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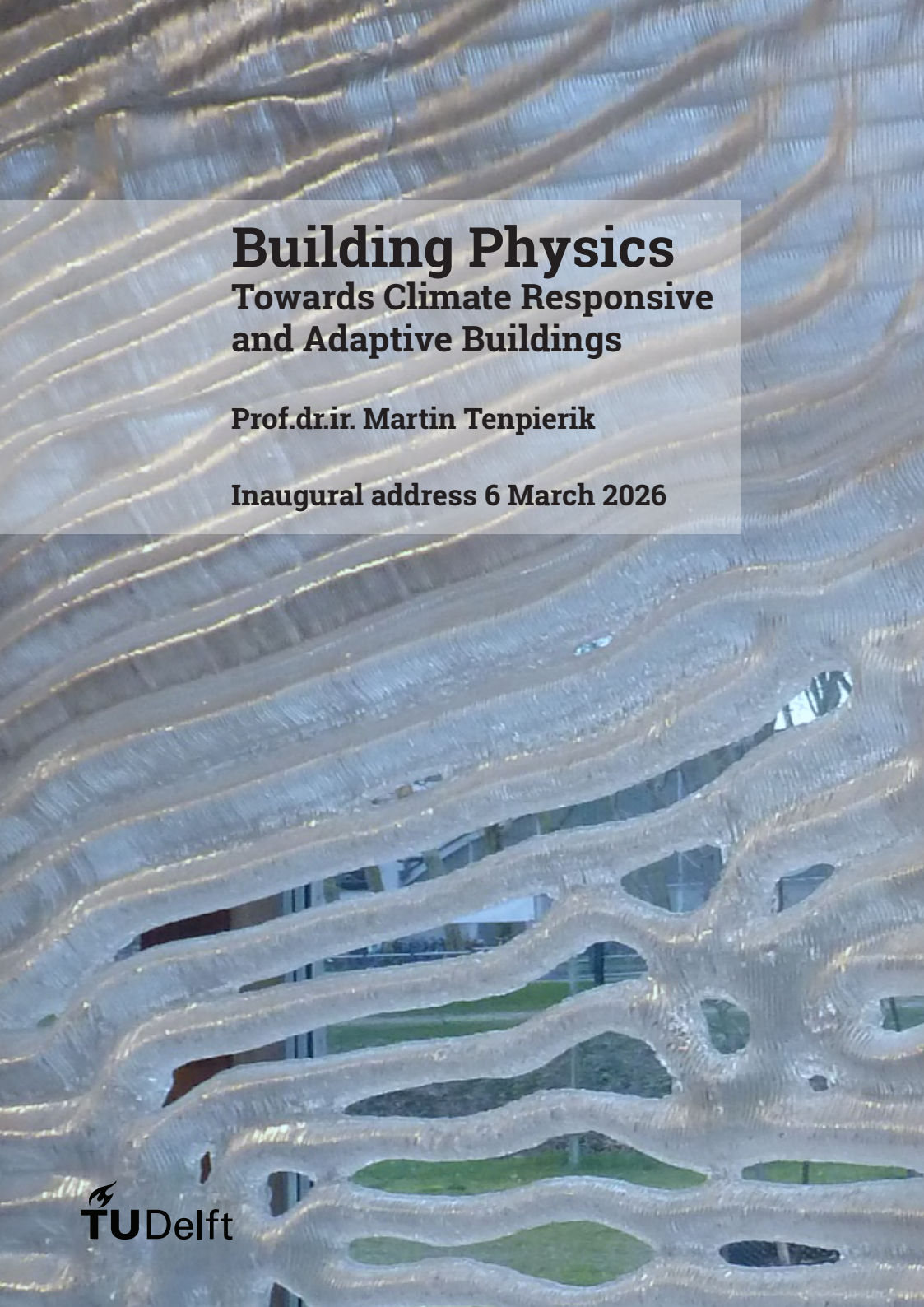

Building Physics

Towards Climate Responsive and Adaptive Buildings

Prof.dr.ir. Martin Tenpierik

Inaugural address 6 March 2026

TU Delft

Building Physics

Towards Climate Responsive and Adaptive Buildings

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van de Technische Universiteit Delft

door prof. dr. ir. Martin Tenpierik

Inaugural address

delivered in abbreviated form on the 6th of March 2026
on the occasion of the acceptance of the position of
full professor of Building Physics
at the Faculty of Architecture and the Built Environment
of the Delft University of Technology

by prof. dr. ir. Martin Tenpierik

Building Physics
Towards Climate Responsive and Adaptive Buildings

Author: Martin Tenpierik

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Building Physics

Towards Climate Responsive and Adaptive Buildings

Geachte Rector Magnificus, leden van het College van Bestuur, Collegae hoogleraren en andere leden van de universitaire gemeenschap.
Zeer gewaardeerde toehoorders.
Dames en heren.

In February 2025, I have been promoted to professor of Building Physics at the Faculty of Architecture and the Built Environment. In this inaugural address I will present the important research and education challenges I see for the coming decades. First, I will briefly introduce the field of Building Physics, its context and some of its history. Then I will elaborate on societal challenges, and on what these imply for research and education. I will conclude with some words of appreciation.

01 Building Physics

According to Hugo Hens, Building Physics "is an applied science that studies the hygrothermal, acoustical and light-related properties of building components (roofs, facades, windows, partition walls, etc.), rooms, buildings and building assemblies. The basic considerations are the user requirements for thermal, acoustic and visual comfort, the user's health requisites and the more-or-less compelling demands and limitations imposed by architectural, material-related, economic and ecological considerations." [1, p. 1]. This definition already shows that three aspects are important: the outdoor environment, the building and its materiality, and the indoor environment.

Over the past decades, attention has been growing, both in academia and in the professional practice, for the energy transition, for adaptation to the effects of climate change, and for health and well-being. Energy and comfort have been given a prominent place in the early stages of the design process.

Building physics provides the fundamental knowledge that underlies zero emissions and comfortable buildings. It addresses the physical processes in and around buildings on a scale ranging from materials and building components, to rooms, to entire buildings and their surroundings. It is thus crucial that this field is well-covered in education, research and valorisation in a faculty of Architecture and the Built Environment.

Building Physics thus has a strong connection with Architecture. This is something I will also later address in this inaugural speech when I show examples of past research projects. As Bert Blocken, now a professor at Heriot-Watt University in Edinburgh, stated in his inaugural speech as full professor at Eindhoven University of Technology in 2012, "Building physics without architecture is an applied discipline without application. Architecture without building physics is art without the required physical and technical background to achieve the intended performance." [2, p. 25].

At TU Delft, the group Building Physics is part of the section Environmental and Climate Design in the department Architectural Engineering and Technology. This section also includes the groups: Indoor Environment, Building Services Innovation, Building Energy Epidemiology and Climate Design and Sustainability. Each group has its own focus, but all together we advance knowledge towards healthy and sustainable built environments.

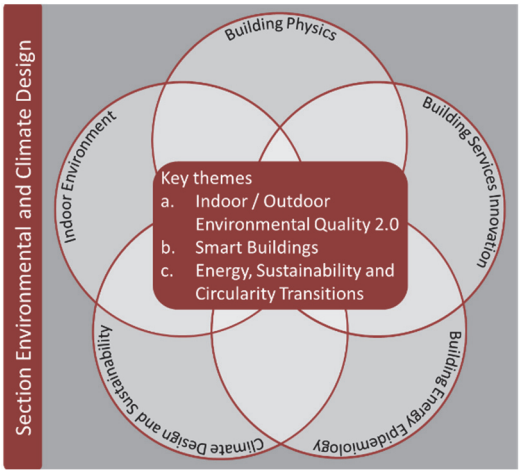

Figure 1: The group Building Physics within the context of the section Environmental and Climate Design (E&CD), including the main (research) themes of the section E&CD.

02 Brief historical perspective

You could say that the earliest principles of building physics already date back to the pre-history, when people sought shelter in caves or simple structures to be protected from the heat and cold, from rain and wind. The scientific foundations of the field can be traced back to the early 19th century to scientists such as Fourier, Pèclet and Rietschel, who developed the fundamentals of heat transfer. Regarding moisture transfer, important work was done by among others Fick and Darcy, who developed the molecular diffusion and fluid flow equations. In 1902, Carrier presented the first 'modern' air-conditioning system. And in the early 20th century, the field of acoustics received important impulses from Berger on sound transmission and Sabine on reverberation time. There have been many more important scientists whose names I cannot all mention.

During the first half of the 20th century, the architects of the Modern Movement were confronted with many complaints regarding poor acoustics, air quality, and failing moisture tolerance. They therefore developed ideas and design concepts to improve 'light, air and space' for people inside buildings. This led to city plans with wide streets and buildings with ample daylight, solar access, and well-designed natural ventilation. An example is the open air school of Duiker and Bijvoet in Amsterdam (figure 2).

Figure 2: Openluchtschool in Amsterdam by Duiker and Bijvoet (source: Stadsarchief Amsterdam / Photographer unknown / 1930).

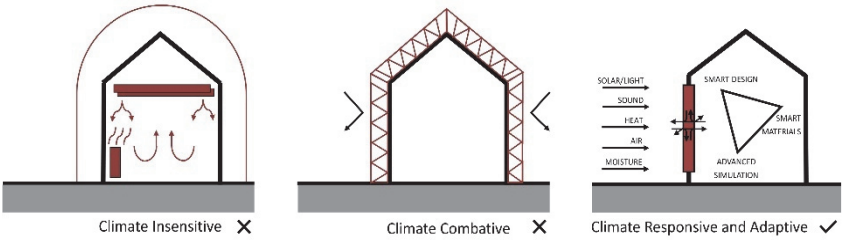

Figure 3: Climate Insensitive, versus Climate Combative, versus Climate Responsive and Adaptive Design.

Figure 4: Climate Insensitive (left) and Climate Combative Design (right).

In the 1930s, also moisture problems that led to blistering of paint layers and peeling off of plaster layers caught the attention. All this gave a boost to the field of building physics that started studying daylight access, natural ventilation and moisture transfer.

The advent of modern air-conditioning opened up unprecedented opportunities for designing buildings in which the indoor climate could be fully controlled within narrow comfort bands. A side effect was that, especially after the Second World War, this led to many buildings around the world that were designed in a similar way irrespective of the climate in which

they were located, as represented by many examples from the International Style. These buildings we can classify as *climate insensitive* (figure 3 left, 4 left). Besides the issue of whether narrow comfort bands are actually healthy, many of these buildings suffered from high operational energy use, mostly generated by burning coal, oil and natural gas.

Then in 1973, the Yom Kippur War and the stop in the delivery of crude oil by the OPEC countries led to a steep increase of the oil price. This is known as the first oil crisis. From then on, many countries started to develop requirements for the level of thermal insulation in buildings. In the Netherlands, for instance, in 1979, the Dutch standardisation organisation, formulated the thermal insulation index as part of the standard NEN 1068 [3]. Over the years, building codes have become tighter and tighter regarding energy performance, which has culminated in the Netherlands in the current Nearly Zero Energy Buildings and Overheating requirements (known as BENG and TO_{juli}) and accompanying calculation method (NTA8800). As a consequence of these developments, many buildings have become much more energy efficient. However, in several buildings, like in modern houses, we see an increased risk of overheating in summer. These buildings can be classified as *climate combative* (figure 3 centre, 4 right).

03 Climate Change

The risk of overheating in buildings will only increase in the coming decades as a result of global warming. Consequently, cooling loads of buildings will increase. The most recent emissions gap report from October 2024 by the United Nations Environment Programme (UNEP) stipulates an average global temperature increase of 2.6 to 3.1 °C by the end of this century and relative to pre-industrial levels. This estimate is based on current pledges by governments to reduce greenhouse gas emissions [4]. The year 2024 saw for the first time a 1.60 °C global average temperature increase above pre-industrial levels, partially explained by global warming, El Niño, cleaner air and fewer clouds [5]. In their most recent climate scenarios from 2023, the Royal Dutch Meteorological Institute KNMI predicts that by the year 2100 the annual average temperature in the Netherlands increases by 0.9 °C in the low scenario up to 4.4 °C in the high scenario [6].

The World Health Organisation predicts that between 2030 and 2050 every year an additional 250,000 people will die because of climate change and its effects such as undernutrition, malaria and heat stress [7]. Over the past years, we have already witnessed how global warming has led to extreme weather, like heavy rain with floods, extreme droughts, and heat waves [8].

Currently, buildings are responsible for 32% of global energy use and have a share of 34% in global greenhouse gas emissions, with construction materials responsible for 18% of these emissions [9]. The EU 2030 Climate Target Plan [10] and the European Climate Law [11] therefore set high ambitions for reducing greenhouse gas emissions by 2030 and for becoming carbon neutral by 2050. The recently recast European Directive on the Energy Performance of Buildings calls for so-called Zero Emissions Buildings by 2050 [12]. Many countries in Europe are therefore undergoing an energy transition to tackle the climate crisis, the biggest societal challenge of the century. At the same time, Europe is undergoing a Renovation Wave to improve the existing building stock, with an important role for the New European Bauhaus initiative [13].

Overall, so far, much attention has been given to urban energy networks, building services (e.g., heat pumps, photovoltaics panels, heat recovery ventilation systems), standard insulation materials and air tightness of buildings. These technologies and materials are important for decarbonising the built environment and will enable us to reach the 2030 targets. However, to truly achieve zero-emissions buildings in a warming climate that are also healthy and comfortable, more is needed than what the current state of technology can offer; in particular, the final steps towards carbon neutrality will become increasingly challenging. This will require an even stronger emphasis on building physics and its principles during the design process, starting from the very first stages, in order to design buildings that are *climate-responsive and climate adaptive* (figure 3 right). An interesting example in this light is the building of the *Energy Academy Europe* in Groningen (figure 5).

Figure 5: The building of the Energy Academy Europe in Groningen.

Figure 6: Casa de Pilatos in Sevilla, Spain. Top left: vegetated courtyard; bottom left: bare courtyard; right: open windows in-between the courtyards.

A historical example is the Casa de Pilatos in Sevilla, Spain (figure 6). This historical house has multiple courtyards. One of them is made of stony materials and heats up under the hot summer sun. As a result, warm air in this courtyard will rise. Two other courtyards are vegetated which remain much cooler due to evapotranspiration by the plants, shrubs and soil. The part of the house in-between the courtyards has open windows that enable a relatively cool breeze from the vegetated to the bare courtyard through that part of the house, creating a comfortable indoor environment.

04 Climate Responsive and Adaptive Building Systems (CRABS)

Climate responsive and adaptive building systems (CRABS) are the most effective way to achieve the sustainable and healthy buildings of the future. As passive climate control, they are an important intermediary between the indoor and the outdoor environment and can conserve, recover, prevent, promote, distribute, store or buffer energy and mass flows (figure 7). These include heat, air, moisture, light and sound. With his doctoral dissertation from 2017, Remco Looman already laid important foundations for Climate Responsive Design in temperate climates [14]. From 2004 till 2011, also the IEA Annex 44 on 'Integrating Environmentally Responsive Elements in Buildings' was active [15].

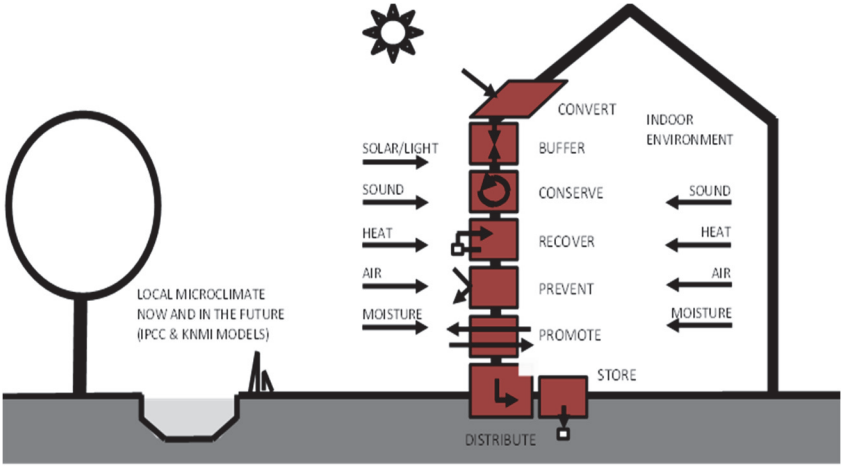

Figure 7: Basic principles of Climate Responsive Design extended towards Climate Adaptive Design (extended and modified from [14]).

Climate responsive means quickly (passively) reacting to changes in short-term environmental conditions; a change in environmental stimulus leads to a quick change in one or multiple material or system properties. *Climate adaptive* here means slowly responding to changes in long-term climate conditions, to adapt to climate change, or being capable of still functioning properly under changed climate conditions.

My doctoral research studied vacuum insulation panels (figure 8) and analytical models for their integration into buildings. This research planted the seed for my interest in smart and advanced materials for buildings. Since then, I have worked on the integration of phase change materials and electrochromic glazing in facades, and in general on passive climate design strategies for buildings. I have also worked on novel sound absorption products based on geometric principles. This research received ample attention and prototypes were shown on many (inter)national exhibitions. The Double Face 2.0 research, on which I collaborated with Michela Turrin, Yvonne Wattez, Tudor Cosmatu and Stavroula Tsafou, was nominated by popular science magazine KIJK for the best tech idea of 2019 and was exhibited at the prestigious Architecture Biennale in Venice in 2018 (figure 9).

My research - figure 10 provides an non-complete overview of past research projects - made me realise that novel and smart materials and building components are essential for climate response and adaptive buildings because they enable (passive) changes in material or system properties. Smart materials or responsive materials are defined as engineered materials that have (a) propert(y)(ies) that can be changed in a controlled way based on external stimuli. Moreover, recent advances in simulation techniques allow for optimising and shaping CRABS such that their behaviour is tuned to specific climatic and user needs, responsive to environmental stimuli and adaptive to climate change. Due to these advances, now is the right time to develop such systems which are climate responsive ánd adaptive, are based on new developments in materials technology, and are well-integrated into the architecture of buildings.

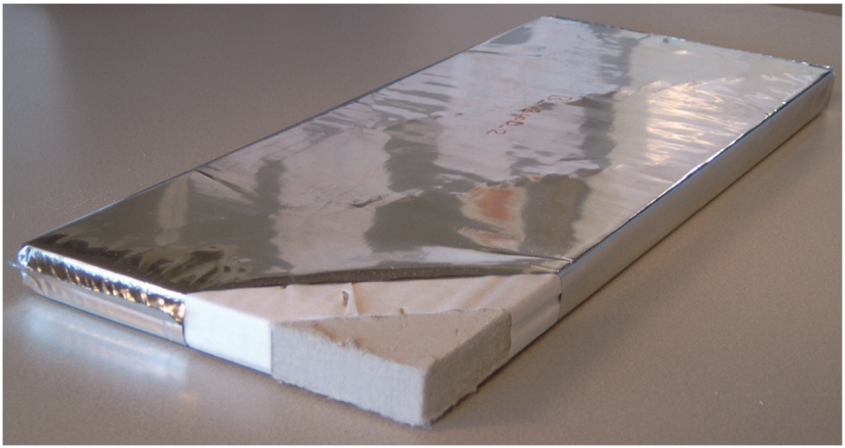

Figure 8: Vacuum insulation panel with a fumed silica core and an envelope of a metallised film laminate. PhD researcher: Martin Tenpierik.

Figure 9: Prototype of the Double Face 2.0 research project exhibited at the Venice Biennale in 2018. Researchers: Martin Tenpierik, Michela Turrin, Yvonne Wattez, Tudor Cosmatu, Stavroula Tsafou. (Photo: Michela Turrin).

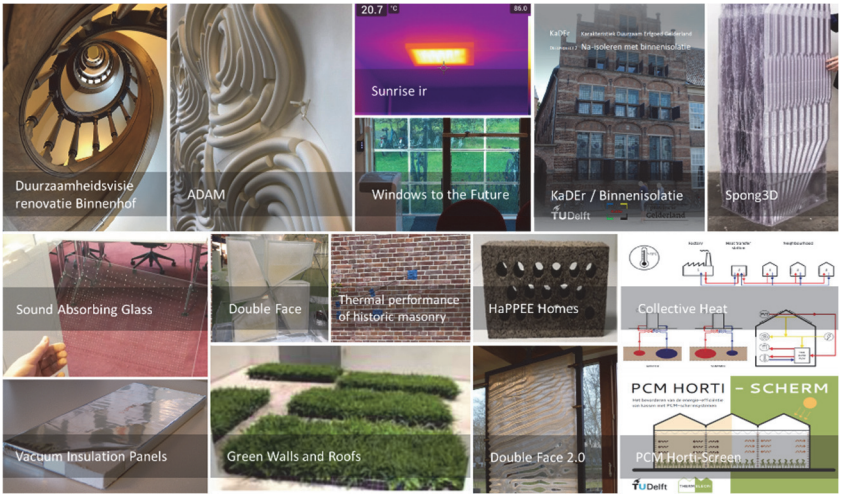

Figure 10: Non-complete overview of past research project.

My research includes four themes related to CRABS and building physics: (1) novel, smart and bio-based materials and components, (2) advanced simulation and control algorithms, (3) climate responsive and adaptive architectural design approaches and (4) existing and historic buildings.

05 Novel, smart and bio-based materials and components

Novel smart materials and components are essential for CRABS. Many current materials and components have changeless properties and do not respond to diurnal and seasonal differences in climatic circumstances, let alone be adaptive to climate change. For instance, thermal insulation has a year-round constant thermal resistance, while, ideally, in a temperate climate, a high resistance would be required in winter but a lower one under certain conditions in summer. Smart materials open up a hitherto unexplored opportunity for re-designing facades as passive thermal control elements becoming responsive to short-term and adaptive to long-term climate variations. Examples include phase change materials, coatings with high reflectance in the solar spectrum (0.4-0.8 μm) and high emissivity in the mid-infrared range (8-12 μm), switchable thermal insulation and smart glass like electrochromic glass (figure 11).

Besides, to limit the environmental impact of building materials, materials from bio-based origin will have a prominent place in future buildings. Some of these are also capillary active, meaning that inside them moisture can also be transported in liquid form. The precise properties of many of these materials and their behaviour when integrated in buildings are still unknown.

Responsiveness generally means that a system changes state based on environmental stimuli and that it cycles in a reversible process without significant deterioration. The restrictions this imposes on the materials and systems, and the relation between environmental conditions, response time, geometry and performance is generally not well understood yet. Besides, combinations of smart materials and building components in one building may lead to synergistic or conflicting combined behaviour. Also such interactions are not entirely understood. This applies to all sub-domains of building physics.

Figure 11: Research prototype of small electrochromic glass (EC) panels developed by Brite Solar as explored in the Windows to the Future project. EC glass can change its opacity by a small electric potential, ranging from clear to tinted. Researchers: Martin Tenpierik, Zara Huijbregts, Eleonora Brembilla, Alessandra Luna-Navarro, Thaleia Konstantinou, Tillmann Klein, Juan Azcarate Aguerre, Philomena Bluyssen, Marco Ortiz-Sanchez, Tim Jonathan, Wout Hoogendoorn, Spyros Bousios.

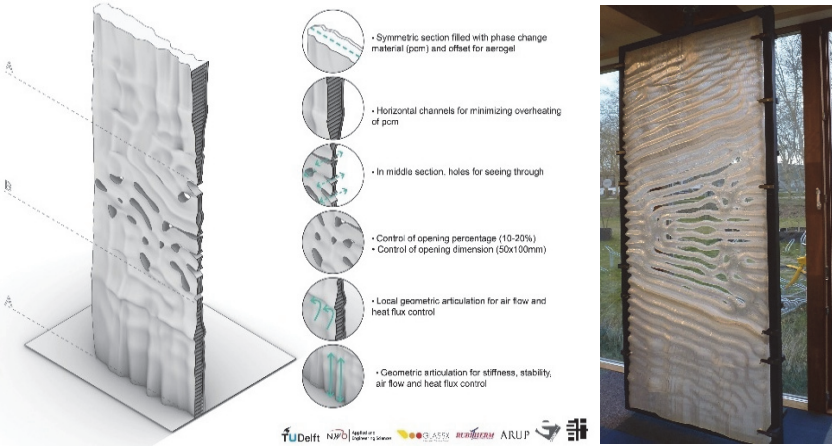

Figure 12: Principles and photo of the Trombe wall developed during the Double Face 2.0 research project. The photo shows the prototype at the Green Village. Researchers: Martin Tenpierik, Michela Turrin, Yvonne Wattez, Tudor Cosmatu, Stavroula Tsafou. (Illustration: Tudor Cosmatu).

An example of research in which this relation between environmental conditions, response time, geometry and performance played a key role was the before mentioned Double Face 2.0 project, funded by NWO (figure 12). The aim was to develop a lightweight and translucent Trombe wall to harness the energy from the sun during winter. A traditional Trombe wall is a passive system consisting of thick stone-like material placed behind a layer of glass and air. In winter, it captures the heat from the sun during the day and buffers this as sensible heat in its material. In the evening and at night, this heat is radiated into the space from the back of the wall and opened vents enable an airflow between the cavity and the room. The Trombe wall thus delays the moment at which the solar heat is available to the moment this heat is needed.

Because of the desired translucency and the lightweight character, phase change materials (PCM) were selected as the means to temporarily buffer the heat from the sun. Phase change materials (figure 13) are materials that can store or release significant amounts of heat during a change of phase, like melting and solidification. An example is ice and water. If you add heat

to ice, it melts. If you remove heat from water, it solidifies. By adding a thin layer of translucent aerogel insulation material, the heat could be better trapped inside the PCM. Because of that, a rotation was needed to rotate the PCM towards the sun during the day and towards the room during the evening and at night. Interestingly, this rotation enabled us to also use the Trombe wall in summer to capture and buffer heat from the inside of the building during the day and release that heat to the outdoor environment using ventilation with outdoor air at night. By optimising the inner structure enclosing the PCM and the geometry of the outer surface, the melting process and the heat transfer to and from the surrounding air could be tuned. Related research by Jeroen van Unen, while working on his MSc thesis, showed that a flat version of this Trombe wall could lead to a mean[1] reduction of the cooling demand by 50% and a of the heating demand by 36% in a temperate climate [16].

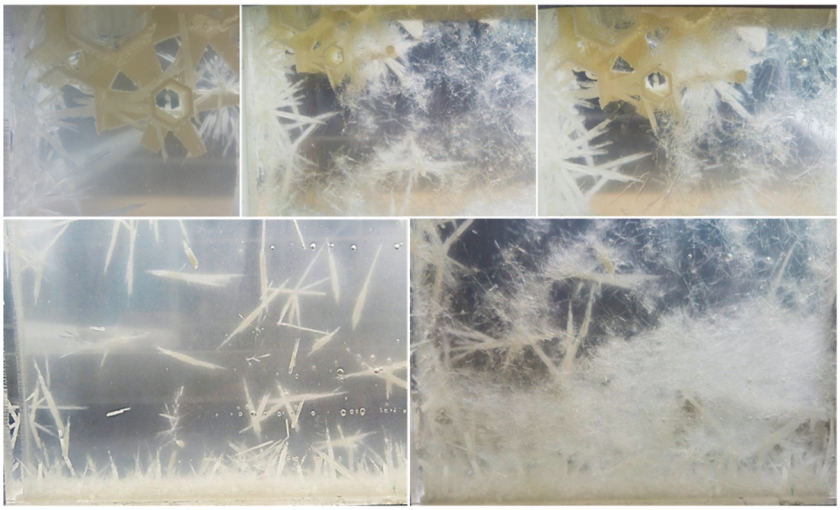

Figure 13: An example of a hydrated salt phase change material during different stages of the phase change process. Depending on the speed of the transition, crystal structures appear where the solidification process is taking place. Here plastic elements were added to the PCM volume to act as nucleating trigger points.

[1] Mean of many simulated room sizes, window sizes, orientations, functions, etc.

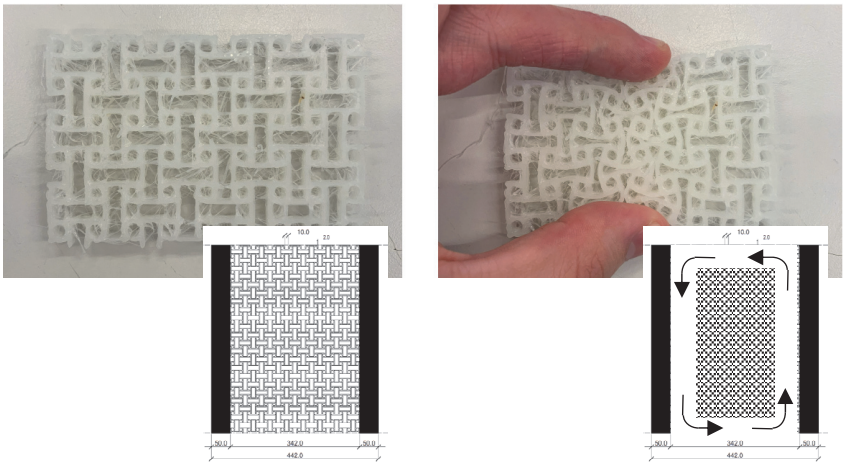

Figure 14: Elastic meta-material that allows for the design of switchable insulation [17]. MSc thesis and photos: Armand Alouche.

An example of switchable thermal insulation was designed by Armand Alouche during his graduation project, a former student of mine [17]. He used elastic meta-materials that undergo a shrinkage in all directions if compressed in one direction. Materials scientists call this a negative Poisson's ratio. Normal materials, on the other hand, have a positive Poisson's ratio, which means that if compressed in one direction, they enlarge in the other directions. This elastic meta-material allows for fully filling a cavity inside a façade in its normal, uncompressed state, and allows air channels around the material in its compressed state. If the material completely fills the cavity, air flow is inhibited and the façade is in a thermal insulating state. If air channels are present an air flow can transport heat from one side of the façade to the other side, reducing its effective thermal resistance (figure 14). An alternative idea to create this type of switchable thermal insulation is by using air channels with operable vents around static thermal insulation [18].

Besides, a good acoustic performance is also an essential characteristic of future buildings. Traditional porous sound absorbers generally absorb well in the higher frequency ranges. In classrooms and open plan offices, however, lower frequencies, like the 125 Hz band, can deteriorate speech

intelligibility. Porous absorbers need to become thick to absorb well in that frequency range. Tuned absorbers and thin low frequency absorbers could provide promising solutions. The recent emergence of acoustic meta-materials[2] combined with advances in manufacturing techniques and faster algorithms that solve the acoustic wave equation allow us to also explore new avenues for highly tuned and thin solutions for sound absorption.

An example of a research project into customisable, thin, low-frequency sound absorption was Acoustics by Digital Design and Additive Manufacturing (ADAM) funded by STW. The research team consisted of Arjan van Timmeren, Sevil Sariyildiz, Michela Turrin, Foteini Setaki, Fengnian Tian and me. During this project, we developed a tuned sound absorbing product based on quarter wavelength tubes. The concept of a customisable absorber fabricated with additive manufacturing constitutes a powerful

Figure 15: Research prototype of a customisable thin sound absorption product for low frequency sound absorption based on quarter wavelength tubes, as developed in the ADAM research project. Researchers: Foteini Setaki, Fengnian Tian, Arjan van Timmeren, Sevil Sariyildiz, Michela Turrin, Martin Tenpierik.

[2] Sound absorbers that use engineered local resonators that are subwavelength in scale.

Figure 16: Research prototype of the Sound Absorbing Glass project, created with a pulse laser. Researchers: Anne Struiksma, Martin Tenpierik, Fred Veer, Ate Snijder, Maarten Hornikx and Bram Botterman.

combination that opens up new markets and suggests new strategies concerning the acoustic treatment of spaces. During this project we were able to develop prototypes with customized sound absorption performance in the low-frequency range by combining tubes of different length and radius. The tubes were curled to make the absorber as thin as possible. Due to the resulting geometric complexity the products were manufactured based on 3D printing (figure 15). Tests in the reverberation chamber showed that the absorption appeared where the theory predicted it would be, allowing theoretical optimisation for the specific needs of a room.

Around the same time, Anne Struiksma, Fred Veer, Ate Snijder and I from TU Delft and Maarten Hornikx and Bram Botterman from TU Eindhoven started exploring how glass could be made sound absorbing. The objective of this study was to develop transparent glass-based sound absorbing panels for historic monuments; or in other words, to create a sound absorber from a material which is inherently non-absorbing. During the project we explored the possibilities of perforating thin glass sheets with small sub-millimetre holes, thereby creating so-called micro-perforated absorbers. Based on acoustic simulations and tests of small samples in an impedance tube, the

project in the end resulted in a prototype of a micro-perforated glass panel (figure 16). This research led to a customisable, fully transparent, albeit very expensive, sound absorber. Finally, several MSc theses looked into bio-based sound absorbers based on mycelium, hempcrete or sheep wool.

06 Advanced simulation and control algorithms

New and existing buildings will increasingly include combinations of multiple CRABS. However, detailed performance evaluations of innovative CRABS are still lacking, especially when they are combined and synergistic or conflicting effects are expected. Moreover, for many smart materials and smart building components simulation models still need to be developed to enable a detailed performance analysis. Besides, approaches need to be developed that connect high fidelity simulations on the component level, like computational fluid dynamics or wave-based acoustics simulations, to simulation models on building scale, for example through surrogate models or coupled simulations. And algorithms need to be developed for controlling the state of CRABS based on weather forecasts and predicted changes in occupants' needs, for instance using predictive control. Important keywords here are multi-scale physics, multi-domain modelling, spatial resolution (detailed versus coarse), temporal resolution (steady-state versus transient), predictive control, and uncertainties. Advances in the fields of computer science and computational design, such as artificial intelligence, optimisation algorithms and model predictive control, will start playing a key role in future building physics simulation.

An example of a project in which simulation on different scale levels played an important role was the earlier mentioned Double Face 2.0 project. We had to combine detailed simulations on the melting and solidification behaviour of the phase change materials with simulations on façade and room level to see the impact on the heating and cooling demand.

Finding an optimal control strategy plays a key role in the currently running Sunrise IR project (figure 17). Together with three housing associations and several companies, Juan Carlos Prazmowski, Gerdien de Vries and I are studying the energy performance of electric infrared heating panels in social

housing in the Netherlands. Since the energy use of IR panels to a large extent is affected by the behaviour of the inhabitants in these houses, the consortium intends to develop a control strategy that both includes the technological perspective as well as the user perspective. The idea is that such a control strategy can minimise the energy consumption for heating.

Figure 17: Infrared image of an electric infrared heating panel installed in a social house as part of the Sunrise IR project. Researchers from TU Delft: Juan Carlos Prazmowski, Gerdien de Vries, Martin Tenpierik. Housing Associations and companies: Centrada, Cazas Wonen, Wonion, Welnu, BeNext, De Buitenwacht, W/E Adviseurs.

07 Climate responsive and adaptive architectural design approaches

An important aspect of my research has always been the relationship between climate design and architecture; the question of how passive climate design may shape architecture and building constructions has always intrigued me. Several past research and MSc thesis projects explored how building physics could act as triggers for design creativity. Building physics was leading the process of form-finding. Examples here are the earlier mentioned Double Face 2.0 and ADAM projects.

Moreover, solutions from the past, like traditional insulation materials, together with modern demands often lead to bulky design. An important question therefore is how we can integrate CRABS in buildings so that they are in line with the architectural design concept. But also, which early-stage design method(s) can best develop architectural design towards climate responsive and adaptive design and deal with climate uncertainties? And how can passive climate design trigger design creativity? The development and integration of CRABS thus is also a pressing design question that goes beyond integral design - i.e. a design process in which all relevant fields or aspects are considered from the start of the design process - but is on a

deeper level informing the design development. You could also call this SMART design: Site-specific, based on Measured performance, Adaptive, Responsive and considering Time.

08 Dealing with existing and historic buildings

Even though in Europe many new buildings are needed, renovating the existing building stock is an even bigger challenge. For instance, in the Netherlands about 900,000 new housing units need to be developed until 2030 [19]. However, the number of existing houses that require energetic upgrades until 2030 is in the order of 2,500,000. Especially the houses with a poor energy label are lagging behind in this renovation wave [20].

These houses with poor energy label, or buildings in general, include listed buildings that cannot easily be refurbished. Because of monumental value, they often cannot be insulated from the outside. Quite often they lack a cavity facade. As a result, insulation can only be added on the inside of the façade. This introduces moisture risks, like interstitial condensation, mould growth, and frost damage, if insufficient consideration is given to material choice and detailing. The proper detailing and installation of vapour barriers requires skilled craftsmanship. Alternative insulation materials, like capillary active insulations materials, have become available. However, their long-term behaviour is not yet fully understood. Besides, insulating historic buildings typically also goes hand in hand with air tightening them. This reduces the air exchange between the indoor and outdoor environment, necessitating additional ventilation measures.

Furthermore, in 2024 20% of households in the Netherlands said to suffer from moisture and mould in their homes, especially in rental homes [21]. This is an increase as compared to 2021 when this percentage was 15%. Moisture and mould can have a serious effect on the health of people living inside these homes. Also this shows that much attention is needed for renovating existing houses and providing proper ventilation.

An example of a related research project was Energetic Performance of Solid Masonry Facades of Historic Houses, commissioned by the

Netherlands Cultural Heritage Agency. Together KU Leuven and TU Delft performed field tests of the insulation value of masonry facades and commissioned airtightness tests of historic houses. Besides, we monitored and simulated two cases in which the masonry facade was insulated on the inside. A key conclusion from this research was that it is extremely difficult to predict the hygrothermal response of such facades with simulations if the material properties and boundary conditions are not precisely known. And even if these are known, it remains challenging. These results suggest using more sophisticated probability-based simulation approaches.

09 Building physics in education

As mentioned before, building physics provides the fundamental knowledge that underlies zero emissions and comfortable buildings. It addresses the physical processes in and around buildings on a scale ranging from materials to entire buildings, focussing on heat and moisture transfer, energy-efficiency, natural ventilation, acoustics, and daylight. It is thus crucial that this field is well-covered in the curriculum of the Faculty of Architecture and the Built Environment, and of the Faculty of Civil Engineering. Moreover, climate responsive and adaptive design of buildings is much more knowledge driven. There are many variables to consider which cranks up the need for knowledge. Designing becomes an ever more multi-dimensional problem with many interactions between variables that requires optimisation to find a good balance between all objectives.

Quite often, students see fundamental knowledge as a barrier to design creativity. In my experience, such knowledge, for instance on building physics or on new materials, can actually be design drivers that trigger creativity. Examples of student graduation projects where this was actually the case were the projects of Eve Farrugia (figure 18) [22] and of Valeria Piccioni (figure 19) [23]. In these projects fundamental knowledge led to new design paradigms and triggered creativity leading to innovation in design. Passive design principles based on solid building physics are thus essential for good architecture and building design. I teach my students to go beyond simple integration and how knowledge of building physics can

Figure 18: PCM-based Trombe wall for the city of Seville (left) and Amsterdam (right), designed using CFD and heat transfer models [22]. MSc thesis and illustrations: Eve Farrugia.

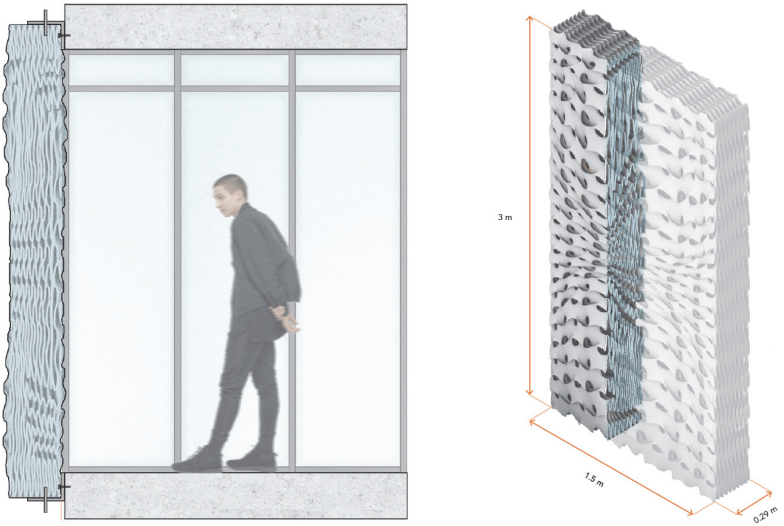

Figure 19: 3D-printed mono-material façade with designed air cavities for thermal insulation, designed using heat transfer models [23]. MSc thesis and illustrations: Valeria Piccioni.

trigger their creativity and drive their design conception. In this way they become designers that conscientiously include environmental performances in their design in a research-driven design approach. This approach has led to highly successful MSc theses of several of my students leading to (nominations for) awards, journal papers, conference presentations and presence at exhibitions like the Dutch Design Week.

Moreover, due to new design challenges stemming from societal and environmental challenges, building design has become more complex. Digital tools, also in the field of building physics, are becoming increasingly important to support these complex challenges. I also see the uptake of parametric design, simulation and optimisation processes in the building physics profession. Besides, for the operation of buildings nowadays large datasets from sensors are gathered that need to be analysed and interpreted, or used for predicting the required state of the building and its systems in the nearby future (predictive control). We should therefore prepare our students for this by giving them the right skills and tools. This includes a deep understanding of building performance simulation and data analytics. Recent developments also show the increasing importance of AI for building physics, as both design alternatives generator or as large dataset analyser. This requires our students to become better acquainted with AI, its use and limitations, its potential biases and weaknesses.

Regarding didactics in a broader sense, blended forms of learning will be an important means to let students learn on their own pace in their own environment, creating room for them to breath. The contact time on campus can then be dedicated to deepening of the knowledge, placing this in context and applying it to practical cases. To facilitate such learning in the field of building physics, I see good opportunities for digital adaptive learning technologies. Based on data and algorithms, such tools tailor the learning process to the individual needs of students by adjusting the difficulty level and providing personalised feedback and assignments. Such tools will revolutionise the way we teach the fundamentals to our students. An example of such a tool is the language learning app Duolingo.

I thus underscore the ambition that our students become architects and engineers equipped with ample fundamental knowledge of building physics, with architectural design skills to integrate this knowledge and with simulation and data skills to support their design development. I envision that our students, if equipped with these skills, can make a difference in helping the built environment transition to a sustainable future.

10 Research facilities and collaboration

To conduct the research into climate responsive and adaptive building systems, high-quality research facilities are necessary. Several of my past projects were conducted at the Green Village. The Green Village is a fieldlab for sustainable innovations on the TU Delft campus. It is an outstanding testbed for monitoring innovations in real buildings with real users under real weather conditions under semi-controlled conditions. Recently, also the lab facilities at the faculty of Architecture and the Built Environment have been growing and have been consolidated in the BK Labs structure. We, however, still lack experimental facilities to test CRABS under fully controlled environmental and acoustic conditions. I therefore see opportunities to expand the lab facilities with equipment for controlled experimental studies on CRABS and for material characterisation. Such equipment will be instrumental for high quality research and for securing new research funds.

Figure 20: The Green Village on the campus of TU Delft (photo: The Green Village).

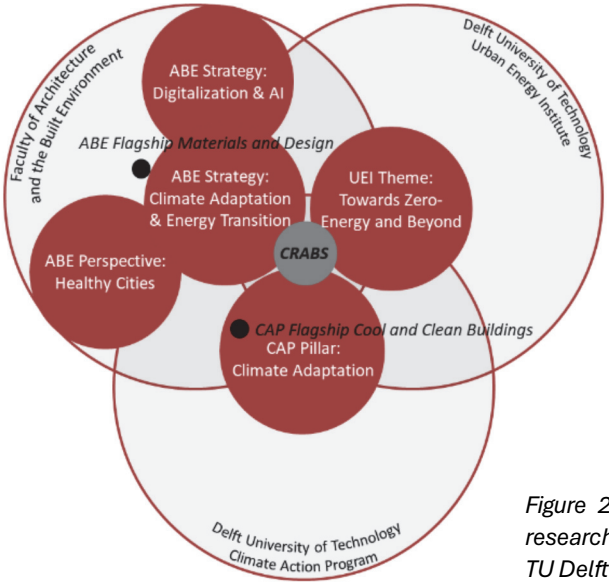

Figure 21: Positioning of the research into CRABS with the TU Delft ecosystem.

Furthermore, I cannot develop all the knowledge and technology required for the sustainable built environment of the future on my own. On the one hand, many MSc students and PhD candidates need to be trained; something I enjoy very much; seeing them grow from young to well-rounded academics. On the other hand, increased collaboration with colleagues from TU Delft and beyond is needed. Together we can develop the knowledge and innovations needed for the sustainable built environment of the future.

11 Words of appreciation

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References

[1] Hens, H. (2007), *Building Physics – Heat, Air and Moisture. Fundamentals and Engineering Methods with Examples and Exercises*, 1st edition, Ernst und Sohn, Berlin.

[2] Blocken, B. (2012), *Urban Physics*, Inaugural lecture spoken on October 5, 2012, at Eindhoven University of Technology.

[3] Tammes, E. (1980), "De thermische isolatie-index van gebouwen", Mikroniek no. 4, april 1980, p. 77-79.

[4] United Nations Environment Programme (2024), Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments. Nairobi, https://doi.org/10.59117/20.500.11822/46404.

[5] Copernicus (2025), 2024 is the first year to exceed 1.5°C above pre-industrial level, press release, 10 January 2025, https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level

[6] KNMI (no date), Kerncijfers KNMI'23, data, https://klimaatscenarios-data.knmi.nl/kerncijfers

[7] WHO (2023), Climate Change. Key Facts, website, 12 October 2023, https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

[8] KNMI (no date), Klimaatverandering, website, accessed 3 October 2025, https://www.knmi.nl/producten-en-diensten/klimaatverandering

[9] United Nations Environment Programme (2025), Not just another brick in the wall. The solutions exist. Scaling them will build on progress and cut emissions fast, Global Status Report for Buildings and Construction 2024/25, https://doi.org/10.59117/20.500.11822/47214

[10] European Commission (2023), Delivering the European Green Deal, website, 9 October 2023, https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en

[11] European Commission (no date), European Climate Law, website, , accessed 3 October 2025, https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en

[12] EU (2024), Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast), Official Journal of the European Union, https://eur-lex.europa.eu/eli/dir/2024/1275/oj

[13] European Union (no date), New European Bauhaus, website, accessed 3 October 2025, https://new-european-bauhaus.europa.eu/index_en

[14] Looman, R.H.J. (2017), *Climate-responsive design: A framework for an energy concept design-decision support tool for architects using principles of climate-responsive design*, PhD dissertation, TU Delft, Delft.

[15] Heiselberg (ed.) (2009), IEA ECBCS Annex 44 Integrating Environmentally Responsive Elements in Buildings - Expert Guide – Part 1 Responsive Building Concepts, https://iea-ebc.org/Data/publications/EBC_Annex_44_Expert_Guide_RBC.pdf

[16] Unen, J. van (2019), The energy and comfort performance of a lightweight translucent adaptable Trombe wall in different buildings and climates, MSc thesis, TU Delft, Delft.

[17] Alouche, A. (2025), *ThermoSense. Responsive Thermal Façade*, MSc thesis, TU Delft, Delft.

[18] Koenders, S.J.M., Loonen, R.C.G.M. & Hensen, J.L.M. (2018), Investigating the potential of a closed-loop dynamic insulation system for opaque building elements, *Energy and Buildings* 173: 409-427, https://doi.org/10.1016/j.enbuild.2018.05.051.

[19] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (2022), National Woon- en Bouwagenda, policy document, https://www.volkshuisvestingnederland.nl/documenten/publicaties/2022/03/11/nationale-woon--en-bouwagenda.

[20] Langen, M. (2025), Woningmarktmonitor: Energietransitie, ABN AMRO, 14 August 2025, https://assets.abnamro.com/api/public/content/wmm-energietransitie.pdf.

[21] CBS (2025), 1 op de 5 huishoudens heeft last van vocht of schimmel in de woning, press release, 10 April 2025, https://www.cbs.nl/nl-nl/nieuws/2025/15/1-op-de-5-huishoudens-heeft-last-van-vocht-of-schimmel-in-de-woning

[22] Farrugia, E.G. (2018), *Thermal Morphology. A geometrically optimized Trombe wall*, MSc thesis, TU Delft, Delft.

[23] Piccioni, V. (2023), *The AM Envelope. A mono-material façade element with complex geometries for structural and thermal performance produced by AM*, MSc thesis, TU Delft, Delft.

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