Living Places: Healthy Homes for People & Planet

A simulation-based evaluation to ensure optimal indoor environment

JENS CHRISTOFFERSEN,[1] STEFFEN MAAGAARD,[2] KASPER REIMER,[3] SIOBHAN ROCKCASTLE,[4] AMBRA GUGLIETTI,[1] NICOLE DI SANTO,[1] LUCILE SARRAN[1]

[1] VELUX A/S, Hoersholm, Denmark
[2] Artelia A/S, Copenhagen, Denmark
[3] EFFEKT Arkitekter ApS, Copenhagen, Denmark
[4] OCULIGHT dynamics,

ABSTRACT: The architectural design of Living Places, the way it is formed, shaped and designed provides the interior with plenty of daylight all year round. The design incorporates window control with its accessories to effectively mitigate overheating and create a comfortable thermal environment. Openable windows with high attention on easy air passages throughout the building certify high indoor air quality. Living Places and its design provide us with an indoor experience over time and space, which is an experience we enjoy and that connects us to the outside, making the outdoor dynamics integrated with the interior. We have used the compass model and simulated the performance, a total of 60.000 indoor climate simulations, to identify the most significant design parameters and to see if it provides the desired result. In addition, we have built a full-scale model and we are collecting insights through simple measurements of the indoor environment. Overall, the simulation shows that Living Places satisfies all main parameters of the 'healthiness' criteria: daylight, thermal comfort, indoor air quality and acoustic quality. It is a building concept that allows abundant daylight and fresh air, enhancing indoor climate quality, and showing how to build sustainability for people and the planet.
KEYWORDS: Living Places, Compass, Indoor Environment, Health, Full-scale demonstration buildings

1. INTRODUCTION

Since spring 2020, nationwide lockdowns caused by the pandemic have forced many to work, learn and live at home. For some, this has renewed their appreciation of their home, for others, the living conditions and indoor environment have become an extra challenge. The role of our buildings is changing and there is an urgency to provide sustainable, healthy and affordable housing solutions. We spend 90% of our time indoors, and the healthiness of our indoor environment has received increasing attention over the last decades and has been the subject of publications and guidelines by governmental agencies and the World Health Organization (WHO). We know we can design homes that enable an indoor environment that is regenerative with a high focus on humans and how it affects our mental and physical health and well-being. Enabling an 'optimal' indoor climate is an essential aspect of house design and WHO has distinguished the following aspects of the 'healthiness' of the indoor environment:

- Thermal environment
- Air quality environment
- Noise environment
- Light environment.

The architectural design of Living Places, and the way it is formed, shaped and designed provide the interior with an abundance of daylight all year round. The design incorporates window control with its accessories to effectively mitigate overheating and create a comfortable thermal environment. Openable windows with high attention to easy air passages through the building certify high indoor air quality. Living Places and its design provide us with an indoor experience over time and space, which is an experience we enjoy and that connects us to the outside, making the outdoor dynamics integrated with the interior.

2. DESIGN AND PERFORMANCE DRIVERS

A home should be designed to enable an indoor environment that is regenerative and focused on humans, their mental and physical health, and well-being. How homes are designed and operated plays a crucial role in supporting physical and mental health. Enabling an optimal indoor climate is an essential aspect of house design.

The Compass model provides the foundation for Living Places and serves as a strategic tool which outlines seven points of relevancy to guide the building and development process. This paper focuses on healthy building principles and presents the outcome of the strategic design and performance drivers to ensure a healthy indoor environment.

The design drivers are; 1) visual, where building design typology ensures plenty of daylight to

Don't mention compass but main principles eliminate the need for electric lighting during the day, 2) thermal environment, with drivers to design for year-round comfort, while ensuring temporal and spatial variations in the thermal environment, 3) indoor air quality, with focus on maximizing ventilation potential through stack effect and optimal positioning of windows, and 4) acoustics to ensure sound is transmitted and spread at optimal levels, through considerations in design, operation and construction.

Figure 1: Visualization of the timber-framed Living Places Concept House.

Table 1: Overview of Living Places

Concept House	Description
Size	144 m^2
Floors	3
Building principle	Timber frame construction
Foundation	Screw pile foundation
Room height	2.6 m
Heating application	Air to water heat pump
Heating source	Radiators
Ventilation	Natural or hybrid

The performance drivers implement the design drivers through the typology of Living Places. Within the 1) visual environment, the drivers are securing sufficient daylight [1] by optimizing the window design and utilising direct sunlight within the different spaces and use by the occupant, without creating high contrast and glare problems. The positioning of windows influences the distribution of daylight in a room. Combining windows in multiple facades/roofs determines the amount of 'useful' daylight throughout the day with the changing sun position. Strategic window position will take into account the relation between the view to the outside and occupants ability to supply information of orientation, give experience of weather changes and allow us to follow the passage of time and nature over the day and year. The thermal environment ensures temporal and spatial variations using sufficient ceiling height, careful building depth, and strategic location of openable windows supported by sensors to regulate the indoor climate [2]. Proper use of solar shading will reduce solar heat gain and potential overheating. Additional use of ventilation strategies (e.g. natural or mechanical) to cool indoor spaces via outdoor air, sometimes referred to as ventilative cooling, commonly uses increased ventilation airflow rates and night ventilation. From an energy-conscious perspective (e.g. minimize or eliminate cooling systems), using a natural ventilative cooling principle by opening windows is a very direct and fast method of influencing the thermal environment, either by increased air motion or by use of temperature difference between outdoor and indoor temperatures. Additionally, maximizing ventilation potential through the stack effect and optimal positioning of windows will safeguard high indoor air quality, as well. In addition, the use of low off-gassing labelled products and material, demand-controlled ventilation and zone subdivision of individual rooms with proper filtration support high performance. One important function of the building envelope is to protect the interior from unwanted outdoor noise. Ensuring sound is transmitted and spread at ideal low levels, through considerations in design, operation and construction will minimize noise disturbance that could affect our sleep and other negative effects.

Design actions: optimizing window position etc.
Pictures of thermal concept, daylight concept etc.

2.1 Simulations

The Active House specifications [3] include the vision and knowledge needed to meet the technical requirements for achieving the design concept's performance levels and a holistic approach (biodiversity, local culture, and location). We use an Active House Radar according to the Active House specifications, together with a Multivariable Building Simulations tool to explore the solution space for each parameter to reach a target indoor climate level according to the Compass model and the healthy building principles.

With a Multivariable Building Simulations (MIBS) method, the project engineering partner has established a platform of tools, in which a design team can explore the entire solution spectrum when the 'optimal' design is to be found. The tools can inform the building design team which drivers can achieve the best possible basis for a healthy indoor environment (see example in figure 2).

Figure 2 shows an example of indoor climate simulations for a sleeping room to evaluate the thermal environment and indoor air quality. The upper chart shows the thermal environment, where

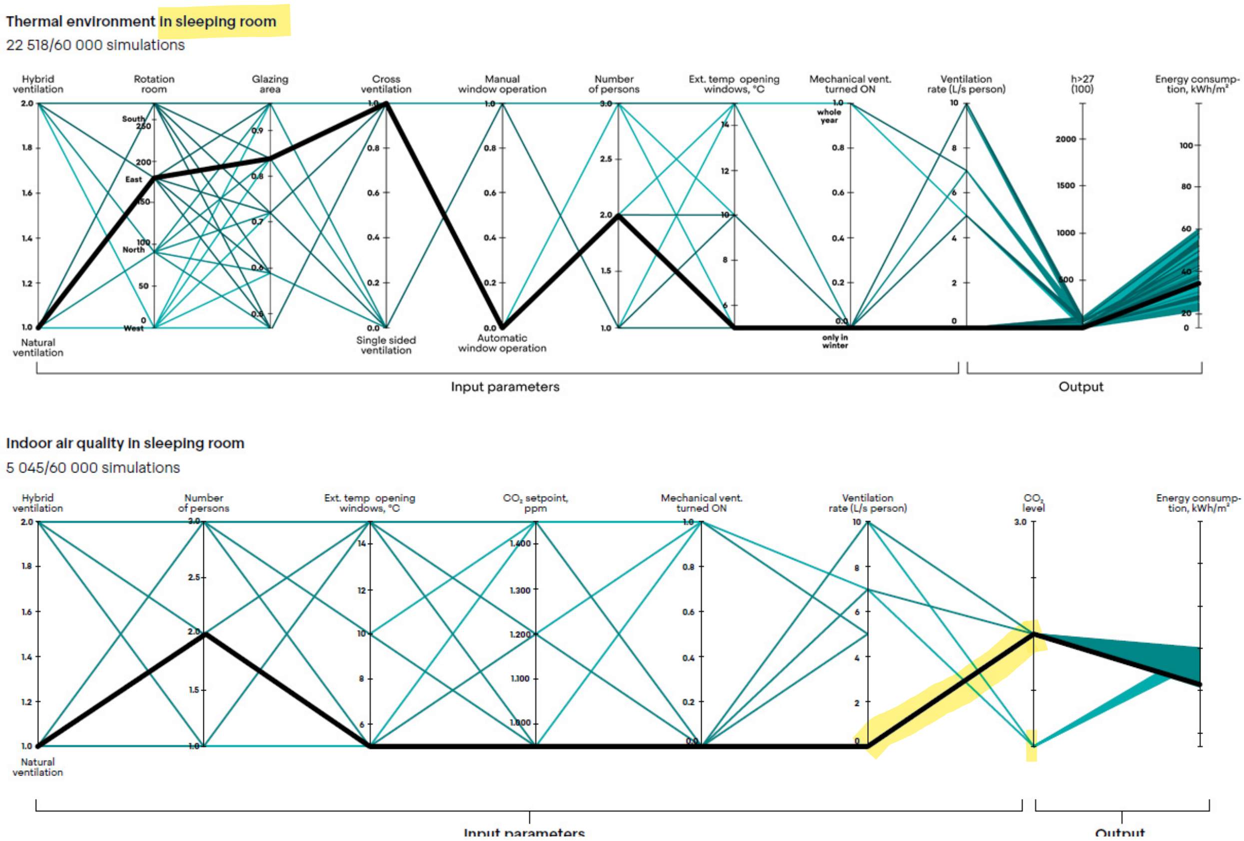

Figure 2: The charts shows the indoor climate simulations for a sleeping room, where one solution with natural ventilation have been selected to get the best possible trade-off between energy consumption, temperature, and indoor air quality. The charts show one of the possible scenarios for the project to ensure a good healthy indoor.

the black line illustrates one input parameter with natural ventilation (left starting point) that has been selected to get the best possible trade-off between output parameters of energy consumption and indoor temperature. The other key input parameters are: room orientation, glazing area, whether the room is single-sided or cross-ventilated, whether the windows open manually or automatically, number of people, outdoor temperature for automatic opening, time with mechanical ventilation, and the ventilation rate. The lower chart show the input parameters for the indoor air quality in the sleeping room. By setting key design and performance criteria, using these design tools will illustrate a possible solution space, and by taking different decision the solution space can either increase or decrease, and show immediately how an adjustment in the design will affect the other design parameters and what the impact will be on the selected output parameters.

3. RESULTS

As part of the Living Places project, and essential for the evaluation of the indoor environment, a total of 60.000 indoor climate simulations have been performed on a room basis to identify the most significant design parameters. We have essentially separated the analysis depending on ventilation principle, natural ventilation and hybrid ventilation, and performed 30.000 simulations for each scenario. Each scenario, as illustrated in figure 2 example, has a set of input parameter variations which is evaluated to an output criteria for the thermal and atmospheric indoor climate, as well as energy consumption (heating and fan). Based on these analyses, the most sensitive design parameters have been used to find the most resilient building design depending on ventilation principles.

Using a parallel coordinate plot a lot of different paths to the design "goal" have been showcased (see fig. 2), but also paths that cannot fulfil the ambitious requirements to the indoor environment. As an example, depending if the building use solely a natural ventilation solution or if it use a hybrid solution, the most influential parameters in relation to thermal comfort and air quality are different as well as similar. There are common parameters such as the number of people in the space for both natural and hybrid ventilation solutions, the specifics differ based on the approach. For natural ventilation, outdoor temperature where the window can be opened and CO_2 setpoint take precedence, while for a hybrid solution, factors like the activation time of mechanical systems ventilation system (winter / all year) and their usage during specific periods become critical.

Table 2: Values and KPI for a good indoor environment based on peer-reviewed research.

Component	Indicator	Parameter	Indoor Climate Class I
IAQ	Particles	Ventilation filtration	ePM1 55%
		Extractor hood efficiency, >75%, l/s	40
	CO_2	Bedrooms, ppm	≤1000
		Vent. rate build, l/s pr. m^2	≥0.5
	VOC	TVOC	300
	Radon	Bq	≤100
	Relative Humidity	RH 95% of time	≥30-≤50
	Temperature	Overheating, 100h > temp	<26.5°
Acoustic		Sound pressure level	<27
Visual	Daylight	$sDA_{300,50\%}$ floor area	≥50%

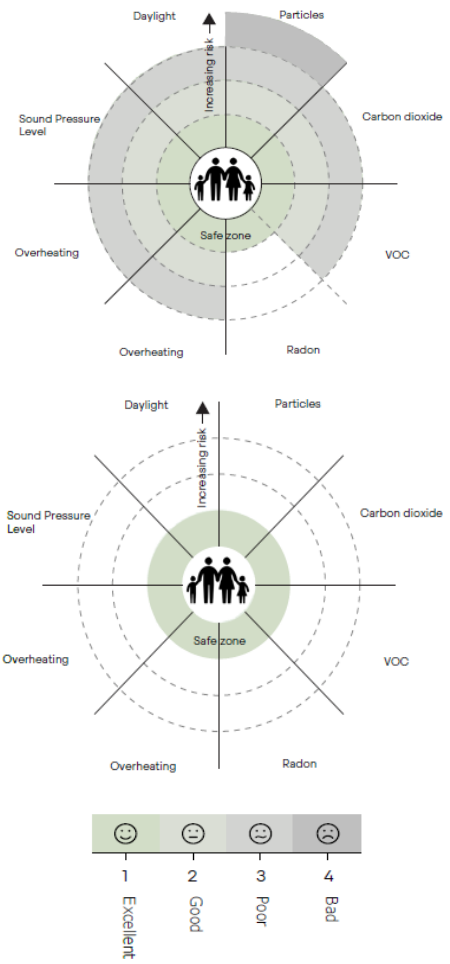

Figure 3: Using an Active House Radar shows that each parameter is described in table 1. The upper radar is a benchmark of a typical EU single-family house and the lower radar is Living Places (lower)

3.1 Overheating

The design incorporates window control effectively to mitigate overheating, regardless of the building's orientation. Versatility and flexibility are valuable attributes in creating a comfortable thermal environment and the simulation results demonstrate that all rooms at all three-floor levels consistently meet or exceed thermal comfort requirements as defined in the Danish Building legislation as hours above 27°C (e.g. 100h) and 28°C (e.g. 25h), which are commonly used indicators of potential thermal discomfort. The number of hours above 27°C and 28°C is well below the specified limits for thermal comfort. The simulation outcome indicates that the design successfully addresses overheating concerns, as the number of hours above 27° varies depending on building orientation, and floor level. In the living room/kitchen the number of hours above 27°, depending on orientation, varies from 40 to 70 hours (e.g. highest towards the West) to slightly above 50 hours in the top floor bedroom. A similar tendency can be observed with the number of hours above 28 which is less than 25h. The simulations also show how and when to use windows to boost the mechanical ventilation rate with natural ventilation, when the mechanical ventilation can be turned off to save energy and how large windows can be used in specific orientations. In general, the parametric sensitivity analysis indicates that in a naturally ventilated house, the key parameters to fulfil thermal comfort are the outdoor temperature, when windows can open, the number of people, and the air-flow rate when windows are open. In the hybrid solution, the key parameters are set-point and time for activation of mechanical ventilation, and ventilation airflow rate for the mechanical solution and airflow rate when naturally operated.

3.2 Ventilation and indoor air quality

Simulation of the Living Houses shows that the indoor CO_2 level according to [3] is within level 1 (e.g. < 400 ppm above outdoor CO_2 concentration). The parametric sensitivity analysis indicates that with a naturally ventilated house, the key parameters to reduce CO_2 concentration are the CO_2 set-point, air-flow rate (7-10 l/s per person) and outdoor temperature when windows open (> 5 °C) and number of people. Strategically opening windows to allow fresh air circulation, and diluting indoor CO_2 levels will maintain higher air quality. In the hybrid solution, the key parameters are; set-point and time for activation of the mechanical ventilation system (year-round or just in the winter months) and the air-flow rate when the mechanical and natural solution is active in operation during occupied hours. Overall, the hybrid solution and active use of strategic

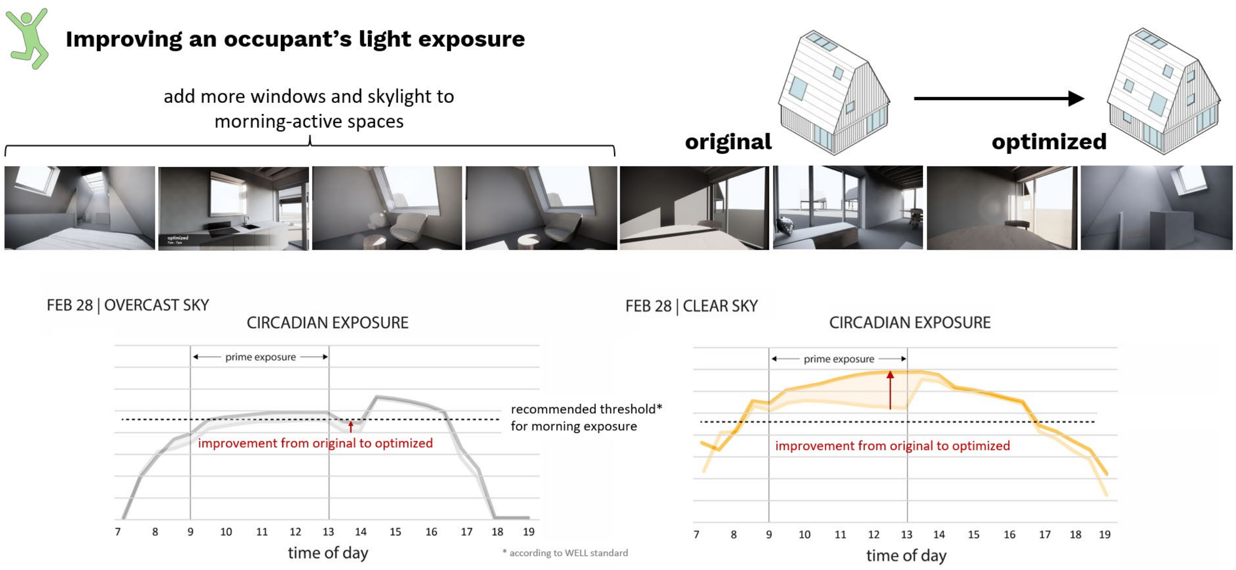

Figure 4: Illustration of daytime recommended threshold level and estimated level of circadian light exposure, February 28, for an overcast sky and a clear sunny sky. The two different lines illustrated with an upward arrow exemplify attention to optimize daylight-specific window openings arrangement to increase the circadian light exposure according to a "walk around" behaviour within the different type of spaces in Living Places.

window openings maintain an energy-efficient solution, adapting to seasonal variations, but winter months and limited window openings show an increase in CO_2 level, if the energy consumption should be maintained low.

3.3 Visual and non-visual effects of daylight

We also took the simulation of the visual environment a step further than just to comply with existing standards and guidelines. An external collaboration partner, OCULIGHT dynamics, simulated Living Places with complementary tools to allow evaluation of how light will affect the occupants, whether it is physiologically (e.g. vitality) or emotionally, or how comfortable a daylit environment will be perceived from an occupant's perspective. To evaluate our overall experience of daylight, we need to know how much light we receive at eye level over the day, across seasons over the year. If our indoor environment provides us with too little light, thereby making us light-deprived, it can have long-term negative consequences on our well-being, affecting our mood, melatonin production, immune system and many other essential aspects of our health and vitality. Whereas being exposed to enough light can be highly beneficial, like promoting higher alertness and better sleep. Within that framework, daylight should be evaluated from a viewpoint perspective as well – or rather, from a large number of viewpoints within the space to represent enough possible perspectives –, and not only based on light reaching a horizontal plane.

The daylight simulation results show that the design of the Living Places offers a very convincing way to utilize daylight, with sufficient daylight provision and good levels of vitality and comfort especially on sunny days over the year, as well as when the sky is overcast. According to the criteria for daylight provision stated in [1], a space is considered to provide adequate daylight if a target illuminance level [e.g. recommended 300 lx] is achieved across a fraction of the reference plane [e.g. recommended 50%] within a space for at least half of the daylight hours. The outcome of the simulation shows that the minimum recommended spatial daylight autonomy (sDA) target of 300 lux is achieved across almost 90% of the reference plane at all three-floor levels, and about 65% of the area reaches the highest level of 750 lux. Additional evaluation shows that a majority of positions and view directions within the space are visually comfortable, with only limited situations that can cause visual discomfort or glare. Figure 4 illustrates the evaluation of light exposure and its contribution to health potential from a human-centric perspective [4]. Attention to optimising daylight-specific window opening arrangements to increase the circadian light exposure according to a "walk around" behaviour could influence the way we recommend occupants to spend time in the brighter areas of the spaces, especially in the morning, when the light signal is essential to let our body know the day is up and make sure we receive the proper light exposure and the right time. Figure 4 shows a recommended threshold level and the estimated circadian exposure to promote sufficient light exposure over each hour depending on sky type, time of year and improvement of daylight-specific window opening arrangement. Even a worst-case scenario, February 28, illustrates that the recommended light exposure when the sky is overcast is just fair, while a clear sunny sky provides sufficient exposure the whole day.

3.4 Indoor measurements

Indoor CO_2 measurements (spring) in each room of the two unoccupied Living Houses, indicate that the indoor CO_2 level is above the simulation levels. The house with a hybrid ventilation solution and maintained 'in-use' mechanical air flow (e.g., 10 l/s per person, bedrooms), shows measured IAQ score, according to [3], at level 2 (e.g. 550 ppm above outdoor CO2 concentration), while the naturally ventilated building solution is about level 3 (e.g. 800 ppm above). The thermal measurements also show a higher performance in the building with the hybrid solution (e.g. CLT house) than the natural ventilated solution (e.g. timber-frame). According to [2,3] these early spring measurements are merely to confirm the simulations, and an extended measurement protocol is expected next year.

4. DISCUSSION

Effectively window control strategies with its solar shading accessories are a crucial aspect, especially in regions or times where high outdoor temperatures can impact indoor comfort. A building design's ability to maintain a good thermal environment across various orientations underlines its adaptability. Although there is some variation in the number of hours above certain temperature thresholds, this information can be valuable for fine-tuning specific design elements but the number of hours to evaluate summer comfort is well below the specified limits and it indicates that the design successfully addresses overheating concerns.

Optimizing daylight-specific window openings for circadian light exposure based on a "walk around" behaviour within different types of spaces involves strategically considering the placement and characteristics of windows and the spectral composition of the glazing material used. The simulation shows that future evaluation should consider a spatial analysis of each area and view position within the building to understand the natural patterns of daylight. By incorporating a mix of direct and diffuse daylight, as well as, adopting the scientific recommendation for indoor light exposure, future design considerations will pay special attention to spaces that are frequently traversed or used for specific activities in terms of daylight optimization. As illustrated in Living Places, this aims to bring brighter, cooler light in the morning and during the day to promote wakefulness and alertness, and gradually transition to warmer, softer light in the evening to support relaxation and sleep. A higher emphasis on substantial daylight provision is essential for our visual perception and to minimize the use of electric light during daytime. A report by RAND Europe [5] shows that on average, 5% of European households are affected by self-reported perception that their dwelling is too dark, which could have an impact on the probability of switching on the electric lighting.

5. CONCLUSION

We have used the compass model and simulated the performance to see if it provides the desired result. In addition, we have built a full-scale model and we are collecting insights through simple measurements of the indoor environment. Overall, the simulation shows that Living Places satisfies all main parameters of the 'healthiness' criteria: daylight, thermal comfort, indoor air quality and acoustic quality. It is a building concept that allows abundant daylight and fresh air, enhancing indoor climate quality, and showing how to build sustainable for people and the planet.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the invaluable contribution of the project partners – VELUX, EFFEKT Architects and Artelia Denmark. We would also like to thank our inspiring collaboration with OCULIGHT dynamics.

REFERENCES

1. EN 17037:2018+A1:2021. Daylight in Buildings.
2. EN 16798-1:2019. Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics-Module M1-6.
3. Active House 2020. The Active House Specifications 3rd edition.
4. Brown TM., Brainard GC., Cajochen C., et al. (2022) Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. *PLOS Biology 2022; 20(3): e3001571.*
5. RAND Europe. Poor indoor climate: Its impact on health and life satisfaction, as well as its wider socio-economic costs. RAND Corporation. Report no. RR-A1323-1. 2012.