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PRINCIPLES AND TOOLS FOR BIOCLIMATIC BUILDING DESIGN
- an applied review and analysis in cold climates –

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Abstract: The comparison between climate and comfort represents a fundamental step for the implementation of energy efficiency in buildings. It determines the design strategies that are best suited for a specific climatic context, as well as the level of architectural complexity. In cold climatic contexts, this would suggest the use of compact shapes and extremely airtight and well-insulated envelopes, in order to minimize heat losses. However, when combined with high internal gains, these measures might cause overheating problems in the warm and transitional seasons. That is especially the case of office buildings, where mechanical cooling is included as default even in cold climates (Norway), drastically increasing their energy use. It is therefore becoming a necessity to consider there the adoption of passive strategies for cooling, traditionally identified with warmer climates. The aim of this paper is first to revise the existing methods and tools for bioclimatic building design, and then reflect on how these could be applied to assess the suitability of different passive strategies in relevant building cases. The first part of this research will be conducted through literature review. The second part will analyse relevant buildings in cold climates with especial focus on passive design, to reflect on how they could have been affected by the use of these bioclimatic building design tools.

Keywords: bioclimatic building design, passive strategies, thermal comfort, psychrometric chart, pre-early design stage

Introduction

As Reyner Banham postulated in his *Architecture of the well-tempered environment* (Banham, 1984), indoor comfort can be provided passively by the building, or actively by the use of energy. However, in order to design energy efficient buildings, passive strategies must be considered during the early design phase (Lechner, 2009). It is important as well to have a close collaboration between architects and engineers throughout the building design process in what is called "Integrated Energy Design" (Heiselberg, 2007). This is fundamental to ensure their mutual understanding of the project and the means to reach their common goals, making use of their different competencies and ways of thinking and working.

Problem statement

Traditionally, the choice of passive design strategies for climatic control in buildings was based on experience (vernacular architecture). Even today, the most common methods in use in many countries are experience-based (rules of thumb, building standards and norms, etc.). However, new building morphology, typologies (e.g. office buildings), elements and materials are challenging these pre-design methods to move towards research-based approaches.

This is the case of the Building Bioclimatic Charts that were developed in the second half of the 20th century. The most extended one is the Givoni-Milne bioclimatic chart (Milne and Givoni, 1979), that studies how to reach thermal comfort within the psychrometric chart. It considers as well the potential for extending the comfort zone by means of different passive design strategies for climate regulation. However, being developed primarily for warm climates, this method seems to be insufficient for identifying the correct measures for climate adaptation in energy efficient buildings in cold climates, under specific conditions (Finocchiaro et al., 2010). The use of extremely stringent envelopes, in combination with the high internal gains characterizing office buildings, is implying here the use of strategies for passive cooling, natural ventilation and solar control, once identified with warmer climates.

Purpose and methodology

In the first part of this paper, it will be offered a short review of the principles and tools for bioclimatic building design, reflecting on their suitability for cold climates. This section relies primarily on literature review.

The second part studies how these methods and tools could be adapted and applied to assess the suitability of different strategies for climate control in office buildings in cold climates, with especial focus on passive design. This is explored in two different case analysis.

Principles and tools for bioclimatic building design

The term *bioclimatic building design*, combining *biology* and *climate*, refers to the design of buildings in accordance to the local climate (Olgyay, 1963). Thus, the architectural design is linked to the physiological and psychological need for health and comfort. It also implies maximizing the utilisation of the available natural resources, prior to any energy supplement by active means.

Climate classification

The most widely used system is the Köppen-Geiger climate classification (Köppen and Geiger, 1930), based on temperature and precipitation. Following this scheme, a *cold climate* (represented by the letter D, also called *snow*) would be represented by an average temperature of ≥ 10°C for the warmest month and ≤ 0°C for the coldest month (-3°C according to some authors). The discrepancy in the temperature range for this type of climate is due to the fact that this classification is done according to the natural vegetation systems that are associated to each climatic zone (to represent long term mean climate conditions). The correspondence between these and the monthly mean temperature of the coldest month differs in some cases, e.g. for North America and Europe (Wilcock, 1968).

In the last years, a more specific climate classification for analysing the performance of energy efficiency measures in buildings was developed for the ASHRAE (Briggs et al., 2003b). Primarily designed in the United States for the implementation of energy codes and standards in buildings, it may also be applied in design guidelines and energy analysis in buildings. It uses SI units and climate indices based on the Köppen-Geiger system (Strahler, 1969), so that it can be adopted anywhere in the world. According to this system, a *cold climate* would include those regions with heating degree days (HDD) 18°C > 3000 (Briggs et al., 2003a).

The ASHRAE climate classification seems more adequate for energy analysis in buildings in general, which makes it more suitable for the present study.

Thermal comfort

An internationally-accepted definition of thermal comfort is ”that condition of mind which expresses satisfaction with the thermal environment” (ISO, 2006)

The evolution of indoor thermal comfort theories follow a continuous line from the first studies on thermal neutrality (static approach) conducted by Fanger (Fanger, 1970), to the ones on adaptive thermal comfort (de Dear and Brager, 1998, Humphreys and Nicol, 1998), to the newest developments towards transient thermal environments with the theory of thermal alliesthesia (De Dear, 2011).

The *static approach* is an analytical method derived from the assumption that the combination of skin temperature and core temperature of the body provide a sensation of thermal neutrality. The heat produced by the metabolism should be equal to the heat loss from the body. This approach to thermal comfort is based on the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied People (PPD). It is used mainly for mechanically ventilated buildings, where thermal neutrality is an achievable demand.

The *adaptive approach* considers that contextual factors and past thermal history modify thermal expectations and preferences of the occupants in the building, through behavioural adjustment and psychological adaptation. It is a numerical method, used for natural or hybrid ventilation in buildings, where the occupants are tolerant of a significantly wider range of temperatures, according to seasonality.

The *transient approach* investigates thermal pleasure derived from environmental or metabolic transients. The thermal alliesthesia studies how thermal comfort in buildings can improve by allowing a broader variety of thermal solutions in different spaces, or in the same space in different moments in the year (seasonality) or the day, to mimic natural environments. This theory is still in an early stage of development.

Being this research focused mainly on the implementation of passive strategies for climate control, the adaptive approach seems to be the most relevant one here. Nevertheless, since its range of application is for mean monthly outdoor temperatures between 10°C and 34°C, which are not that common in cold climates, the static approach to thermal comfort will be considered in this study.

Building bioclimatic chart

The concept of constructing buildings in accordance to the climate is as old as humanity, but bioclimatic architecture was not recognised as a science until the Olgyay brothers started publishing their studies on climate-conscious design. They created the first Bioclimatic Chart in the early 50s and developed it in their book *Design with climate* (Olgyay, 1963). It was based on a Cartesian system with dry bulb temperature and relative humidity as coordinates, and shows the potential of wind and solar radiation on human thermal comfort. This method is suitable for application outdoors or for lightweight buildings in warm and humid regions, where there is little difference between indoor and outdoor conditions (Givoni, 1969), since it uses outdoor temperatures directly in the chart.

Soon after, Baruch Givoni adapted those concepts in his book *Man, climate and architecture* (Givoni, 1969), to create the first Building Bioclimatic Chart (BBCC). He used an Index of Thermal Stress (ITS) to evaluate the human requirements for the indoor environment to which the building design should respond. He also changed the graphical representation by using the psychrometric chart, to better show the hygrometric relations between the different parameters, and in a way that was already accepted and widely used by engineers since 1904, when it was first published by Willis Carrier (Gatley, 2004). In addition, he plotted into the chart the comfort zone and the areas of influence of different passive strategies (Milne and Givoni, 1979). This BBCC is still today the most widely used around the world, and it has been constantly updated according to new studies on the field. However, being developed for residential buildings with relatively light construction in warm climates, it does not take into consideration the effect of highly insulated and airtight envelopes in cold climates, especially when combined with high internal gains (office buildings).

There have been developed several computer programs to help analysing the building bioclimatic chart for its application onto energy efficient design. Amongst them, Climate Consultant© seems to be the most complete, up-to-date and user friendly. Developed by the UCLA Energy Design Tools Group, it is based on the theoretical work by Givoni and Milne (Givoni, 1969, Givoni, 1994, Milne and Givoni, 1979) and intended to support the book Climatic Building Design by Watson and Labs (Watson and Labs, 1992). It uses weather data in EPW format (Energy Plus Weather, exhaustive selection of weather stations around the globe, freely available) and can analyse it according to four different comfort models in the Psychrometric Chart. Yet it was designed to be applied on residential or small non-residential buildings in mild climates (Milne, 2015).

Case analysis

With the increased consciousness of living on a finite planet, there has been a proliferation of low-energy buildings, passive house, net zero emission buildings, zero emission buildings or even plus energy buildings. However, this number becomes drastically reduced when limiting the sample to office buildings in cold climates, with a special emphasis on energy efficiency through passive design strategies.

The cases chosen here for their level of innovation and integration, while offering a very different approach to energy efficient design in cold climates are: Manitoba Hydro Place (new built, Winnipeg, 2008) and Powerhouse Kjørbo (refurbishment, Bærum, 1979-2014).

This analysis will focus first on the local climate, to then study the spontaneously created microclimate (because of the stringent envelope and high internal gains) and the selection of passive strategies for climate control. The results will be then compared to similar conventional solutions, to understand the effect of the choices made under the design process.

Manitoba Hydro Place

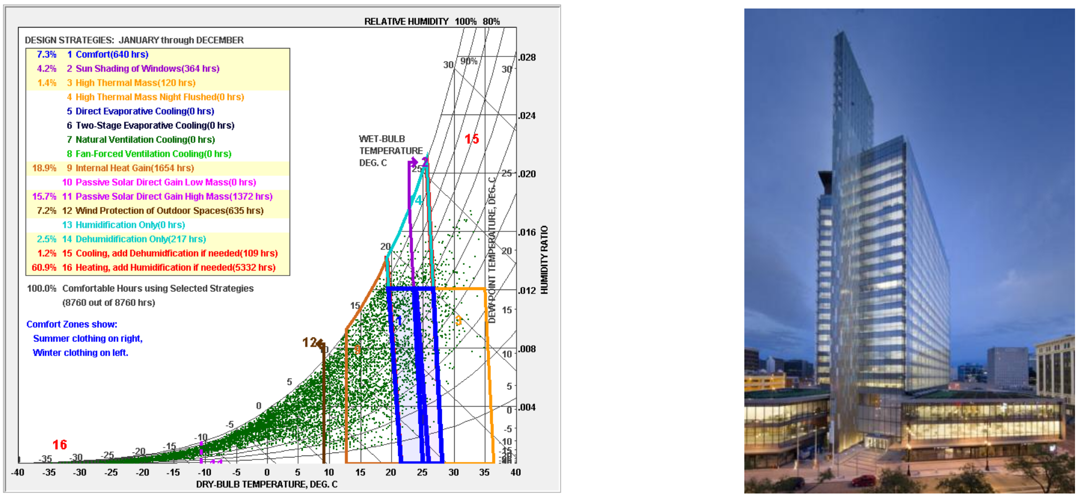
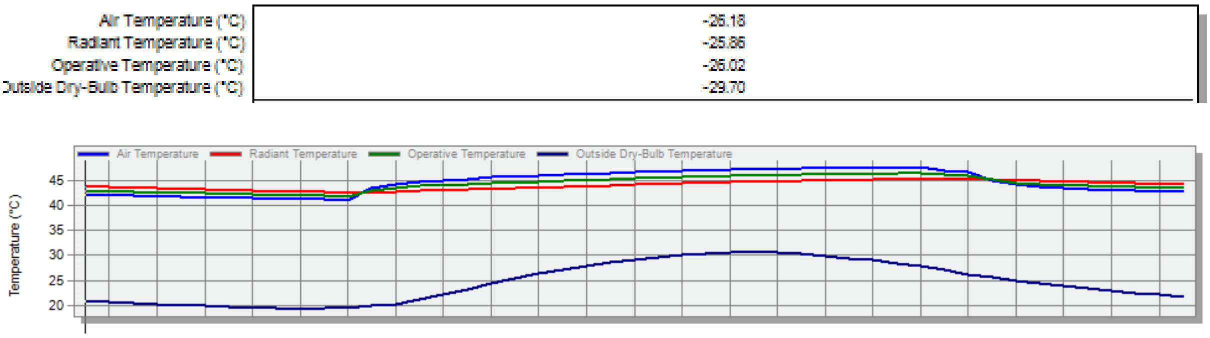


Figure 1. Left: bioclimatic chart for Winnipeg, from Climate Consultant© (Milne, 2015). Right: Manitoba Hydro Place, Winnipeg (Canada). Image: AIA top ten.

This office building is located in Winnipeg, Canada. It was designed by KPMB Architects in cooperation with Transsolar KlimaEngineering. The Köppen-Geiger climate classification for Winnipeg is Dfa: cold (T_{hot}>10, T_{cold}≤0), without a dry season and with hot summers (T_{hot}≥22). In the ASHRAE climate classification, it corresponds to zone 7: *very cold,* with an average of 5703 HDD (5000 < HDD 18°C < 7000). According to the BBCC and the 2030 Palette (Milne, 2015), the most relevant passive design strategies for this location are aimed at maximizing solar gains in combination with interior thermal mass, and minimising heat losses (low mass envelope, compact, airtight, super insulated and protected from the wind). See Figure 1.



Air Temperature (°C)	-26.18
Radiant Temperature (°C)	-25.86
Operative Temperature (°C)	-26.02
utside Dry-Bulb Temperature (°C)	-29.70

Figure 2. Winter and summer design temperature for the office block to the west, without environmental control systems (Design Builder / Energy Plus). We can appreciate that the indoor air temperature is respectively 3°C and 18°C higher than the outdoor air temperature. This is due to the effect of the solar gains and envelope alone in the first case, and in combination with the internal gains in the second case.

If we consider though the temperature increase indoors due to the effect of the solar gains plus envelope and internal gains, prior to the implementation of environmental control systems, it becomes quite relevant the incorporation of those two factors (envelope and internal gains) into the BBCC. For the west office block, the solar gains and envelope alone help increasing the temperature +3°C compared to the outdoor values in winter, while together with the internal gains they produce a difference of +17°C in the summer. The indoor temperature becomes -26°C in winter and 47°C in summer, far away from comfort. See Figure 2.

The design of this building includes in fact several passive cooling strategies. It relies on a tempered buffer respiratory system with double-glass curtain walls to the east and west, and a series of three-floor-high atria to the north and six-floor-high atria to the south, to preheat the incoming air, minimising also the need for insulation materials. This system provides for fresh air all year round, in combination with a solar chimney for air extraction by stack effect, and elevated floors for air intake by displacement ventilation. In addition, each south atrium includes a water feature to humidify/dehumidify incoming air depending on the seasonal needs. It also utilizes a geothermal heat pump system for radiant heating and cooling via the exposed overhead concrete slab. Besides, it allows for operable windows and includes automated solar shading to prevent overheating. The U-values for the envelope are very low, ranging between 0.02 and 0.23 W/m^{2}K, and it is very airtight and relatively compact ($C=4.836*V_t^{2/3}S_G=0,63$ (Florensa and Roura, 2001)).

Due to its climate responsive design, its total energy consumption was of 138 kWh/m2 in 2011 , which implies a 66% of energy savings, compared to the Canadian Model National Energy Code for Buildings (Kuwabara et al., 2013).

Powerhouse Kjørbo

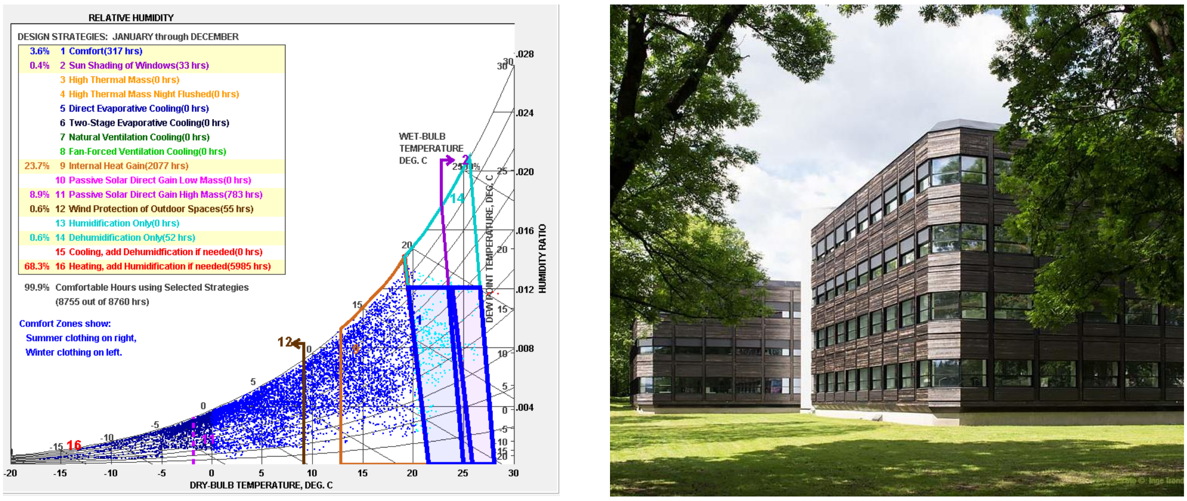


Figure 3. Left: bioclimatic chart for Oslo, from Climate Consultant© (Milne, 2015). Right: Powerhouse Kjørbo, Oslo (Norway). Image: Norwegian Green Building Centre.

This case is a refurbishment of two office blocks linked by the elevators and stairs. It is a pilot project for the Zero Emission Building Centre and was developed by the Powerhouse consortium as a ZEB. It is located in Bærum, near Oslo (Dfb), with a cold climate, without dry season and with warm summers ($T_{mon10} \geq 4$). Classified in ASHRAE as zone 5: *cool*, with 3700 HDD (3000 < HDD 18°D < 4000). The recommendations from the BBCC and the 2030 Palette are very similar to the previous case, though with a lower efficiency for thermal mass because of the higher cloud coverage throughout the year. See Figure 3.

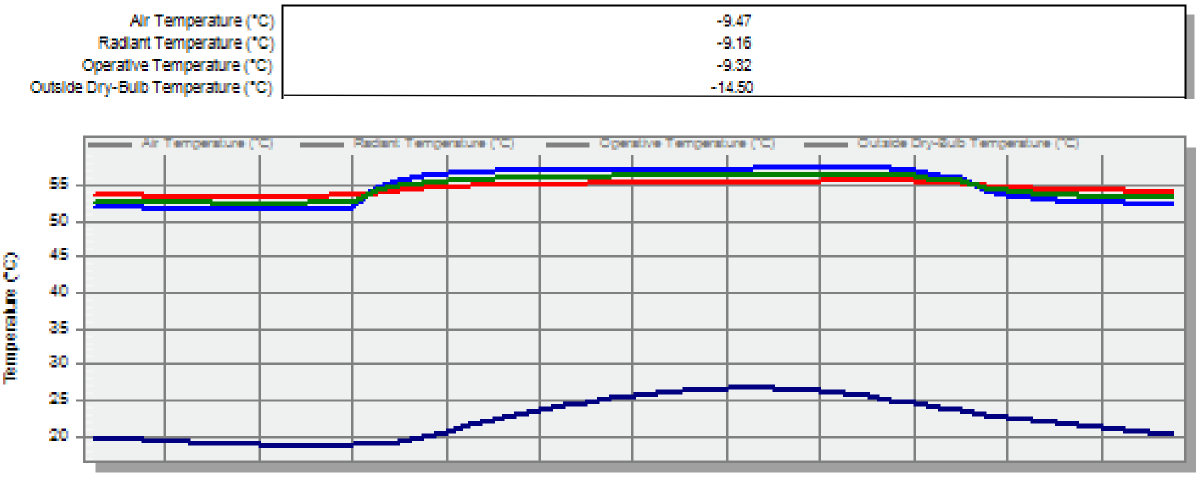


Figure 4. Heating and cooling design temperatures for the open landscape office without environmental control systems (Energy Plus). In this case, the difference between the indoor and outdoor air temperature is of around 5°C in the first case (envelope) and 30°C in the second (envelope and internal gains).

This office building is the case with highest compactness (0.76) and most stringent envelope, with an infiltration rate of just 0.23 ach and U-values between 0.08 and 0.8 W/m^{2}K (corresponding to the Norwegian Passivhaus Standard). This makes it possible to have a temperature increase in the winter of around 5°C indoors, compared to the outdoor conditions. See Figure 4. On the other hand, it also explains the extremely high air temperatures that could be reached indoors in the summer without environmental control systems. Then the highly insulated and airtight envelope does not allow the solar and internal gains to escape the building, creating a cumulative effect and reaching a temperature increase of around 30°C. This is due to the long summer days and the low angle of the sun that helps its penetration through the windows.

On the contrary, this building makes extensive use of thermal mass, leaving the concrete slabs exposed for thermal regulation in combination with the ventilation system (air intake from the façade on the top, distributing it in the central core, next to the concrete slabs for cooling of the structure). It maximizes daylighting as well, in conjunction with effective exterior solar screening to prevent overheating. Its building integrated ventilation solution makes use of the stairs and corridors for air distribution, allowing as well for opening the windows for natural ventilation in the warmer periods. Natural and hygroscopic materials with low emissivity help also in lowering the ventilation needs.

Together with the installation of sensors and a control system for lighting, equipment and installations, the total delivered energy was lowered to 45 kWh/m^{2}a including the operational energy for office equipment and server. As a reference, the Norwegian Building Code TEK-10 sets the total energy consumption for office buildings to 150 kWh/m^{2}a, so it achieved a reduction of 30% (Throndsen et al., 2015). If we exclude the consumption for the server and equipment to appreciate better the effect of the building envelope, it becomes around 20 kWh/m^{2}a, 80% lower than the typical case (Jensen et al., 2015).

Discussion and conclusion

As seen in the cases analysed, the very stringent envelopes used in cold climates have a very relevant effect in the indoor temperatures, especially in the summer. This is due to the fact that they are optimised for heat conservation in the winter, but it has a similar effect in the summer, when we need to dispose of the unwanted heat. When adding the high internal gains that are typical of office buildings, as well as the long days and low angle of the sun characteristic of high latitudes, these tend to create overheating problems.

It is also interesting to see the effect of these two different approaches to a similar problem. In the Manitoba Hydro Place, the main element for environmental control consists of a series of buffer zones along the façades. These allow for a higher flexibility in the regulation of the indoor conditions prior the use of mechanical systems, with the pre-heating or pre-cooling of the incoming air. On the other hand, it has a very limited effect in the winter (3°C temperature increase), unless it is combined with other heating systems. The summer temperatures obtained in the energy simulations also confirm the need for the combination of natural ventilation with evaporative cooling in the south atria for the pre-cooling of the incoming air.

On the other hand, the Powerhouse Kjørbo is a more typical case, relying on a highly insulated and airtight envelope, together with a very compact shape. This is reflected on an improved behaviour in the winter, with a temperature increase of 5°C. However, it also means that the unwanted heat produced or stored in the summer has it more difficult for escaping the building. This could cause severe overheating problems (up to 57°C) without environmental control systems, which supports the use of different passive strategies to avoid them.

Consequently, this research underlines the need for updating the existing methods for bioclimatic building design (BBCD), in order to consider the spontaneously generated microclimate, as a result of the use of stringent envelopes in combination with high internal gains in cold climates office buildings.

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