Bioclimatic performance of two different building envelopes in a cold/temperate climate

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ABSTRACT: Adaptation and mitigation for climate change are fundamental to ensure a viable future, both for the planet and for the people. More specifically, increasing sustainability in the built environment would have a significant effect in this direction. In addition, the wellbeing of all occupants could be enhanced by paying special care to indoor environmental quality. Increasing the use of passive strategies could in turn promote energy and resource efficiency, thus reducing operational costs and improving comfort. In this line, high-performance building envelopes tend to focus on insulation and airtightness, but could also provide thermal mass and moisture buffering at their inner surface. By storing excess heat and moisture, they can stabilise indoor temperature and relative humidity, restricting their daily and seasonal variability. This article investigates therefore the effect of two different envelope solutions, in relation to the hygrothermal behaviour of an office building in a cold/temperate climate. Following this, a comparison is made between a typical layered configuration with conventional insulation and an innovative one that includes also thermal mass and moisture buffering. Then, the hygrothermal performance of the two envelopes is simulated using EnergyPlus with DesignBuilder. Next, the analysis is divided into two parts. The first one examines the resulting indoor climate under normal operation with occupants, to show its psychrometric and dynamic behaviour. The second one is restricted to a fully passive operation, to explore its thermal autonomy, resilience and habitability. The objective of this work is to study the effect of different envelope materialities on the bioclimatic performance of the building. This can in turn reflect its energy efficiency, thermal comfort and thermal safety. The consequent increase in thrivability, resilience and sustainability may produce a more ethical architecture, with higher respect both for the user and for the environment.

KEYWORDS: passive strategies; thermal comfort; building performance simulation; hygrothermal buffering; thermal resilience.

1. INTRODUCTION

High-performance building envelopes tend to focus on insulation and airtightness, in combination with active mechanical systems, to provide comfort. However, this energy-intensive approach to space conditioning may lack robustness in case of extreme climatic events or power outages. This possible weakness may be counteracted by adding thermal mass and moisture buffering at their inner surface. The passive storage of excess heat and moisture may contribute then to stabilising indoor temperature and relative humidity, thus restricting their daily and seasonal variability. This could then help keeping comfortable conditions after a power failure or save energy under normal operation.

The objective of this work is to explore the effect of different envelope materialities (heavyweight vs. lightweight) on the bioclimatic performance of the building. This can in turn reflect its energy efficiency, thermal comfort and thermal safety. The consequent increase in thrivability, resilience and sustainability may produce a more ethical architecture, with higher respect both for the user and for the environment.

2. METHODS

The case analysed in this study is *Baumschlager-Eberle 22/26*, an office building in Lustenau (Austria) with automated natural ventilation, instead of a conventional mechanical ventilation system. It was chosen because of being a rather extreme example of passive design optimisation for cold climates, resulting in very stable indoor conditions throughout the year.

Within the building, we focused on the office on the *southeast corner* of the second floor. Being an intermediate floor, its interaction with the outdoor climate is limited to the façade. Then, the southeast orientation is the most critical for the warm season, with the highest solar radiation during working hours. It is therefore the one with the highest potential for the implementation of passive cooling strategies.

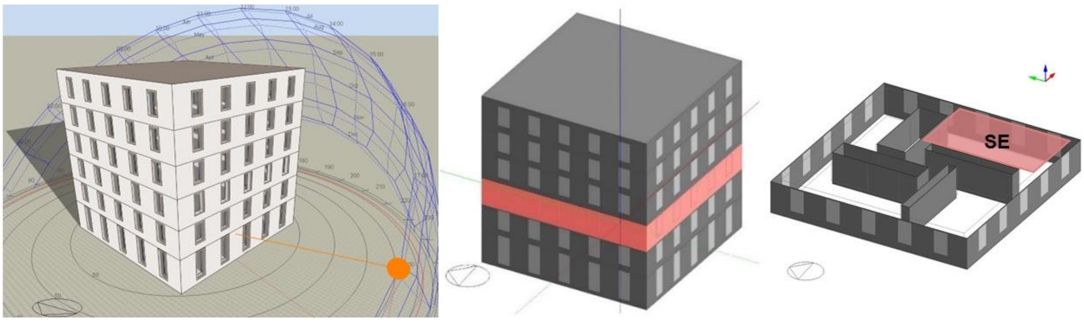

Figure 1. The whole building was modelled in DesignBuilder, but the analysis was focused on the southeast office on the second floor. Images from DesignBuilder.

The *energy concept* of the building is referred to as “Concept 22/26” (Eberle and Aicher 2016). Its objective is to keep room temperatures throughout the year between 22 and 26°C, to achieve a comfortable indoor environment while minimising the use of resources (materials, space, energy). To do so, the building has a high-performance envelope, very airtight and insulating. Moreover, the mechanical HVAC system was replaced by a building automation system that operates window opening for natural ventilation (fresh air and cooling), in combination with a lighting system for backup heating (to complement internal and solar gains). Indoor temperature, relative humidity and CO2 concentration are measured by sensors in every office, to ensure user comfort (Junghans and Widerin 2017).

However, the model used in this exercise will not include the automated controls, using the same *operational schedules* for both solutions to ensure comparability. If the automation system was active, it would regulate window opening and lighting to achieve comfort, regardless of the diverse contribution of the envelope. There would be then a difference in the operation of building systems to compensate for disparities in fabric behaviour.

		heavyweight	lightweight
wall	U-value (W/m2 K)	0.13	0.13
	Internal heat capacity (KJ/m2 K)	*85.76*	*17.26*
	Infiltration rate (ac/h)	0.037	0.037
window	U-value (W/m2 K)	0.7	0.7
	Solar transmittance factor (SHGC)	0.55	0.55

Table 1. Main characteristics of the original heavyweight building envelope (Junghans and Widerin 2017) and the alternative lightweight best practice (DesignBuilder). The only parameter that differs is its internal heat capacity, significantly reduced in comparison to the original solution.

In this paper, the original heavyweight envelope is compared to a best-practice lightweight solution for Austria, provided by DesignBuilder. This allows the study of the effect of combining external insulation with internal thermal mass, versus the more conventional focus in insulation alone. Therefore, the main characteristics of the envelope are the same in both cases, except for the *internal heat capacity*, much higher for the heavyweight fabric.

The original *heavyweight solution* (Table 1) uses Porotherm bricks and lime plaster. The alternative *lightweight solution* consists of an outer metal cladding and an inner gypsum board, with extruded polystyrene in between.

The high-performance building envelope allows the use of *internal gains* to cover most of the heating demand in the cold seasons. Then the lighting system functions also as backup heating for unoccupied hours and is therefore resolved with low-efficiency luminaries (fluorescent tubes, 5 W/m^2). The equipment (11.5 W/m^2) corresponds to one computer and two screens per user. A downside of having natural ventilation directly from the façade is the reduction in the occupancy density 0.05 people/m^2). To protect the users from drafts, they have to sit at a distance from the windows. In this case, this is resolved by placing the circulation by the façade, instead of by the core.

The typical meteorological year (TMY) *weather file* for Lustenau was obtained from Meteonorm (Remund 2008) by interpolation from the nearest weather stations (lat. 47.25°N, long. 9.39°E, alt. 405m).
With a mean temperature of the warmest month of 19.6°C and 0.6°C for the coldest, it corresponds to a *Köppen climate type Cfb* (temperate, with warm summer and no dry season). Also, with 2980 HDD18 and 1277 CDD10, it gives an *ASHRAE type 4A* (mixed and humid). In this temperate (borderline with cold) climate, only about 9% of the hours fall inside the comfort zone, before the application of passive strategies for climate adaptation (Figure 2). The heat map shows a thermal variation span between -10°C and 30°C, with July as the warmest month and January as the coldest.

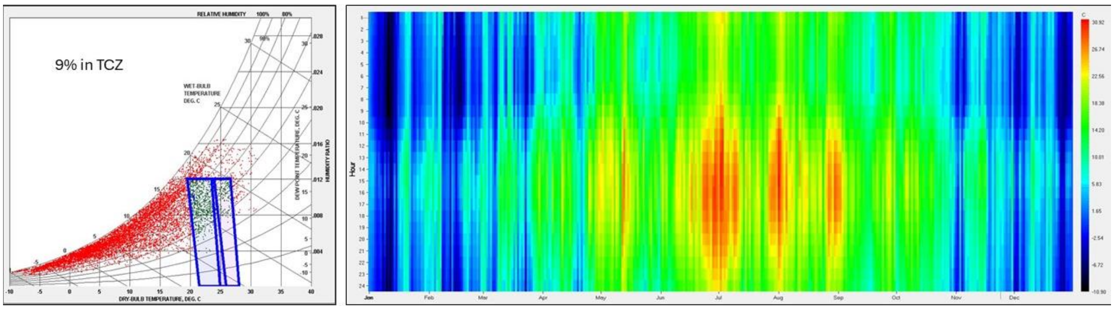

Figure 2. Psychrometric chart and heat map for the outdoor climate in Lustenau (Austria).

The *BPS analysis* of the building was carried out in EnergyPlus with DesignBuilder as a graphical user interface (GUI). These tools were chosen because of their capability for simulating the behaviour of thermal mass and moisture buffering of the materials in use, as well as the possibility for extensive tailoring in the operation of building components and systems with EMS coding (energy management systems). (Crawley et al. 2001; Ellis, Torcellini, and Crawley 2008)
Then, moisture buffering properties of the different construction elements were introduced to be able to use the *effective moisture penetration depth calculation method* (EMPD) for heat and mass transfer. This was necessary to produce a more accurate approximation to the indoor relative humidity in the psychrometric chart, considering the moisture buffering capacity of the materials. The EMPD method was chosen over the more detailed HAMT, because it produces very similar results with much shorter simulation time and fewer errors (Woods, Winkler, and Christensen 2013).
Once the model was finished, it was analysed under different operative modes, to study thermal comfort, resilience and autonomy.

2.1. Thermal comfort

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 2023). It is therefore a subjective concept, prone to variations.
The *static approach* to thermal comfort aims to create stable ideal conditions to reduce displeasure in occupants of mechanically conditioned spaces. Following this model, comfortable indoor temperatures would be around 20°C to 25°C in the winter and 24°C to 28°C in the summer.
In contrast, the *adaptive approach* to thermal comfort considers the outdoor climate and the possibility of adaptation for the occupants in naturally ventilated buildings. Around the world, winter indoor comfort temperatures can vary between 10°C and 25°C, while in the summer they span from 20°C to 35°C (Nicol and Roaf 2017).
To study thermal comfort, the model was run with normal operation for all systems and components, but without automated controls, to ensure comparability between the two envelopes.

2.2. Thermal resilience and habitability

A general definition of *thermal resilience* would be "a building's ability to remain at and/or recover to a habitable state after a disruption in energy supply" (Kesik, O'Brien, and Ozkan 2020). Research shows that the design of the building envelope and the inclusion of *passive strategies* should be complemented by *adaptive opportunities* for the occupants (window opening, extra clothing).
Thermal habitability refers then to the hygrothermal conditions that would ensure our thermal safety inside buildings during extreme climatic events (storms, drought, heat/cold waves) and power outages (Wilson

2018). The Resilient Design Institute and the U.S. Green Building Council Resilience Working Group define the *"habitability zone"* as between 12°C and 30°C. With outdoor clothing or blankets in the winter and some airflow in the summer, most people would be safe within this temperature range.

To analyse the thermal resilience and habitability of this building, its normal operation was interrupted by a power outage, first in the winter and then in the summer, to study its thermal response.

2.3. Thermal autonomy

Thermal autonomy is the ability of a space to provide acceptable thermal comfort exclusively through *passive means* (Levitt et al. 2013). It understands building performance from the perspective of the envelope's capability to selectively filter the environment to the occupant's advantage.

To check the thermal autonomy of this building with the two envelope solutions, it was simulated under three operational modes. First, only the envelope was considered, in a fully passive operation without internal gains, to appreciate the effect of the fabric alone. Then, the occupants were introduced, to see how that would affect the indoor environment if systems and components could not be operated. Finally, natural ventilation was activated, assuming that in reality an occupied building would need ventilation at least for fresh air, but also to dispose of the excess heat and moisture provided by the occupants.

3. RESULTS & DISCUSSION

After performing the simulations for the case building with the heavyweight and lightweight envelopes, the results were compared to the expectations for thermal comfort in international standards. The graphical representation of temperature and relative humidity was presented in different ways. The psychrometric chart was used to show the interconnection between temperature and humidity, presenting their total annual amplitude to characterize the indoor climate. Heat maps displayed the contrast between summer and winter, day and night, responding both to diverse outdoor conditions and operational schedules. Finally, linear dynamic distributions reveal variability patterns in more detail.

3.1. Thermal comfort

As explained earlier, for the analysis of thermal comfort, the model included all internal gains and natural ventilation operational schedules, but not the automated controls, to ensure comparability.

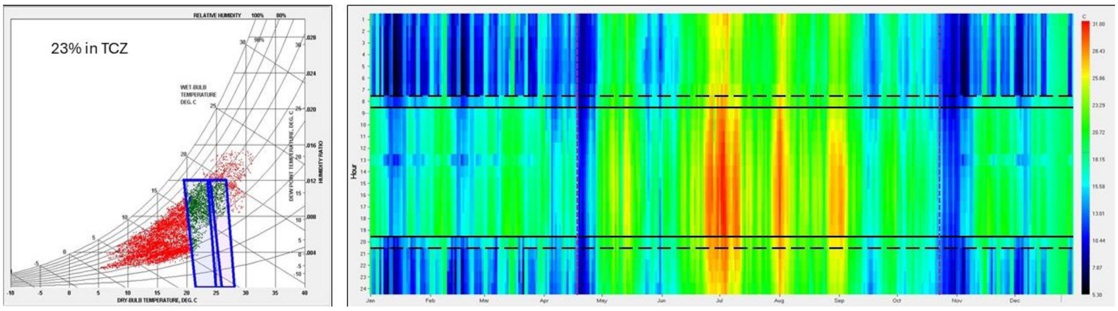

Figure 3. Psychrometric chart and heat map for the resulting indoor environment with the original heavyweight envelope. Working hours are marked in the heat map between the horizontal lines, with daylight saving time between the dashed vertical lines in April and October.

As shown in Figure 3, without the control algorithm only 23% of the hours fall inside the comfort zone (TCZ), in the case of the heavyweight envelope. There is some overheating during working hours in the summer, especially in July, reaching temperatures around 30°C. On the other hand, winter overcooling happens mainly outside working hours, due to the combination of unoccupied spaces (no internal gains) and colder outdoor temperatures. Only some transitional months (April and November) produce overcooling during working hours, because of the combined effect of extra cold outdoor temperatures and higher ventilation rates. This may be avoided in reality by adjusting window opening in those periods.

In contrast, Figure 4 presents a higher percentage of comfortable hours for the lightweight envelope, with 32% in the comfort zone. The overheating and overcooling periods coincide in both cases, since they happen due to outdoor conditions. Nevertheless, the climatic points are more widely spread in this case, creating more severe and frequent overheating and overcooling.

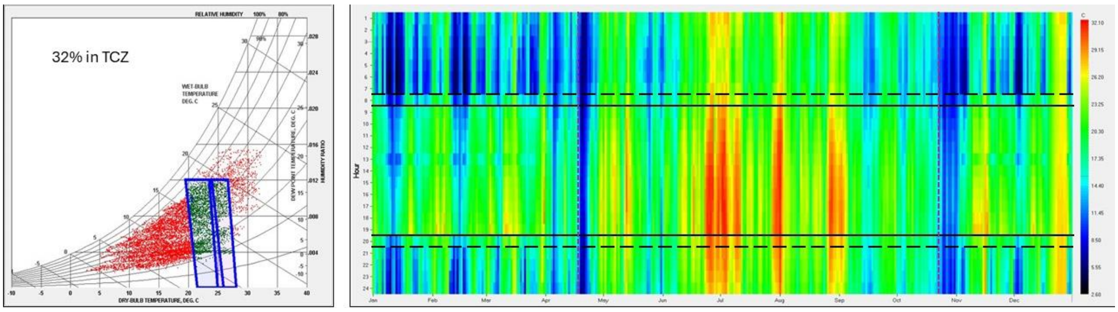

Figure 4. Psychrometric chart and heat map for the resulting indoor environment with the alternative lightweight envelope. Working hours are marked in the heat map between the horizontal lines, with daylight saving time between the dashed vertical lines in April and October.

The linear annual distribution of indoor temperature for both solutions (Figure 5) shows the effect of thermal mass from the heavyweight envelope, restricting thermal variability, especially in the winter. On the other hand, in the summer, higher ventilation rates produce more similar indoor temperatures for both cases, bringing them closer to each other and to outdoor values.

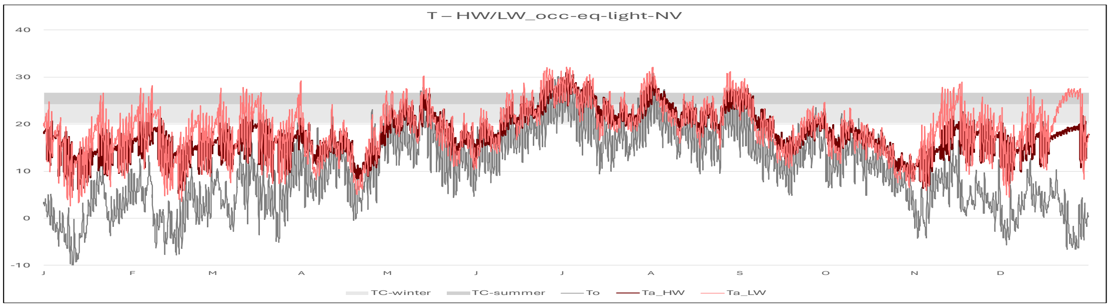

Figure 5. Dynamic annual distribution of indoor temperature. Comparison between heavyweight (dark red) and lightweight (light red) envelopes, in relation to the outdoor temperature (grey).

3.2. Thermal resilience and passive survivability

As explained in the previous section, thermal resilience and habitability were tested by interrupting normal operation with a power outage in the winter or the summer. This can display the thermal evolution of the indoor environment in free-floating mode.

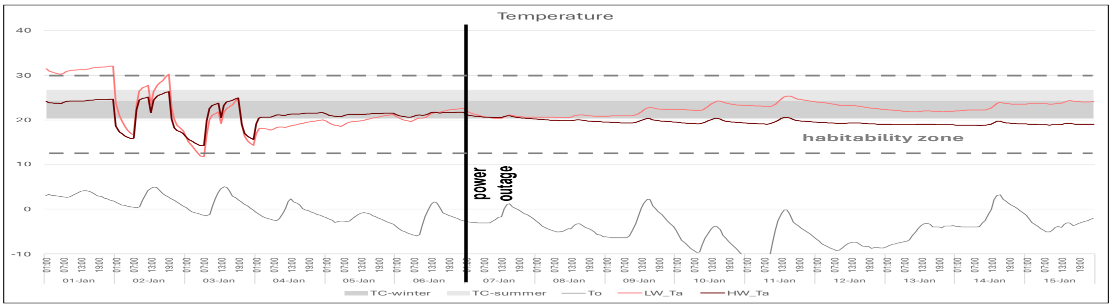

Figure 6. Evolution of indoor temperature after a power outage in the winter, for the heavyweight (dark red) and lightweight (light red) envelopes. Outdoor temperature in grey, for reference. Winter thermal comfort zone in dark grey, according to ASHRAE-55 (2023). Habitability zone between 12°C and 30°C.

When the power outage happens *in the winter* (Figure 6), both constructive solutions keep indoor environment within the habitability zone for more than a week. Yet, the lightweight envelope performs better here, keeping indoor temperatures well within comfort, though with a slight tendency to overheat after a week, due to solar gains. The heavyweight one absorbs more heat, producing indoor temperatures below comfort after just one day, though the decrease is very slow, staying close to comfort.

On the other hand, when the power outage occurs *in the summer* (Figure 7), only the heavyweight solution manages to keep indoor temperatures within the habitability zone for over a week. The lightweight one maintains comfortable temperatures just for a day and after two days it starts producing severe overheating, since it fails to dissipate the cumulative effect of solar gains.

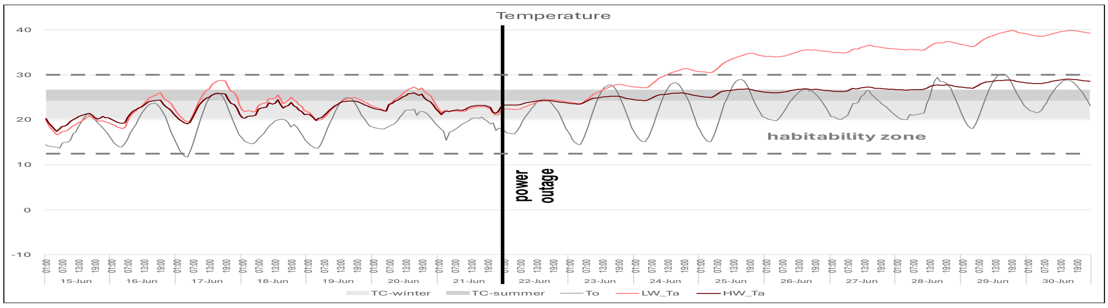

Figure 7. Evolution of indoor temperature after a power outage in the summer, for the heavyweight (dark red) and lightweight (light red) envelopes. Outdoor temperature in grey, for reference. Summer thermal comfort zone in light grey, according to ASHRAE-55 (2023). Habitability zone between 12°C and 30°C.

3.3. Thermal autonomy

As introduced earlier, to analyse the thermal autonomy of both envelope solutions, the building was simulated in three stages: empty, with occupants and adding natural ventilation.

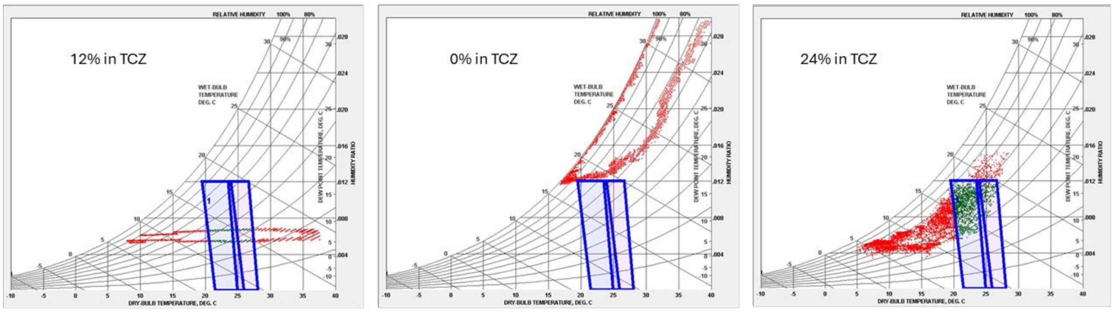

Figure 8. Psychrometric chart with the resulting indoor environment when considering only the effect of the heavyweight envelope (left), including the occupants (centre) and adding natural ventilation through the windows (right).

The psychrometric analysis in Figure 8 shows the effect of the *heavyweight envelope*, reducing short-time temperature variability and keeping very stable values of absolute humidity, though only 12% of the hours are in comfort. Then, after including the occupants, there is a significant increase in relative humidity and temperature, with severe overheating and humidity/condensation problems, and no comfortable hours. Finally, adding natural ventilation helps cool down the indoor environment and lowers relative humidity, thus bringing 24% of the hours inside the comfort zone. There is also a much higher dispersion in the temperature/humidity values, now closer to the original outdoor conditions (Figure 2), though warmer and with less variability (tighter). Still, there is a significant overcooling in the winter, while summer temperatures are more comfortable. Relative humidity is kept between 40-70% most of the time, close to the recommended values of 40-60% for health and comfort.

In the linear annual temperature distribution (Figure 9), it can be appreciated the low daily variability in the empty building (light red), with some overheating in the summer, suggesting the need for shading in the windows. After incorporating the occupants (medium red), there is an important improvement in the winter temperatures, falling now almost inside comfort, while the summer increase is lower in comparison, yet still worsening the overheating problems. At last, natural ventilation (dark red) brings indoor temperatures much closer to outdoor conditions, though keeping a similar winter average as with the empty building and keeping summer values comfortable.

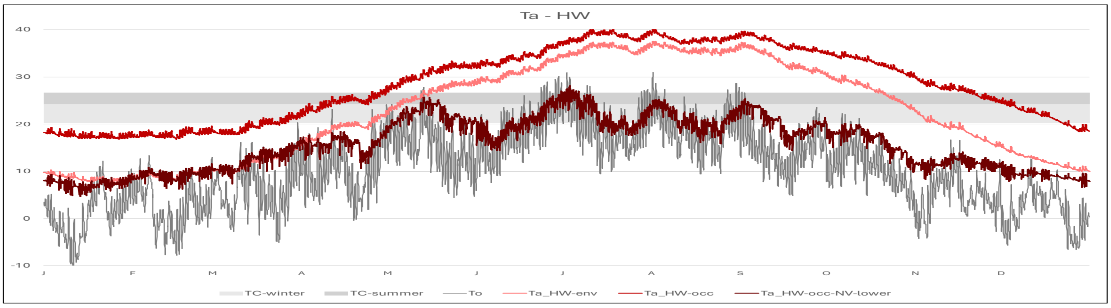

Figure 9. Dynamic annual distribution of indoor temperature from the heavyweight envelope alone (light red), with occupants (medium red) and adding natural ventilation (dark red), compared to outdoor conditions (dark grey).

When it comes to the *lightweight envelope* (Figure 10), while there are more hours in the comfort zone than in the previous case (17% vs. 12%), it also creates more severe overheating and higher dispersion both in temperature and humidity values. Then the occupants produce a significant increase in the temperature and humidity, with higher overheating and humidity problems than with the heavyweight envelope. Lastly, adding natural ventilation improves the indoor environment, lowering temperature and humidity to bring 31% of the hours into comfort. Though this is a higher percentage than in the previous case (24%), it creates more dispersed values and overheating problems, more difficult to regulate through passive means. It also improves winter conditions slightly, with fewer hours under 10°C.

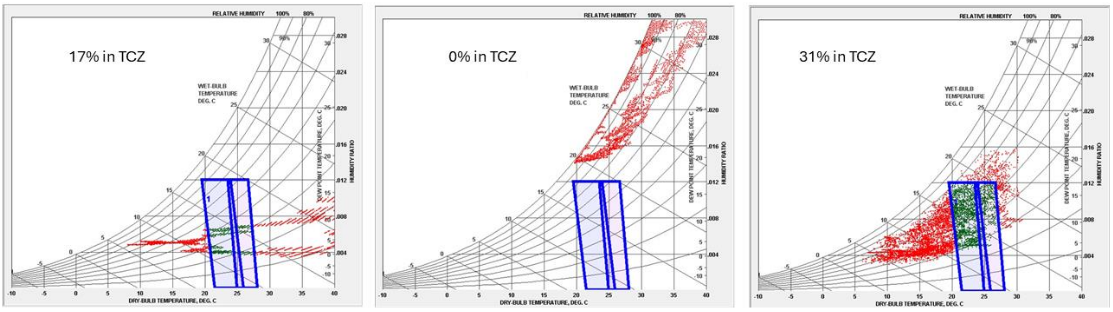

Figure 10. Psychrometric chart with the resulting indoor environment when considering only the effect of the lightweight envelope (left), including the occupants (centre) and adding natural ventilation through the windows (right).

The linear annual temperature distribution (Figure 11) shows the severity of the overheating in summer, with indoor temperatures above 50°C (below 40°C in the previous case) even when empty, and with a much higher variability. On the other hand, winter temperatures are also higher, more comfortable. The inclusion of the occupants encompasses an increase in temperature, bringing winter values to comfort, though increasing overheating in the transitional seasons. Summer temperatures, on the other hand, remain almost unchanged. Finally, natural ventilation manages to reduce summer temperatures to comfortable values, but it also introduces overcooling in the winter, with values closer to those in the empty building. Even though this solution allows a much higher variability than the heavyweight envelope, it also produces a warmer winter environment, more comfortable with these settings.

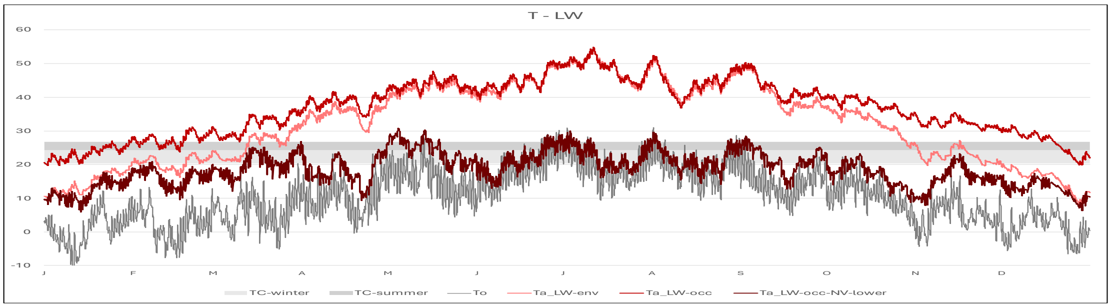

Figure 11. Dynamic annual distribution of indoor temperature from the lightweight envelope alone (light red), with occupants (medium red) and adding natural ventilation (dark red), compared to outdoor conditions (dark grey).

4. CONCLUSION

From this study, it becomes apparent that in this building the heavyweight envelope performed better in the summer, due to the heat absorption capacity of thermal mass. On the other hand, the lightweight solution seems slightly more effective at limiting heat loss in the winter, since it does not absorb so much heat from the indoor environment. The heavyweight construction produces a more stable environment, restricting thermal variations on a daily and seasonal basis, thus flattening the curve. At the same time, the lightweight option, due to its low heat absorption capacity, needs a shorter warmup period, while the heavyweight is slower and needs more time. Even though in the intermediate stages analysed here there were more hours inside comfort for the lightweight solution, the total area of climatic points was closer to comfort for the heavyweight one (less amplitude, more compact) making it easier to improve using passive strategies.

Both options have their pros and cons. However, the heavyweight envelope seems more advantageous for the 22/26 energy concept. The resistance to change provided by the thermal mass and moisture buffering capacity of the materials (many times larger than that of room air in this case) allows short flush ventilation events for fresh air in the winter, with little effect on the indoor thermal conditions, thus keeping comfort. In this *materials-based* space conditioning approach, it is therefore the thermal and moisture buffering of the materials that ensures a comfortable environment. The lightweight envelope would then be more effective for *airflow-based* space conditioning, usually resolved with mechanical systems, where conditioned air flow sustains comfort. Based on active systems, airflow-based space conditioning can provide comfort faster but is more energy-intensive. On the other hand, materials-based space conditioning uses much less energy, since it is based on passive strategies, though it is also slower.

It can be concluded that both envelope solutions may be valid in this climate, but they should be linked to tailored *ventilation* rates and schedules, to ensure comfort and efficiency. Then again, a heavyweight envelope provides more *resilient* indoor conditions in the summer, while a lightweight configuration performs slightly better in the winter.

ACKNOWLEDGEMENTS

This research has been financed by the Department of Architecture and Technology at the Norwegian University of Science and Technology (NTNU) and The Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME-ZEN).

REFERENCES

ASHRAE. 2023. *ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy.* American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Crawley, Drury B., Linda K. Lawrie, Frederick C. Winkelmann, Walter F. Buhl, Joe Huang, Curtis O. Pedersen, Richard K. Strand, R.J. Liesen, D.E. Fisher, M.J. Witte, and J. Glazer. 2001. "EnergyPlus: creating a new-generation building energy simulation program." *Energy and Buildings* 33 (4): 319-331.

Eberle, Dietmar, and Florian Aicher. 2016. *BE2226 - The Temperature of Architecture - Portrait of an Energy-Optimized House*. Book. Basel: Birkhäuser.

Ellis, Peter G, Paul A Torcellini, and D Crawley. 2008. *Simulation of energy management systems in EnergyPlus.* National Renewable Energy Lab.(NREL), Golden, CO (United States).

Junghans, L., and P. Widerin. 2017. "Thermal comfort and indoor air quality of the “Concept 22/26”, a new high performance building standard." *Energy and Buildings* 149: 114-122. https://doi.org/10.1016/j.enbuild.2017.05.020.

Kesik, Ted, William O'Brien, and Aylin Ozkan. 2020. "Towards a Standardized Framework for Thermal Resilience Modeling and Analysis." ASHRAE Topical Conference Proceedings.

Levitt, Brendon, M Ubbelohde, George Loisos, and Nathan Brown. 2013. "Thermal autonomy as metric and design process." CaGBC National Conference and Expo: Pushing the Boundary–Net Positive Buildings.

Nicol, J Fergus, and Susan Roaf. 2017. Rethinking thermal comfort. Taylor & Francis.

Remund, Jan. 2008. "Quality of meteonorm version 6.0." *Europe* 6 (1.1): 389.

Wilson, Alex. 2018. "Resilience as a driver of passive design." In *Activism in Architecture*, 155-164. Routledge.

Woods, J, J Winkler, and Dane Christensen. 2013. *Evaluation of the effective moisture penetration depth model for estimating moisture buffering in buildings.* National Renewable Energy Lab.(NREL), Golden, CO (United States).