VELUX®

Circadian House

Principles and Guidelines for Healthy Homes

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Preface

Much focus on sustainable buildings has been on energy aspects. However, health is the most precious resource we have, and energy is only one aspect of sustainability. A primary goal for sustainability should be to sustain good health and a healthy living environment. This was the starting point for a series of workshops with international experts initiated by the VELUX Group, based on a wish to start a discussion on how to create healthier homes.

This document describes a comprehensive vision to realize healthy homes that support the different biological needs of their occupants, in particular including their circadian rhythms and sleep-wake cycles. It is based on discussions and findings of 5 workshops; ´Light and circadian rhythms´ (WS 1), ´Indoor climate´ (WS 2), ´The historical perspective´ (WS 3), ´ What to monitor and how´ (WS 4) and ´How to wrap-up the specifications´ (WS 5). The workshops were carried out by scientists and consultants specialized in healthy buildings, indoor environment, architecture and planning from November 2012 to August 2013.

Today, most residential buildings are designed or renovated in order to achieve a better energy performance. We acknowledge that there is an urgent need to transform our building stock to a better energy performance level, e.g. by increasing thermal insulation, installing better energy performing windows and improving energy efficiency of heating, cooling and ventilation systems. On the other hand, improving the energy performance of buildings should not result in a negative impact on health, wellbeing and comfort of building occupants. A successful design or redesign of a residential building should aim at the best health and comfort performance in addition to good energy performance. It is important to remember that dwellings are primarily meant to provide a safe and enjoyable living environment for their inhabitants. In that context, it is also important to consider that the primary purpose of *Building Regulations* is to provide for the health, safety and welfare of people in and around buildings.

The principles and guidelines in this document can be used to guide and improve the design of residential buildings of all types, including apartment buildings, and are applicable to both new and existing dwellings.

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What is a Circadian House?

We understand a *Circadian House* as a dwelling that promotes health by synchronising the circadian rhythms of its occupants to the 24h day-night cycle and the seasonal changes of day length.

In this context, health is regarded (referring to the World Health Organisation (WHO)'s definition) as a state of complete mental, physical and social wellbeing, and not merely the absence of disease or infirmity. In other words: a *Circadian House* promotes not just physical health, but also comfort and general wellbeing.

An official definition of healthy housing does not exist. However, in 1990 the WHO identified three levels of environmental conditions that might also be applied to dwellings:

1. Desirable conditions, those which promote health;
2. Permissible conditions, those which are not ideal, but which are broadly neutral in terms of their impact on health;
3. Incompatible conditions, those that, if maintained, would adversely affect health.

According to ISO 16817:2012, circadian rhythm is defined as a characteristic periodic change in a living organism or life-related process. A circadian rhythm is an approximate daily periodicity, a roughly 24-hour cycle in the biochemical, physiological or behavioural process of living beings. Circadian rhythms may be influenced by optical radiation (light).

Vision

During the workshops, several fundamental questions were asked about the link between housing quality, indoor environment, circadian rhythms and health. Questions like: Can a house really support circadian rhythms? Not by just providing for the adequate amount of daylight given the time of day, but also, e.g. by allowing indoor temperatures to follow (to a certain extent) the variation in outside temperatures. Can a building's design really support a healthy and active lifestyle? And how can the indoor environment in our homes promote comfort and wellbeing, rather than just maintain acceptable indoor conditions?

Most buildings that are being built today would probably belong to the 'permissible' category of healthy housing defined by WHO, but shouldn't homes do more than just provide permissible (or tolerable) conditions? With the principles presented in this document, we propose a more ambitious approach; one that aims for desirable conditions that really improve the physical health, comfort and wellbeing of building occupants.

Healthy building has been an aspiration through the entire history of mankind. The Old Testament in the Book of Levicitus provides the rules for avoiding the leprosy plague (dampness) at home. The positive health effects of e.g. sunlight and pure water were acknowledged already by the Egyptians and ancient Greeks. And for the Romans, health of people (in or outside their homes) was the highest law.
Much later, in the 1860s, Florence Nightingale identified five essential points in securing health in dwellings: pure air; pure water; efficient drainage; cleanliness; and light, especially sunlight. 'Do not build good hospitals, build good homes' is her famous quote (still very true).

Humans tend to maximise their comfort, which may not always be beneficial for health. A 'wellness culture' is visible in modern societies. People want to stay healthy, consider what they eat, focus on physical exercise etc. What can architectural design do to further support a healthy lifestyle? Being physically active is a big part of a healthy lifestyle and this is where the home should promote the occupants to be active, without putting additional stress on their lives. A nice, inviting staircase and an easily accessible garden are examples.

Principles

Based on the discussions, the core elements of a *Circadian House* are:

Key principles

- Live in balance with nature - A house in balance with nature allows the occupants to live with and follow the daily and seasonal cycles of the outdoor environment.

- Adaptability - A house whose space and occupants can adapt to changing conditions (daily, seasonal) and needs.

- Sensibility - A house that provides protection against harmful substances, which humans cannot sense, and allows freedom to control parameters that can be sensed.

Key factors

- Variation: the focus on nature's cycles implies that the indoor environment should vary in time and space rather than target uniformity or non-variability.

- Stimulation/absence of stimulation: The level of stimulation from environmental factors (light, sound, air, temperature) should be higher during day than night.

- Outdoor/indoor relation: Outdoor and semi-outdoor areas are designed to be inspiring and easily accessible; and occupants are able to follow (changes in) outdoor conditions in all main living areas of the house.

- Light/darkness: Exposure to high levels of daylight are needed in the main living areas of the house during daytime, with special attention to the rooms that are mainly used in the morning, whereas the bedrooms need to provide complete darkness at night time.

- Electrical lighting should follow, support and supplement change and variation in the light spectrum and intensity through the course of the day and distribution in space.

- Cool/warm: The house should provide temporal and spatial variation in the thermal environment that are logical (and e.g. follow – to a certain extent) outside temperature variations.

- Silence/sounds: The presence of sound and contact to sounds from outdoors are desired during daytime, whereas quiet spaces are needed at night time.

- Rest/activity: The house design should inspire the occupants to be active, but also have areas for rest and restitution.

- Flexibility related to the seasons: the use of outdoor and semi-outdoor spaces should be stimulated outside the heating season.

- The occupants should be able to control the systems that influence parameters that can be sensed, e.g. like lighting level, air quality and indoor temperature.

Building Site and Orientation

The quality of the building site is a crucial element to consider when designing a circadian house, as the site is an integral part of the living environment for the occupants. Ideally, the building site should be located in an area with good outdoor air quality and plenty of daylight and sunlight, and with limited outdoor noise levels. Other aspects are determination of prevailing winds and their seasonal changes. Also, levels of night light pollution should be considered.

Research studies have shown that people living closer to green spaces, including household gardens, neighbourhood parks and large green spaces, have better health profiles than those living farther away. So green building sites with lots of communal plants and trees are preferred.

The orientation of the rooms in the dwelling is another important factor to consider and should be defined based on the needs in each room for sunlight and daylight and considering thermal comfort and outdoor noise.

The main inhabited rooms of the house and the bedrooms should enhance 'seasonal biology' by allowing important seasonal signals to reach the occupants. Special consideration should be given on how to allow the sun to penetrate deep into the rooms in winter.

Contact to nature

Dwellings should have at least one outdoor or semi-outdoor space (e.g. a garden, terrace or balcony) that provides direct contact to nature. Research studies show that improved mood and reduced stress are consistent benefits of living in close contact with nature.

Outdoor spaces must be treated as an extension of the house and designed to inspire the occupants to spend as much time as possible outside, offering a close contact to nature in all seasons of the year. Outdoor spaces should be designed for a variety of activities such as dining, playing, working, relaxing etc. People affected by the seasonal changes in day length will benefit from extra exposure to high levels of daylight in outdoor and semi-outdoor spaces. Also, exposure to daylight and sunlight outside allows our body to produce vitamin D, which people in modern societies often lack due to the large amount of time spent indoors.

Balconies and terraces should be shielded from wind and have good connections to relevant rooms of the house in order to maximise their use.

A garden is recognized to have a positive therapeutic effect. A garden should be arranged and designed so that it inspires to active outdoor life. Studies show that gardens will be more likely to ameliorate stress if they contain rich foliage, flowers, a water feature, congruent nature sounds (bird songs, moving water) and visible wildlife, particularly birds. Green outdoor environments also have sustained benefits for social, emotional, and cognitive development in children.

View to outside

Views to the outdoor surroundings are crucial in order to maintain contact with nature and satisfy our needs for orientation in time and place while indoors.

There is clear evidence of the benefits of window views, particularly views offering contact to life and nature. A good view can have restorative benefits (leading to e.g. stress relief) and sometimes even result in quicker recovery time after illness and less post-surgery pain medication.

It is important to analyse view content on-site and make sure that all main living and activity rooms in the house have generous views to the sky and ground, and to natural and/or urban landscapes around the house.

Shading systems should be designed so that adequate views to the outside can be maintained in the rooms even at moments when it is necessary to block direct sun penetration. To this effect, it is important to consider proper control of sunlight in summer.

Healthy Light

Light is used by individuals for image forming light detection (vision) under a range of varied lighting levels and for a variety of non-image forming light detection (non-vision) tasks including as a daily time cue for sleep timing and as a modulator of levels of alertness. In addition, there is increasing evidence that human biology can be affected by changing light levels across the seasons. Seasonal depression has been linked to reduced light exposure in winter, whilst vitamin D synthesis requires light exposure around 300nm in the UV range and attenuated levels of vitamin D have been linked to increased vulnerability to both developmental and somatic diseases in adults. It should also be noted that UV light also has strong germicidal actions that can prevent the spread of some diseases in buildings. The principles and guidelines for Healthy Light should incorporate all of these divergent biological roles of light. How our biology responds to light intensity, spectrum, timing, duration and its spatial distribution is highly complex and varies greatly between image- and non-image forming light detection tasks. "Good healthy lighting" incorporating all of the important biological functions of light has been largely ignored in architecture until very recently.

Healthy lighting should consider the following factors:

- *The total daily light dose, which varies between individuals and as we age;*
- *Healthy light is linked to healthy darkness at night;*
- *Light sources with a broad daylight spectrum;*
- *Light received at eye level;*
- *Levels of UV-rich light reaching the skin;*
- *Timing, variation and duration of light exposure over the day and across the seasons.*

The dynamic variation of light is a critical factor in setting and maintaining our 24h daily rhythms – our circadian rhythms, which in-turn play a key role in the regulation of the sleep/wake cycle. Sleep disruption has been linked to poor cognitive function, stress, depression, poor social interaction, metabolic and cardiovascular disease, and an increased susceptibility to infection and even cancer. As a result an appropriate light signal during the day and darkness at night are critical in maintaining key aspects of our overall health. Outdoor daily light exposure allows us to regulate our sleep/wake timing, levels of alertness and the synthesis of vitamin D. The reality is, however, that we spend most of our time indoors where we are exposed to relatively low light levels of a limited spectral range, and where the patterns of light and darkness occur at irregular intervals. Until recently in the history of our species, the dwelling space was used primarily as a space for sleep with most activities taking place outside. Today, work, entertainment, socializing, eating and sleep all take place in the same or similar physical spaces. Collectively, the consequences of poor light exposure and the subsequent impact upon health are placing a substantial burden on the individual, society and the broader economy.

In order to align our body clock, morning light is the most important signal for entrainment. Light in the morning also increases our levels of alertness, allowing increased performance at the beginning of the day. Whereas reduced light levels in the evening promote sleep at night. For those times when seasonal daylight is not available in the morning, electric lighting can be used to support our non-visual light needs; mimicking the morning, daytime and evening periods in spectrum, intensity and dynamics.

Although much is still unknown about the specifics of how light interacts with our non-visual light systems, the data we have already can be used to suggest some important approaches to the nature of daily light exposure:

- The intensity of light should provide opportunities for exposure to high daylight levels at the level of the eye, within the range of more than 1,000 lux up to around 5,000 lux, and should be designed to minimize visual discomfort.
- The light dose per day exposed to >1,000 lux should on average be more than 200 minutes with high intensity boosts, especially, in the morning.
- Good spatial distribution of daylight and sunlight is achieved by distributing windows in multiple external walls and the roof rather than placing them with only one orientation.
- Where possible, natural light should be allowed entry into the living spaces to provide exposure to natural levels of light in the UV range.
- Daylight with minimal spectral filtering should be delivered at those times of day when it is most needed for circadian regulation.
- A dwelling should follow the natural cycle of light and dark exposure - allowing high exposure to daylight in rooms used in the morning and in the main activity rooms used throughout the day, and complete darkness in the bedrooms at night.
- It is important to carefully consider exposure to darkness during the sleeping periods – as circadian and alertness regulation requires both light and dark periods over the day.

Lighting recommendations and design criteria are needed for all occupants of the living and work spaces, taking into account the requirements for older vs. younger adults and even those with special medical needs such as the visually impaired. A more flexible and dynamic solution is needed with options for both the provision of additional artificial light and the introduction of more natural light. It is now evident that daylight is not just a stimulus for vision, but acts as a key element in the regulation of many areas of human health. Sunlight through windows are an efficient means to deliver natural light, ideally compensating for the move of almost all sectors of society from the outside environment into covered dwelling spaces.

Healthy Indoor Air

Opening windows brings in fresh outdoor air and provides contact to the outside and rapid changes of indoor air quality. It allows you to sense changes in weather during the day and over the year. Contact to the outside is important for the well-being of occupants in residential buildings.

Airings should be a part of the daily cycle. It is executed by many families and associated with wellbeing, comfort and health. Operable windows ideally should be combined with a general system for basic fresh air supply using ventilation grilles in the facades or mechanical ventilation.

Opening windows provides the occupants with an immediate change in the indoor environment, i.e. with a direct effect on air temperature, air velocity and air change rates. Efficient airings can be achieved by having more than one operable window and by locating these windows towards different orientations or at different heights in each main room. There should also be good options for cross and stack ventilation between rooms through the building.

Ventilation devices should be designed in such a way that occupants can prioritize privacy and silent operation when they prefer minimum sensory stimulation, e.g. during night time, but without compromising the basic requirements for ventilation. Control of the systems (and the momentary fresh air supply) is important. For more information about control of ventilation, see also under 'building controls'.

Many indoor air pollutants often present in dwellings cannot be sensed by humans and the house should, therefore, offer protection from these 'stealth pollutants'.

To minimize adverse health effects from indoor air pollution, the primary strategy should be source control, for example:

- Minimize, or preferably eliminate, emission of substances from building materials, which have documented health risks;
- Minimize, or preferably eliminate, emission of substances from consumer products, which have documented health risks;
- Minimize exposure to excess levels of outdoor airborne pollution;
- Minimize exposure to particle emissions from indoor sources like cooking;
- Minimize exposure to radon gas from the ground by investigating the local radon exposure and following local regulations as a minimum;
- Provide occupants with information and guidance that will support their choice of low pollutant-emitting furniture, household equipment, consumer products, cleaning agents, etc.

The kitchen can be the most affected room due to the pollutants (particles, NOx, etc.) emitted from the stove and oven when cooking. The negative health effect is increased if the kitchen is in open connection with the dining area, as exposure to cooking-related particles are not limited to the kitchen area in that case. The most effective means of reducing pollutant exposure from cooking is by using an efficient cooking hood and ensuring that it will be turned on and in use whenever the kitchen is used for cooking. The cooking hood should be sufficiently quiet so that it does not annoy the occupants, but should be audible so that it is not forgotten.

In kitchens and bathrooms, exposure to (excess peak levels of) moisture is also an issue. Well-functioning ventilation systems and adequate cooking hoods also take care of that.

Note that periodical exposure to pollutants in small and non-harmful doses, particularly as a child, will decrease the risk of developing allergies at a later stage in life. The effect is referred to as the hygiene hypothesis and is related to the functioning of the immune system.

In previous centuries, ventilation with high air change rates using natural ventilation was used to prevent spread of infectious diseases in patient rooms in hospitals. Maybe this approach can also reduce the spread of infectious diseases in homes. Note that UV light was also considered germicidal.

Natural ventilation is prioritised for the supply of fresh outdoor air. Natural ventilation can be combined with mechanical ventilation (hybrid ventilation). In that case mechanical ventilation with heat recovery is used only during cold periods to reduce energy use for heating. At other times, the ventilation can be natural and the ventilation rates can be substantially higher, which will help prevent overheating and also improve indoor air quality.

Current building regulations and ventilation design practices treat the entire house as one unit/zone. Consequently, some parts of the house will be ventilated too much and some too little (most notably: bedrooms). A room-by-room approach (demand-controlled ventilation) would provide better indoor air quality. Demand-controlled ventilation will further improve the situation and at the same time limit the energy use for ventilation.

Emissions from Building Material and Consumer Products

Emissions of volatile organic compounds (VOC) from building materials, furnishing, decoration and consumer products need special attention. All interior materials emit chemicals to the indoor air and it is important to choose products that have low emissions and do not emit substances at hazardous levels. It is possible to select building materials on the market with special labels that guarantee low emission levels.

When choosing building and interior materials, different emission labels can be used. Many labelling schemes are available in the EU, but not all are required by regulation. Chemical products require a hazard classification, which addresses the chemical content of those material,s but does not address emissions to indoor air. The German AGBB label (AGBB = Ausschuss zur gesundheitlichen Bewertung von Bauprodukten or Committee for Health-related Evaluation of Building Products) provides limits for emissions of selected substances. The French VOC label (Émissions dans l'air intérieur) also has limits for a selected set of substances and is obligatory in France from September 2013. Both labels are based on tests of emission described in ISO 16000. Other emission labels that can be used are the Nordic (Scandinavian) Ecolabel, the European Ecolabel, the Finnish M1 label and the Danish Indoor Climate label.

Not only building materials emit chemicals to the air. Also furniture, electrical appliances and even toys can lead to deterioration of the indoor air. Occupants will bring in their furniture and belongings, and rooms will have different uses over time dependent on occupant needs. Therefore, the design of the house must be robust towards such changes in use and in emission loads over time. This applies especially to the design of the ventilation system: it should be able to accommodate different loads and uses.

Materials should also be easy to clean. A clean house is one of the primary measures against spread of disease. Note that it is not just cleaning intensity that matters in terms of indoor air quality, also the cleaning method should be considered and the cleaning products that are used.

Bedrooms should have easy access to places where bed linen can be vented periodically. This will reduce the moisture content of the bed linen and, thereby, reduce the prevalence of house dust mites. House dust mites thrive in moist sleeping environments and are a cause of allergy.

Healthy Thermal Environment

Preferably indoor temperature varies over the course of the day, in parallel with the outdoor temperature, which typically increases during the day and drops during the night. The indoor temperature should also follow the seasons (with limitations, of course), with minimum levels during the winter and maximum levels in summer.

Solar gains through windows have a large impact on the indoor temperature and should primarily be controlled with shading. Solar gains provide spatial variation of temperature in the rooms with local warm and cool spots. During winter with little solar gains, a local 'hot spot' should be provided for in e.g. the living room, typically with a high temperature (vertical) radiant heat source. This 'hot spot' allows the occupants to seek a warm or cool position in the room that suits them and may thermally differ from the position of others in the same room. This 'hot spot' can look like a fireplace or gas stove in older houses, but then in a modern form without the air pollution side effects, e.g. hot water based local heating systems.

In many cases healthy heating implies that radiant heat is used, not convective heating or warm air heating. Floor heating or radiant panels are good examples of radiant heating systems.

It should be possible to control the heating at room level, e.g. with thermostats on radiators or adjustable wall thermostats. It is important that the thermostats are effective at generating a fast enough response in change of room temperature when turned up or down.

A healthy environment implies that the right thermal environment is provided for. The dwelling and e.g. its heating system should be designed for adequate thermal comfort both in summer and winter.

Architectural spaces should ideally promote people to have an active and healthy lifestyle, as opposed to being more passive. A thermally comfortable environment is not necessarily one that favours physical health. An example is a study by Van Marken, Lichtenbelt & Kingma, in 2013 which showed that for persons exposed to an indoor temperature at the low end or even just below the comfort range, non-shivering thermogenesis is activated which leads to increased metabolism. It is thus a quality of the indoor environment if there is some temperature variation and temperatures in winter are a bit on the cold side (and in summer on the warm side).

In summer the main issue is to keep the dwelling cool and avoid too high temperatures from excess solar gains. Overheating can normally be avoided by the use of solar shading and natural ventilation through window openings. Additional summer ventilation can be achieved by cross ventilation or stack ventilation (e.g. with windows and/or skylights in adjacent walls/roofs). Bedrooms are particularly important and must be designed and located to minimise overheating, e.g. by choosing a north/east location.

Night cooling is particularly efficient during warm periods, especially, if the dwellings have adequate thermal mass. Additional thermal mass will increase the capacity of the building to reduce temperature variations and, thereby, provide more robust thermal comfort.

Additional active mechanical cooling should be used as a last resort only to be applied when passive measures are insufficient.

As 70% of the time spent in dwellings for the average resident is in the bedroom, the environment in the bedroom has a huge impact on our health and wellbeing. Inadequate thermal conditions in the bedroom can affect sleep quality, both in winter and in summer. The temperature in the bedroom influences body temperature, which has a substantial influence on sleep. It is especially the room temperature that a person is exposed to while falling asleep that has a large influence on the sleep quality, larger than the room temperature during the sleep.

Research suggests that a lower room temperature (as low as 16°C) during sleep than when awake is preferred. This has to do with thermal insulation of duvets and blankets that in most cases overcompensate for the reduced activity level during the sleep. The maximum temperature in a bedroom should be several degrees lower than in other rooms. It is important that a light duvet and light night dress is used during warm periods.

Bedrooms ideally have a north or east orientation, not a south or west orientation.

The heating system must have additional heating capacity and must e.g. be able to heat up the house after a winter vacation. Cold draughts from entrance doors must be considered (and can be avoided e.g. with two entrance doors in cascade) to avoid excessive use of heating and unnecessarily cooling down of living spaces.

Acoustics

Sound from the outside can be allowed to a certain extent during the day, but the occupants should be able to control the indoor level. Sounds that are "expected" and "wanted" are more acceptable and desired, e.g. the sounds of street life through an open window during daytime. Research is insufficient, but the existing data indicate that variations in sound levels and exposure to noise (unwanted sounds) can have a negative impact on wellbeing. High traffic noise levels indoors cause stress and should be avoided, especially in bedrooms.

There is often a trade-off effect, for example higher noise levels can be accepted in combination with the satisfaction of a specific need e.g. fresh outdoor air through open windows. This, however, requires that the occupant is in control.

Installation noise levels should be kept below 25-30 dB (A) in the main living spaces. At night, even lower noise levels are desired. It is important that occupants can adjust the momentary settings of ventilation systems manually in order to limit the noise levels when needed.

Also, noise from heating and cooling systems must be limited. Modern, energy efficient buildings have an increasing amount of complex building service systems (e.g. heat pumps) and the noise from these systems has been a problem in quite a few cases.

Adequate sound insulation between rooms and adjacent dwellings (neighbours) is important to allow for acoustic privacy. Both quiet and noisy activities must be possible without disturbing others or being disturbed by others.

Reverberation time is an important parameter for the acoustical experience of indoor spaces. Often buildings with 'soft' interior surfaces are being appreciated more by occupants and visitors. The right acoustics inside certainly supports overall wellbeing.

Building Controls

It is important that the functioning of control systems is transparent and comprehensible for the occupants and they can easily adjust the interior daylight levels, electric lighting, temperature, fresh air supply etc. according to their personal needs. Automatic systems are often of advantage, but always see to it that easy-to-use options to override the systems are available. Feedback indicators on e.g. indoor air quality and temperatures (telling you that the systems have understood that you want some kind of change and giving you information about the current status of e.g. temperature, CO_2-levels, etc.) are a plus as they help occupants to use the building service systems 'as intended'.

It is important that many indoor climate parameters can be controlled at the individual room level, not just at building level. Automated control strategies that work in one kind of room may not work in other room types. For example, let us look at ideally automatic control strategies for ventilation:

- Bedrooms: Automatic control based on presence detection or CO_2 concentration is preferable;
- Living rooms: Automatic control based on CO_2 concentration is preferable;
- Kitchen: Automatic control based on relative humidity or maybe even fine particles is preferable; an alternative is a cooking hood that is activated automatically when the furnace/stove is in use;
- Bathrooms and toilets: Automatic control based on presence detection or relative humidity is preferable.

Control strategies, where possible, should support the circadian rhythms of residents. For example, the control strategy for electric lighting could include light sources with varying spectrum and intensity enabling programming according to time of day and type of room. Also, e.g. heating systems could be programmed to anticipate daily temperature changes.

A building control system needs to be robust toward different kinds of occupant use, toward failures/problems of parts of the systems, toward incorrect design assumptions (e.g. number of persons per room) and against occupant misuse.

At least, the following systems require some central control in combination with manual override options and an interface:

- Mechanical ventilation systems;
- Heating systems;
- Window opening systems;
- Solar shading systems;
- Electric lighting systems.

Simple, autonomous or advanced, central control?
The control system approach can be simple-autonomous or advanced with central control. The simple-autonomous approach is based on autonomous controls of e.g. window openings, radiator thermostats and solar shading. Each can be sensor-based and based on sophisticated algorithms, but each simple-autonomous control unit should operate independently of other controls. Positive and negative feedback/interference between controls should be carefully considered.

The advanced-central approach is based on an advanced system with central control with local sensors connected to a central control unit. The central unit controls all systems in the house based on sophisticated algorithms. An example is the use of presence (PIR) sensors that detect activity after a period without occupancy, which will automatically lead to an airing (or flush) ventilation cycle.

Commissioning & Post Occupancy Evaluation

When you construct circadian houses it is important to make sure that the design criteria (see e.g. the Appendix) are met when the buildings are finished and operational. Adequate verification at the different building stages is essential to ensure that the house will perform as originally planned. Evaluations should be made during the design phase, upon delivery and during use of the house.

The following aspects should be considered in this context:

- What should be checked or measured?
- When and for how long should this be done?
- Should the performance be evaluated in all rooms and dwellings or just in a selection of them?
- Where in the rooms should measurements take place?
- How to evaluate the performance: qualitative and/or quantitative?
- Which standard guidelines should be valid for measurements, simulations and e.g. questionnaires?
- What is the rationale behind the verification steps?

It often makes sense to make a systematic inventory of the building occupants' experiences. If so, choose a (Pre-) Post-Occupancy Evaluation based on questionnaires and structured interviews. Ideally, also create a 'benchmark' level of experience while the occupants are still living in their old homes (before moving into the new homes – test situation). The questionnaires to be used should be validated; and validated scales for subjective well-being, sleep-quality ratings, mood and alertness, etc. should be used. Aspects that can be included in a (Pre-) Post-Occupancy Evaluation are for example:

- Sleep patterns, e.g. with sleep diary, objective measurement of the 24h rest-activity cycle (actiwatch) and/or use of the Karolinska Sleepiness Scale (KSS);
- Self-reported health and well-being (e.g. using the WHO (Five) Well-Being Index or PANAS);
- Satisfaction with the indoor environment (e.g. with standard questions on satisfaction with lighting, thermal environment, indoor air quality, etc.).

The (Pre-) Post-Occupancy Evaluation, while living in the house, should include the elements mentioned above and be distributed several times to the occupants, taking into account seasonal effects. Care should be taken not to include elements which could be perceived by the residents as invasive (e.g. physiological or biochemical measurements using saliva, blood samples and/or urine for analyses, cortisol, melatonin or body temperature and heart rate). If possible, the same aspects should be evaluated after the occupants move out.

At the building level, the measurement program should include details about for example installation noise measurements (e.g. dB(A) as well as dB(C) to ensure that low-frequency noise is identified), inside and outside particle measurements, interior light levels during daytime, artificial lighting levels, fresh air supply and exhaust, and indoor temperatures. The time-frame is a minimum of one to two weeks of pre-measurement after the house has been certified for occupation and building control systems have been tested for operation. The measurement program should deliver data for the buildings as a whole and at room level.

Further reading

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Appendix: Activity and room-based considerations

The table below describes several design aspects (occupant needs) and their Key Performance Indicators (KPI's). In the third column, some suggestions are given on what criteria to use, both quantitative and qualitative. The last column describes specifics to take into account when designing specific rooms (e.g. bedrooms or kitchens).

Note that the performance indicators and criteria presented in this appendix should be regarded as general guidance on how to design when you aim at realizing a Circadian House. The requirements should be tailored for the specific situation when used for a concrete project.

Need	KPI	Standard criterion	Remarks
Light	Light source	Daylight should be used as the primary light source in all main rooms/areas occupied during daytime.	-
	Daylight levels when awake	Provide opportunities for exposure to high levels of daylight – range from more than 1000 lux up to around 5000 lux - design to minimise visual discomfort. The daily light dose per day exposed to >1000 lux should on average be more than 200 minutes with high intensity boosts, especially in the morning	A dwelling should follow the natural cycle of light and dark exposure - allowing high exposure to daylight in rooms used in the morning and in the main activity rooms used throughout the day. Opportunities for exposure to high light levels (>1000 lux) are particularly important in bedrooms, bathrooms, breakfast area and the main activity rooms that are used during daytime. Secondary rooms and circulation areas should, preferably, also have windows for daylight provision and contact to the outdoors. Also the house should have good adjacent outdoor spaces for daylight exposure (terrace, garden, balcony, etc.).
	Daylight levels when asleep	Sleeping rooms should ensure minimal night-time exposure to light, e.g. with adequate black-out blinds or curtains.	It is important to carefully consider exposure to darkness during the sleeping periods. Bedrooms should be completely dark during the sleeping period.

Need	KPI	Standard criterion	Remarks
	Electrical lighting	Electrical lighting should be used as a supplement to daylight when daylight is not available or insufficient (e.g. early morning (winter) and evening periods). Electrical lighting should follow the variation in spectrum and intensity experienced with daylight at the respective times of the day (e.g. morning, midday and evening spectrum). Colour rendering index (CRI) should be higher than 90.	Special attention should be given to the morning rooms in order to provide the occupants with the high light levels they need in the winter period. Special attention should be given to the rooms used at night during sleeping hours, e.g. bathroom and circulation areas. Electric light sources used inside the building should be carefully designed to the context of the space, time-of-use etc. As an example, a blue-rich LED light source should be avoided in bedrooms, especially for bedside lamps. But a more blue-rich light source could be used in bathrooms as a morning wake-up source. Provide adequate levels of artificial lighting suitable for the visual tasks performed by the occupants and for their biological needs.
Contact to the outdoor	Content of view	View to the outdoors should allow for visual contact with the sky, the ground and landscape components.	-
	View in multiple directions	It is preferable with opportunities for a view in multiple directions.	-
	Privacy	Some rooms and activities of the house require privacy from the outdoors, in which case it should be possible to block the view from the outside (curtains, shutters).	Privacy is especially important to consider in bathrooms and bedrooms, as well as other rooms depending on the situation of the house and the occupants' wishes.

Need	KPI	Standard criterion	Remarks
Adequate fresh air supply	CO_2 / bioeffluents concentration	The fresh air supply is such that the maximum CO_2 concentration is 1,000 ppm (or 600 ppm above the outdoor CO_2 concentration). Note that this is the amount needed to prevent olfactory discomfort from bioeffluents. If you aim at just preventing physical health problems, you can allow higher CO_2 levels, e.g. up to 1,500 ppm. An alternative to the CO_2 concentration (as proxy for bioeffluent concentration) could be presence of occupants.	It is possible – and preferable – to attain high ventilation rates and low CO_2 concentrations indoors by natural ventilation. (With natural ventilation systems, the risk of acute health symptoms is minimized as there is no need for maintenance of mechanical systems, which can become the source itself). This can be achieved by locating operable windows towards different orientations or at different heights within each room, and by providing good options for cross and stack ventilation through the building. Be aware of the use of CO_2 sensors, e.g. with demand controlled ventilation systems. These will give rise to problems unless high quality and well calibrated sensors are used…
Air quality source control	Particles	The PM 2.5 concentration is less than 20 μg/m³ (yearly average) or less than 40 μg/m³ (daily average) (based on WHO air quality guidelines).	Exposure inside to PM 2.5 from outdoor sources can be partly avoided by selecting an 'unpolluted building site' far enough away (>300 m) from busy roads, industry, agriculture etc. In case this is unavoidable: use extra supply filtering in ventilation grilles and mechanical ventilation systems, and design the façade for extra air tightness. Smoking and other particle producing activities (like burning of candles) indoors should be avoided. High levels of fine particles in kitchens during cooking activities can be largely avoided by adequate hoods/source ventilation.

Need	KPI	Standard criterion	Remarks
	Gases, Volatile Organic Compounds (VOC's)	For specific exposure limits for VOC's: see the 'WHO guidelines for IAQ' report.	Use source control where possible. For example, select low emission building materials and low emission installation components where possible. Avoid building site with polluted soil if possible. Certain cleaning products may cause problems, low emission products are preferred. Children's rooms can contain many toys and electronic devices, which may emit high levels of chemical substances. These substances can build up when the rooms are unoccupied and unventilated.
	Excess moisture and mould	At normal use indoor, the absolute humidity level should not be higher than 3 g/kg above the outdoor levels.	Source control (e.g. peak ventilation of bathrooms during showers) is the first choice. Several studies found strong associations between dampness and moulds in buildings and asthma plus other health problems. But no exact limits can be given yet for safe mould concentrations or humidity levels. Follow the EU precautionary principle ('exposure as low as reasonably achievable') and keep inside humidity at the level as described to the left. In kitchens, the main strategy should be to 'catch' cooking moisture (and other cooking related pollutants) at the source, e.g. with high efficiency cooking hoods (that do not disturb the general mechanical ventilation system, if there is any). Recirculation cooking hoods should be avoided. Maintenance of both hood system and general mechanical ventilation systems that serve the kitchen area and e.g. the bathroom is important. Clothes should not be dried indoors.
	Radon	Radon concentration should be kept below 100 Bq/m^3.	Radon is mainly a problem in areas with Radon rich soil. Make a test on site if in doubt whether anti-Radon measures should be taken (e.g. installation of a separate extraction ventilation system for the crawl space).

Need	KPI	Standard criterion	Remarks
Cool environment in summer	Maximum operative summer temperature	The maximum operative temperature during warm periods (with a running mean outdoor temperature T_{rm} - see EN 15251 – of 12°C or more) is below the adaptive maximum indoor temperature levels as described in Annex A2 of EN 15251 for naturally ventilated buildings.	In bedrooms, temperatures should be lower than in other rooms (e.g. by 2°C) as one is more sensitive to high temperatures when falling asleep. Therefore, bedrooms are ideally placed to the north or east. Especially, the temperature *in* the bed (under sheets etc.) matters; always correct for the clo value of the mattress and the bedding.
	Air motion summer	Air motion from personally controlled devices, e.g. operable windows and table fans, compensate for increased air temperature. Air velocities up to 1.0 m/s are acceptable (but only when under direct control by occupants) with a temperature offset that can be determined from e.g. figure A2 in EN 15251.	-
Warm environment in winter	Minimum operative winter temperature	The minimum operative temperature during cold periods (with T_{rm} below 12°C) is above 20°C or class B level for winter as described in EN 15251.	In bedrooms and circulation areas, lower temperatures can be allowed. Bathrooms require a higher temperature (e.g. by 4°C) than other rooms, as you sometimes spend time there naked.
	Draft & other local discomfort - winter	Airspeed levels should be below 0.20 m/s in winter in living zones. For criteria for other kinds of local discomfort (e.g. radiant asymmetry), see the class B requirements for local discomfort in ISO EN 7730 and/or EN 15251.	Natural ventilation openings must be located so that airings can be made without disturbing defined working/sitting areas in the house. Draft should also be addressed when selecting ventilation system components (esp. air inlets).
Quiet environment	Installation noise level	Installation level, e.g. from ventilation or heating systems, below 25-30 dB (A).	In bedrooms this should be below 20-25 dB (A). Levels up to 45-50 dB (A) are temporarily allowed in bathrooms and kitchens (to allow for moisture peaks).
	Internal wall sound insulation	Acoustical wall insulation should comply with local building regulations.	For extra acoustic privacy or to guarantee sleep quality in bedrooms, better sound insulation may be required than described in the standard building regulations. In those cases requirements for hotel rooms can be used for inspiration. Special attention is needed for rooms used during the day for work at home: here also extra sound insulation might be needed.

Need	KPI	Standard criterion	Remarks
	Facade sound insulation	Acoustical insulation of facades should also comply with local building regulations.	Modern stereo installations are very powerful and have a lot of low frequency noise to be considered when designing or analysing wall insulation between dwellings. Urban zones have special problems and ask for extra insulation of facades. In more noisy environments (e.g. next to busy roads), bedrooms should be placed on the quiet side of the building.
Effective control of indoor climate	Potential for control of light exposure	Daylight penetration should be adjustable, e.g. by curtains or solar shading. Also electric lighting should be adjustable (and ideally even the lighting colour).	-
	Potential for control of ventilation	Air exchange rate should be adjustable by occupants in a large range (e.g. between 0.1 and 10 air exchange rates). Operable windows and other natural ventilation devices should be easily adjustable. If a mechanical ventilation system is in place: make sure that the system has at least 3 different settings that can be influenced by the end users.	The relevance of insect screens in summer should be considered. Bathrooms ideally have operable windows to supply for extra natural ventilation when wanted by the occupant. Mechanical ventilation systems should be adjustable at least in the kitchen and bathroom.
	Potential for control of temperature in winter (heating)	Thermostats or other temperature control devices should allow for control of the heating system in winter. The preferred temperature range is about +/- 4°C around a standard set point.	The first choice is control options at room level, not just at building level.
	Potential for control of temperature in summer (heat influx)	Operable windows, solar shading systems, etc. should allow for control of the thermal environment indoors in summer.	Limitation of solar influx in summer is especially important in bedrooms.

Need	KPI	Standard criterion	Remarks
	Potential for control of installation noise	Noise producing climate systems (e.g. for ventilation or heating) are adjustable with at least 3 different settings (3 different noise levels).	When automatic control of climate systems producing noise is used, make sure the systems can be overruled manually.