RETHINKING HVAC SYSTEMS:

THE POSSIBILITIES OF PASSIVE AND BIO-INSPIRED TECHNIQUES IN RESIDENTIAL BUILDINGS

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ABSTRACT

This research addresses the dual environmental impact of the building sector, operational energy use and embodied carbon, by investigating passive and bio-inspired techniques as alternatives to conventional HVAC systems. Focusing on temperate climates, techniques are categorized into three layers following the Behling Diagram: architectural form, passive systems, and active systems. Each technique is analyzed through literature review and applied to a test design for a residential building in The Hague, Netherlands. A ranking system evaluates both architectural integration, based on visual comfort, spatial quality, and social value, and carbon efficiency, calculated per supplementary m2. Results show that *form & orientation* and *sunspaces* perform best across both metrics. The results are combined into a catalog, which can be used during early design phases. While the methodology highlights promising strategies for sustainable design, it is also acknowledged that limitations related to context-specific performance and material assessment are present. This study offers a comparative framework to support low energy-impact architectural decision making.

KEYWORDS

Passive design, bio-inspired design, installation techniques, temperate climate, carbon footprint, building system catalog

I. INTRODUCTION

The development of our built environment is increasingly influenced by two major challenges: the rising threat of climate change and concerns over energy scarcity and security. The building and construction sector alone account for nearly 40% of global energy consumption (1). With the rising population, increasing comfort expectations, and more time spent indoors, energy demand, particularly for building services, is expected to continue to grow. HVAC systems are especially energy-intensive, responsible for 20% of building energy use globally and up to 50% in developed countries (2).

In addition to the rise in operational carbon emissions, material use in construction presents another major concern. Over the last century alone, material extraction has increased by 34 times, with Europe now consuming early 16 ton of material each year (3). Around 30% of these raw materials are used in the building sector (4), contributing significantly to a building's embodied carbon. This material intensity, combined with a twelvefold increase in fossil fuel use over the same period (5), shows the double burden of energy and resource dependency in the building sector.

Historically, architecture relied on passive and climate responsive solutions for a comfortable indoor climate. These so called bio-inspired systems mimic strategies found in nature to improve building performances with minimal material and energy input (5).

This paper looks revisits these techniques in contemporary architecture, addressing the central question: *Which passive and bio-inspired techniques can be integrated in a residential building as alternative for conventional HVAC systems, reducing both operational and embodied carbon?*

To answer this, the paper develops a ranking system that evaluates passive and bio-inspired techniques based on typology, energy performance, material requirements, and architectural integration. The goal is to encourage architects and engineers to prioritize low-impact strategies from the earliest stages of design. As said by Toroxel & Silva (6), ''passive and bioclimatic strategies, coupled with integrating renewable energy sources and using energy-efficient systems, pave the way for developing carbon-neutral building''. The future of sustainable architecture lies not in sophisticated technologies added as an afterthought, but in passive, nature-based principles integrated as a fundamental design principle.

II. METHODOLOGY

The research is divided in two parts: first, a technical analysis of various passive and bio-inspired techniques; second, their application in a test design. Based on the test design, a ranking system is developed to assess both architectural integration and the carbon footprint of each technique.

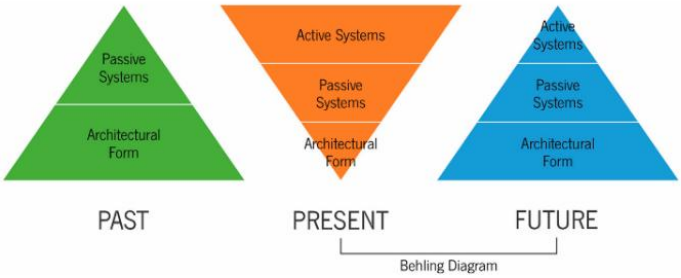


Fig. 1: *Behling Diagram with addition of the tringle representing the past. Fernandes, J. (2014)*

The techniques studied in this paper are based on the Behling Diagram (Fig. 1), which reorders the present architectural hierarchy to prioritizing form and passive systems over active installations (7). The three layers (architectural form, passive systems and active systems) are analyzed separately for techniques effective in a temperate climate:

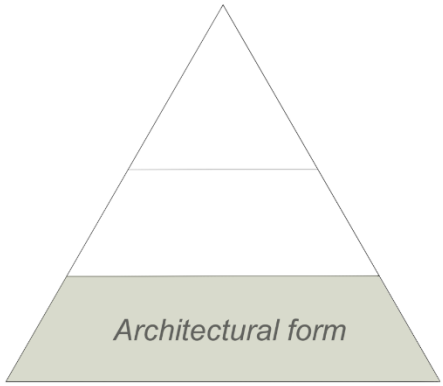
Layer 1:	Architectural form:	shape, orientation, fenestration, and shading
Layer 2:	Passive systems:	Trombe wall, sunspaces, vegetation use, labyrinth thermal system
Layer 3:	Active system:	algae facade

The analysis of the techniques is based on literary review, focusing on how each technique functions and its potential for energy reduction.
These techniques are then applied individually to a test design, which is a residential building in The Hague, Netherlands, representative of a urban setting within a temperate coastal climate.

Since passive systems often define the building's exterior character (unlike hidden active systems), the research evaluates both architectural value and carbon impact. Each technique is assessed architecturally for visual comfort, spatial quality, and social value, using case studies and design research.
The material use and related carbon footprint are calculated per system and per supplementary area. The carbon footprint per m2 are compared against the previously assessed energy efficiency to allow for a fair cross-comparison.
Finally, two ranking systems are created: one for architectural value and one for carbon efficiency. The results are compiled into a catalog, highlighting the most suitable techniques for low-impact residential design.

III. LAYER 1 : ARCHITECTURAL FORM

Prior to the implementation of numerous systems aimed to ensure visual, thermal, and acoustic comfort, the architectural form of a building can already enhance the building's efficiency. Features such as form, orientation, window-to-wall ratio, and envelope configuration significantly influence comfort and offer early opportunities to reduce a building's energy demand. Architectural form is seen as the first foundational layer of the architecture of the future, relying on natural means over active systems. This chapter examines the primary design factors contributing to these outcomes.



3.1. Shape

While the shape of a building is often defined by functional, esthetic and economic considerations, it is also closely related to the building's energy performance. Research conducted on a high rise office building in Amsterdam showed that the larger the envelope skin, the higher the amount of heat loss and gain though the skin was. In this research, Raji et al. (8) researched 12 shapes in three different climates (temperate, sub-tropical, and tropical). Fig. 2 shows the results for the temperate climate, where the oval form (shape 3) uses the least amount of energy (about 81,6 kWh/m2). The researchers concluded that compact shapes are more desirable for energy savings, yet narrow plans, like shape 6, better function for spaces along the building's perimeter, having more natural light and less electric lighting needs as a result.

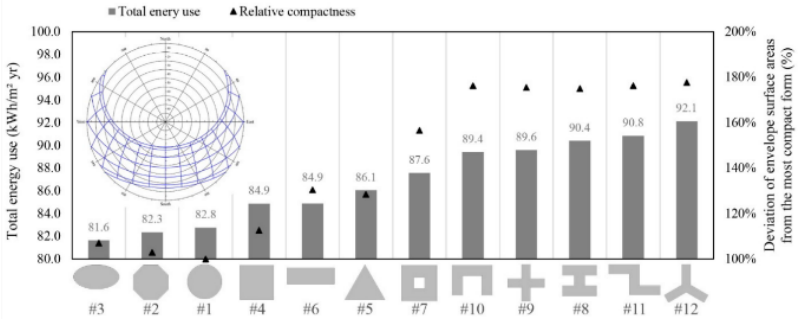


Fig 2. *Building total energy use of 12 plan shapes (WWR = 50%) in association with their compactness in Amsterdam. Raji et al. (2017)*

3.2. Orientation

Orientation plays a critical role in a building's energy-saving potential and influences the effectiveness of passive solar systems such as Trombe walls, solar spaces, and solar chimneys (1). Beside energy efficiency, proper orientation enhances indoor environmental quality by improving daylight access and visual comfort. Due to its relatively low cost and high impact, numerous studies have investigated optimal orientation strategies. For instance, a rectangular building aligned with its long facade facing south maximizes solar gain in winter and minimizes intense radiation on the east and west surfaces during summer, allowing for effective solar shading on the south side (6). Extending the building's long axis along the east-west direction offers three key benefits: improved daylight penetration, reduced summer overheating from west-facing facades, and optimized winter solar gain from the south. Mid-day summer sun can also be managed with shading devices without sacrificing daylight or views (8). Lavafpour & Surat (9) stated 15° east of south as the optimal orientation for minimizing solar radiation on east and west facades, thereby reducing

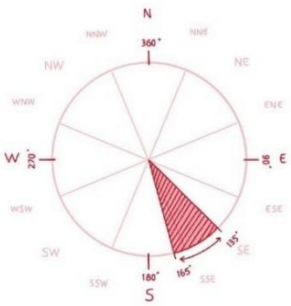


Fig 3. *The ideal orientation based on Lavafpour & Surat (2011) and Karimimoshacer & Shahrak (2022). Author's work (2025)*

overheating risks. Karimimoshaver & Shahrak (10) concluded in their research 135° as ideal for thermal comfort. Despite minor variation, both studies suggest the long axis should ideally be oriented between 135° and 165°, leaning toward a south-southeast direction (Fig. 3). Research by Pacheco et al. (11) stated that combining the right shape and orientation can lead up to energy savings of 36%.

3.3. Fenestration

Fenestration, in the form of windows and doors, provide visual connection to the environment and natural lighting, but also acts as significantly thermal bridges affecting energy performance. Research has explored the optimal window-to-wall ratio (WWR) to balance energy efficiency and visual comfort. A study by Bokel (12) on an office building in Groningen, the Netherlands, found that a higher window to wall ratio of 50% has a disadvantage. The test, done on a south-facing façade with double glazing windows (U = 2,57 W/m2K), showed that higher window areas increased the cooling load significantly without decreasing artificial light loads. Similarly, Ochoa et al. (13) analyzed energy consumption for heating, cooling, lighting and ventilation for different window sizes and orientations. In a temperate climate like the Netherlands, larger windows were found to increase energy consumption due to more heat transfer. However, reducing the WWR negatively impacted lighting and visual comfort. Using a model with double glazing (U = 1,7 W/m2K), they concluded an optimal WWR of 50-70% for north-facing, 60% for south-facing, and 50-60% for east and west-facing windows. It was noted by the researchers that no additional shading devices were incorporated, which might have impacted the results.

3.4. Shading

While a building's fenestration is important for solar heat gain and visual comfort, it can also lead to overheating in summer (6). Managing the solar radiation through windows is thus essential for maintaining indoor thermal comfort, while minimizing the reliance on mechanical cooling. Research by Amirifard et al. (14) stated that exterior windows account for 28% of a building's total heat gain, increasing to 40% with infiltration. Shading devices can be installed both internally and externally, with external shading being more effective as it prevents solar radiation from entering the building. Options for external shading include eaves, overhangs, and brise-soleils (6), which block high summer sun while allowing low winter sun for solar gain (Fig. 4). Nearby structures and vegetation can also provide (seasonal) shading.

Florides et al. (15) demonstrated that effective shading can reduce cooling energy consumption by 7% in buildings without additional insulation and up to 19% in buildings with 50mm insulation in walls and roofs. These energy savings, however, are context-specific and should be used as a guiding reference for the energy efficiency of the techniques employed.

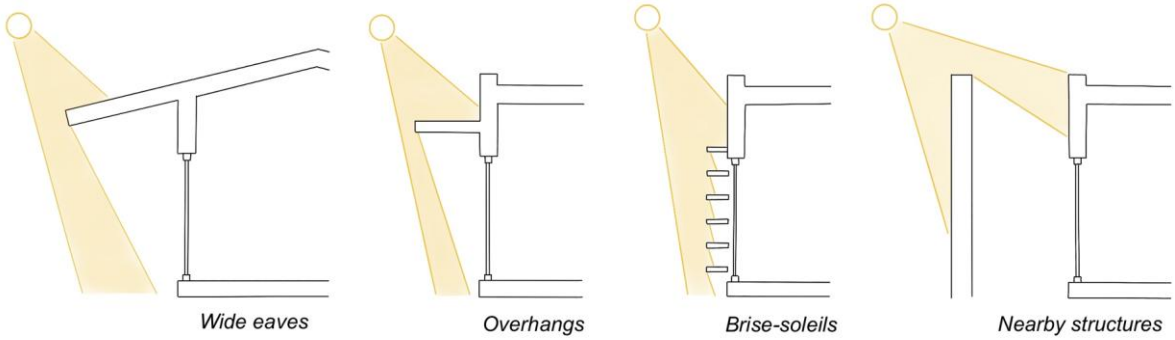
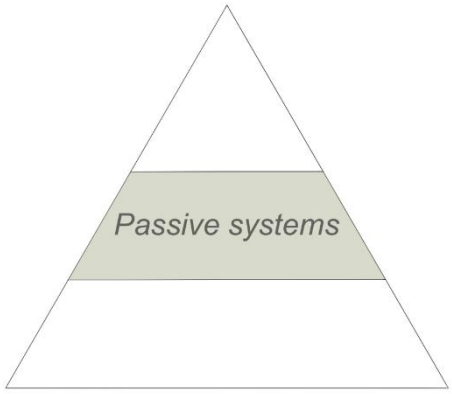


Fig 4. *External shading devices, based on Toroxel &Silva (2024). Author's work (2025)*

IV. LAYER 2: PASSIVE SYSTEMS



In contemporary architecture, active systems are placed in the building to create thermal comfort. Yet, techniques based on natural processes like radiation, conduction or convention offer solutions with no to little energy use to often enhance the thermal performance of a building significantly (6). These passive systems are often in direct contact to the local climate, making use of solar radiation, wind and geothermal characteristics. This chapter evaluates four passive techniques appliable in temperate climates.

4.1. Trombe wall

The Trombe wall, also known as a storage or solar heating wall, is a passive design strategy that uses solar energy to heat, ventilate, and improve thermal comfort in buildings (16).

The classic Trombe wall

The classic Trombe wall consists of a high thermal mass wall placed behind a glazed panel, separated by an air channel (1). Solar radiation passes through the glass, is absorbed by the wall, and re-radiated as longwave heat, which is trapped in the air gap. Vents at the top and bottom enable natural convection, drawing cooler indoor air into the channel and releasing warmed air back into the room, thus reducing heating demand. The Trombe wall, typically constructed from high thermal-mass materials like brick, stone, concrete, or adobe, store heat during the day and releases it at night, contributing to a more stable indoor climate (17).

This technique is mainly used in Northern Europe and the Middle East, utilizing low-angle winter sun for heating (1). In warmer seasons, they can also contribute to cooling by reversing airflow: opening dampers allows warm indoor air to rise and exit via the glass façade (Fig. 5), drawing in cooler air through a window opposite the wall (6).

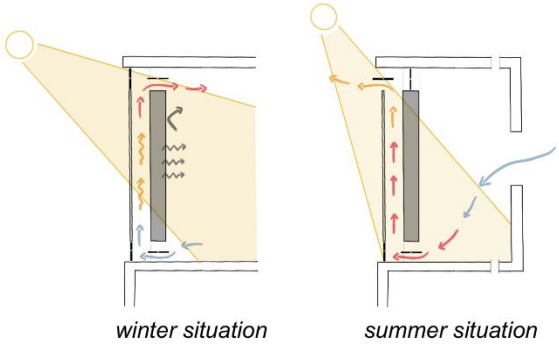


Fig 5. Summer & winter working of the Trombe wall. *Author's work (2025)*

The composite Trombe wall

The composite Trombe wall is an adaptation of the classic design, incorporating an additional insulating panel between the thermal mass and the interior. With a closed air channel, it traps more solar radiation, even on cloudy days. Heat is transferred via conduction from the unventilated air gap to the thermal mass and then into the building. The added insulation significantly increases the wall's thermal resistance by limiting heat loss through the air channel (17). The system includes a control mechanism to prevent reverse thermos-circulation, when the thermal mass becomes cooler than the indoor air. While this mechanical element can been seen as a disadvantage when aiming for a fully passive system, it also enables occupant to have control over the airflow. The composite Trombe wall has proven most effective in cold or overcast climates, making it suitable for regions like the Netherlands (18).

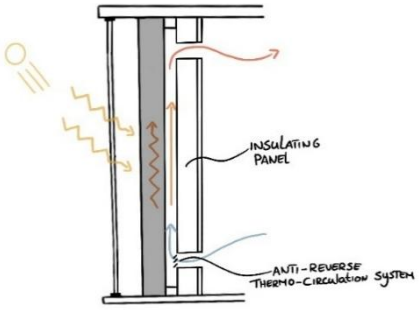


Fig 6. Composite Trombe wall with extra insulating panel and anti-reverse thermos-circulation system. *Author's work (2025)*

The efficiency of a Trombe wall is influenced by several parameters, including its dimensions. Abdeen et al. (19) defined that the optimal design, consisting of a 1.7 m high wall, a 0.3 m thick thermal mass, and a 0.22 m deep air channel. With this, the researchers measured a 38,19% increase in comfort during a typical winter week in Alexandria, Egypt.

4.2. Sunspaces

A common limitation of Trombe walls is the lack of visibility and natural light on the south façade. A proposed solution is the transformation of the air channel into a usable space, commonly referred to as a sunspace (20). Functioning similarly to a Trombe wall, a sunspace collects solar heat within a glazed enclosure and distributes it to adjacent rooms, reducing the need for additional heating. Beyond thermal benefits, sunspaces also enhance visual comfort and provide an appealing extension of usable living space (21). Like Trombe walls, sunspaces are typically south-oriented to optimize solar gain. However, local climatic conditions must be considered. In temperate climates, though conditions are favorable, their efficiency depends on the integration of additional measures such as natural ventilation, shading devices, and proper thermal insulation to prevent overheating or heat loss (21,22). Sunspaces can be integrated into buildings in various ways, most commonly as glazed balconies or attached greenhouses.

Glazed balconies

Glazed balconies offer a practical and impactful solution for both new and existing buildings due to their relatively simple implementation. As a long-used architectural element, balconies remain popular in multi-family housing and dense urban areas (23). Several studies have stated that the presence of balconies, especially in urban areas, increases habitants wellbeing and sense of livability in the city (24–27). Adding glazing to balconies enhances thermal comfort in colder climates and contributes to sustainable development by reducing heating demand. However, in warmer regions, or even in northern climates, glazed balconies can cause overheating if not properly managed (23). To minimize this, additional passive strategies such as night ventilation and shading are essential. According to Saleh (28), west-facing glazed balconies should be avoided, and south-facing ones require solar protection. Operable dampers, as illustrated in Fig. 7, can allow the glazed balcony to function effectively in both winter and summer (29). Research has shown that glazed balconies can provide up to 10°C increase in temperature (30,31). With the right solar exposure, meaning south-facing glazing, reductions up to 30% of the building's heating load can be achieved (29,32). See Appendix A for a thorough explanation of the efficiency.

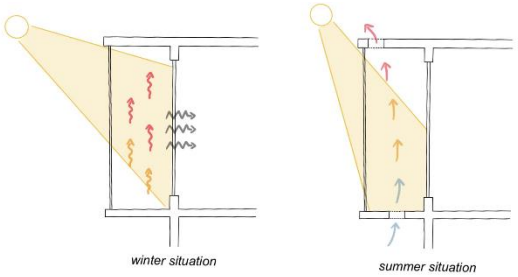


Fig 7. Summer and winter situation of the glazed balcony. *Author's work (2025)*

Sunspace

Besides glazed balconies, sunspaces can also take the form of greenhouses attached to buildings, often functioning as additional living or transitional space. These sunspaces typically have a high window-to-wall ratio (WWR), sometimes with glazed roofs, to maximize solar gains (6). While beneficial during winter, excessive glazing can cause overheating in summer and heat losses during winter nights (33). To address this, shading and ventilation are essential. Bataineh & Fayez (22) concluded that combining these measures can reduce annual heating and cooling loads by up to 42% in a living room in Amman. Research on sunspaces in several cities in Europe (Milan, Dublin, Athens and Florence) has confirmed that sunspaces are effective in winter but again stress the need for passive cooling to prevent overheating (21). Plants are commonly kept in greenhouses, supporting cooling in summer, yet they can also reduce heating effectiveness in winter by absorbing energy and promoting evaporation (6).

Form and size of the sunspace has a great influence on its effectiveness, it was researched by (34) and (35) that the optimal depth of a sunspace is 150cm, resulting in the highest indoor temperature.

Looking at the shape of the sunspace, an 'even span' has showed to perform the best for heating and cooling according to Gupta & Tiwari (36). A ventilated sunspace can save up to 36% on energy consumption (35) (see Appendix A).

4.3. Vegetation

Thermal comfort is increasingly important as global temperatures rise. In the Netherlands, tropical days over 30 °C now occur around five times per year, compared to just once a century ago (37). With the prediction of more frequent heatwaves later this century (38), the demand for cooling continues to grow, even though the need to limit energy use remains. Passive design strategies offer effective solutions by reducing cooling loads without relying on energy-intensive systems. In addition to building-integrated elements like sunspaces, Trombe walls, and shading devices, the use of vegetation, both on building surfaces and beside the building, can significantly reduce thermal gains and improve overall building performance (6).

Green envelope

Green facades and roofs are increasingly used in architecture, often to enhance thermal performance and biodiversity in dense urban areas. However, greenery has also highly beneficial characteristics when it comes to cooling via surface evaporation and plant transpiration (39). Evaporative cooling is an often used passive strategy, where heat is extracted from the environment as water evaporates. According to Chenvidyakarn (40), each gram of evaporated water removes approximately 2550 J of heat. Green roofs and façades utilize this principle through surface evaporation and plant transpiration, making them effective cooling elements in architectural design (39). In addition to improving biodiversity and carbon storage, they contribute to thermal comfort in urban environments. A Dutch study found that double-skin green façades can lower cooling loads by up to 20% (41). Further research showed that 30cm grass provides the most effective cooling (42) (Appendix A). Next to the cooling function of green surfaces, they contribute also to the thermal mass of the building in winter, adding extra resilience against heat loss (Fig. 8).

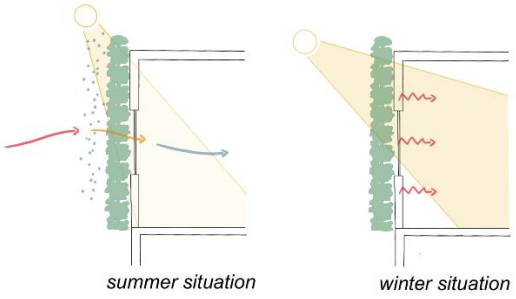


Fig 8. Summer and winter situation of green envelope. *Author's work (2025)*

Shading with trees

Beyond a green envelope, vegetation placed strategically around buildings can enhance seasonal shading and reduce cooling loads. Both on urban and building level, trees and plants offer a great cooling effect. Deciduous trees, in particular, provide effective summer shading and allow winter solar gain when leaves fall. Moss et al. (43) estimated the average cooling contribution of a single tree at 4.8–9.1 kW across four cities in England. For optimal seasonal performance, such trees are best placed along south and southwest façades (6). Kamal (44) revealed in their study local cooling effects of up to 5°C, contributing to urban heat island reduction. Florides et al. (15) found that proper shading can cut cooling loads by 7% in uninsulated buildings and up to 19% in those with 50 mm insulation.

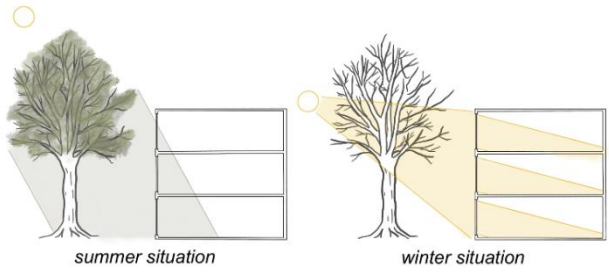


Fig 9. Summer and winter situation with trees. *Author's work (2025)*

4.4. Labyrinth thermal system

While many passive techniques rely on environmental factors such as thermal buoyancy, solar orientation, or prevailing winds, other strategies draw inspiration from nature itself. A passive cooling system based on the structure of a termite mound is one of these so called bio-inspired principles.

Typology

A labyrinth thermal system uses an underground, labyrinth-shaped structure, typically made of concrete, to cool incoming outdoor air before it is distributed throughout the building (Fig. 10). While primarily used for cooling, the system's thermal mass can also serve to pre-heat air during colder periods. The mass is maintained at a stable temperature through ground heat exchange or night-time ventilation. Low-energy fans drive air through the structure, allowing cool night air to reduce the temperature of the thermal mass (45). During the day, as outdoor temperatures rise, incoming air passes through the pre-cooled structure, lowering its temperature before entering the building (5).

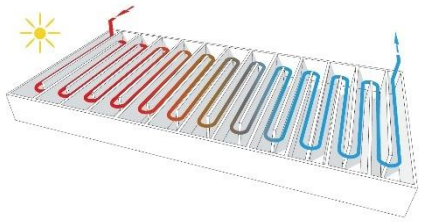
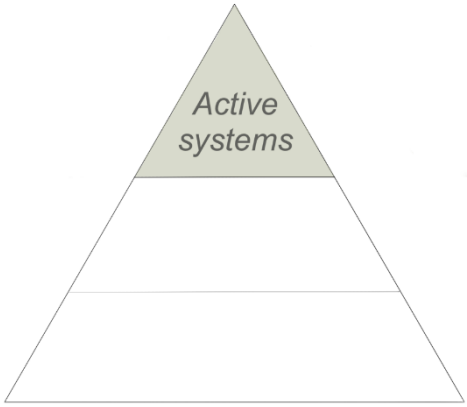


Fig 10. *Principle of a labyrinth cooling system. Burohappold (2013)*

Similar to earth-tube systems, labyrinth cooling relies on geothermal exchange, but it has several advantages. Unlike earth-tubes, which require additional buried piping, labyrinth systems are often integrated into the building's existing underground structure, minimizing excavation needs (45). Additionally, labyrinth systems can accommodate larger air inlets, allowing for higher intake airflow rates and an increased efficiency.

Geothermal systems can operate year-round, as the earth maintains a relatively stable temperature. A study on a campus building in Seoul, South Korea, demonstrated that a labyrinth thermal system reduced annual air conditioning energy loads by 31.3%, and peak loads by approximately 40%, thus lowering the intensity of energy required for thermal comfort (45). The energy consumed by the system's fans accounted for just 1.5% of the total annual energy savings. The system operated 30% of the year for cooling, achieving an average temperature reduction of 3.1°C to 3.7°C, and 70% for heating, with temperature increases ranging from 7.5°C to 13.3°C.

V. LAYER 3: ACTIVE SYSTEMS



Previous chapters have shown that architectural form and passive systems can contribute to significant energy savings without or minimal use of active energy sources. However, no passive system can yet provide all the required energy for heating and cooling. Even though active systems are still required to do so, bio-inspired solutions can be used for this over fossil-based options. This chapter explores how an algae façade can function as active system.

5.1. Algae facade

The bio-inspired installation systems analyzed so far are all based on passive strategies, yet they also exist in active form. The use of algae is a growing field of interest, since it offers a promising alternative to address the challenges and demands of the twenty-first century (46). Micro-algae grown in photo-bioreactors is one of these researched technologies. Utilized in building, these algae photo-bioreactors can produce energy and biomass via photosynthesis.

Fig. 11. *Case model for algae façade in Hamburg, Germany. Source: International Building Exhibition*

Algae cultivation can be either done in an open or closed system. Whereas the open pond system is cheaper, the use of a closed system is much more efficient (46). In order to create said closed system, transparent pipes or panels are utilized. The algae that is produced in this system require water to live in, CO2 as nutrient, and sunlight for photosynthesis (47). Test done by on a photo-bioreactor façade panel show that, in Northern Europe's climatic conditions, flat panels have significant higher production rates than tubular bioreactors. These panels function as followed: Transparent bioreactor panels are filled with water and microalgae, which are continuously supplied with nutrients and carbon dioxide. Sunlight passes through the panels, enabling the algae to photosynthesize and grow while absorbing solar energy. As the algae multiply, they provide dynamic shading and thermal insulation for the building (48). Different panels are connected in series, stimulating circulation through all of them. During the day, the water inside the panels is heated, which can be up to 35°C (47). The water is circulated through the building, where at the service area biomass is collected and heat extracted. The produced heat is used for heating the building and preheating hot water. Excess energy can be stored in geothermal boreholes and used again via heat pumps. The extracted biomass can be, at an external location, converted into biogas, algae oil or left like biomass which can be used for food and medicine for example (46).

The photo-bioreactor can operate all year round, due to the high efficiency of the system. Research on the real-world application of an bio-reactor panels concluded they are able to produce 150 kWh/m2 thermal energy and 30 kWh/m2 bioenergy, respectively (48). With the panels faced to the southwest and southeast, an efficiency of 38% of sunlight to heat and 10% light to biomass was determined. In addition, 80% of the produced biomass of this system was returned to the building for heat and electricity generation after being generated into methane in an outdoor plant. Not only do the algae function as heat and biomass producer, they also extract CO2 from the air. Research by Kim & Han (49) concluded that 13% of the CO2 level was reduced by the algae façade compared to a standard building with 200 occupants. The overall building's energy consumption can be reduced by 50% when the algae façade is properly integrated, with the possibility of 100% when solar panels are used for the heat pumps and heat exchangers (48) (50).

VI. TESTING OF THE TECHNIQUES

To quantify and qualify the researched techniques equally, they are tested on a hypothetical design. The architectural value and carbon footprint of implanting these techniques is analyzed and later on ranked in order to compare the systems to each other.

The test design is located in Binckhorst The Hague in the Netherlands, where climate change is already effecting rainfall patterns, temperature, and sea levels (51). The Hague serves as a representative urban setting within a temperate coastal climate zone. Its dense urban setting and environmental policy goals make it an good testing area for low-impact architectural strategies.

This chapter describes first the parameters of the test design, secondly the qualitative architectural value of the implemented techniques and lastly the quantitative values based on the carbon footprint.

6.1. Binckhorst The Hague

The Binckhorst area in The Hague is undergoing a significant transformation from its industrial past into a vibrant, mixed-use urban area. This redevelopment has an emphasis on sustainability, creative industries, and residential living (52), making it the optimal area for exploring innovative architectural solutions.
The proposed test building is a mid-rise residential structure designed to accommodate nine apartments. Some of the key specification are as followed:

- Dimensions: 25m length, 10m depth and 10m height
- Floor area: approximately 750m2
- Layout: nine two-room apartment, each +/-80m2

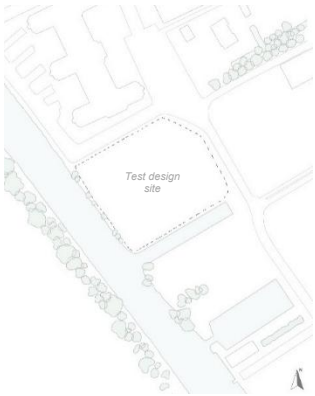


Fig 2. *Test design site, Binckhorst, The Hague. Author's work (2025)*

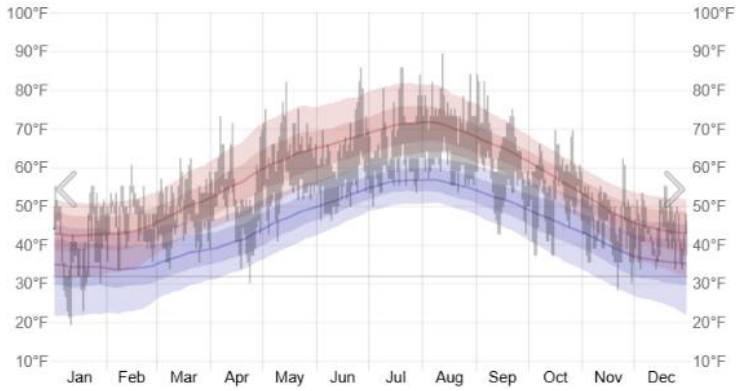


Fig 13. *2024 annual weather of Rotterdam weather station. WeatherSpark (2025)*

The Hague is categorized, based on the Olgyay and Olgyay's simplified climate classification (53), as a maritime temperate climate. This climate is characterized by mild summers, cool winters, and relatively high humidity. Weather data from the nearby Rotterdam – The Hague Airport weather station (approximately 14,5km southeast of Binckhorst) is used as representative for the site (Fig. 3).
The average monthly temperature variation in The Hague is 13,4 °C. Direct and diffuse solar radiation are fairly balanced throughout the year. About 35% of daylight hours are sunny and 65% are cloudy or hazy with low solar intensity. The sun altitude peaks at 61,3° around June 21 and drops to 14,5° around December 21 (8).

6.2. Architectural value

The techniques studied for the architectural form, passive- and active systems are tested on the test building in The Hague. How the techniques were implemented in the test design is based on case study analysis done in Appendix B and the literary research in this paper. Each technique is implemented and studied separately from each other (see Appendix C).
Appendix C.2.1. describes the added architectural value based on three criteria: visual comfort, spatial comfort, and social value. The conclusions based on this analyses were used to create a ranking system (Appendix C.2.2) with which the architectural value of the techniques can be compared to each other. It was concluded that the form & fenestration and sunspace score the best on the three mentioned design aspects. Form & fenestration due to high visual and spatial comfort and the sunspace due to good spatial comfort and an added social value. Envelope shading and the Trombe wall score less, the shading due to low social value and minimal spatial and visual comfort and the Trombe wall due to less visual and spatial comfort.
The ranking criteria and results for the architectural value are shown in table 1.

	Technique	Visual comfort	Spatial comfort	Social value	Total score*
ARCHITECTURAL FORM	Form & orientation	3	3	2	8
	Fenestration	3	2	1	6
	Envelope shading	2	2	1	4
PASSIVE SYSTEMS	Trombe wall	1	1	2	4
	Glazed balconies	2	3	1	6
	Sunspace	2	3	3	8
	Green envelope	1	1	3	5
	Tree shading	2	1	3	6
	Labyrinth thermal system	3	1	1	5
ACTIVE SYSTEMS	Algae façade	2	1	3	6
	*total score: 3-4 = less good; 5-6 = ok; 7-9 = good.				

	Visual comfort	Spatial comfort	Social value
SCORE 1	Obstructs visual comfort	No contribution to spatial comfort	Adds no social value
SCORE 2	Obstructs partly visual comfort	Contributes to some spatial comfort	Adds some social value
SCORE 3	Obstructs no visual comfort	Enhances spatial experience	Enhances the social value

Table 1. Ranking of the architectural value. *Author's work (2025)*

6.3. Carbon footprint

Next to the architectural value, the carbon footprint is calculated to analyze how sustainable the techniques actually are. In Appendix D.1.1 t/m D.1.7 the carbon footprint per technique is calculated, which is used in Appendix D.2 to convert to the kg CO2/m2 based on the supplementary area needed for the system. As done for the architectural value, also the carbon footprint is compared to each other with a ranking system. The scores are based on the amount of CO2 per m2 and the efficiency of the techniques (Appendix D.3.). The ranking showed that form & orientation and the sunspace score the best on both embodied carbon and efficiency. The other techniques score similarly to each other, which a good balance between the embodied carbon and efficiency.
The ranking criteria and results for carbon footprint are shown in table 2.

	Technique	Embodied carbon	Energy efficiency	Total score*
ARCHITECTURAL FORM	Form & orientation	3	3	6
	Fenestration	3	1	4
	Envelope shading	3	1	4
PASSIVE SYSTEMS	Trombe wall	2	2	4
	Glazed balconies	2	2	4
	Sunspace	2	3	5
	Green envelope	3	1	4
	Tree shading	3	1	4
	Labyrinth thermal system	1	3	4
ACTIVE SYSTEMS	Algae façade	1	3	4
	*total score: 2 = less good; 3-4 = ok; 5-6 = good.			

	kg CO2/m2	Energy efficiency
SCORE 1	>100	0 – 20%
SCORE 2	0 – 100	21-30%
SCORE 3	< 0	> 30%

Table 2. Ranking of the carbon footprint vs energy efficiency. *Author's work (2025)*

VII. CATALOG

The researched techniques are presented in a catalog, which can be found in appendix E. The catalog provides information on the technical performance during summer and winter, the added architectural value including the ranking, and the carbon footprint compared to the efficiency, also with ranking. The catalog can be used as guiding tool wile designing low energy-impact residential building in a temperate climate.

VIII. DISCUSSION

While the environmental impact and potential energy savings of the discussed systems offer valuable insight, several limitations must be acknowledged. First, it is difficult to accurately determine the efficiency of the passive systems based on case studies and literature. Performance depends heavily on context, climate, orientation, and surroundings, so no fixed value can be assigned. To assess the exact saving in the test design, detailed and complex calculations would be needed. This was not done due to time and data limitations.

Additionally, comparing systems based solely on material use, as done in this paper, doesn't capture their full environmental impact. Some may use more material initially but offer greater long-term energy savings, making them more sustainable overall. A rough estimate was made in this paper to analyze this by comparing the carbon footprint to the efficiency of the techniques, yet more detailed calculation are needed to create a more reliable overview. Especially the material use needs to be researched more thoroughly. In this paper, only the main materials used were analyzed. Smaller materials used in vents and mounting materials for example were left out.

Lastly, the comparison made of the architectural value focused only on three criteria. When implementing the techniques in a design, other criteria are most likely to influence the decision process. The overview does not give a full spectrum of design criteria and will need to be supplemented with criteria specific to a design case.

IX. CONCLUSION

This research was driven by the need to address the building sector's double impact on climate change, through high operational energy use and embodied carbon from material consumption. In response to this, the research explored passive and bio-inspired techniques as a sustainable alternative to conventional HVAC systems, focusing on the question:

Which passive and bio-inspired techniques can be integrated in a residential building as alternative for conventional HVAC systems, reducing both operational and embodied carbon?

Through a two part methodology, consisting of literature based analysis and application in a test design, the research evaluated techniques across three layers: architectural form, passive systems and active systems. By ranking the techniques on architectural value and carbon footprint, the research provides a framework for early-design decision making.

The results from the research show that form & orientation scores best for the architectural form layer on both architectural value and carbon footprint. For the passive systems layer, the implementation of a sunspace was concluded to be most beneficial for both rankings. The algae facade evaluated for the active systems layer scored low for carbon footprint but well for energy efficiency. Also the architectural value was concluded to be relatively good.

The rankings as presented in this paper can be used by architects and engineers in decision making for integrating passive and bio-inspired techniques in early design stages. Additional calculation for specific case studies will need to be conducted for more thorough conclusions.

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A. APPENDIX A: ADDITIONAL RESEARCH

Additional research referred to in the paper is per techniques added in this appendix.

A.1 Trombe wall

This chapter analyzes two adapted Trombe walls which show the best results for a mild temperate climate like The Hague: 1) the composite Trombe wall and 2) the PCM Trombe wall.

Composite Trombe wall

The Composite Trombe wall is a modification of the classic wall with an extra insulating panel behind the thermal mass. Due to the closed air channel, the majority of the solar radiation is trapped, even on cloudy days. Via conduction, heat is transferred from the unventilated air channel to the thermal wall, and from the wall to the interior. The insulated panel, situated between the thermal wall and the interior, increases the thermal resistance of the wall significantly by insulation the ventilated air channel (17).

Where the classic system works completely passive, the composite Trombe wall makes use of a system to prevent reverse thermo-circulation, which happens when the thermal mass becomes colder than the ambient air in the room. The use of this mechanical system can be seen as a disadvantage when aiming for a fully passive system, yet also as an advantage since it gives occupants the ability to control the airflow into the ventilated channel.

The composite Trombe wall has shown to be most effective during winter in cold or cloudy climates, making it a valid option to utilize in a climate like the Netherlands (18).

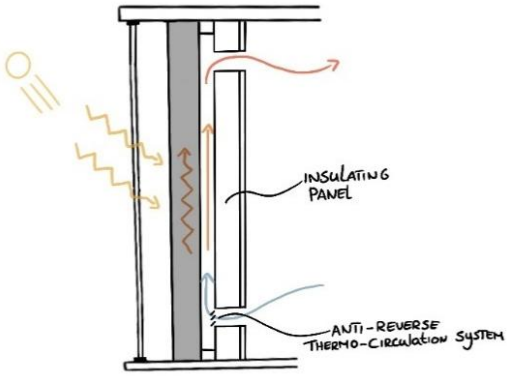


Fig A.1. Working of the Trombe wall, based on Bosu et al. (2023). *Author's work (2025)*

PCM Trombe wall

A newer alternation made of the Trombe wall, is one that includes phase change materials (PCM). Trombe walls require a thermal storage medium to capture and transmit heat, often realized in a thick wall from bricks, concrete or adobe. However, these walls often form a bottleneck for structural engineers due to the heavy load of the material. Creating these walls by these new, phase change materials addresses this problem (54). PCMs are capable of storing more energy in a smaller and lighter volume than normal building materials. A study concluded that a 3,5cm wall with phase change material could replace a 15cm concrete wall, and still perform the same (55).

Phase change materials, which can be composed of various organic and inorganic substances like hydrated salts, paraffins, sugar alcohols, and palm oils are known for their ability to transition between solid, liquid, and gaseous states in response to changes in ambient temperature (56). While changing from state, energy is captured and stored or released and returned. PCM Trombe walls are especially well equipped for refurbishment project, due to their light weight.

Multiple studies have been done on the performance of PCMs in Trombe walls (57). Research by (58) stated that this type of Trombe wall is worthwhile for low energy house application, but optimalization of the melting temperature of the materials and wall thickness is needed. (59) tested various PCMs, concluding that for a south facing Trombe wall an 8 cm hydrated salt wall performed better than a 20cm concrete wall and a 5cm paraffin wall. While experimental researched has been done, it should be noted that a lack of recommendations on how to use PCMs still exists (57).

Efficiency

The efficiency of a Trombe wall is determined several parameters, under which the dimensions. (19) concluded the optimal structure of a Trombe wall consists of a 1,7m high wall, 0,3m thick thermal wall and 0,22m deep air channel. With this, the researchers measured a 38,19% increase in comfort during a typical winter week in Alexandria, Egypt. Further research by (60) revealed that the best indoor temperatures could be reached when the Trombe wall was faced south. Calculating the exact savings of a composite Trombe wall is stated to be very difficult due to the many parameters that effect the performance, under which the material of the thermal mass and climatic changes (18). A study done for typical Tunisian building showed that a composite Trombe wall of 8m2 could provide 77% of the energy demand of a 16m2 floor area (61). To calculate the exact savings, research needs to be conducted in relation to a specific site and building.

A.2 Sunspaces

The efficiency of sunspaces is strongly dependent on climate, shape, orientation and additional cooling techniques. Research by (30), conducted in Finland, showed that the air inside glazed balconies was at least 5,0°C warmer than the outside air throughout the year. A similar study was done in Muncie, Indiana, where the indoor temperature of the glazed balcony was about 6,7°C warmer than the outside air during the heating season (31). Lastly, a Portuguese research on vernacular glazed balconies showed a temperature difference of 10°C on average during the winter between the balconies' and outside temperature. Narrow glazed balconies, extending across the length of the building, have been stated to be more efficient due to minimal heat losses from adjacent spaces while providing maximum natural light incidence (33). Studies done with computer simulations show that with the right solar exposure, meaning south-facing glazing, reductions up to 30% of the building's heating load can be achieved (29,32).

Sunspaces can be conducted in ventilated or unventilated spaces, depending on their required use. (35) revealed in their research that a ventilated sunspace can save up to 36% on energy consumption. Form and size of the sunspace has a great influence on its effectiveness. Research showed that the thickness of the inner wall of the sunspace can vary according to the local climate (62). The researchers stated that by increasing the volume of the walls and floor of the sunspace, the storage capacity increased. The weight of the structure however should also be taken into account since it can be troublesome for the structural engineering of a building. Furthermore, it was researched by (34) and (35) that the optimal depth of a sunspace is 150cm, resulting in the highest indoor temperature. Looking at the shape of the sunspace, an 'even span' has showed to perform the best for heating and cooling according to (36).

A.3 Green envelope

Green surface areas are especially beneficial for enhancing thermal mass and blocking solar heat gain through walls and roofs. A study conducted in France reported a 6% reduction in annual energy demand due to extensive green roofs (63). Another study done in the Netherlands revealed that a double skin green facades can reduce the cooling load about 20% (41). Throughout the years, integrated elements have been produced to simplify the integration of green facades and roofs. Laboratory tests done on a vegetated porous concrete tile concluded that the element could reduce the inlet temperature from 50°C to 24°C (42). The authors also stated that 30cm grass on the concrete tile provided the best heat reduction for the inlet temperature of 50°C.

The temperature decrease caused by trees has both effect on reducing urban heat island and energy savings since less cooling is needed. Shade provided by trees can achieve 7% reduction in cooling load for a building with single walls and up to 19% for a 50mm insulated building (15). Furthermore, shading and evapotranspiration from trees can reduce up to 5°C of the surrounding temperature (44).

B. APPENDIX B: CASE STUDY ANALYSIS

To determine the added architectural value of the techniques, case studies are analyzed per passive and active technique.

B.1. Trombe wall: Case study

In 1967, the first detached Trombe wall house was constructed in Odeillo, France, by architect Jacques Michel (Fig. A.2). The south oriented façade is almost complete composed of a Trombe wall, creating an interesting sight of a glass covered black wall.

Apart from a set of balcony doors, this architectural statement offers little visual connection to the outside. While it presents a striking appearance and supplies 70–90% of the building's heating load, the limited daylight penetration raises concerns about indoor visual comfort (20).

Fig A.2. *Jacques Michel's first Tombe wall house in Odeillo. François, M. (1967)*

Fig A.3. Floor plan *Tombe wall house in Odeillo. Source: https://jjureidini.wordpress.com/wp-content/uploads/2011/01/plan-section.jpg*

The floor plan (Fig. A.3) reveals that bedrooms are limited to small east- and west-facing windows, while main living areas, such as the living room and study, are mainly lit from the north windows. Research shows that rooms directly adjacent to the Trombe wall benefit most from the passive heating effect, while thermal performance reduces in rooms further away (20). This case illustrates the importance of carefully balancing Trombe wall placement for both thermal and visual comfort.

A more recent adaptation of the Trombe wall with additional visual and structural advantages incorporates phase change materials (PCMs). These materials store thermal energy more efficiently than conventional masonry, allowing for thinner, lighter walls, making it also applicable ideal for retrofitting (54,55). PCMs absorb and release heat during phase transitions, enhancing thermal performance, though further research is needed to optimize material selection and application (57,59).

Researchers at TU Delft have developed an innovative PCM Trombe wall using salt hydrates combined with insulating aerogel (64). The wall, shown in Fig. A.5, is extremely thin (35–40 mm) and capable of rotating to adjust its orientation throughout the day. In winter, the PCM layer faces the glass during the day and rotates toward the room at night; in summer, the orientation is reversed to facilitate cooling (Fig. A.4). Façade vents enable a natural airflow, further enhancing the performance. Simulations for various building types in the Dutch climate demonstrated heating energy savings of approximately 36%. When rotated as described, comparable cooling savings can be achieved during summer (65).

This recent development offers a promising solution to the limitations observed in the Odeillo case study, where limited access to daylight and outdoor views was a big concern. The PCM Trombe wall still provides substantial energy savings while significantly improving visual connection and natural light access.

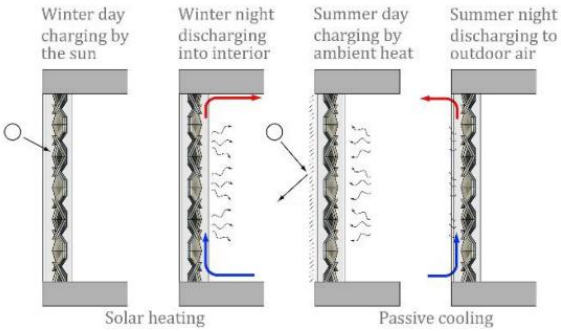


Fig A.4. Principle of the latent heat storage unit. Tenpierik et al.

Fig A.5. PCM Trombe wall. Tenpierik et al.

B.2. Sunspaces: Case study

In Drenthe, the Netherlands, a two family house is realized which utilizes a solar space on the southern side of the building. The aim of the building is to use as little energy as possible for heating and cooling and preferable be built with bio-based materials and reused components (66).
The Greenhouse building is built up by a wooden structure and straw insulation, with a 6cm layer cob (a mixture of straw, sand and soil) on the walls and 30cm layer on top of the concrete foundation. Due to the right exposure to or shading from the sun, this thermal mass provides slow heating and cooling.

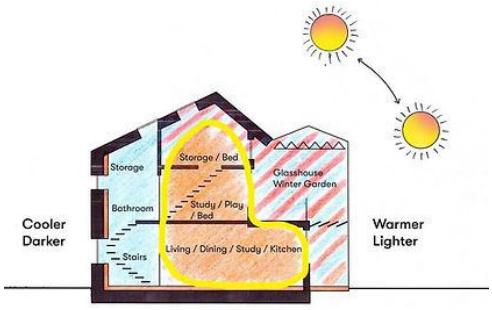


Fig A.6. *Function division in the Greenhouse according to solar heat exposure. Superuse on site (n.d.)*

Microclimates are created inside the building by grouping functions that need more or less heat. The living areas are located next to the sunspace to make the most use of the solar space, while hallways, stairs and bathrooms are located to the darker and cooling side of the building (Fig. A.6)

The solar space reduces heat loss of the southern façade since the wall and windows are protected from rain and wind by the glass. Together with individually managed curtains, the sunspace adds 2,0 m2K/W to the thermal performance of the south façade (66).

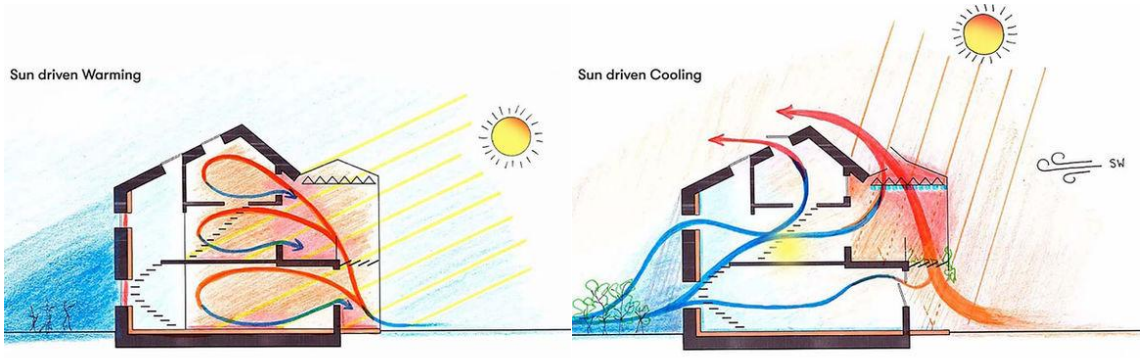


Fig A.7. *Summer and winter situation of the sunspace, showcasing the potential for both heating and cooling. Superuse on site (n.d.)*

As shown in A.7, the sunspace can provide both heating and cooling. The sun heats the air inside the greenhouse, creating a stacking effect. The heated air can either be pulled in the building for heating or exit the greenhouse by opened vents in the roof, pulling cool air in from the northside of the building.

This case study shows that, combined with the right orientation of the building, function layout of the building is essential to distribute passive heating and cooling generated by the sun space. It also shows that a solar space can contribute to the energy efficiency of a building while also providing a meaningful area for all the occupants.

B.3. Green envelope: Case study

The 2017 Kö-Bogen II is a commercial and office building located in Dusseldorf, Germany, and is currently known for its largest green façade in Europe (Fig. A.8). A total of 30.000 plants is incorporated into the buildings design, offering both an interesting architecture and very sustainable building (67). The plants, a native hardwood specie called hornbeam, improve the cities microclimates, projects against the solar radiation, stores moisture, reduces urban hear, binds CO2 and supports biodiversity. The benefits of the hedges on the ecology is similar to that of 80 full grown deciduous trees. 40% of the energy that is absorbed by the plants is converted into water vapor, creating a cooling effect around the building (68).

It is learned from this case study that a green façade and roof not only contribute to the indoor climate, keeping it cool in summer and insulated in winter, but also effect the temperature outside the building. A green oasis in the city, like Kö-Bogen, has its benefits on so much more than the building's energy savings.

Fig A.8. *Kö-Bogen II, Düsseldorf, Germany. Ingenhoven Architects (2021)*

B.4. Labyrinth thermal system: Case study

One of the most renowned building which utilizes a labyrinth thermal system is the Eastgate center in Harare, Zimbabwe. While the Eastgate building is located in a subtropical climate, projects with a similar principles can also be found in temperate climates. In London, the Davies´ Alpine House is located in Kew Gardens and cooled by a concrete labyrinth in the basement. A glass façade allows the air inside to heat up (Fig. A.9). When the temperature accelerates 18°C, vents at the bottom of the glass façade are opened and air is pulled into the building. Four low energy fans pull the air into the at night cooled labyrinth to cool the air while heated up air can leave the building via vents in the roof. An additional shading system is integrated into the building, to prevent overheating in summer due to the high amount of glass (Fig. A.10).

This case study shows that the combination of several passive systems can contribute to both an architecturally interesting and energy efficient building. The in this case combined sunspace, labyrinth thermal system and shading device create a both thermally comfortable and appealing building.

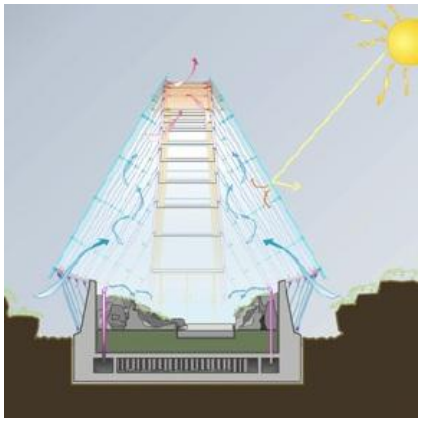


Fig A.9. *Climatic scheme of the Davies' Alpine House. Source: Environment - Davies' Alpine House (n.d.)*

Fig A.10. *Shading system of the Davies' Alpine House. Source: Environment - Davies' Alpine House (n.d.)*

A comparable system was implemented in Melbourne, Australia, where mechanical cooling was entirely avoided. The fans consumed only 10% of the energy required by a conventional cooling system (5). In addition to the labyrinth structure, the building also treats 100,000 L of sewer water daily, which is then used for air conditioning, mimicking also how some termite species regulate temperature using moisture. The water circulates through exterior tubes, cooling at night before being stored in the basement using phase change materials (PCMs). This integration of passive systems led to an estimated 85% reduction in energy use, 87% lower GHG emissions, and 70% less water consumption compared to similar buildings (69).

B.5. Algae façade: Case study

The BIQ House in Hamburg, Germany, is the world's first building to incorporate a fully integrated algae bioreactor façade. The building was part of the International Building Exhibition and accommodates 15 apartments plus a penthouse. In the design, 129 photo-bioreactors, with a dimension of 2,7x0,7x0,08m each, are placed on the southwest and southeast façade, providing 50% of the building's energy demand. Additionally, the panels provides dynamic shading and thermal insulation as the algae density increases, reducing solar heat gain and adapting to seasonal change. The panels are mounted on a steal frame, and are able to move with the path of the sun, optimizing solar gain.

Fig. A.11. *BIQ House, Hamburg, Germany. IBA Hamburg (2013)*

The required CO2 for the algae to grow is provided by the pressurized air, injected at the bottom of the panel. Where previous algae harvesting systems needed regular cleaning of the glass, this system creates air bubbles in the panel which creates turbulence that 'cleans' the glass from the inside.

The BIQ House shows how well energy saving techniques can be combined with architecture. Its algae façade system not only generates renewable energy but also serves as a dynamic shading and insulation element. This reduces the need for additional materials required for thermal regulation and solar control, showcasing a holistic approach to sustainable building.

C. APPENDIX C: ARCHITECTURAL VALUE

This chapter describes the implementation of the techniques in the test design in Binckhorst The Hague. After evaluating the techniques separately, the techniques are tested on their visual comfort, spatial experience, and social value added to the area. Lastly, a ranking is made of the architectural value of the different techniques.

C.1. Orientation, fenestration and shading: Application in the test design

The architectural form layer, consisting of orientation, form, fenestration and shading, is integrated in the test design to evaluate its architectural value. The architectural integration of these techniques into the test building is based on the research mentioned of this paper and climatic conditions of the Binckhorst area.

The rectangular shape is applied, oriented towards the south-south-east (Fig. A.12). The building is designed to achieve energy savings of up to 36%.

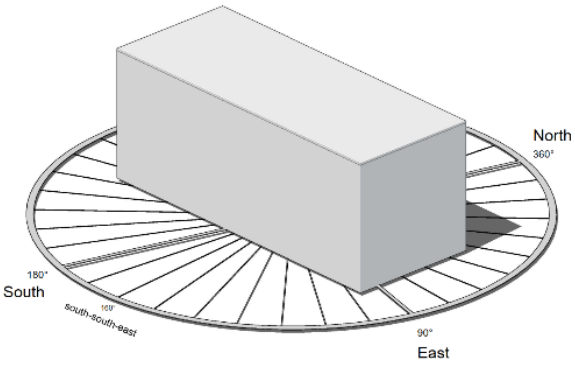


Fig A.12. Application of the ideal form and orientation on the test design . *Author's work (2025)*

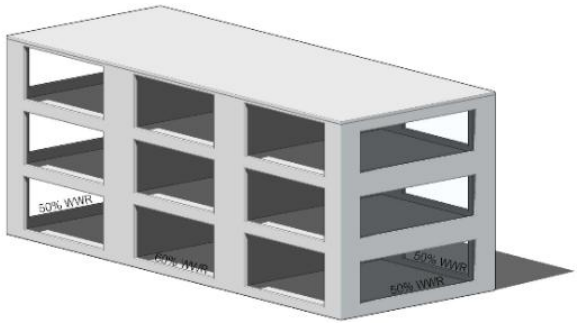


Fig A.13. Application of the ideal WWR on the test design . *Author's work (2025)*

The fenestration design is based on the research stating the optimal Window-to-Wall Ratio (WWR) for buildings in the Netherlands: 50-70% for north-facing facades, 60% for south-facing facades, and 50-60% for east and west-facing facades. As illustrated in Fig. A.13, the building incorporates a 50% WWR on the north, west, and east facades, and a 60% WWR on the south facade.

Additionally, the south side of the building is equipped with overhang shading. These overhangs, which are 1300mm deep, maintain a visual connection to the outdoors while protecting the interior from solar radiation during the summer months, while allowing for solar gain in winter (Fig. 14). This solar shading strategy is capable of reducing annual energy consumption by up to 19%.

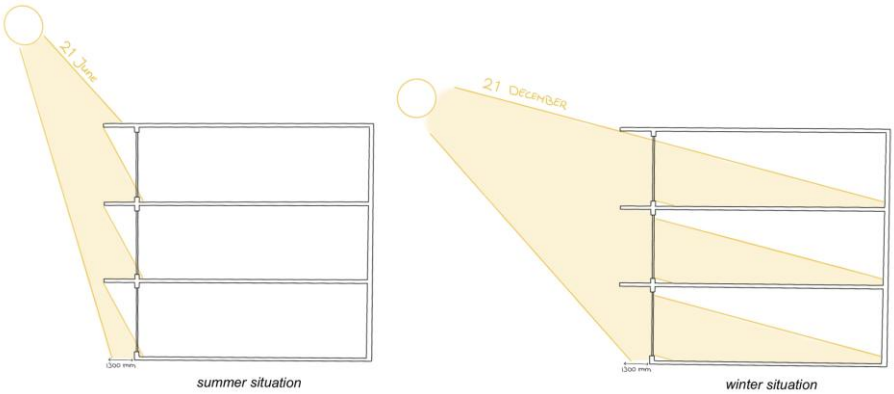


Fig A.14. Application of overhang shading on the test design building. *Author's work (2025)*

C.2. Trombe wall: Application in the test design

To investigate both the architectural integration and performance of the Trombe wall, the technique is applied in the test design. Based on the insights gained from the Odeillo case, where limited daylight and visual connection were concerns, the Trombe wall is only applied to parts of the façade to maintain visual comfort (Fig. A.16). While the PCM Trombe wall shows strong potential, the composite wall is selected for this study due to its simplified design and proven performance.

Research by Abbassi et al. (61) showed that the increase of area Trombe wall increases the energy efficiency. They noted that this area is of course limited to the south area available to place the Trombe wall. Additionally, Jaber et al. (70) researched the most efficient wall ratio to use. Fig A.15 shows that the energy savings keep a nearly steady value after a 37% ratio is acquired. Both researches were conducted for a Mediterranean climate.

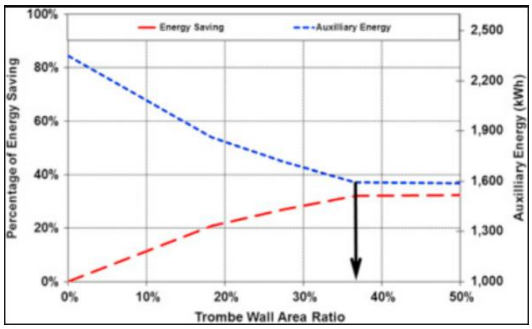


Fig A.15. Energy efficiency vs Trombe wall ratio. Abassi et al. *(2014)*

Comparing these values to the test design with 9 apartments with each a 8x3 = 24m2 south-facing façade, this means a 0,37*24m2 = 8,88m2. Together with the research by Abbassi et al., a 10m2 Trombe wall was chosen for the test design. Abbassi et al. (61) conducted a research with a 8m2 Trombe wall for a 16m2 floor area. In the test building, a hypothetical 20 m² living room is assumed, justifying the proportions for the Trombe wall. Assuming similar performance to Abbassi et al.'s study, with 77% energy savings for the area with the Trombe wall, and considering that this system covers 40% of each apartment's floor area, the total energy reduction for the building is estimated at approximately 30% (77%*0.4), assuming no additional passive strategies are applied.

From an architectural standpoint, additional windows are required to ensure sufficient daylight and visual comfort. Fig. A17 shows three design options: placing the Trombe wall on the left or right side of the façade (top options) provides better daylight distribution than the central placement (bottom). Placing the Trombe wall in the middle of the façade can be beneficial depending on the function of the room but is for a living room not recommended.

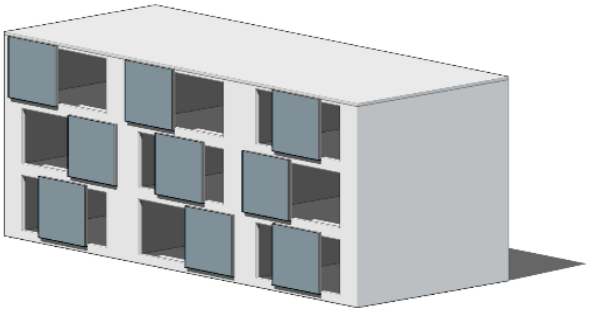


Fig A.16. Application of the composite Trombe wall on the test design . *Author's work (2025)*

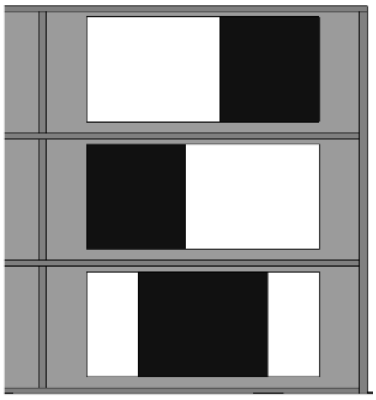


Fig A.17. Different placement options of the Trombe wall on the test design (right, left, and central). *Author's work (2025)*

C.3. Sunspaces: Application in the test design

Both the glazed balcony and sunspace are reviewed on their efficiency and architectural integration when applied in the test design.

Looking at the glazed balconies, each apartment has a balcony of 1,5m deep extended over the length (5m) of the apartment (Fig. A.18). The earlier mentioned researches (34,35) concluded that the ideal depth for a sunspace would be 150cm. Based on this research and to give the occupant a reasonable outdoor space, this same depth is applied. The efficiency of the glazed was concluded to be able to reach 30% of energy savings and the ability to preheat the air in the glazed area 5 to 10°C. When viewing the glazed balcony from an architectural point of view, it does provide less visual comfort than without the implementation of the balcony. While the 1,5m overhang does provide good shading for the indoors (Fig. A.19), less natural light enters the room which can be seen as a disadvantage.

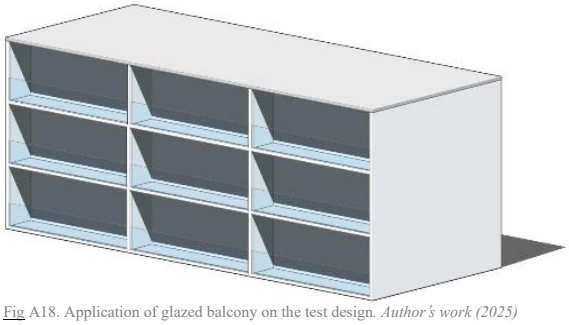


Fig A18. Application of glazed balcony on the test design. *Author's work (2025)*

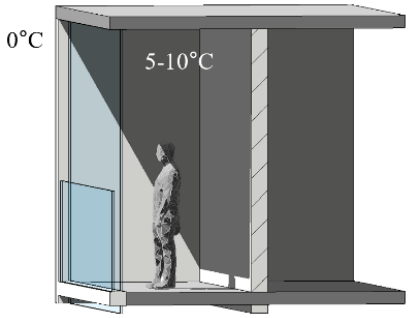


Fig A.19. Architectural integration of the glazed balcony. *Author's work (2025)*

Besides the glazed balcony, the sunspace covering the whole south façade is also analyzed (Fig. A.20). The same depth of 1,5m for the sunspace is applied, resulting in 36% energy savings according to (35). The sunspace in this case is however ventilated, creating a comfortable situation in both winter and summer.

From an architectural perspective, the sunspace appears to be somewhat small (Fig. A.21) While a depth of 1,5m is sufficient for a glazed balcony, it is relatively limited for a joined outdoor area. The Greenhouse, Drenthe, case study also shows the benefits of a larger sunspace, where it can truly be utilized as an addition to the living area. Further research will need to be done to determine the right dimensions for both energy efficiency and functionality when applied in the test building.

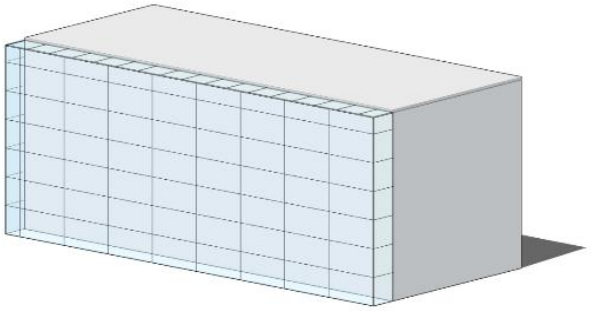


Fig A.20. Application of the sunspace on the test design. *Author's work (2025)*

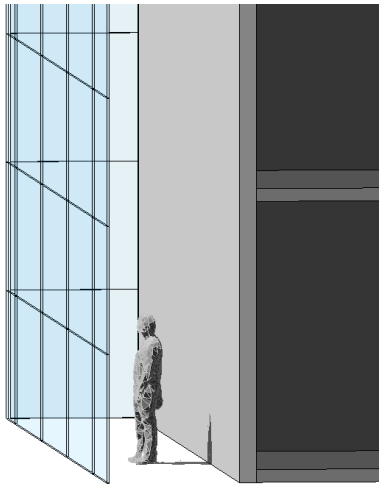


Fig A.21. Architectural integration of the sunspace. *Author's work (2025)*

C.4. Green envelope: Application in the test design

Both cooling techniques, a green envelope and tree shading, are applied in the test design. Orientation and seasonal are important factors, particularly for deciduous trees. Based on previous studies, the building is oriented south-southwest with a 60% WWR on the south facade.

As shown in Fig. A.22, green roofs and façades are integrated into the design. In temperate climates, these strategies can reduce annual energy use by 6-20%. While visually engaging, it should be noted that this integration limit other facade integrations architecturally.

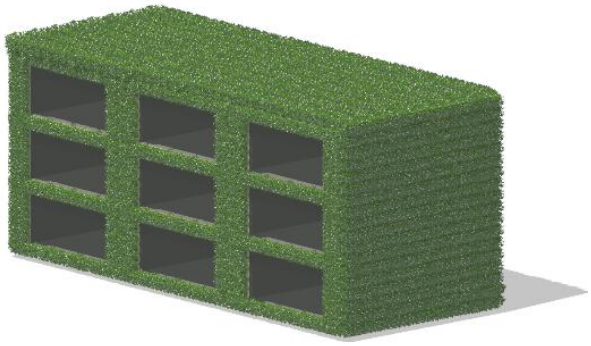


Fig A.22. Application of a green roof and façade the test design. *Author's work (2025)*

Fig. A.23 also illustrates how a 16 m tall deciduous tree, positioned from the stem 6.7 m from the façade, shades the building from the high summer sun while allowing solar access in winter. In line with previous studies, the combination of green surfaces and insulation can cut cooling demand by up to 19%, while shading and evapotranspiration can lower surrounding air temperatures by up to 5°C. It should be taken into account that the integration of close-by trees can reduce visual comfort and natural light penetration in summer, which can be seen as a disadvantage.

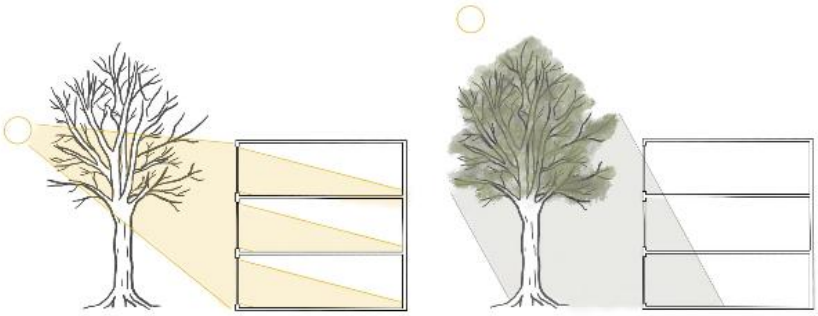


Fig A.23. Summer and winter situation with the integration of deciduous trees. *Author's work (2025)*

C.5. Labyrinth thermal system: Application in the test design

To integrate the labyrinth thermal system in the test building, a basement must be incorporated into the design. As illustrated in Fig. A.24, an exploded view shows the system's layout within the foundation. 200mm thick concrete walls, having a high thermal mass, are positioned approximately one meter apart to form the labyrinth. Air is driven through the system by low-energy vents. Based on the performance of comparable case studies, this setup is expected to reduce annual energy consumption by around 31%. Because the labyrinth is located underground, it does not affect the building's architectural appearance.

Other passive strategies, such as a sunspace, can support the system's operation by contributing to natural airflow and preheating the intake air.

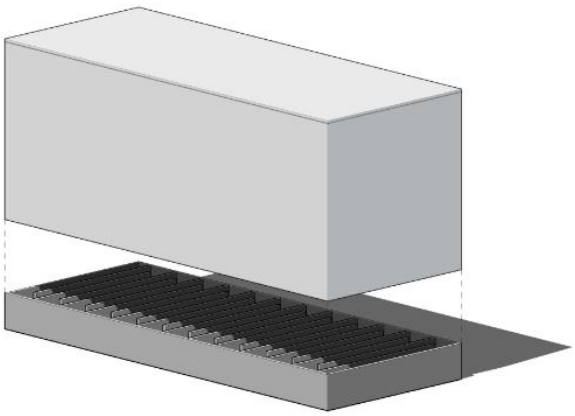


Fig A.24. *Application of a labyrinth cooling system in test design. Author's work (2025)*

C.6. Algae facade: Application in the test design

The photo-bioreactor panels are incorporated in the test design to view their efficiency and architectural integration. The BIQ House is taken as reference for the implantation of the façade panels, where 129 panels are used for a gross floor area of 1600m2. Converted to the test design, with a floor area of 750m2, this makes for a total of 60 panels. Again the dimensions of 2,7x0,7x0,08m are used for the panels, with each time 5 panels abreast. The panels are estimated to deliver 50% reduction on the annual energy consumption.

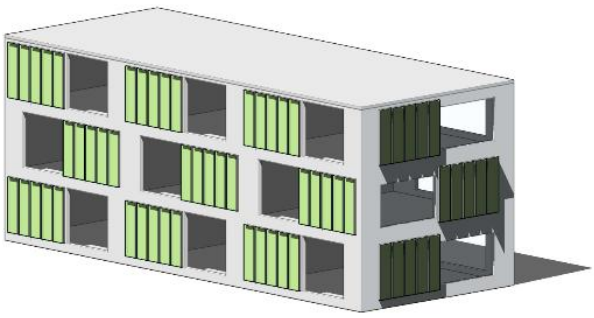
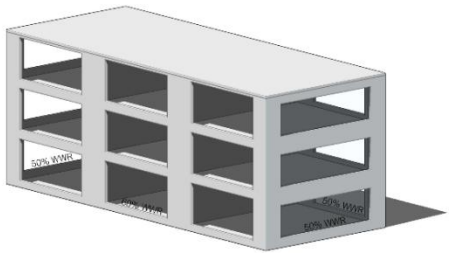
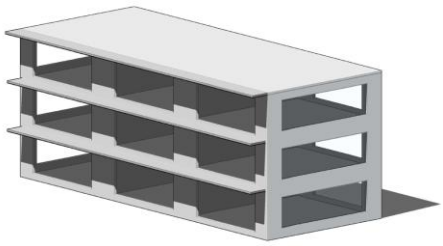
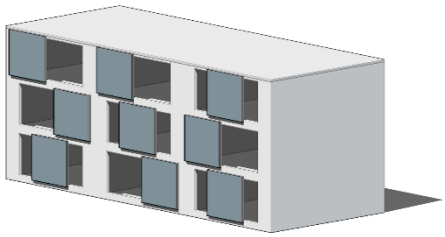
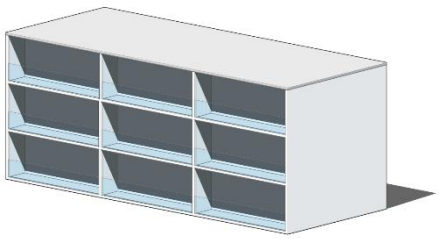
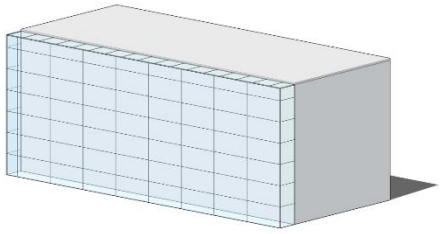


Fig A.25. *Application of an algae façade in the test design. Author's work (2025)*

C.2.1. Testing of the architectural value

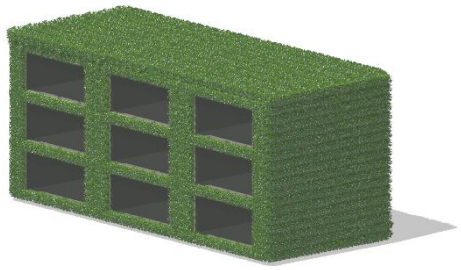
The techniques are reviewed based on three architectural parameters: visual comfort for residents, spatial experience and social value for the area. The findings are based on the research by design done in the test building and on the conclusions of the analyzed case studies.

Form and orientation Visual comfort The use of a rectangular shapes performs better for functional spaces along the building's perimeter. Since the longitude facade is oriented towards the south, a higher percentage floor area makes optimal use of solar path. Spatial comfort The right form and orientation enhances routing in the area and the experience of the building. Social value Placing the most inviting facade (south) stretched out over the plot, room for social gathering is formed. 	**Fenestration** Visual comfort The 60% facade openings to the south create maximal daylight penetration for the residents. Spatial comfort Due to the large window opening on all facades, the apartments are expected to feel spacious. However, the layout of the apartments is viewed as more of a challenge if the high amount of wall openings is to be kept. Social value The amount of fenestration is not viewed as a social contributor to the area. The building can however be viewed as inviting due to the amount of openness. 
Shading Visual comfort The overhangs can create a reduced visual comfort in summer, since the shading also reduces daylight, creating a more shaded interior. Spatial comfort When the overhangs, as applied currently in the test design, are also utilized as outdoor space it could enhance the spatial comfort of the	**Trombe wall** Visual comfort As seen in the case study of Trombe wall house in Odeillo, does the Trombe wall in itself not contribute to visual comfort. Additional windows have to be places, as done in the test design, to create a comfortable indoor space. Spatial comfort The Trombe walls in itself do not contribute to spatial comfort.

building. If kept only as sun shading, it does not. Social value The shading does not contribute to social values of the area. 	Social value As shown in the Odeillo case study, the Trombe wall can be seen as an architectural statement and in that case also as statement for the area. 
Glazed balconies Visual comfort The glazed balconies provide enough light for the interior, yet even as the overhang shading it reduces direct daylight penetration, especially in summer. Spatial comfort The balconies provide an extra space for the residents to be outside, even comfortably during winter, enhancing the spatial comfort. Social value The glazed balconies in itself do not provide extra social value for the area. 	**Sunspace** Visual comfort The sunspace provide enough light for the interior, yet it reduces direct daylight, especially in summer. Spatial comfort The sunspace can be utilized as extra outdoor space for the residents, even comfortably during winter, enhancing the spatial comfort. Social value The sunspace can be utilized not only for the residents but also created as social space for residents or visitors of the area. 
Green envelope Visual comfort The green envelope does not hinder the visual comfort for residents. Spatial comfort The green facade in itself does not contribute to the spatial comfort of the building.	**Shading with trees** Visual comfort The trees can create a reduced visual comfort in summer, since the shading also reduces daylight, creating a more shaded interior. Yet, greenery also enhances people's perception of the area and visual comfort.

<table>
<tr>
<td>Social value

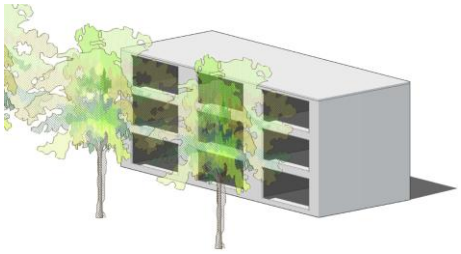
As seen in the Kö-Bogen case study, do green building surfaces contribute significantly to the area. The green surfaces create a natural cooling effect and comfortable humidity of the air.

  </td>
<td>Spatial comfort

The trees in itself does not contribute to the spatial comfort of the building.

Social value

Not only do the trees contribute to a natural cooling effect, greenery also enhances social gathering in an area.

  </td>
</tr>
<tr>
<td>Labyrinth thermal system

Visual comfort

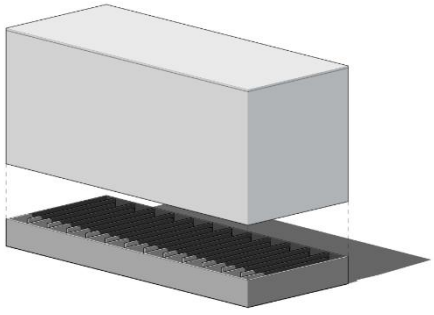
The labyrinth thermal system is applied in the interior of the building, so it does not hinder visual comfort.

Spatial comfort

The labyrinth thermal system does not affect spatial comfort.

Social value

The labyrinth thermal system does not contribute to social values of the area.

  </td>
<td>Algae facade

Visual comfort

As seen in the BIQ House case study, can an algae facade also function as shading system. The algae density can be adjusted to create less or more solar penetration, enhancing visual comfort.

Spatial comfort

The algae facade does not affect spatial comfort.

Social value

The algae facade can be seen as an architectural statement, as seen in the BIQ House. This interesting attribution to the design can enhances the surrounding area, creating a signature piece architecture.

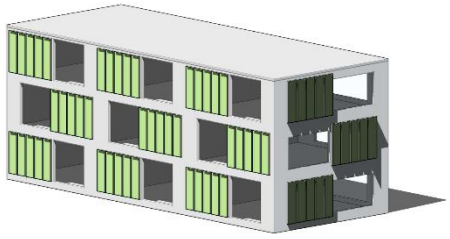
  </td>
</tr>
</table>

Table. A.1. Architectural value of the passive and bio-inspired techniques. *Author's work (2025)*

C.2.2. Ranking of the architectural value

Based on the architectural value determined in the table above, the following ranking is made. For each system, three scores are assigned, 1 being the lowest and 3 the highest. The scores are based on the following requirements:

	Visual comfort	Spatial comfort	Social value
SCORE 1	Obstructs visual comfort	No contribution to spatial comfort	Adds no social value
SCORE 2	Obstructs partly visual comfort	Contributes to some spatial comfort	Adds some social value
SCORE 3	Obstructs no visual comfort	Enhances spatial experience	Enhances the social value

	Technique	Visual comfort	Spatial comfort	Social value	Total score*
ARCHITECTURAL FORM	Form & orientation	3	3	2	8
	Fenestration	3	2	1	6
	Envelope shading	2	2	1	4
PASSIVE SYSTEMS	Trombe wall	1	1	2	4
	Glazed balconies	2	3	1	6
	Sunspace	2	3	3	8
	Green envelope	1	1	3	5
	Tree shading	2	1	3	6
	Labyrinth thermal system	3	1	1	5
ACTIVE SYSTEMS	Algae façade	2	1	3	6
	*total score: 3-4 = less good; 5-6 = ok; 7-9 = good.				

Table. A.2. Ranking of the architectural value. *Author's work (2025)*

The ranking shows that the form & orientation and sunspace score the best on architectural added value. However, it should be noted that fenestration, glazed balconies, tree shading and an algae facade still provide well scoring values. This ranking can be used for architects and engineers to make well considered choice architecturally when implementing these techniques to the design.

D. APPENDIX D: CARBON FOOTPRINT

Passive techniques are often implemented to reduce energy demand and, consequently, greenhouse gas emissions. However, the environmental impact of extracting and processing materials required for these systems is not always addressed. To better understand the actual sustainability of the discussed strategies, the material use required for their realization is analyzed. This chapter analyzes the embodied carbon for each of the researched techniques after which they are compared to each other. The carbon footprint is firstly calculated for the entire system after which it is converted to the kg CO2 per supplementary area needed to implement the technique in the design. Based on both the efficiency and carbon footprint of the technique, a ranking is made.

The material use and amounts is based on rough estimates, due to time and data limits. The given values are based on the Construction Material Pyramid from CINARK and LCA sources, yet the results should only be taken as a guiding reference. More specific calculations are needed to draw clear conclusions from the carbon footprint of the researched techniques.

D.1.1. Carbon footprint: Shading

Of the architectural form techniques applied in the test design, only the shading system requires additional material compared to the standard design of the building. The overhangs, each 1.3 m wide and 25 m long, add a total of 32.5 m2 per floor. Assuming a floor thickness of 200 mm made from cross-laminated timber (CLT), the additional material volume has a total of 19,5 m3 ((32,5m2*3)*0,2m). Based on the Construction Material Pyramid from CINARK (71), this application results in a reduced environmental footprint, with an estimated saving of -12.948kg CO2 eq.

	material	group	impact / m3	volume [m3]		area [m2]		thickness [mm]		result
1	Glulam and cross-laminated-timber CLT	trae	-664.0 kg CO2eq/m3	19,50	m3	97,5	m2	200	mm	-12.948,0 kg $CO_{2\ eq}$

Table A.3. *Carbon footprint results of CLT based on the Construction Material Pyramid.* CINARK (2024).

D.1.2. Carbon footprint: Trombe wall

Stazi et al. (72) studied different material configurations for Trombe walls, comparing traditional setups with optimized alternatives. Their research showed that replacing a conventional 40 cm thick concrete wall with a 20 cm aerated concrete wall and double glazing could reduce CO2 emissions by 55%, while maintaining energy performance. Similarly, Ji et al. (73) used a 50 mm insulation board with an Rc-value of 1,4 m2K/W to achieve an efficient Trombe wall setup.
In the test design, each apartment includes a 10m2 Trombe wall, resulting in a total of 90m2 across the project. To reduce environmental impact, the design uses a 20 cm aerated concrete wall for thermal mass, combined with double glazing and a 53 mm wood fibre insulation board to achieve the required Rc-value of 1,4 m2K/W. Additional vents are not included in this analysis, as their dimensions and material use depend on more detailed calculations yet to be made. Based on the Construction Material Pyramid (71), the total CO2 emissions for the Trombe walls are estimated at approximately 8.053kg CO2 eq.

show result in pyramid ↑	reset calculation	type project name	m^2	

	material	group	impact / m3	volume [m3]		area [m2]		thickness [mm]		result
1	Glass pane, double-glazed	komponenter	4580.0 kg CO2eq/m3	1,80	m3	90	m2	20	mm	8.244,0 kg $CO_{2\ eq}$
2	Aerated concrete blocks	mineralsk	5.6 kg CO2eq/m3	18,00	m3	90	m2	200	mm	100,8 kg $CO_{2\ eq}$
3	Wood fibre insulation	biobaseret	-61.1 kg CO2eq/m3	4,77	m3	90	m2	53	mm	-291,4 kg $CO_{2\ eq}$

Table A.4. *Carbon footprint results of Trombe wall based on the Construction Material Pyramid.* CINARK (2024).

D.1.3. Carbon footprint: Glazed balcony

The main additional material used in sunspaces is glass. In the case of glazed balconies, additional structural materials are often unnecessary, as the balcony is typically already integrated into the architectural design. However, a full greenhouse-style sunspace requires extra support, commonly steel profiles, to carry the load of the extensive glazing.

In the test design, each glazed balcony includes 24m2 of double glazing, resulting in a total of 216 m2 across the project. Double glazing is chosen for its improved thermal performance, reducing heating and cooling demand (22). The associated CO2 emissions for this glass is approximately 19.786 kg CO2 eq (71).

show result in pyramid ↑ | reset calculation | type project name | m^2

	material	group	impact / m3	volume [m3]	area [m2]	thickness [mm]	result
1	Glass pane, double-glazed	komponenter	4580 kg $CO_{2\ eq}$/m3	4,32 m3	216 m2	20 mm	19.785,6 kg $CO_{2\ eq}$
							19.785,6 kg $CO_{2\ eq}$

Table A.5. *Carbon footprint results of glazed balconies based on the Construction Material Pyramid.* CINARK (2024).

D.1.4. Carbon footprint: Sunspace

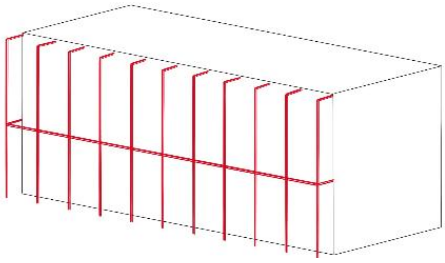


Fig A.26. Sunspace structure. *Author's work (2025)*

The sun space integrated in the test design include three glazed facades and a glass roof, covering a total of 317,5 m2. To support this structure, a steel frame is required. The Greenhouse building by Superuse is used as a reference, as it shares similar dimensions and structural layout. Two steel profiles of 40x80x2,5 (74) are combined (with a total cross-section area of 0,002m2) are used, to simplify the calculation, for the whole structure. Based on the structural arrangement (Fig. A.26), a total length of 174,5m of steel is estimated, resulting in a volume of 0,35m3. When combining the steel structure with the glass surfaces, the total CO2 emissions are estimated at approximately 36.240 kg CO2 eq (71).

show result in pyramid ↑ | reset calculation | type project name | m^2

	material	group	impact / m3	volume [m3]	area [m2]	thickness [mm]	result
1	Glass pane, double-glazed	komponenter	4580 kg $CO_{2\ eq}$/m3	7,50 m3	375 m2	20 mm	34.350,0 kg $CO_{2\ eq}$
2	Structural steel	metal	5400 kg $CO_{2\ eq}$/m3	0,35 m3	m2	mm	1.891,1 kg $CO_{2\ eq}$
							36.241,1 kg $CO_{2\ eq}$

Table A.6. *Carbon footprint results of the sunspace based on the Construction Material Pyramid.* CINARK (2024).

D.1.5. Carbon footprint: Vegetation

Since green envelopes consist of complete systems, including structural framing, irrigation, planting medium, and vegetation, the environmental impact is assessed based on the system as a whole. A life cycle assessment (LCA) conducted by Reyhani (75) compared various green facade systems. The most sustainable option was found to be a modular panel system, where plants (Pteropsida) grow in embedded pockets without soil. Water and nutrients are delivered via an integrated irrigation system, supported by a panel and frame structure. The study also accounted for the carbon uptake and payback over time. The climate change impact of this system was estimated at -40,39 kg CO2/m1.

Applied to the test design, with approximately 800m2 of facade area covered in greenery, this results in a total estimated reduction of -32.310 kg CO2 eq.

While trees are not manufactured building elements, their environmental contribution can still be analyzed. A Dutch study on carbon sequestration found that 1 hectare of European beech trees stores approximately 8,6 tons of CO2 annually, with about 100 trees per hectare and an average lifespan of 95 years (76). This translates to a total storage capacity of -8.170 kg CO2 per tree over its lifetime. In the test design, three mature beeches are integrated on site, resulting in a combined CO2 reduction of -

24.510 kg. Although soil and surrounding vegetation may also contribute to carbon uptake, these effects are not included in the current calculation.

D.1.6. Carbon footprint: Labyrinth thermal system

To assess the environmental impact of the labyrinth thermal system in the test design, only the thermal mass walls within the underground structure are considered. Mechanical components such as vents and air distribution systems are excluded from this calculation, as are the outer walls of the labyrinth, which are assumed to overlap with the building's foundation.

The labyrinth consists of 24 concrete walls, each with a volume of 5,16 m3, resulting in a total of 123,84 m3 of concrete. Based on the Construction Material Pyramid (71), this corresponds to an embodied carbon impact of approximately 26.626 kg CO2 eq.

show result in pyramid ↑	reset calculation	type project name		m^2					
	material	group	impact / m3	volume [m3]		area [m2]		thickness [mm]	result
1	Concrete C20/25	mineralsk	215.0 kg CO2eq/m3	123,84	m3	619,2	m2	200 mm	26.625,6 kg $CO_{2\ eq}$

Table A.7. *Carbon footprint results of labyrinth thermal system based on the Construction Material Pyramid.* CINARK (2024).

D.1.7. Carbon footprint: Algae facade

An algae façade system consists of numerous components, glass panels, framing, rubbers, pumps, piping, and cleaning agents, among others. In a life cycle assessment study, Mata et al. (77) investigated both the embodied and operational carbon footprint of photo-bioreactor systems. They reported that the construction materials account for 1,72 kg CO2 per kg of biomass produced, while the operational phase, including the biological CO2 fixation by the algae, results in an impact of 66,4 kg CO2 per kg biomass. In the calculation, electricity used during operation is included but excludes the embodied emissions of equipment like pumps and heat exchangers.

To estimate the impact of integrating an algae facade in the test design, biomass production must first be defined. Using the BIQ House as a reference, Roedel & Petersen (47) reported an annual production of 900 kg of biomass from 129 façade panels. Applying this ratio to the 60 panels for the test design, this results to approximately 420 kg of biomass. Based on the total carbon footprint of (1,72+66,4) 68,34 kg CO2/kg biomass, the algae façade contributes approximately to 28.703 kg CO2 per year.

D.2. Carbon footprint per supplementary area

To fairly compare the techniques to each other, the total embodied carbon is divided by the area needed by the technique. These numbers are based on the implementation of the techniques in the test design. Because of this, the CO2 per supplementary area could differ when applied on a different project. The given values can be used as guidance techniques but should be recalculated for each individual case.

Following supplementary areas are determined per used technique.

Envelope shading	total of 113m2 additional floor area
Trombe wall	total of 90m2 Trombe wall
Glazed balconies	total of 216m2 of glazing
Sunspace	total of 375m2 of surface area of the sunspace
Tree shading	the trees provide shading for 250m2 of the facade
Labyrinth thermal system	total floor area of 250m2 needed
Algae facade	total of 113m2 bio-photoreactor panels

The kg CO2 per m2 are as followed:

Technique	*Total embodied carbon (kg CO2)*	*Supplementary area (m2)*	*kg CO2 / m2*
Envelope shading	-12.948	113	-114,58
Trombe wall	8.053	90	89,48
Glazed balconies	19.786	216	91,60
Sunspace	36.240	375	96,64
Green envelope	-32.310	800	-40,39
Tree shading	-24.510	250*	-98,04
Labyrinth thermal system	26.626	250	106,50
Algae facade	28.703	113	254,01
*m2 based on the area south facade the trees provide shading for.			

Table. A.8. Carbon footprint per m2 per technique. *Author's work (2025)*

D.3. Efficiency per techniques

The efficiency of the techniques are based on the literary research done in this paper and design implementation in the test design. The calculations can be found in appendix C.1. Following table shows the efficiency per technique:

Technique	*Efficiency (%)*
Form & orientation	36
Envelope shading	19
Trombe wall	30
Glazed balconies	30
Sunspace	36
Green envelope	20
Tree shading	19
Labyrinth thermal system	31
Algae facade	50

Table. A.9. Efficiency per technique. *Author's work (2025)*

D.4. Ranking of the carbon footprint

Based on the CO2/m2 determined in the table above, the following ranking is made. For each system, two scores are assigned, 1 being the lowest and 3 the highest. Both carbon footprint and energy efficiency are part of the ranking to compare the embodied carbon produced to the energy savings it can provide. The ranking shows the best scoring for form & fenestration and the sunspace, yet none scores lower than a 4, meaning the carbon footprints are quite in balance with the saved energy.

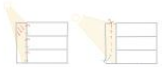
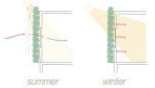
	kg CO2/m2	**Energy efficiency**
SCORE 1	>100	0 – 20%
SCORE 2	0 – 100	21-30%
SCORE 3	< 0	> 30%

	Technique	Embodied carbon	Energy efficiency	Total score*
ARCHITECTURAL FORM	Form & orientation	3	3	6
	Fenestration	3	1	4
	Envelope shading	3	1	4
PASSIVE SYSTEMS	Trombe wall	2	2	4
	Glazed balconies	2	2	4
	Sunspace	2	3	5
	Green envelope	3	1	4
	Tree shading	3	1	4
	Labyrinth thermal system	1	3	4
ACTIVE SYSTEMS	Algae façade	1	3	4

*total score: 2 = less good; 3-4 = ok; 5-6 = good.

Table. A.10. Ranking of the carbon footprint vs energy efficiency. *Author's work (2025)*

ARCHITECTURAL FORM | PASSIVE TECHNIQUES | ACTIVE TECHNIQUES

	Shape and Orientation	Fenestration	Envelope shading	Sunspace	Shading with trees	Glazed balconies	Green envelope	Labyrinth thermal system	Trombe wall	Algae facade
Technical working	 building form	summer winter	 summer winter	 summer winter	 summer winter	 summer winter	 summer winter	 summer winter	 summer winter	 summer winter
Architectural added value	Visual comfort • optimal use of solar path Spatial comfort • enhances routing and area experience Social value • can create room for social gathering **8**	Visual comfort • maximum daylight penetration Spatial comfort • potential layout difficulties due to large wall openings Social value • no added social value **6**	Visual comfort • reduced visual comfort in summer Spatial comfort • overhangs pose potential for additional outdoor space Social value • no added social value **4**	Visual comfort • reduces direct sunlight, especially in summer Spatial comfort • can be utilized as extra outdoor space, even in winter Social value • creates a social space for residents and visitors of the area **8**	Visual comfort • reduced visual comfort in summer Spatial comfort • no added spatial comfort Social value • enhances natural cooling of the area and creates potential for social gathering **6**	Visual comfort • reduces direct sunlight, especially in summer Spatial comfort • can be utilized as extra outdoor space, even in winter Social value • no added social value **6**	Visual comfort • no added visual comfort Spatial comfort • no added spatial comfort Social value • creates a natural cooling effect and humidity balance in the area **5**	Visual comfort • the system is applied in the basement so no visual comfort is hindered Spatial comfort • no added spatial comfort Social value • no added social value **5**	Visual comfort • the system obstructs daylight penetration Spatial comfort • no added spatial comfort Social value • can be seen as architectural statement **4**	Visual comfort • the algae panels can be used as adaptable shading systems Spatial comfort • no added spatial comfort Social value • can be seen as architectural statement and signiture piece of an area **6**
Carbon footprint	0,00 kg CO2/m2 / 36% energy reduction **6**	0,00 kg CO2/m2 / 0% energy reduction **4**	-114,58 kg CO2/m2 / 19% energy reduction **4**	96,64 kg CO2/m2 / 36% energy reduction **5**	-98,04 kg CO2/m2 / 19% energy reduction **4**	91,60 kg CO2/m2 / 30% energy reduction **4**	-40,39 kg CO2/m2 / 20% energy reduction **4**	106,50 kg CO2/m2 / 31% energy reduction **4**	89,48 kg CO2/m2 / 30% energy reduction **4**	254,01 kg CO2/m2 / 50% energy reduction **4**