [m^2/KW] **direction of heatflow**		
	Upwards	**Horizontal**	**Downwards**
0	0	0	0
5	0.11	0.11	0.11
7	0.13	0.13	0.13
10	0.15	0.15	0.15
15	0.16	0.17	0.17
25	0.16	0.18	0.19
50	0.16	0.18	0.21
100	0.16	0.18	0.22
300	0.16	0.18	0.23

Table 5.4: Calculated effective thermal conductivity of unventilated air layers with high emissivity surfaces according to (*NEN-EN-ISO 6946:2017* 2022)

Thickness of air layer [mm]	**Thermal resistance** [m^2/KW]	**Effective thermal conductivity** [W/mK]
0	0	0
5	0.11	0.0454
7	0.13	0.0538
10	0.15	0.0667
15	0.17	0.0882
20	0.18	0.1111
25	0.18	0.1388
30	0.18	0.1667
50	0.18	0.2777
60	0.18	0.3333
150	0.18	0.8333

5.3. Software validation

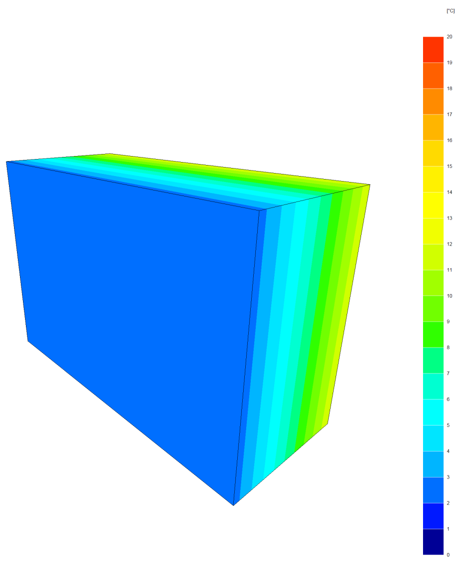
Prior to the thermal analysis of the design concepts, to validate the accuracy of the software, a hand calculation is performed for a solid concrete block, the results of which are compared with the results obtained by TRISCO.

The total heat transfer resistance of concrete block is calculated according to the equations 5.4 and 5.5 while the heat transfer resistance of the concrete layer is calculated according to the equation 2.6.

$$R = R_{si} + R_{concrete} + R_{se} \tag{5.4}$$

$$R_{si} = \frac{1}{a_{si}}; R_{se} = \frac{1}{a_{se}} \tag{5.5}$$

Solving the system of equations, taking into account the heat transfer coefficients of air for the inner and outer surface, it follows that the total heat transfer resistance of the concrete block is R = 0.32 m^2/KW. The heat transmittance can then be calculated according to equation 2.7, which results to a thermal transmittance of 3.16 W/m^2K. By comparing the calculated value, with the U-value obtained from TRISCO, which can be found in Appendix A (see Figure A.1), it is observed that the result are merge.



Colours

Col.		Type	CEN-rule	Name	Pat.	λ [W/mK]	ε [-]	θ [°C]	h [W/m²K]	q [W/m²]	θa [°C]	hc [W/m²K]	Pc [W]	θr [°C]	C1	C2	C3
2		BC_SIMPL	NIHIL	inside				20.0	7.70	0							
5		BC_SIMPL	NIHIL	outside				0.0	25.00	0							
8		MATERIAL		concrete		1.700											

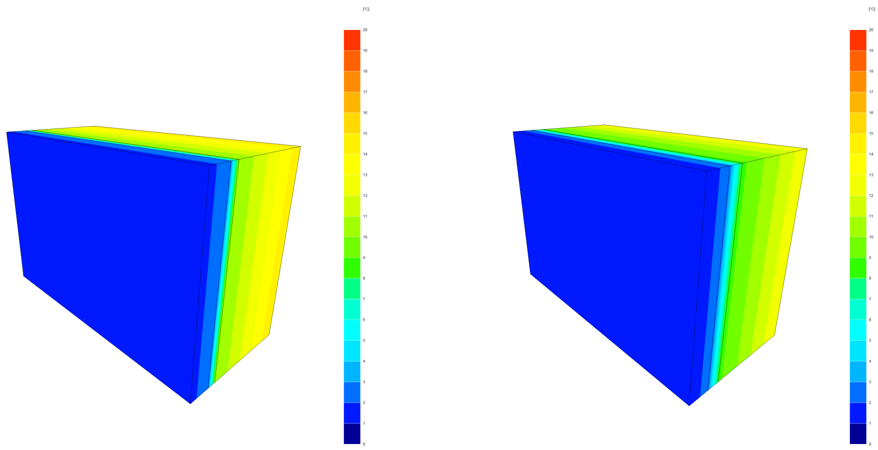
Figure 5.2: Representation of the thermal properties and the boundary conditions for a solid concrete wall

5.4. Results of thermal analysis

In this section, the evaluation of the thermal performance of the five concepts for the insulated and the conductive state will be presented.

5.4.1. Influence analysis

The first round of simulations was carried out in order to gain an insight into the effect of the air cavity on the thermal transmission of the structure. For this reason, two individual cavities with thicknesses of 20 mm and 30 mm were modeled.



(a) 20 mm cavity (b) 30 mm cavity

Figure 5.3: Temperature graph from TRISCO of the 20 mm and 30 mm air-cavity block.

Table 5.5: Results of TRISCO for 20 mm and 30 mm air-cavity block

Model	**Thickness**	**Cavity size**	$\mathbf{T_i}$	$\mathbf{T_o}$	λ_{eff}	q_{in}	q_{out}	**U**
	[mm]	[mm]	[°C]	[°C]	[W/mK]	[W]	[W]	[W/m^2K]
Single cavity	270	20	20	0	0.1111	9.66	9.66	2.01
Single cavity	280	30	20	0	0.1667	8.47	8.47	1.76

As it can be seen in Table 5.5, the introduction of an air-cavity into a concrete block contribute the reduction of the thermal transmittance as compared to the case of a single concrete block. In addition, a larger cavity benefits the whole system since increasing the cavity width can substantially decrease the thermal transmittance, due to the fact that conductive heat transfer is reduced. However, according to the literature findings of Section 2.5.2 a balance should be found to ensure that the benefits come with increasing the air cavity are not undermined by convection. For this reason for the modelling of the design concepts only cavities of 10, 15 and 20 mm width will be examined, where the effect of convective heat transfer is minimum.

5.4.2. Thermal analysis of concepts

The second round of calculations had as target the estimation of the U-values of the design concepts. In Table 5.6 the geometrical properties of the concepts are shown.

Table 5.6: Geometry input

	Concept	No. cavities	Cavity size [mm]	Inner wall thickness [mm]	Outer wall thickness [mm]	Length l [mm]	Width w [mm]	Height h [mm]
0	**Mineral wool**	-	-	200	50	600	425	400
1	**Folding bubble size (10x10)**	6	20	200	50	600	430	400
2	**Sliding bubble size (10x10)**	15	10	200	12	600	380	400
3	**Anchored bubble size (10x10)**	9	10	200	12	600	392	400
4	**Self-Puffing**	8	20	200	12	600	386	400
		11	15	200	12	600	397	400
		15	10	200	12	600	390	400

Concept 1: Folding multi-layer insulation

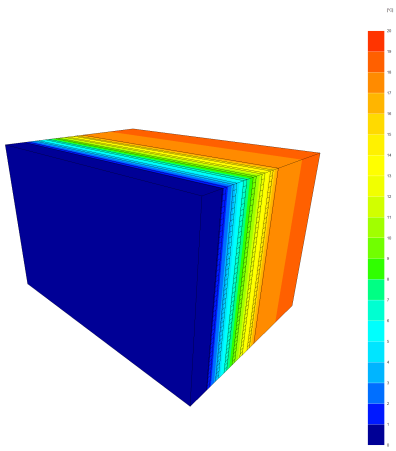
In this concept the core consists of 6 layers of membranes with a cell size of 10 mm alternating with 6 layer of air of 20 mm, reaching a total thickness of 175 mm. The films are made of PET and consist of 10x10 mm encapsulated air bubbles, which extend in the entire length of the element. In the insulated state, the distance between the adjustment membranes is kept below 20 mm to ensure that convective heat flows are minimised. On the other hand, in the conductive state, the outer rolls are rolled up leading to the creation of a 60 mm cavity which is filled with air. In this way, the convective heat flow is enhanced and the thermal resistance of the structure is reduced.

As Table 5.7 indicates, in the insulated state, this concept can reach a U-value of 0.54 W/m^2K and in the conductive state the U-value of the system is 0.65 W/m^2K. Then the thermal resistances of the system were calculated which range from 1.9 m^2/KW for the insulated state to 1.5 m^2/KW for the conductive state.

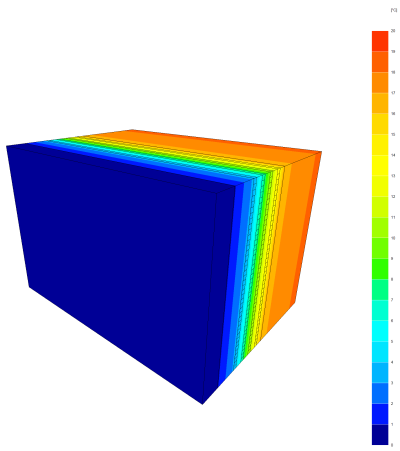
The similar results in the thermal transmittance values are also reflected in the temperature diagrams that are depicted in Figure 5.4, suggesting that there is no significant change between insulating and conducting state as the system has the same performance.

Table 5.7: Results of TRISCO for concept 1

	Concept	λ_{con} [W/mK]	λ_{PET} [W/mK]	λ_{bubble} [W/mK]	λ_{cav} [W/mK]	q_{in} [W]	q_{out} [W]	U [W/m^2K]	R [m^2/KW]
1	**Insulated**	1.7	0.19	0.067	0.1111	2.57	2.57	0.54	1.9
1	**Conductive**	1.7	0.19	0.067	0.3333	3.14	3.14	0.65	1.5



(a) Concept 1 insulated



(b) Concept 1 conductive

Figure 5.4: Temperature graphs from TRISCO of folding multi-layer insulation for the insulated and the conductive state.

Concept 2: Sliding multi-layer insulation

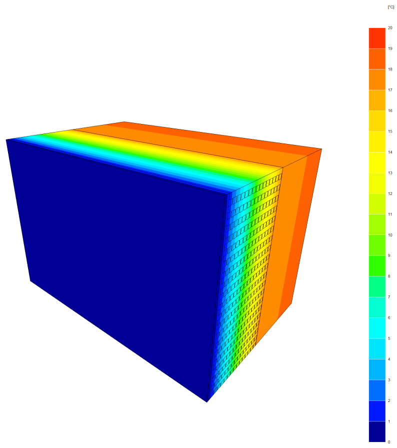
In concept 2, more narrow cavities are considered compared to concept 1. Here, in the insulated state the core consists of 15 layers of membranes with a width of 10 mm, which are inflated and placed the one next to the other reaching a total thickness of 180 mm. Similarly to concept 1, the films are made of PET and consist of 10x10 mm encapsulated air bubbles, which extend the entire length of the element. On the other hand, in the conductive state, the core is compressed by removing air from the system, leading to an 85% reduction in core thickness. In this state, heat flow is governed by conduction.

As Table 5.8 indicates, in the insulated state, this concept reached U-value of 0.55 W/m^2K and in the conductive state the U-value of the system was increased to 1.87 W/m^2K. Then the thermal resistances of the system were calculated which range from 1.8 m^2/KW for the insulated state to 0.5 m^2/KW for the conductive state.

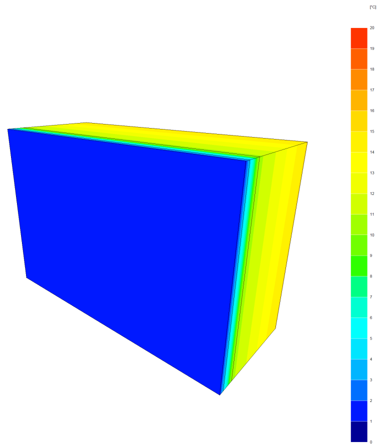
Likewise concept 1, concept 2 does not satisfy the required thermal performance in the insulated state, since the R-value is lower than 4.5 m^2/KW, showing a weakness of this core structure. However, in contrast to concept one, here a greater difference is observed between the high-insulation and low-insulation states, which leads to the conclusion that by fully discharging the core, a lower thermal resistance can be achieved, since the solid parts have a higher thermal conductivity compared to air.

Table 5.8: Results of TRISCO for concept 2

	Concept	λ_{con} [W/mK]	λ_{PET} [W/mK]	λ_{bubble} [W/mK]	λ_{cav} [W/mK]	q_{in} [W]	q_{out} [W]	U [W/m^2K]	R [m^2/KW]
2	**Insulated**	1.7	0.19	0.067	0.067	2.66	2.66	0.55	1.8
2	**Conductive**	1.7	0.19	-	-	8.98	8.98	1.87	0.5



(a) Concept 2 insulated



(b) Concept 2 conductive

Figure 5.5: Temperature graphs from TRISCO of sliding multi-layer insulation for the insulated and the conductive state.

Concept 3: Anchored insulation
In concept 3, the core consists of 9 layers of membranes with a width of 10 mm, between which layers of air of the same thickness are interposed, reaching a total thickness of 180 mm. Similarly to the aforementioned concepts, the films are made of PET and consist of 10x10 mm elongated encapsulated air bubbles. In the insulated state the bubbles of the membranes are filled with air while in the conductive state the membranes are flat and at the same time there is air inside the narrow cavities that separate the membranes. During the transition between the high insulated and the low insulated state the thickness of the core remains constant.

As Table 5.9 indicates, in the insulated state, this concept reaches a U-value of 0.42 W/m^2K and in the conductive state the U-value of the system is 0.46 W/m^2K. Then the thermal resistances of the system can be calculated, ranging from 2.4 m^2/KW for the insulated state to 2.2 m^2/KW for the conductive state.

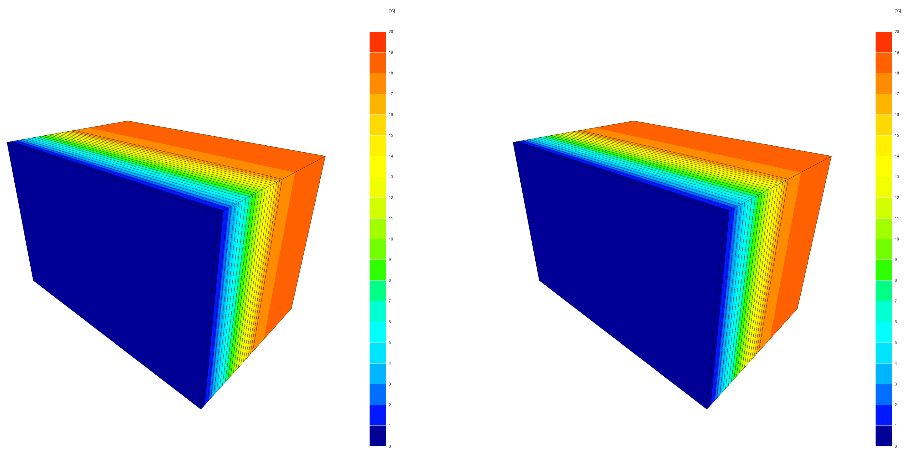
The outcomes of the analysis proved that concept 3 performs better in the insulated stated as compared to the concept 1 and 2, but even in this case the R value is not satisfactory. However, an interesting conclusion can be drawn from this analysis in comparison with the second concept. More precisely, the introduction of a narrow vertical air cavity between two neighboring membranes benefits the the thermal performance of the system. An explanation to this, might be the fact that radiative heat transfer is reduced in the vertical cavity, due to the larger surface scattering radiation inside the cavity compared to the bubble. As a result, the heat flow due to radiation is reduced leading to an increase in the thermal resistance of the system. Conductive heat flow is also expected to decrease in this configuration while given the small size of the cavity, convective heat flow is expected to be small. In addition, a very small difference is observed between the high insulation and low insulation state due to the presence of air within the cavities in the conductive state, which is the main contributing factor for the stabiliasation of the value of the thermal resistance of the system.

A solution that could help increase the thermal resistance in the insulated state would be to apply a low-emissivity coating to the films that could further reduce radiative heat transfer. However, even in this case, the value of R in the conductive state would follow the same increase, since the non evacuation of air cavities decreases the shift potential.

Concept 4: Self-puffing insulation
In concept 4, the core consists of a honeycomb structure, which is made of a low-emissivity aluminum foil material, aiming to reduce the heat transfer by radiation. Additionally, based on the outcomes

Table 5.9: Results of TRISCO for concept 3

	Concept	λ_{con} [W/mK]	λ_{PET} [W/mK]	λ_{bubble} [W/mK]	λ_{cav} [W/mK]	q_{in} [W]	q_{out} [W]	U [W/m^2K]	R [m^2/KW]
3	**Insulated**	1.7	0.19	0.067	0.067	2.00	2.00	0.42	2.4
3	**Conductive**	1.7	0.19	-	0.067	2.21	2.21	0.46	2.2



(a) Concept 3 insulated

(b) Concept 3 conductive

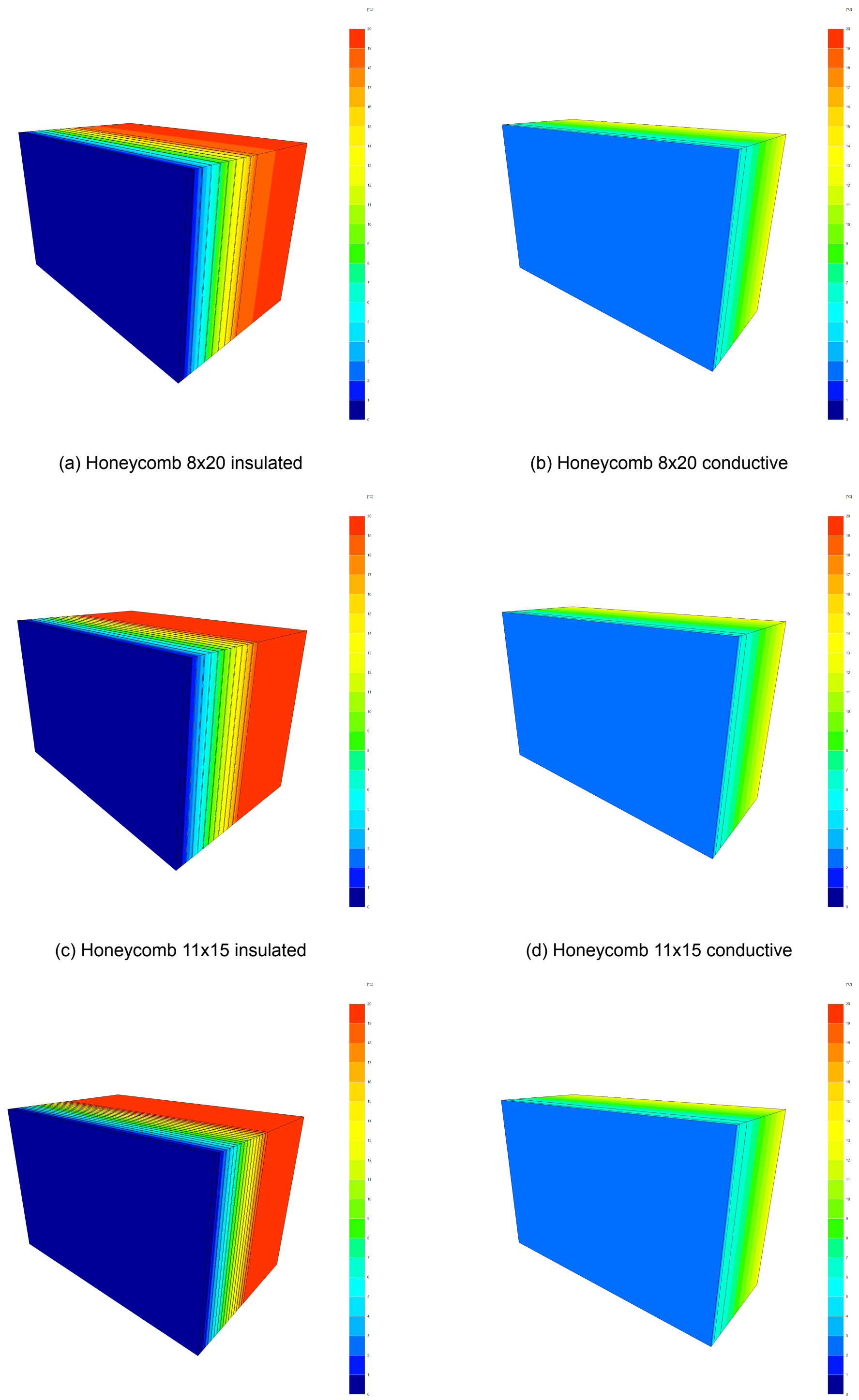
Figure 5.6: Temperature graphs from TRISCO of anchored insulation for the insulated and the conductive state.

of the previous analysis, vertical thin air-cavities perform better than small air-pockets, therefore the honeycomb layers in this concept are modelled as thin vertical cavities with varying widths. Three different cavity sizes are considered for the simulations namely, 10, 15 and 20 mm resulting in total core thickness of 174, 185 and 178 mm respectively. The temperature graphs of the three alternatives are shown in Figure 5.7.

Table 5.10: Results of TRISCO for concept 4.

	Concept	Cavity size [W/mK]	λ_{con} [W/mK]	λ_{foil} [W/mK]	λ_{cav} [W/mK]	q_{in} [W]	q_{out} [W]	U [W/m^2K]	R [m^2/KW]
4.1	**Insulated**	20	1.7	200	0.0417	1.14	1.14	0.24	4.2
4.1	**Conductive**	20	1.7	200	-	13.40	13.40	2.79	0.4
4.2	**Insulated**	15	1.7	200	0.0313	0.86	0.86	0.18	5.6
4.2	**Conductive**	15	1.7	200	-	13.40	13.40	2.79	0.4
4.3	**Insulated**	10	1.7	200	0.0209	0.64	0.64	0.13	7.5
4.3	**Conductive**	10	1.7	200	-	13.40	13.40	2.79	0.4

The result of the analysis showed that dividing the core into more compartments, for the same width of the insulating layer, has a positive effect on the thermal resistance of the system, since minimizes the convective heat transport of the air. Solid conduction can be reduced by employing solid conduction paths that are relatively long in comparison to the panel thickness. This is indeed the case of the honeycombs of 20 and 10 mm cavities. As Table 5.10 indicates, in the insulated state, the honeycomb of 20 mm has a thermal resistance of 4.2 m^2/KW and a thermal transmittance of 0.24 W/m^2K, while by reducing the size of cavity to half and simultaneously doubling the number of cavities, leads to a higher thermal resistance of 7.5 m^2/KW and a lower thermal transmittance of 0.13 W/m^2K. Furthermore,



(a) Honeycomb 8x20 insulated

(b) Honeycomb 8x20 conductive

(c) Honeycomb 11x15 insulated

(d) Honeycomb 11x15 conductive

(e) Honeycomb 12x10 insulated

(f) Honeycomb 12x10 conductive

Figure 5.7: Temperature graphs from TRISCO of the several patterns of the self-puffing insulation for the insulated and the conductive state.

applying a low-emissivity cavity surfaces made of an aluminum film, contributes to a great extent on the reduction the radiative heat flows.

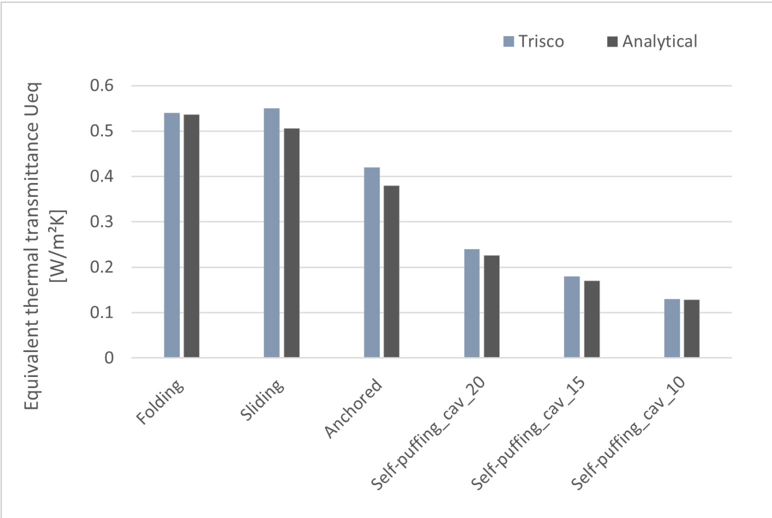
For the conductive state, the system is compressed to remove all the air trapped inside the cavities, all three variants perform in the same manner. More precisely, the thermal resistance of the system is 0.4

m^2/KW and a thermal transmittance of 2.79 W/m^2K, which is very close to the case of a solid concrete block. This configuration is governed by the conductive heat flows between the solid surfaces of the inner membranes.

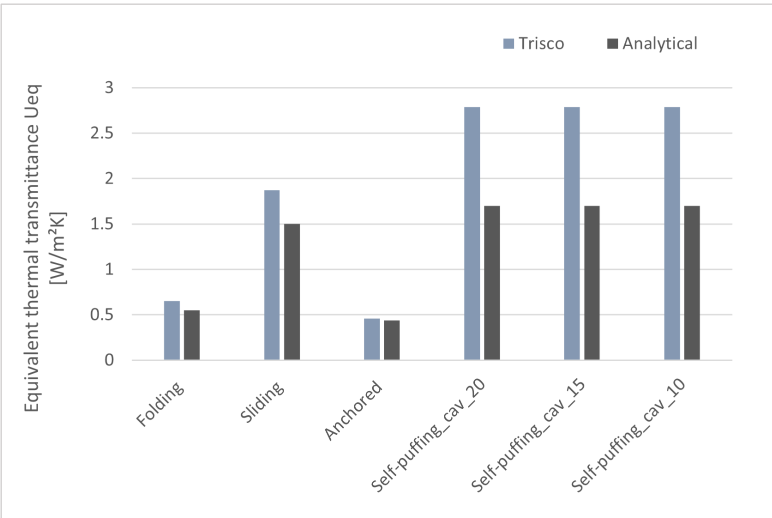
5.5. Model validation

In this section the results of the numerical simulations are validated by means of comparing the U-values obtained from TRISCO with the U-value calculated according to analytical formulas.

Most of the input parameters in the model are material properties. Apart from the standard thermal conductivity values of concrete and PET, several values for the thermal conductivity of air inside the cavity and the bubbles were calculated for the model. The results of the comparison showed that the calculated values of thermal conductivity for cells are similar to the results of previous research (see Appendix A).



(a) Insulated state



(b) Conductive state

Figure 5.8: Comparison of results from analytical models and numerical simulations.

Then, the U-values of each concept are indicated in Figure 5.8. For the insulated state, the results from both methods are similar. A deviation is observed in the conductive state for the self-puffing insulation with a core made of reflective material. This deviation can be explained from the fact that the analytical formulas are not taken into account heat transfer due to radiation, which leads to the estimation of a lower value of thermal transmittance, which is indeed reflected in the charts of Figure 5.8.

5.6. Conclusion

Through the simulation of heat transfer in the examined concepts, some interesting conclusions can be drawn regarding their thermal behavior:

Among the four concepts analyzed, variant 2 and 3 of the self-puffing insulation performed better in both insulated and conductive states. In the insulated state, they could reach a thermal resistance of 5.6 m^2/KW and 7.5 m^2/KW respectively which is higher than the minimum required according to the Dutch building codes. On the other hand, in the conductive state they could both achieve the minimum thermal resistance that is very close to the value of an uninsulated solid concrete block.

In the case of the self-puffing insulation, three different cavity divisions were simulated namely; 8 11 and 15. Among them, the third variant performed the best. Therefore increasing the number of the cavities within the same thickness of the insulation layer is beneficial for the system since the radiative and convective heat flows are significantly reduced, leading to the increase of the overall thermal resistance.

In air-cavities less than 20 mm radiation becomes significant and contribute on a high degree to the global heat transfer. Therefore, to increase the overall thermal resistance of the façade system in the insulated state, it is necessary to use a low-emissivity coating for the core. Finally, The pattern of the vertical thin air cavities performs better than the bubble-like pattern.

6

Multi-criteria analysis

6.1. Introduction

In this chapter, a multi-criteria analysis will be presented on the basis of which the final concept for the adaptive insulation system will emerge. All design alternatives will be scored against the design criteria that were established in Chapter 3.

Initially the criteria will be weighted according to their level of importance to the adaptive insulation system. The rating for thermal performance will be based on the findings of Chapter 5. The highest scoring alternative will be selected as the final design.

6.2. Multi-criteria analysis methodology

An important aspect of the design making process when it comes to projects or products is the multi-criteria analysis (MCA). An MCA establishes preferences between options by reference to an explicit set of objectives that the decision making body has identified, and for which it has established measurable criteria to assess the extent to which the objectives have been achieved.

An important feature of the MCA is a performance matrix, in which each row represents an option and each column represents the performance of the option against each criterion (scoring). In this stage, each option's expected outcome is assigned a number on the scale of preference for each option and criterion. A hypothetically less preferred options score lower and a hypothetically more preferred options score higher.

The next step included the creation of a weighting system, in which each criterion is weighted according to its relative importance. In this way, the criteria can have a higher or a lower impact on the final design. The higher the assigned weight, the more influence the criterion has on the final evaluation.

6.3. Weighting system

As previously stated, not all criteria contribute equally to the design goal. The designer should decide which criteria have the greatest impact on the final result and which have the least. In this regard, for the assessment and the final selection of the façade system, the Pugh Matrix method is used in order to create a weighting system.

Pugh Matrix, is a qualitative technique for ranking a set of multidimensional options, often used in the engineering field for making design decisions. This method follows a systematic approach in which a score is assigned to each sub-criteria based on their level of importance to the development of the adaptive insulation system. Depending on the level of importance of each sub-criteria, the score can range from 1 to 3, with 1 being the least important and 3 the most important sub-criteria (*Pugh Matrix – Continuous Improvement Toolkit* n.d.). In Figure 6.1 a representation of the the weighted sub-criteria of each criteria category is given.

Among them, the **thermal resistance** and the **range of shift** have the highest weight factor of 3, due to the fact that they are fundamental performance criteria that the new insulation system should meet, as they are closely related to its primary function. The **response time** is an important parameter when designing an adaptive technology, however for the present study it is considered to be one of the soft criteria required for system development. For this reason it has a weight factor of 1.

From the sub-criteria that are related to the design feasibility and ease of manufacturing, **durability** has the highest weight factor of 3 while **maintenance**, **constructability**and **technological complexity** have a weight factor of 2.

Following the weighting of criteria is the scoring of concepts. Each concept is scored against the others for the defined sub-criteria. The score of each concept is calculated as formula 6.2 indicates. According

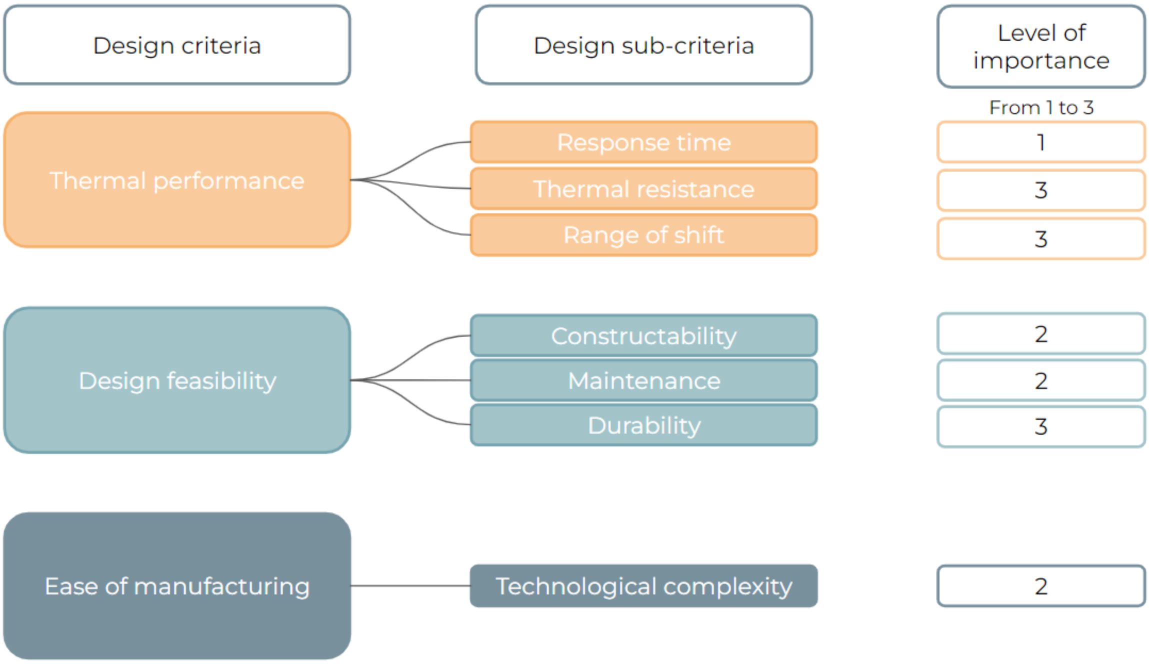


Figure 6.1: The figure represents a summary of the design criteria and the sub-criteria along with their weights

to which, the score for each concept is the product of the weight of the sub-criteria s_i and the score of each concept c_i for the examined sub-criteria. The final score, is the result of he summation of the individuals scores of each concept.

$$Score = c_i \cdot s_i \tag{6.1}$$

$$FinalScore = \sum (c_i \cdot s_i) \tag{6.2}$$

6.4. Scoring of concepts

6.4.1. Thermal performance

The assessment of thermal performance depends on three parameters; the thermal resistance, the range of achievable R-values or U-values and the response time. The thermal resistance and range of achievable U-values for the insulated and conductive states were based on the calculations in Chapter 5. In this regard, all design alternatives are scored against each other and the scores are then multiplied with the weight factors as Figure B.1 indicates in Appendix B. The highest rating goes to the design that can reach the maximum thermal resistance in the insulating state, which is in accordance to the Dutch Building Regulations, and the lowest in the conductive state.

The response time estimate is based on the assumption that systems that must inflate and deflate require a longer time to shift from insulating to conductive state and vice versa, compared to mechanically actuated systems. It should be noted that the response time for inflating and deflating the honeycomb and closed-cell core was on the order of a few seconds during the creation of small prototypes which were designed in the early stages of the study. However, for larger scale façade panels, the response time is expected to be longer.

From the result of the analysis 'Self puffing' insulation alternative A emerges as the concept with the highest score in terms of thermal performance.

6.4.2. Design feasibility

For the assessment of design feasibility the concepts are scored against each other for the sub-criteria of constructability, maintenance, and durability. The results of the analysis are presented in Figure B.2 which can be found in Appendix B.

In this stage of the analysis, constructability is based on the flexibility of the system to be used in different details and interfaces. The design alternatives incorporating the outer layer as part of the insulation system are considered to be more complex and difficult to design at the interface with the windows. For this reason they get a lower score. In terms of maintenance, the highest score goes to the design that does not need regular maintenance and at the same time allows access to its components in order to replace or restore them. Finally, durability is measured in terms of expected life time. Therefore, the highest score goes to the concept with the highest expected durability to weather and forces.

The results of the analysis indicate Anchored insulation as the concept with the highest score for the category of design feasibility.

6.4.3. Ease of manufacturing

For the last criterion, of ease of manufacturing, the evaluation depends on overall cost in terms of production and installation. The results of the analysis can be found in Figure B.3 in Appendix B. As indicated in the performance table for this criterion, the highest score goes to the design that has the lowest technological complexity and is thus easier to produce. Among the five concepts that are compared, Anchored insulation has the highest score.

6.5. Performance matrix

The final section of this chapter summarises the outcome of the separate scoring of the concepts in a performance matrix where the combined scoring of all criteria are indicated. The result of the multi-criteria analysis indicates 'Self puffing' insulation alternative B as the concept with the highest score considering the sums of the scores of the individual categories. In this regard, this concept will be finalised in the following chapter.

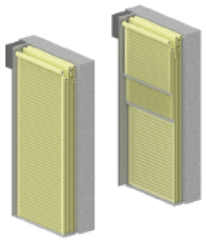
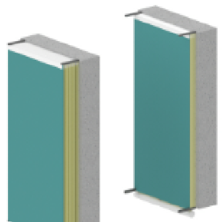
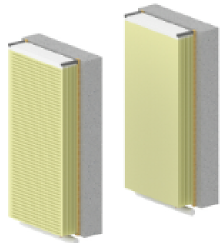
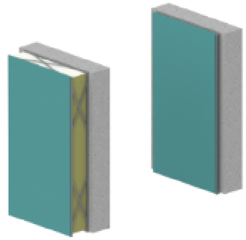
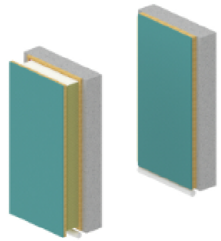
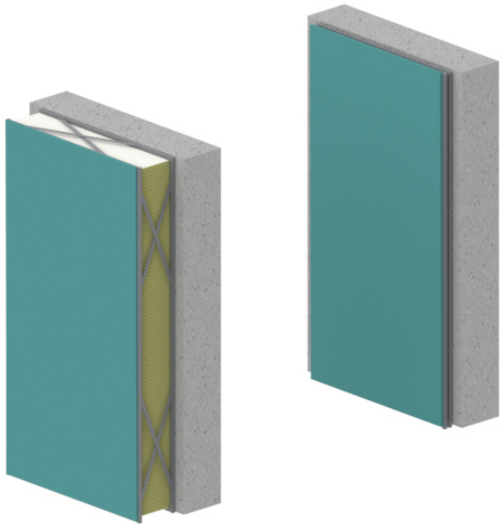
Concept / Criteria	 1. Folding insulation	 2. Rail track insulation	 3. Anchored insulation	 4. "Self-puffing"insulation A	 5. "Self-puffing"insulation B
Thermal performance	9	11	11	21	20
Design feasibility	10	12	16	12	12
Technological Complexity	2	4	6	2	4
Final Score	**19**	**27**	**33**	**35**	**36**

Figure 6.2: Performance matrix of the adaptive insulation concepts

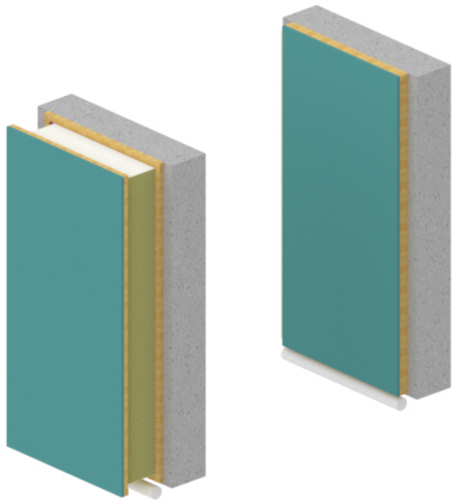
6.6. Discussion

The research through design stage was completed by comparing the alternative preliminary designs using a performance matrix with the aim of finding standout concept.

From this process, alternatives A and B of the self-puffing insulation concept ended up with the highest scores compared to the other solutions, and with a small difference between the two, alternative B was chosen for further development, receiving the highest score. This result was mainly influenced by the result of the thermal analysis which highlighted the inability of other concepts to satisfy the sub-criteria set at the beginning of this project.



(a) Alternative A



(b) Alternative B

Figure 6.3: Concept of ”Self-puffing” Insulation.

More specifically, in terms of thermal performance, both alternatives can reach a high range of shift according to the outcomes of Chapter 5. However, alternative A is expected to have a lower response time since its structure consisting of a scissor system facilitates the compression and decompression of the panel, while on the other hand the inflation and deflation of the core of alternative B requires more time. Both alternatives, have a lower score for the design feasibility criteria, compared to the other solutions. The feature of the moving façade increases the complexity for constructing and maintaining this system and the requirements for water and air-tightness. The structure of alternative A allows easy access for maintenance, which is an advantage of this system but at the same time, there is always the risk of creating unwanted thermal bridges at the metal scissor location. The latter was taken into account when choosing whether to develop this alternative further. The actual cost of all the preliminary concepts that were examined, is something difficult to predict at this point. Nevertheless, variants A and B of self-puffing insulation, require a higher level of expertise to be produced due to the incorporation of the moving external layer on their systems. Therefore, is expected to have higher maintenance and installation costs.

Finally, it should be mentioned variant A presupposes that in the conductive state the insulation panel is aligned with the rest of the façade so that it becomes invisible, a fact that was considered more difficult to capture in a more detailed version in relation to variant B. Therefore, variant B was selected to be developed into a final stage.

7

Application to the building envelope

7.1. Introduction

In this chapter, the focus will be on the application of the adaptive insulating panel to a building envelope. First in the section 7.2 the prevailing design alternative, resulting from the multi-criteria analysis, will be studied in detail. Then in section 7.3 the potential facade application will be explored.

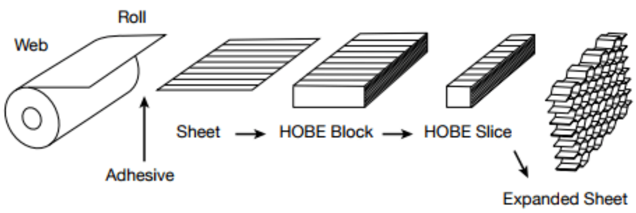
7.2. Final design

7.2.1. Material selection and manufacturing process

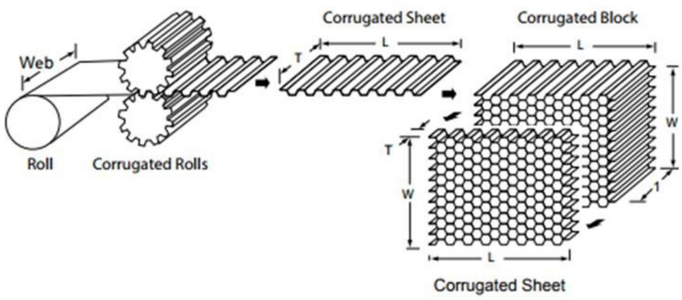
Honeycomb core

Honeycomb cores can be produced from a wide variety of materials including, fire-resistant aramid paper (Nomex® and Kevlar®), aluminum, thermoplastics with the most commonly used polypropylene and cardboard paper. The latter produces a cushioning end product while the former's are characterized by their stiffness and strength. Honeycomb manufacturing procedure relies on two different methods; the expansion and the corrugated method (see Figure 7.1). Based on the manufacturing method, different cell sizes and cell wall thicknesses can be produced. Normally, the corrugated process of honeycomb manufacture can produce products of higher density.

The expansion method begins with stacking sheets of material which are passed through a printer to print the adhesive lines. The adhesive lines are then processed to form a ”Honeycomb Before Expansion” block, known as a HOBE block. The HOBE block can either be expanded and cut to the desired wall thickness or the HOBE block is trimmed into the appropriate wall thickness (T) and subsequently expanded, forming one set of parallel cell walls of honeycomb. The final stage of the expansion process includes the cut of the expanded block in to the desired height (W) and length (L). The second method relies on the use of a corrugated roller, for the production of corrugated sheets. In this process, the flat sections of corrugated sheet are treated with adhesive to create a bond and then are stacked into blocks. As last step, the corrugated block is trimmed into the appropriate core thickness (Guida 2008).



(a) Expansion process



(b) Corrugated process

Figure 7.1: Manufacturing methods of honeycomb structure (Clarke 2017).

For the selection of the material that will form the core it was important to first set a list of criteria, as the characteristics of the material will determine the performance of the system. Therefore, for the core material the two main requirements can be summarized as follows:

- Low emissivity: This attribute is important for the minimisation of the thermal transfer due to radiation
- Durability: It is important that the material that will compose the core is durable and does not need frequent replacement.

The original idea for this concept was to use a stretchy material that it could be easily inflated and deflated. However, during the development of this concept the focus shifted towards the use of flexible aluminized fabric, with high stretching resistance, for the production of the honeycomb core.

External cladding
In the chosen concept, the external cladding is part of the insulation system and can move with it during the transition from the insulated to the conductive state. Therefore, research is focused on selecting a lightweight material that could be incorporated into the exterior of the insulating panel. For the exterior skin material two main directions could be followed. The first considers the case of a transparent or translucent cladding with the use of materials such as glass and textiles. However, for a transparent or translucent façade, light transmission should be considered for the design of the core geometry, which will lead to modifications in the porosity level and the distribution of pores. Alternatively, the second approach which is in line with the principles of this study, opaque materials could be selected to give the desired finish to the insulation panel.

Thus, for the examined case, wood panels are chosen for façade cladding. Among the different wood species, hardwood are considered most suitable option for the construction of timber panels compared to softwoods. Due to their structure, hardwoods have higher levels of strength and durability which lead to a longer service life and a higher resistance against weather. To ease the maintenance process, the wooden cladding is cut into stripes.

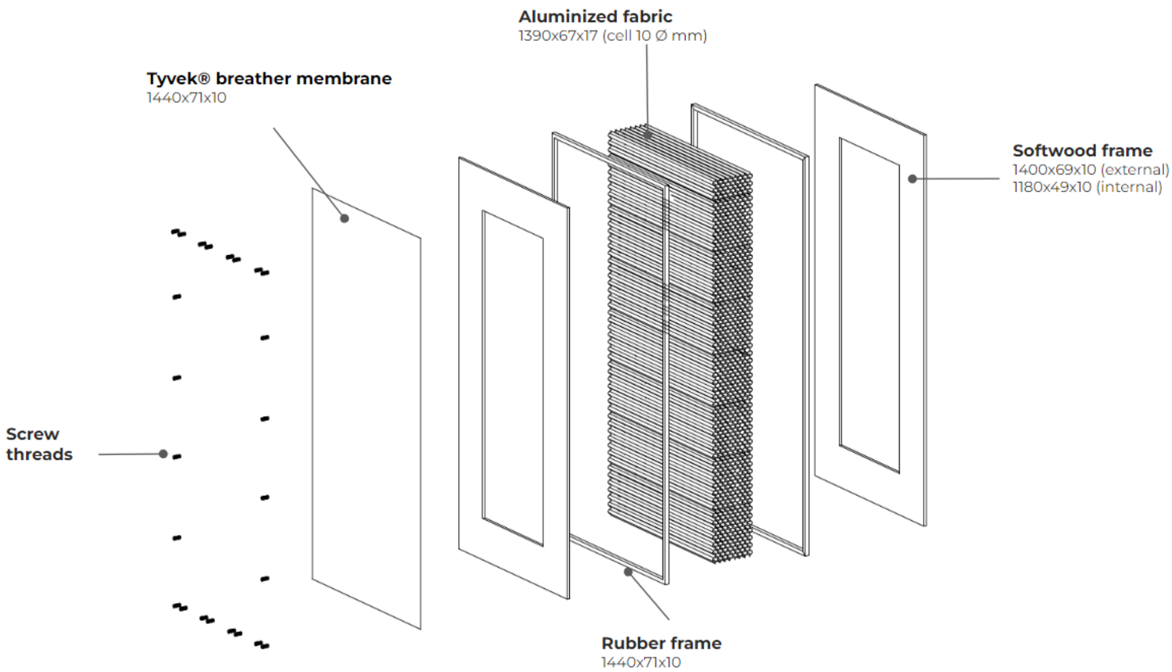
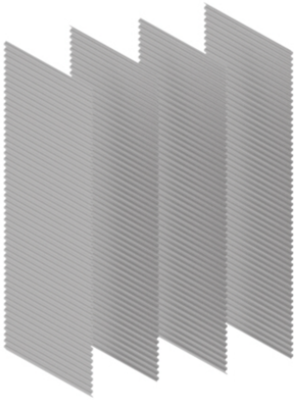


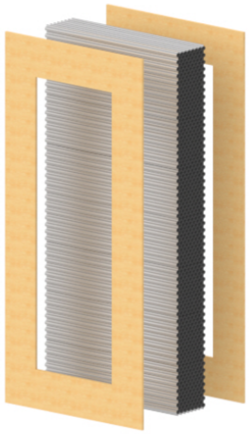
Figure 7.2: Exploded view of final insulation component.

7.2.2. Element assembly sequence



Step 1: The aluminized fabric is cut into corrugated sheets of the desired cell size.

Step 2: The glue is applied to the flat sides of the corrugated sheets which are then stacked with their flat surfaces held together to form a honeycomb block.



Step 3: Two wooden frames are glued to the outer layers of the honeycomb core to provide stability.

Step 4: A secondary weather protection layer is placed on the cold surface of the insulation.

Step 5: Screw threads are placed along the sides of the front wooden frame to create a wire where the wooden cladding will fit.

Step 6: Rubber frames are applied on the edges of the panel for protection against friction and facilitation of sliding movement..

7.3. Façade application

7.3.1. Façade typology

In this thesis, the architectural application of the insulation panel into the building envelope considers the element as an infill component in which the outer skin is integrated into the system. The secondary structure, is chosen to be a concrete wall which constitutes the load-bearing structure of the façade and is responsible of transferring the wind loads and the self-weight into the primary structure of the building. The infill component will be placed on the outer side of the façade. The system to be designed resembles the typology of the cavity wall system. Typically, a cavity wall system consist of an inner leaf with load-bearing properties, a thermal insulation layer and outer weatherproofing layer, separated from the inner structure by introducing an air cavity in between. However, an important difference between the adaptive façade system and the cavity wall is based on the mobility of the outer layer as well as the fluctuating thicknesses of the internal cavities of the first façade system. Thus, there will be some deviations from the original construction methodology followed for a cavity wall system in order to adjust it for the construction of the adaptive facade.

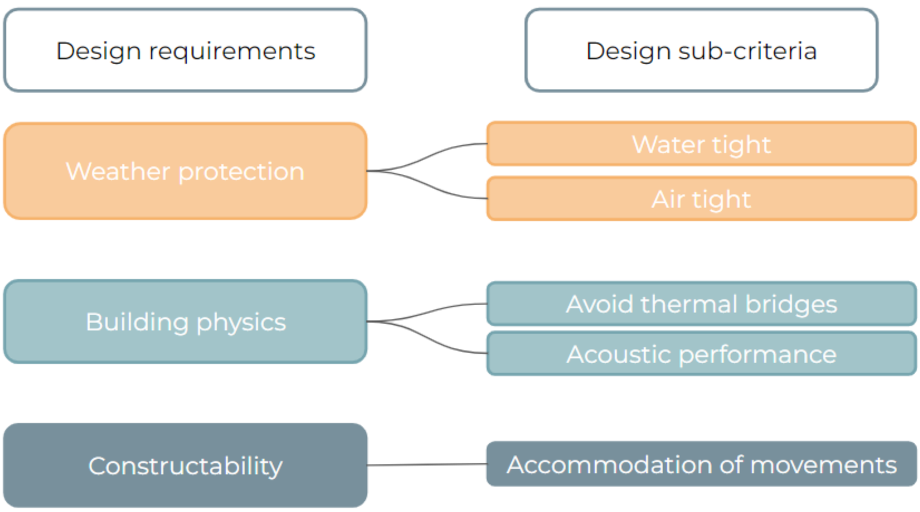
7.3.2. Façade support alternatives

The initial idea was to connect the adaptive insulation panels with the concrete wall behind with the use of adhesive. However, when developing this concept, the alternate direction of the suspension was followed in order to avoid welding. Consequently, the façade panel can be suspended from its top edge wooden frames and mounted to the concrete wall. In addition, it was considered a challenge to inflate a panel with the typical dimensions of a 3 x 1.5 m facade unit, which led to the creation of half-sized panels covering a floor height. In this way, the weight of the panel can be significantly reduced and the inflation will be more efficient.

7.3.3. Design requirements for façade application

The building envelope has a multi functional character since, it protects the inner space from the external parameters, it regulates the energy transfer and defines the shape and the unique architectural character of the building. This multi functional role reflects to the complexity of its design.

The objective of this section is to define a list of requirements that will determine the design logic for the integration of the adaptive insulation panel into the façade. An important parameter influences the list of requirements is the position of the insulation layer. As it is already mentioned, the insulation panel will serve as an infill component and it will not have a load-bearing function. Therefore, the design requirements can be summarized as follows:



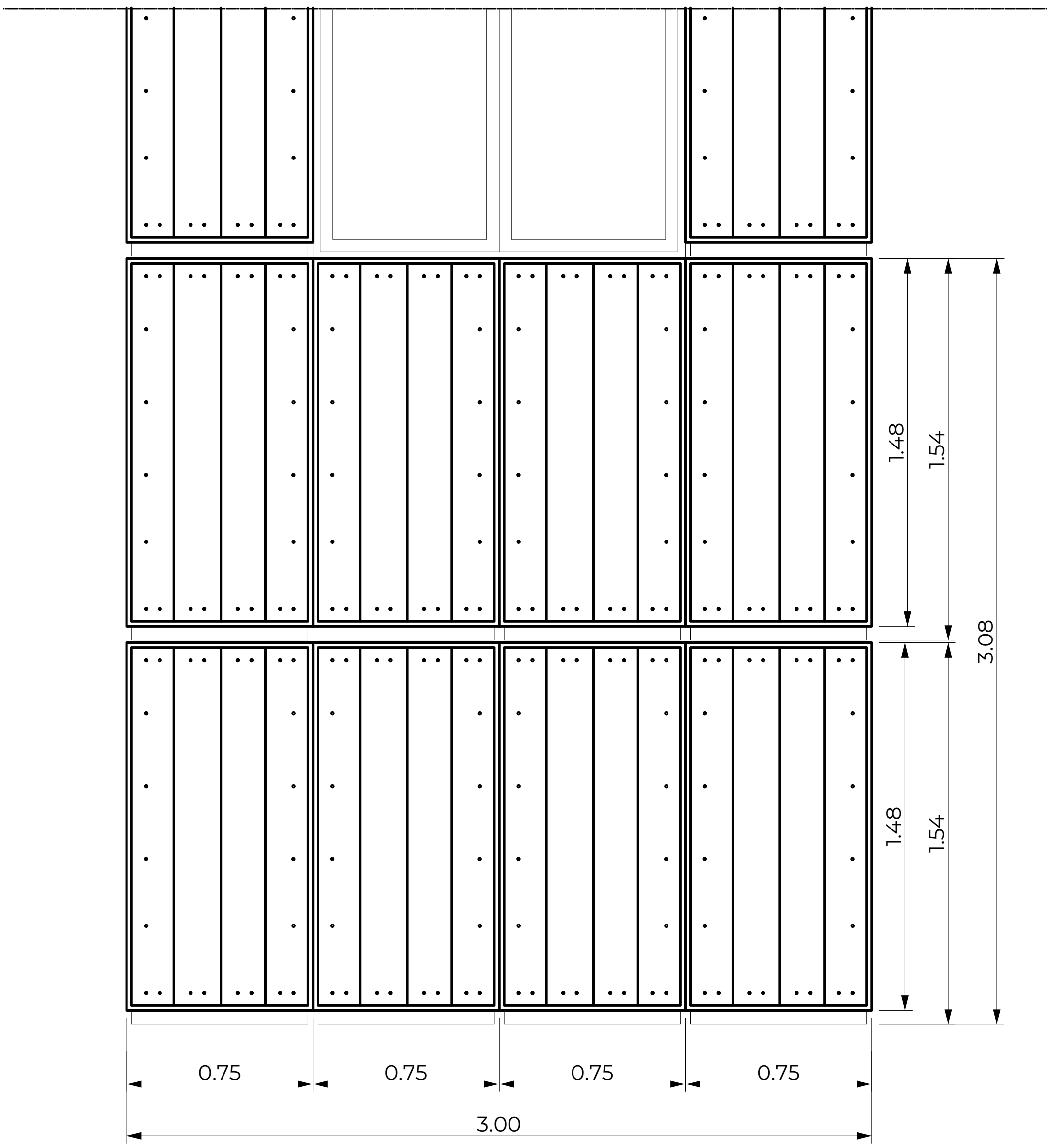
The weather protection can be achieved with the use of two membranes externally and internally, which combined provide effective condensation control and air tightness. The internal membrane is placed next to the concrete wall for vapour control and the second membrane is a permeable membrane which is applied between the wooden cladding and the insulation core.

To avoid thermal bridges additional insulation foam is applied in the window frames. Furthermore, the honeycomb core of the insulation panel could be beneficial for sound absorption purposes, since wave-like shape of the honeycomb can contribute to the scattering or sound.

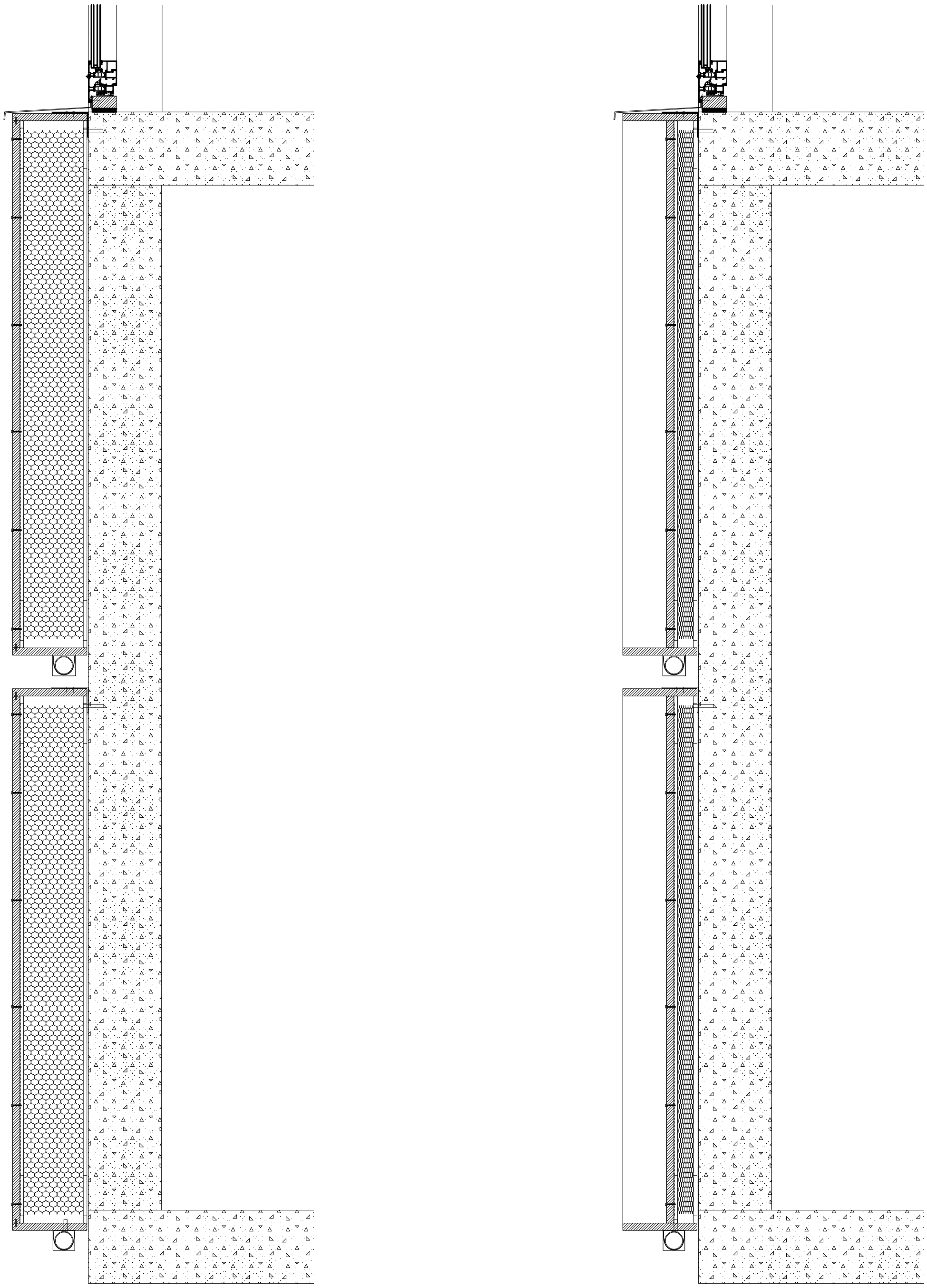
Finally, the accommodation of movements due to thermal expansion was taking into account in this project by creating small gaps in the connection to the concrete wall and the facade system as well as the connection of wooden cladding and wooden cover.

7.3.4. 2D drawings

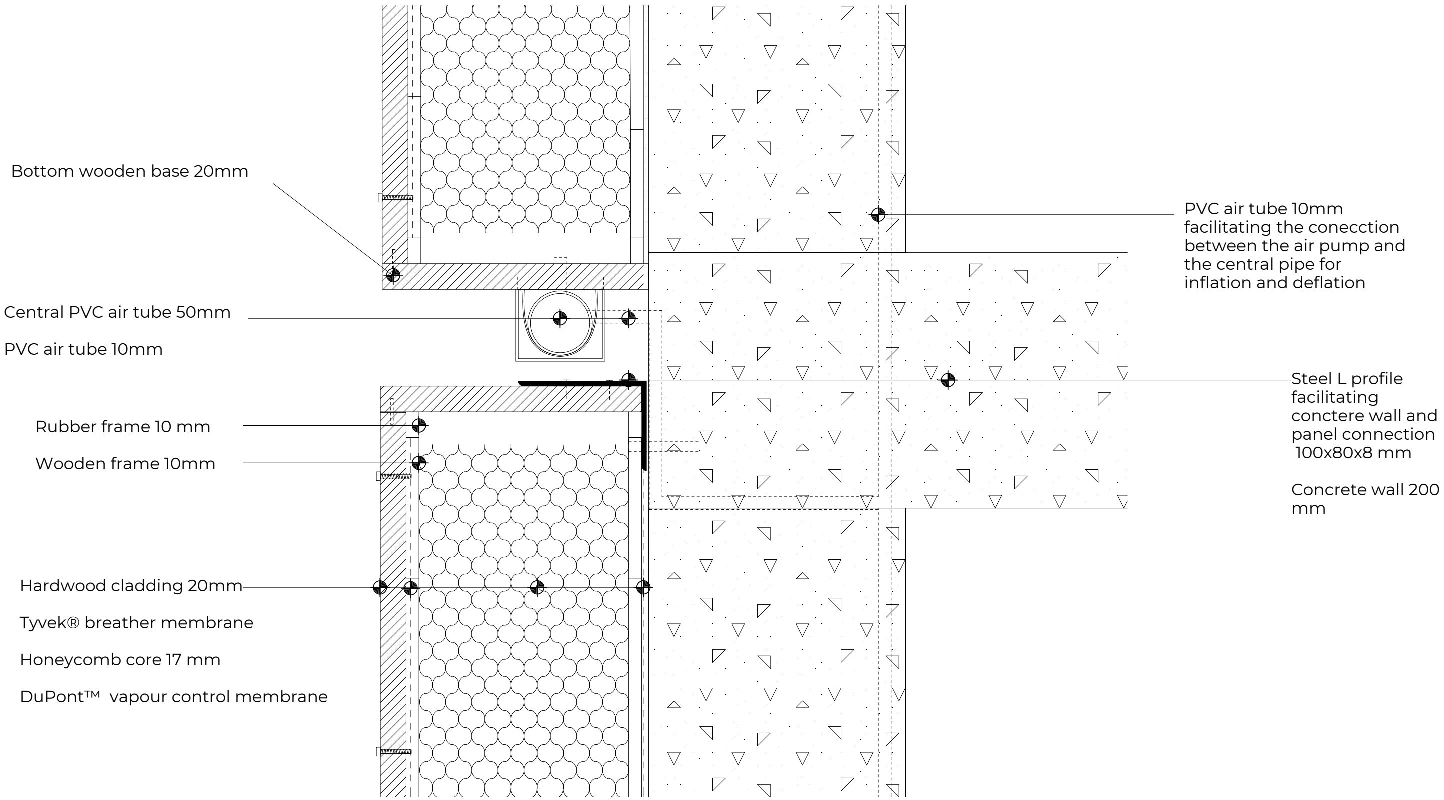
Elevetion of Façade
Scale 1:20



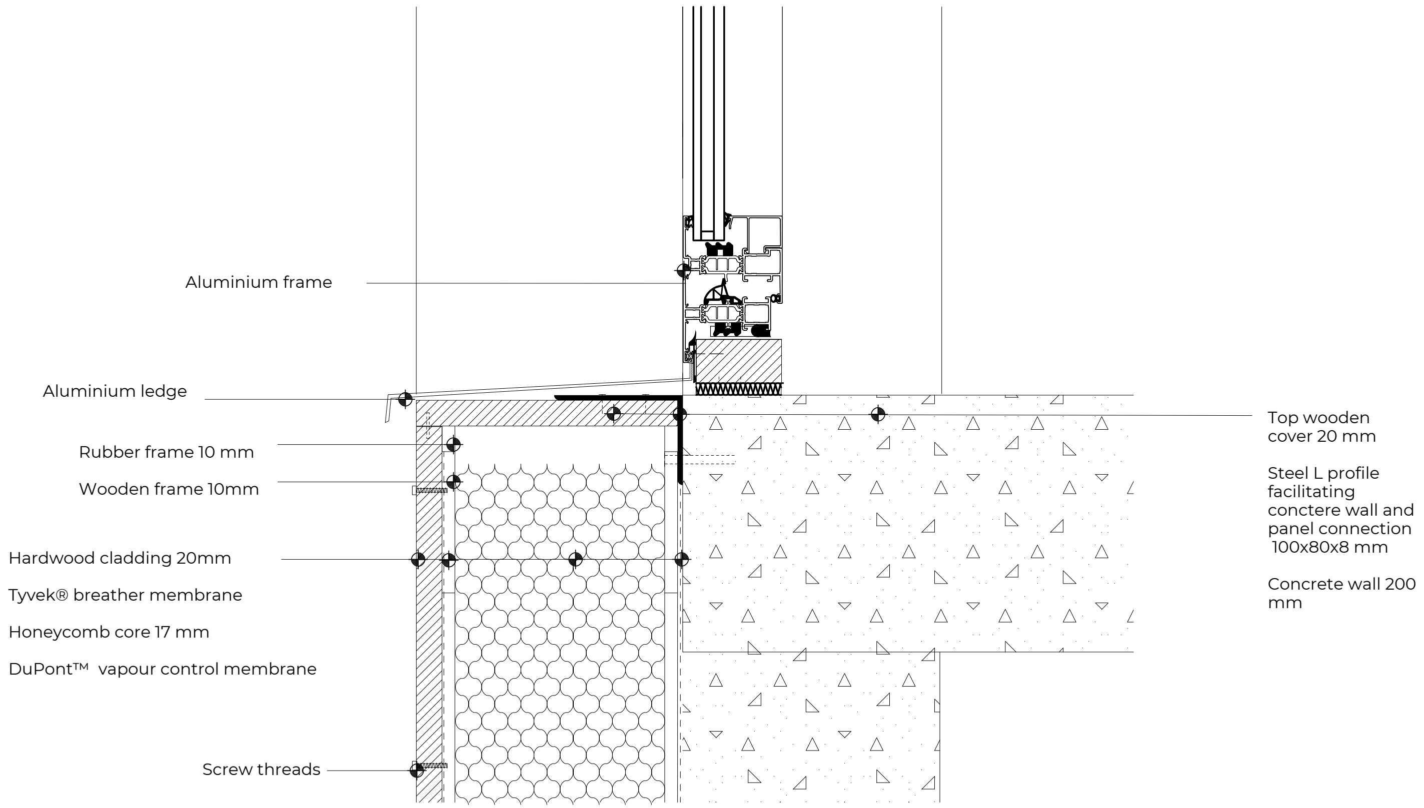
Vertical Section of Façade
Insulated and Conductive states Scale 1:15



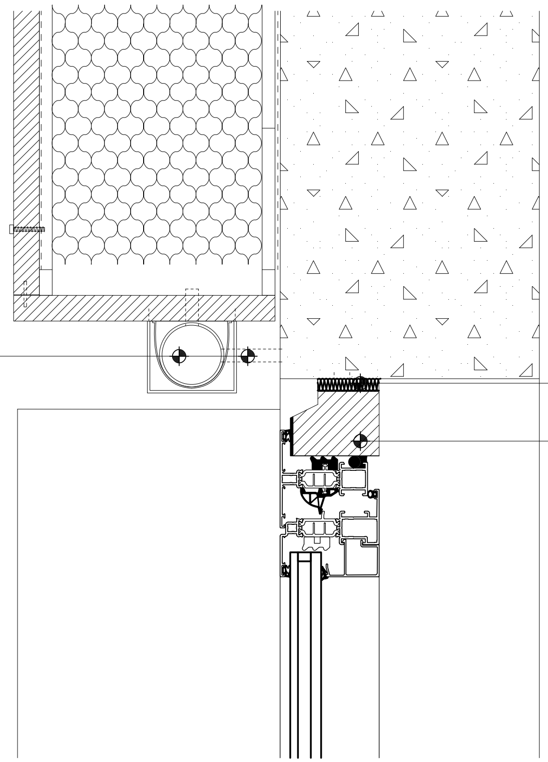
Vertical Section Panel to Panel
Scale 1:4



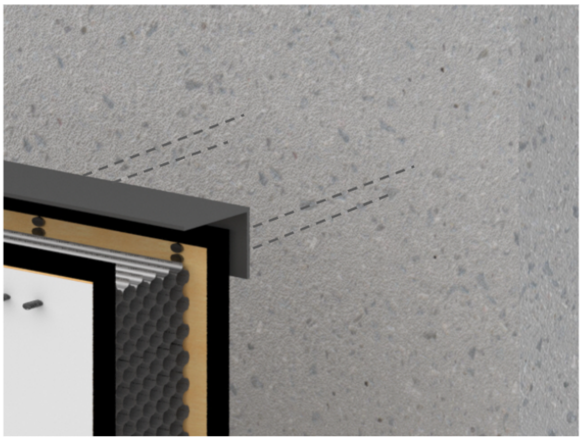
Vertical Section Panel to Bottom Window
Scale 1:4



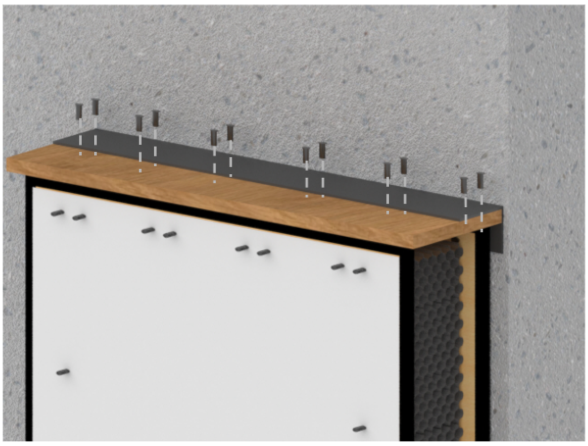
Vertical Section Panel to Top Window
Scale 1:4



7.3.5. Façade assembly sequence

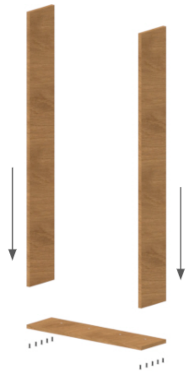


Step 1: An L-shaped steel profile is placed on the upper edge of the panel and screwed to the concrete wall. The steel element extends across the width of the insulation panel.



Step 2: A wooden slab is fitted between the top part of the insulation panel and the L-shaped profile. Screw threads are used to connect the steel element with the wooden slab.

Step 3: A wooden slab will be the base on which the facade system will rest. Holes of 10 ∅ mm are created on the bottom wooden slab to accommodate the PVC air tubes.



Step 4: Screw threads are added to the bottom plate. The side wood elements are pushed down to fit the screw thread wire.

Step 5: Sleeve nuts are screwed into the screw threads leading to the creation of a reverse π-shaped element which will be used as the cover of the insulation panel.

Step 6: Each panel is run by a 50 ∅ mm PVC pipe for air supply, which has attached smaller pipes of 10 ∅ mm. The air supply system is inserted into the openings of the bottom part of the wooden plate.

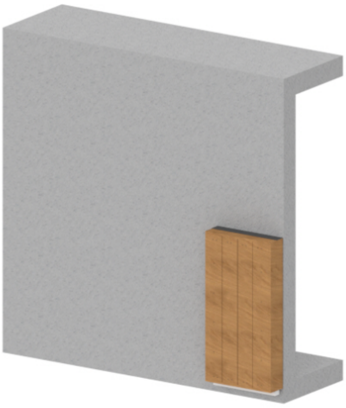
Step 7: The cover box of the air supply system is fixed to the π-shaped wooden element employing steel angles profiles.

Step 8: The π-shaped wooden element and the air supply system are ready to be fixed to the facade panel.

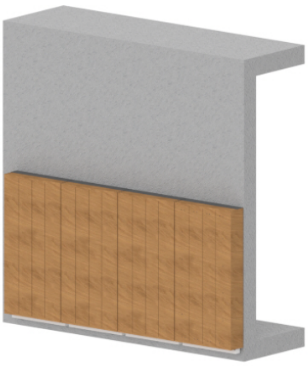
Step 9: The insulating panel is now hermetically sealed on all sides.

Step 10: Vertical wooden plates compose the external skin. Wood is fitted on the screw threads. A space is kept between the wooden plates to accommodate the movements due to thermal expansion.

Step 11: Sleeve nuts are then screwed into the screw threads to secure the external skin in place.



Step 12: The facade panel is ready.



Step 11: At the same time, the adaptive insulation panels, are placing next to each other following the same procedure.

Step 12: When the installation of the first row of facade panels is finished, the second row of panels is suspended from above following the same procedure.

8

Discussion

8.1. Introduction

This study aimed to develop a novel thermal insulation, which has a low complexity in terms of actuation and integration into the building envelope and at the same time can achieve a high level of efficiency in terms of thermal shift. Therefore, a methodology based on a research through design was followed to identify the final design. The intention of this section is to shed light on the possible limitations of the method followed as well as the limitations of the final product itself.

8.2. Assumptions and Limitations

8.2.1. Geometry input

- The thermal performance of the adaptive insulation was studied through numerical analysis using the steady-state software tool TRISCO. This is a widely used thermal simulation tool, with a simple interface and quite easy to use, but it comes with a certain degree of limitations. The first limitation concerns the geometry input. TRISCO works with orthogonal blocks and simple geometries. Considering this restrain, all cellular structures served as inputs for the model were represented with rectangular blocks instead of circular. Although, this deviation from the original shape is expected to affect the results obtained, it is unlikely to cause a significant difference in the results.
- In addition, the model can only be built within TRISCO instead of being imported from a CAD software, a limitation that contributed to the exclusion of a wide range of non-homogeneous materials consisting of varying pore sizes from the research process.

8.2.2. Calculation method

- The evaluation of the thermal performance of the examined concepts was carried out by calculating the thermal transmittance (U-value) for the insulated and conductive states, in steady-state conditions, where a constant independent of time heat flow is applied. In reality, the conditions are unsteady-state and the heat flux varies, but this does not affect the calculation of U-value.
- Inside a cell, all modes of heat transfer are present. However for simplification reasons, the dimensions of the cells and cavities composing the core material geometry were kept below 20 mm in order to minimize the effect of convective heat transfer. Consequently, the thermal conductivity of air was calculated considering the coupling of radiation and conduction.
- The validation of the model was realised by comparing the results of the numerical simulations with values obtained from analytical formulas. The analytical formulas successfully validated the numerical results, indicating the accuracy of the model. It should be mention though that, a deviation is observed in the results of TRISCO and formulas for the conductive state for the self-puffing insulation with a core made of reflective material. This deviation can be explained from the fact that the analytical formulas are not taken into account heat transfer due to radiation, which leads to the estimation of a lower value of thermal transmittance.
- Experimental data from previous researches were not available for comparison in order to tested the efficacy of the model to simulate the thermal performance of adaptive insulation concepts. In addition, the laboratory equipment which was available during the time that this project was conducted required a long time to carry out only one test and was characterized by a lack of precision, so for these two reasons it was not chosen as a means of validating the research. Nevertheless, prototypes need to be made in order to validate the adaptive insulation experimentally in order to derive statistical data for its safe application.

8.2.3. façade application

- The dominant idea of the preliminary design solutions as it emerged from the multi-criteria analysis was further developed, with the aim of creating a final design as well as the assembly sequence for its integration into the building shell. In this regard, the design of the air-supply system was realised through detailing the connection of the façade panel and the air-pipes. However, in this representation, the number as well as the actual dimensions of the pipes are based on assumptions.

- The efficiency of the adaptive insulation depends on the size of the insulation panel. The study suggested that a panel with the typical dimensions of 3x1.5 m and a depth of 17 mm is more difficult to be inflated and deflated. Therefore, it is suggested to use as an upper limit 1.5x0.75 m units. Furthermore, this system cannot be applied to every interface without the appropriate modifications in size. In this study, the insulation panel was considered to have the same dimension with the windows in the opposite case, the dimension of the panel need to be modified.

- This study was carried out based on the principles governing an opaque building envelope, hence aspects such as light transmission through the building envelope were excluded from the core design. Based on this, the adaptive insulation product developed is not universally applicable to all façade typologies, as its installation is specifically addressed to opaque building shells. Its integration into a semi-transparent or transparent building shell is possible, with the necessary modifications to its structure.

  For the opaque envelope, wood was chosen to form the outer skin and the cover elements of the panel. The choice was made primarily because of the low thermal conductivity of the material and secondarily for aesthetic reasons. The proposed design solution which incorporates the wooden structure defines the architectural character of the building which might be considered as a limitation of this system for wide application. However, it should be noted that the choice of wood in this project does not preclude the use of a different non-transparent material such as aluminum, as the adaptive insulation system and the technology remains the same. However, in the case of aluminium, adjustments in the detailing of the façade system are required.

8.3. Discussion on the results

Despite the limitations, this study advances knowledge in the area of adaptive insulation technologies. It identifies the barriers to the limited application of this type of technologies in the building envelope and provides information aimed at facilitating their integration into the building envelope. The more significant contributions of this research are listed below:

- Compared to non-adaptive insulating materials, the prevailing concept of self-puffing insulation has a performance that is comparable to current state-of-the-art insulating materials in the insulated state. As Figure 8.1 indicates, the mean thermal conductivity of the self-puffing insulation, when is switched to the insulated state is lower than that of conventional insulation materials and also lower than similar gas-filled panel technology.

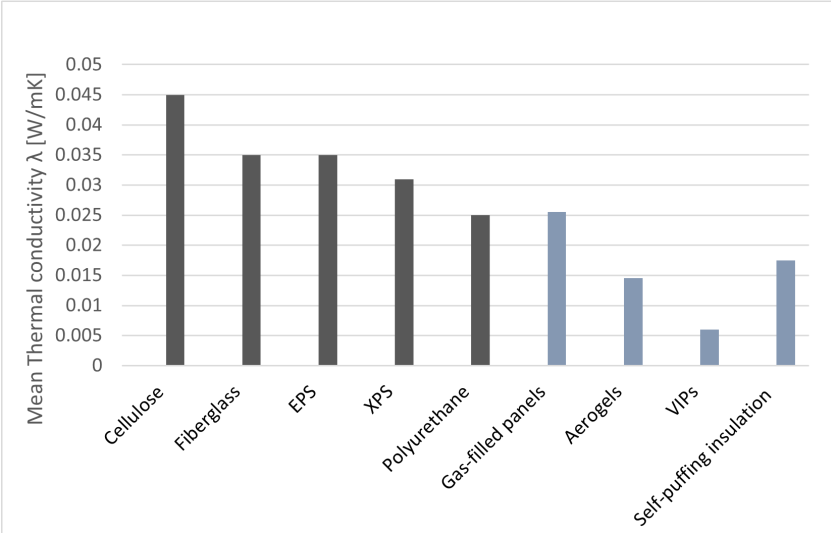


Figure 8.1: Comparison of self-puffing insulation with traditional and state-of-the art insulation materials in the insulated state.

- Compared to the other adaptive insulation technologies that have been found in the literature. The superiority of the self-puffing insulation lies in the thermal performance, simpler structure as well as in the activation system, which does not use complex mechanical means as other technologies propose. A fair comparison between the adaptive insulation technologies is a difficult task since the comparison includes various parameters such as performance, cost, technological complexity, actuation system, reliability and the dimensions of the system. In addition, the majority of the examined adaptive technologies had either not been tested yet or the research had mainly focused on the design of the control system, so the necessary data for a comparison of the thermal transmittance were missing. Table 8.1 shows a comparison of the U-values for the insulated and conductive states of the adaptive insulation technologies and the self-puffing insulation. This comparison proves that the self-puffing insulation can suggest a promising system since in the insulated state has the highest performance compared to the similar technology of mechanical contact and the pipe-embedded technology, while when the system is shifted to the conductive state, self-puffing insulation suggests also a good alternative since her performance is comparable to the other two adaptive technologies.

Table 8.1: Comparison of self-inflating and adaptive insulation technologies in terms of U-values for the insulated and conductive states.

Adaptive technology	**U-high** [W/m^2K]	**U-low** [W/m^2K]	**Study**	**Note**
Self-puffing	2.79	0.13		
Active vacuum	-	-		No data
Mechanical contact	3.01	0.29	Kimber, Clark, and Schaefer 2014	
Suspended particles	-	-		No data
Pipe-embedded	1.657	0.185	Koenders, R. Loonen, and Hensen 2018	
Phase change	-	-		No data
SPONGE3D	-	-		No data

- The cost-effectiveness is difficult to be predicted as it is already mentioned in Chapter 6. Compared to traditional insulation, the self-puffing insulation is expected to have a higher production ans installation cost as it requires the appropriate equipment for its function. The transportation cost is expected to be lower than that of traditional insulation since, the panels can be transported while they are deflated which significantly decreases their volume. The air-pump will require energy for operation which could be decreased with the use of a high COP pump. Although the higher initial investment that is a disincentive for the wide use of this technology, the energy profit it can yield in the long term can counteract the high cost, considering also the increasing trend on the energy prices.

9

Conclusions and Recommendations

9.1. Introduction

The present thesis, explores the potential of developing a novel insulation system for façade application. This chapter summarizes the findings from answering the research questions and provides recommendations for future research.

9.2. Conclusions

The main research question of this thesis is formulated as follows:

To what extent can parameters affecting heat transfer capacity be used to create an adaptive insulation system that can be applied to a building envelope?

The answer to the main research question results from the answers to the sub-questions.

Sub-questions:

- **What are the main parameters influencing the heat transfer capability of a system?**

  The literature study revealed that there are three possible mechanisms that have the ability to control the transition from an insulated to a conductive state. The first method involves modifications of the physical properties of the fluid, through a reversible pressurization/evacuation cycle. The aim of this method is to change the gaseous thermal conductivity of the system through modifications on the heat carrier's density. For the effectiveness of the method it is important to ensure a high level of vacuum. Therefore, it is suggested to artificially create small pores or voids in the void volume and thus facilitate the achievement of the pressure-sensitive molecular regime. The second direction includes strategies to control the mobility of heat carriers, which is achieved by modifications on the geometry of the insulating material such as bringing two solid surfaces into/off contact. In this way, trade-offs are possible between a solid conductivity that facilitates heat transfer and a gaseous conductivity characterized by a high resistance to heat transfer. The third mechanism, approaching the switch with transitions from one form of energy to another. Various technologies that their working principle is based on the above mentions strategies, where reviewed to gain an understating on the theoretic application of each of them.

- **What are the main design criteria for the development of an adaptive insulation system?**

  The second sub-question is answered based on the conclusions of the literature study. One of the main challenges to the development of adaptive insulation technology is the unavailability of standardized data. Therefore, the aim was to create design guidelines that integrate the aspect of thermal performance and constructability.

  The thermal performance is based on the review of current technologies which suggest that for an adaptive insulation system it is important to achieve a high range of thermal conductivity values in order to be able to switch between a high insulated and low insulated state. Furthermore, various studies propose two main direction for further enhance the thermal performance in the insulated state which are the incorporation of porosity and additional cavities in the structure of the core material. At the same time, it is crucial to include aspects related to its construction. Therefore, the requirements that the traditional and the state-of-the-art insulation materials must be taken into account. Finally, the investigation of adaptive insulation technologies from various technological sectors, underlined the possible obstacles to their application in the building envelope, which was taken into account during the development of the design guidelines.

- **What is the relationship between core geometry and thermal efficiency?**

  Numerical simulations using the software tool TRISCO are used for the estimation of the thermal performance of design alternatives. In this thesis, the thermal performance of each system is measured by its thermal resistance and the range of achievable R-values.

  The core geometry is composed by different types of cellular structure which benefits of the gaseous conduction in order to achieve a lower thermal conductivity value. Convection can be disregarded when the width of the air cavity is less than 20 mm. Therefore, for honeycomb core the cavities are kept below 20 mm and the cells of the closed-cell core, are designed as elongated cells with their long dimension perpendicular to the direction of heat flow. At the same time, in air-cavities less than 20 mm radiation becomes significant and contribute on a great extent to the global heat transfer. Therefore, an additional method to improve the thermal resistance is to use reflective materials for the creation the adjacent surfaces. Regarding swichability, the simulations revealed that technologies whose structure and working principle enables them to be fully evacuated from air can achieve a lower value of the thermal resistance in the conductive state and consequently a higher shift potential.

- **How can adaptive insulation system be integrated into a building envelope?**

  The fourth sub-question is answered in the last chapter of this thesis. An opaque building envelope is selected where the adaptive insulation panel can be considered as an infill component for application to the building envelope.

  The shift from the insulated to the conductive state and vice versa is realised with a dual function pump placed in the basement of the building, which serves as actuator, supplying the insulation panel with air through PVC tubes connected to its bottom. Each insulation panel involves a pipe of 50 mm for air supply incorporating smaller pipes through which the solid part of the façade can be inflated or deflated based on the necessity. It was considered more efficient to include one PVC pipe in each panel rather than using one for each row of panels due to the fact that it would be easier to replace in case of damage, putting only one panel out of service instead of one row. To airtight seal the insulation panel, it is suggested to create a solid box which provides coverage on the top, bottom part and the sides of the panel creating a π-shaped element. The rubber frames of the insulating panel have been dimensioned to fit exactly on the inner of π-shaped element. On the other hand, front coverage is ensured with the use of wooden cladding which is attached to the insulation panel. A small gap between the outer skin and the wooden box is kept around the perimeter considering thermal expansion during the service life of the project. This entire unit can then be suspended from its top and mounted using a steel L-shaped element to the concrete wall.

  Finally, for the efficiency of the system and in order to overcome the obstacles of compression and decompression, it is suggested to use smaller units instead of a panel with the typical dimensions of 3x1.5. By following this strategy, the weight of the panel can be reduced and therefore inflation and deflation are achieved more efficiently. For the examined case, the windows are considered to have the same dimensions with the solid units, which facilitates the application. However, the insulation panels is possible to be reshaped for application to smaller surfaces by modifications in its dimensions.

9.3. Recommendations for future work

The recommendations provided in this section are the product of observations made during the study of this thesis and the analysis of the results.

- **Testing of physical models**

  The research focused on the design exploration and the investigation of the thermal performance of the different design alternatives by processing numerical simulations, through which the final design emerged. However, the emerged design is still on a research level since laboratory tests need to be carried out. In this regard, it is proposed to perform tests on prototypes in order to evaluated the thermal performance of this system and to compare it with the results of the numerical simulations. Additionally, it is important to determine the appropriate dimension of the air-supply system, since the used dimensions of the pipes are based on the findings of similar applications.

- **Improvements on the design alternatives**

  The performance table of Chapter 6 showed two concepts as the most promising for development in terms of thermal performance, design feasibility, and ease of construction, where between the two, the one with the slightly higher score was selected for the facade application. Consequently, with appropriate improvements, the second design alternative could be selected for further exploration. Both of them consist of a honeycomb core which successfully achieved the thermal performance target set at the beginning of this research and stood out compared to the other core alternatives. Therefore, a suggestion for research is the further development of the honeycomb core by examining for example the effect of different types of filling gas on the thermal transmission and the technological complexity of the system.

- **Extend the application for different façade typologies**

  The concept of the adaptive insulation could be further explored for the case of a translucent or transparent façades. In this study, an opaque building envelope was considered, therefore parameters related to the light transmittance were not taking into account for the design of the core geometry which is important for instance for the case of a glass façade.

- **Design of the operational system**

  The contribution of the final design to the reduction of energy consumption due to heating and cooling demand is an important aspect to be investigated in the future. In Chapter 5, the research focused on the thermal analysis of the different design principles in order to retrieve the U-value for the insulated and the conductive state while the contribution of the system to the energy savings was not studied. Therefore, an interesting direction in this aspect is the design and control of the adaptive insulation system. Therefore, the parameters that trigger the change between thermal states as well as the response time and switching frequency need to be investigated in a future research.

  Furthermore, the location effect on the performance of adaptive insulation in the building envelope could be the subject of new research. Consequently, it is proposed to consider, for example, the energy performance when adaptive insulation is placed on the roof of the building compared to the façade.

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A

Results of Trisco simulations

The results of thermal analysis simulations:

```
TRISCO - Calculation Results

TRISCO data file: concrete_solid.trc

Number of nodes = 65026
Heat flow divergence for total object = 3.48126e-005
Heat flow divergence for worst node = 0.020766

U_trisco = (Q/(ti-te))/A1 = 3.16 W/(m².K)
  Q = 15.15 W
  ti = 20.0000°C
  te = 0.0000°C
  A1 = 0.24 m²

Col.
Type      Name                  tmin    X    Y    Z      tmax    X    Y    Z
                                [°C]                     [°C]
_____________________________________________________________________________
_____
  2  BC_SIMPL  inside             11.80    5   43   40     11.80    5    5
  26
  5  BC_SIMPL  outside             2.52   30   60   32      2.52   30    3
  14
  8  MATERIAL  concrete            2.52   30   60   32     11.80    5    5
  26

Col. Type      Name                    ta   Flow in  Flow out
                                     [°C]       [W]       [W]
_____________________________________________________________
  2  BC_SIMPL  inside                        15.15      0.00
  5  BC_SIMPL  outside                        0.00     15.15

Temperature factor (EN ISO 10211-2) = 0.590
  hi = 7.70 W/(m².K)
  Rsi = 0.13 m².K/W
```

Figure A.1: U-value of concrete block obtained from TRISCO

```
TRISCO - Calculation Results

TRISCO data file: bubbles_rollers_insulation.trc

Number of nodes = 110044
Heat flow divergence for total object = 1.66403e-005
Heat flow divergence for worst node = 0.134063

Col. Type      Name                    tmin    X    Y    Z      tmax    X    Y    Z
                                       [°C]                     [°C]
  2  BC_SIMPL  outside                 0.42   48   47    0      0.43   48   13   40
  3  MATERIAL  air cavity              1.48   42   60   40     17.36   25   10    0
  5  BC_SIMPL  inside                 18.61    5   54   40     18.61    5    1    0
  6  MATERIAL  air bubble              0.72   43   46    0     15.58   27    5    0
  7  MATERIAL  PET                     0.73   43   46    1     15.46   27    0    1
  8  MATERIAL  concrete                0.42   48   47    0     18.61    5    1    0

Col. Type      Name                      ta   Flow in  Flow out
                                       [°C]       [W]       [W]
  2  BC_SIMPL  outside                           0.00      2.57
  5  BC_SIMPL  inside                            2.57      0.00

Temperature factor (EN ISO 10211-2) = 0.930
  hi = 7.70 W/(m².K)
  Rsi = 0.13 m².K/W
```

(a) Insulated

```
TRISCO - Calculation Results

TRISCO data file: bubbles_rollers_insulation_cond.trc

Number of nodes = 110044
Heat flow divergence for total object = 1.11968e-006
Heat flow divergence for worst node = 0.130078

Col. Type      Name                    tmin    X    Y    Z      tmax    X    Y    Z
                                       [°C]                     [°C]
  2  BC_SIMPL  outside                 0.52   48    4    0      0.53   48   16   40
  3  MATERIAL  air cavity_20           4.19   36   60   40     16.78   25    0    0
  4  MATERIAL  air cavity_60           0.90   43   21    0      3.33   37    0   40
  5  BC_SIMPL  inside                 18.30    5   59   39     18.30    5    2    0
  6  MATERIAL  air bubble              3.15   37   60    0     14.61   27    1    0
  7  MATERIAL  PET                     3.22   37   60    1     14.46   27    1    1
  8  MATERIAL  concrete                0.52   48    4    0     18.30    5    2    0

Col. Type      Name                      ta   Flow in  Flow out
                                       [°C]       [W]       [W]
  2  BC_SIMPL  outside                           0.00      3.14
  5  BC_SIMPL  inside                            3.14      0.00

Temperature factor (EN ISO 10211-2) = 0.915
  hi = 7.70 W/(m².K)
  Rsi = 0.13 m².K/W
```

(b) Conductive

Figure A.2: Results of TRISCO simulations of Concept 1

TRISCO - Calculation Results

TRISCO data file: bubbles_rail_insulation.trc

Number of nodes = 132553
Heat flow divergence for total object = 0.00025754
Heat flow divergence for worst node = 0.0254154

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	outside	0.40	57	59	0	0.48	57	40	40
4	MATERIAL	wood	0.40	57	59	0	1.35	55	60	40
5	BC_SIMPL	inside	18.55	5	53	40	18.56	5	0	0
6	MATERIAL	air bubble	1.07	55	59	0	17.20	26	13	0
7	MATERIAL	PET	1.17	55	60	1	17.29	25	17	0
8	MATERIAL	concrete	17.22	25	45	40	18.56	5	0	0

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	outside		0.00	2.66
5	BC_SIMPL	inside		2.66	0.00

Temperature factor (EN ISO 10211-2) = 0.928
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(a) Insulated

TRISCO - Calculation Results

TRISCO data file: bubbles_rail_cond.trc

Number of nodes = 95038
Heat flow divergence for total object = 7.44894e-005
Heat flow divergence for worst node = 0.0347959

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	outside	1.50	42	48	39	1.50	42	2	30
4	MATERIAL	wood	1.50	42	48	39	4.14	40	0	31
5	BC_SIMPL	inside	15.14	5	60	33	15.14	5	1	40
6	MATERIAL	air bubble								
7	MATERIAL	PET	4.14	40	47	40	10.74	25	0	33
8	MATERIAL	concrete	10.74	25	48	40	15.14	5	1	40

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	outside		0.00	8.98
5	BC_SIMPL	inside		8.98	0.00

Temperature factor (EN ISO 10211-2) = 0.757
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(b) Conductive

Figure A.3: Results of TRISCO simulations of Concept 2

```
TRISCO - Calculation Results

TRISCO data file: bubbles_anchored_insulation.trc

Number of nodes = 102541
Heat flow divergence for total object = 6.92419e-005
Heat flow divergence for worst node = 0.270919

Col. Type      Name                   tmin    X    Y    Z      tmax    X    Y    Z
                                      [°C]                     [°C]
  2  BC_SIMPL  outside                0.37   45   39   39      0.37   45    0    0
  3  MATERIAL  air cavity_10          1.50   42   40   40     18.72   26    0   40
  4  MATERIAL  wood                   0.37   45   39   39      1.02   43    0    0
  5  BC_SIMPL  inside                18.81    5   60   40     19.81    5    1   39
  7  MATERIAL  PET                    1.02   43   40   40     17.35   27    0   36
  8  MATERIAL  concrete              17.72   25   60   40     18.81    5    1   39

Col. Type      Name                     ta   Flow in  Flow out
                                      [°C]       [W]       [W]
  2  BC_SIMPL  outside                          0.00      2.00
  5  BC_SIMPL  inside                           2.00      0.00

Temperature factor (EN ISO 10211-2) = 0.950
  hi = 7.70 W/(m².K)
  Rsi = 0.13 m².K/W
```

(a) Insulated

```
TRISCO - Calculation Results

TRISCO data file: bubbles_anchored_insulation_cond.trc

Number of nodes = 102541
Heat flow divergence for total object = 6.92419e-005
Heat flow divergence for worst node = 0.270919

Col. Type      Name                   tmin    X    Y    Z      tmax    X    Y    Z
                                      [°C]                     [°C]
  2  BC_SIMPL  outside                0.37   45   39   39      0.37   45    0    0
  3  MATERIAL  air cavity_10          1.50   42   40   40     17.72   25    0   40
  4  MATERIAL  wood                   0.37   45   39   39      1.02   43    0    0
  5  BC_SIMPL  inside                18.81    5   60   40     18.81    5    1   39
  7  MATERIAL  PET                    1.02   43   40   40     16.35   26    0   36
  8  MATERIAL  concrete              17.72   25   60   40     18.81    5    1   39

Col. Type      Name                     ta   Flow in  Flow out
                                      [°C]       [W]       [W]
  2  BC_SIMPL  outside                          0.00      2.21
  5  BC_SIMPL  inside                           2.21      0.00

Temperature factor (EN ISO 10211-2) = 0.940
  hi = 7.70 W/(m².K)
  Rsi = 0.13 m².K/W
```

(b) Conductive

Figure A.4: Results of TRISCO simulations of Concept 3

TRISCO - Calculation Results

TRISCO data file: honeycomb_lowemissivity_cav_8x20mm_wood.trc

Number of nodes = 115046
Heat flow divergence for total object = 0.000101467
Heat flow divergence for worst node = 0.962047

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	inside	19.38	5	60	10	19.38	5	60	27
5	BC_SIMPL	outside	0.19	50	29	40	0.19	50	30	40
6	MATERIAL	air-cavity	0.53	48	31	40	18.82	25	1	18
7	MATERIAL	metallic foil	2.81	46	0	34	16.53	27	0	1
8	MATERIAL	concrete	18.82	25	59	15	19.38	5	60	27
12	MATERIAL	wood	0.19	50	29	40	0.53	48	30	40

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	inside		1.14	0.00
5	BC_SIMPL	outside		0.00	1.14

Temperature factor (EN ISO 10211-2) = 0.969
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(a) Insulated

TRISCO - Calculation Results

TRISCO data file: honeycomb_lowemissivity_cav_8x20mm_wood_conductive.trc

Number of nodes = 62525
Heat flow divergence for total object = 0.000864584
Heat flow divergence for worst node = 0.110609

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	inside	12.75	5	0	8	12.75	5	51	0
5	BC_SIMPL	outside	2.23	29	0	1	2.23	29	59	25
7	MATERIAL	metallic foil	6.18	27	1	1	6.18	25	58	24
8	MATERIAL	concrete	6.18	25	1	6	12.75	5	51	0
12	MATERIAL	wood	2.23	29	0	1	6.18	27	59	25

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	inside		13.40	0.00
5	BC_SIMPL	outside		0.00	13.40

Temperature factor (EN ISO 10211-2) = 0.637
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(b) Conductive

Figure A.5: Results of TRISCO simulations of Concept 4 alternative 1

TRISCO - Calculation Results

TRISCO data file: honeycomb_lowemissivity_cav_11x15mm.trc

Number of nodes = 137555
Heat flow divergence for total object = 0.000368315
Heat flow divergence for worst node = 0.925508

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	inside	19.54	5	12	40	19.54	5	51	40
5	BC_SIMPL	outside	0.14	59	3	31	0.14	59	2	31
6	MATERIAL	air-cavity	0.40	57	60	28	19.12	25	59	20
7	MATERIAL	metallic foil	2.10	55	23	9	17.41	27	46	3
8	MATERIAL	concrete	19.12	25	60	0	19.54	5	51	40
12	MATERIAL	wood	0.14	59	3	31	0.40	57	60	27

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	inside		0.86	0.00
5	BC_SIMPL	outside		0.00	0.86

Temperature factor (EN ISO 10211-2) = 0.977
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(a) Insulated

TRISCO - Calculation Results

TRISCO data file: honeycomb_lowemissivity_cav_11x15mm_wood_conductive.trc

Number of nodes = 62525
Heat flow divergence for total object = 1.01695e-005
Heat flow divergence for worst node = 0.0379637

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	inside	12.75	5	10	40	12.75	5	51	40
5	BC_SIMPL	outside	2.23	29	60	34	2.23	29	55	40
7	MATERIAL	metallic foil	6.17	27	59	4	6.18	25	0	34
8	MATERIAL	concrete	6.18	25	60	4	12.75	5	51	40
12	MATERIAL	wood	2.23	29	60	34	6.17	27	0	35

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	inside		13.40	0.00
5	BC_SIMPL	outside		0.00	13.40

Temperature factor (EN ISO 10211-2) = 0.637
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(b) Conductive

Figure A.6: Results of TRISCO simulations of Concept 4 alternative 2

TRISCO - Calculation Results

TRISCO data file: honeycomb_lowemissivity_cav_12x10mm_wood.trc

Number of nodes = 130052
Heat flow divergence for total object = 0.000939149
Heat flow divergence for worst node = 0.494185

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	inside	19.65	5	20	21	19.65	5	32	0
5	BC_SIMPL	outside	0.11	56	0	1	0.11	56	0	0
6	MATERIAL	air-cavity	0.29	54	1	2	19.34	25	60	39
7	MATERIAL	metallic foil	1.56	53	0	0	18.07	26	60	32
8	MATERIAL	concrete	19.34	25	0	24	19.65	5	32	0
12	MATERIAL	wood	0.11	56	0	1	0.29	54	1	1

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	inside		0.64	0.00
5	BC_SIMPL	outside		0.00	0.64

Temperature factor (EN ISO 10211-2) = 0.983
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(a) Insulated

TRISCO - Calculation Results

TRISCO data file: honeycomb_lowemissivity_cav_12x10mm_wood_conductive.trc

Number of nodes = 65026
Heat flow divergence for total object = 0.000755147
Heat flow divergence for worst node = 0.178363

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
2	BC_SIMPL	inside	12.75	5	37	1	12.75	5	1	40
5	BC_SIMPL	outside	2.23	30	59	0	2.23	30	40	39
7	MATERIAL	metallic foil	6.17	28	0	0	6.18	25	40	36
8	MATERIAL	concrete	6.18	25	0	1	12.75	5	1	40
12	MATERIAL	wood	2.23	30	59	0	6.17	28	40	35

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
2	BC_SIMPL	inside		13.40	0.00
5	BC_SIMPL	outside		0.00	13.40

Temperature factor (EN ISO 10211-2) = 0.637
hi = 7.70 W/(m².K)
Rsi = 0.13 m².K/W

(b) Conductive

Figure A.7: Results of TRISCO simulations of Concept 4 alternative 3

The thermal conductivity of air inside a cell is compared to the thermal conductivity obtained from the research of Piccioni 2020, which examines the thermal conductivity of different cell typologies considering all three modes of heat transfer (see Figure A.8). The examined cell has a dimension of 10x10x2 mm which is similar to the examining case of this thesis.

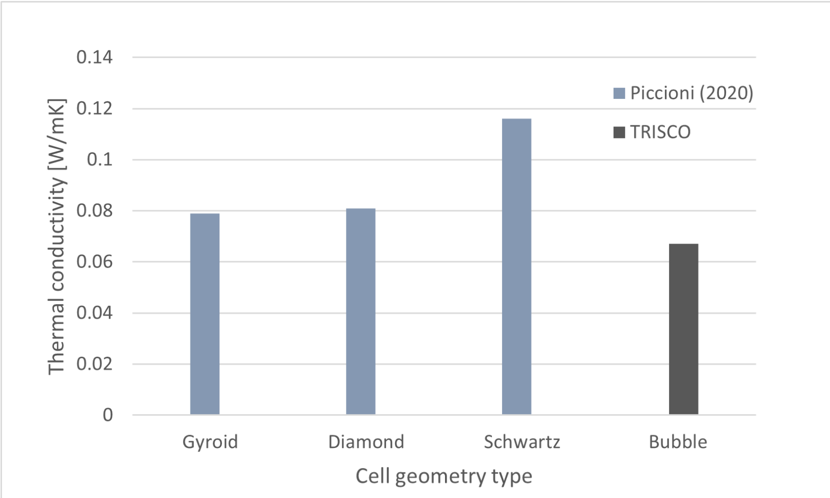


Figure A.8: Thermal conductivity values obtained from the research of Piccioni (Piccioni 2020)

B

Scoring of aspects

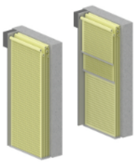
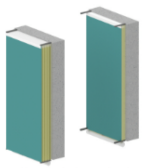
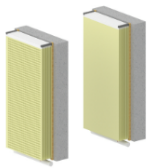
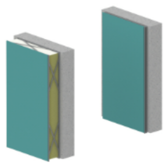
Concept / Criteria	 1. Folding insulation	 2. Rail track insulation	 3. Anchored insulation	 4. “Self-puffing”insulation A	 5. “Self-puffing”insulation B
Response time (weight 1)	3*1	2*1	2*1	3*1	2*1
Thermal resistance (weight 3)	1*3	1*3	2*3	3*3	3*3
Range of shift (weight 3)	1*3	2*3	1*3	3*3	3*3
Score	**9**	**11**	**11**	**21**	**20**
Notes	- Thermal resistance lower than the required. - Low range of shift.	- It requires time for the bubbles of each membrane to fill with air - Thermal resistance lower than the required.	- It requires time for the bubbles of each membrane to fill with air - Core’s configuration results to low range of shift.	+ Reflecting material and configuration are beneficial for the system’s performance .	+ Reflecting material and configuration are beneficial for the system’s performance. - It requires time to inflate and deflate.

Figure B.1: Score for thermal performance.

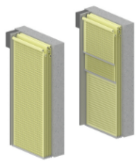
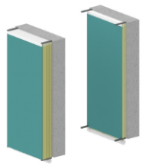
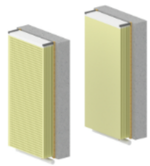
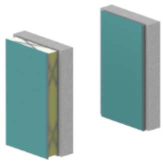
Concept / Criteria	 1. Folding insulation	 2. Rail track insulation	 3. Anchored insulation	 4. “Self-puffing”insulation A	 5. “Self-puffing”insulation B
Constructability (weight 2)	1*2	1*2	3*2	1*2	2*2
Maintenance (weight 2)	1*2	2*2	2*2	2*2	1*2
Durability (weight 3)	2*3	2*3	2*3	2*3	2*3
Score	**10**	**12**	**16**	**12**	**12**
Notes	- Increases panel’s depth - Regular maintenance.	- Possibility of thermal bridge in the location with rails - Moving external layer increases system’s complexity.	+ Simple design + Low maintenance - Possibility of thermal bridge in the location of steel profile.	- Moving external layer increases system’s complexity - Possibility of thermal bridge in the location of steel profile. + Easy access for maintenance	- Moving external layer increases system’s complexity.

Figure B.2: Score for design feasibility.

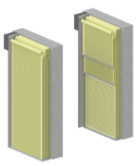
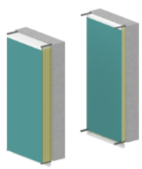
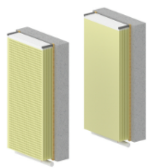
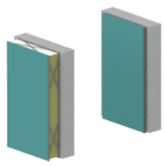
Concept / Criteria	 1. Folding insulation	 2. Rail track insulation	 3. Anchored insulation	 4. “Self-puffing”insulation A	 5. “Self-puffing”insulation B
Technological complexity (weight 2)	1*2	2*2	3*2	1*2	2*2
Score	**2**	**4**	**6**	**2**	**4**
Notes	- Rotational motors increase the overall cost.		+ Low complexity + Low production cost.	- Higher production cost compared to alternative B because it involves more elements.	- High production cost of core.

Figure B.3: Score for ease of manufacturing.