Building performance simulation analysis of an office building without conventional mechanical systems in a cold/temperate climate

Maria Coral Albelda-Estelles Ness

1Norwegian University of Science and Technology-NTNU, Trondheim, Norway

Abstract
This study is part of a project to revise the methodology for bioclimatic building design to improve its usability within cold climate architecture. This paper aims to study the impact that the choice of building performance simulation tool and model settings and simplifications can have on the results we obtain. We start with a more conventional approach to the BPS analysis of an office building without conventional mechanical systems in a cold/temperate climate, with typical model and simulation settings. Then we move into a more tailored approach, as an attempt to further approximate the reported measurements.

Highlights
• high-performance envelope (cold/temperate climate) substantially increases inter-dependence of indoor climate with internal gains, importance of correct schedules and values
• effect of moisture, very relevant both for BPS (settings/results) and bioclimatic analysis
• space conditioning approach: materials-based [vs.] air-based
• warm-up period with internal gains: significance for moisture load into the materials (the higher the load, the longer the loading period)
• from higher ventilation rates for CO₂ control, to lower values for moisture and comfort (allow moisture/thermal loads into materials)

Introduction
This study is part of a PhD thesis that aims to adapt the methodology for bioclimatic building design (BCBD) in cold climates, to account for the effect of highly insulated/airtight building envelopes on indoor climate. BCBD understands architecture as a filter between outdoor climate and indoor comfort (Olgyay, 1963). It encourages the exploitation of useful climatic resources, before adding any mechanical corrections to the indoor climate. It lies therefore at the base of the Trias Energetica and of building certification schemes focused on energy efficiency and thermal comfort (PassivHaus, LEED, BREEAM, etc.).

Building performance simulation (BPS) is a methodology that offers great potential for the analysis, understanding and improvement of building design and operation (Clarke, 2015). However, it is relatively easy to operate BPS tools, producing accurate results is more challenging (Beausoleil-Morrison, 2019). The cause for this is a combination of the inherent complexity of both the BPS tools and the building itself, but more importantly, the user as a modeller (Augenbreg and Malkawi, 2004, De Wit and Augenbreg, 2001). Besides the inaccuracies derived from the necessary need for simplicity when modelling a building and the physical environment, there might be errors derived from the choice of input data or modelling options (thermal zones, thermal bridges, heat and mass transfer). This is especially the case when selecting default models and data, and converts the user into the largest source of uncertainty (Guyon, 1997, Coley, 2017).

This paper aims to study the impact of the choice of BPS tool and model settings and simplifications in the simulation process and results. Improving our understanding of the uncertainties and possible errors in our BPS model can help increase its reliability.

The case analysed in this study is Baumenschlager-Eberle 22/26 (BE2226), an office building in Lustenau (Austria) with high-performance envelope and no conventional mechanical systems (Figure 1). In order to ensure good indoor environmental quality, it includes an automated natural ventilation system with sensors for T/RH/CO₂ (Eberle et al., 2016). It was chosen because of its extensive use of passive strategies, challenging existing conventions for bioclimatic building design in cold climates. In addition, the availability of detailed measurements on-site would make it possible to calibrate the model later to resemble reality more accurately.

The BPS analysis of BE2226 was therefore carried out in two different stages, to better understand the consequences of different modelling approaches. First, we used a conventional approach with an open office geometry, and default options for run period (one year) and heat and mass transfer calculation method (CTF). Then, after comparing the simulation results with the reported measurements, we carried out a one-at-a-time (OAT) crude local sensitivity analysis to find a more accurate base model that could later be used for calibration against measured data. Finally, after adjusting the BPS settings according to the findings, we performed a new simulation to analyse the performance of the tailored model.

Since this study is embedded into a larger research project on BCBD, it needs to focus on the comparison between
climate and comfort. More specifically, it looks at the correlation between outdoor and indoor climates and compares them to the expectations for thermal comfort in the Building Bioclimatic Chart, BBCC (Milne and Givoni, 1979). This in turn gives us an idea of the effect the building envelope has, by filtering the outdoor climate to help provide indoor comfort. Internal gains also play an important role in the configuration of the indoor climate.

The BBCC uses the Psychrometric chart to plot hourly temperature and humidity values from a weather file, to check how many of them fall inside the comfort zone. It also provides graphical information on the possibilities for extending the comfort zone using passive strategies for climate control. The most complete tool we found for bioclimatic building design is Climate Consultant (Milne, 2015). As the BBCC relies on hourly values of temperature and humidity, those will be the main parameters under study in this paper.

**Case building**

The case analysed in this study is Baumschlager-Eberle 22/26, an office building in Lustenau (Austria) with a high-performance envelope and automated controls (Figure 1). It was chosen because of its extensive use of passive strategies, challenging existing conventions for bioclimatic building design in cold climates.

The energy concept of the building is referred to as “Concept 22/26” (Eberle et al., 2016). Its objective is to limit the room temperatures throughout the year between 22 and 26°C, to keep a comfortable indoor environment while minimising the use of resources (materials, space, energy). In order to do so, the building envelope has a very low heat transfer and a high thermal capacity (Table 1). Moreover, the HVAC system has been replaced here by a building automation system that operates window openings for natural ventilation, and a lighting system for backup heating.

The extensive use of passive strategies includes:
- compact shape, as a cube of around 24 x 24 x 24 m3, to minimize heat loss
- exposed thermal mass indoors, to flatten temperature fluctuations
- high levels of insulation
- very airtight envelope (n50=0.51 on blower door test)
- window-to-wall ratio around 20%
- near-floor-height windows, good daylight distribution
- triple glazing

- narrow vertical panels (VIP) by each window, acting as vents for natural ventilation (cooling / fresh air)
- window position by the inner surface of external walls, for shading
- high ceilings (3.4m) to allow temperature and CO2 stratification, thus limiting the need for natural ventilation in the heating season

**Table 1: Main characteristics of the building envelope** (Junghans and Widerin, 2017)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>wall</strong></td>
<td></td>
</tr>
<tr>
<td>U-value (W/m² K)</td>
<td>0.138</td>
</tr>
<tr>
<td>Internal heat capacity (KJ/m² K)</td>
<td>85.76</td>
</tr>
<tr>
<td>Infiltration rate (ac/h)</td>
<td>0.037</td>
</tr>
<tr>
<td><strong>window</strong></td>
<td></td>
</tr>
<tr>
<td>U-value (W/m² K)</td>
<td>0.7</td>
</tr>
<tr>
<td>Solar transmittance factor (SHGC)</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The high-performance building envelope allows the use of internal gains (Table 2) to cover most of the heating demand in the cold seasons. The automated natural ventilation is then limited to providing fresh air to meet indoor air quality requirements. In the warm seasons, it is also used for passive cooling.

**Table 2: Internal gains** (Junghans and Widerin, 2017)

<table>
<thead>
<tr>
<th>Occupancy density (people/m²)</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment (W/m²)</td>
<td>11.50</td>
</tr>
<tr>
<td>Lighting (W/m²)</td>
<td>5.0</td>
</tr>
</tbody>
</table>

A downside of having natural ventilation directly from the façade is the reduction in the occupancy density. In order to protect the users from drafts, they have to seat at a distance from the windows. In this case, this is resolved by placing the circulation by the façade, instead of by the core. A side effect of this approach is a lower occupancy density, compared to other more conventional office buildings (0.05 people/m² instead of 0.1).

On the other hand, to be able to use the lighting system as backup heating, it has to be resolved with low-efficiency luminaries, to provide enough heat. In this case, they used fluorescent tubes with a nominal power of 5 W/m², instead of the standard 3 W/m². The use of the lighting system as backup heating is mostly needed only in the heating season when very low temperatures are expected in the early hours of the working day. This could be understood as a kind of electric space heating solution. The underlying concept here is to assign several functions to already necessary building elements and systems, to increase resource efficiency.

The equipment considered for the internal gains corresponds to one computer and two screens per user. The nominal power is 11.5 W/m², which matches the estimates in the current building standards.

As for the outdoor climate, we created the weather file for Lustenau with Meteonorm, a global climatological database originally developed for planning solar energy systems and sustainable buildings (Remund, 2008). For this analysis, it was used the TMY weather file corresponding to the most recent measurements, with temperatures from 2000-2009 and solar radiation from 1991-2010. Average temperatures of -0.6°C for the coldest and 19.6°C for the hottest month give a climate classification Cfb in the Köppen-Geiger scale, which is
temperate humid continental with warm summers. With 2980 HDD (18°C) annually, it corresponds to the ASHRAE climate zone 4A, (borderline with 5A, with 3000 HDD), mixed humid.

**Building performance simulation tool**

BPS tools can both enhance or limit the choice of passive strategies for climatic control, depending on how accurate (informing our choices), intuitive (attractive, easy to use), transparent (adaptable) and complex (physical processes) they are.

In this respect, a good choice for BCCD would be Energy Plus with Design Builder. The latter provides a good graphical interface and at the same time, it includes detailed descriptions of the climatic, material and technical characteristics of the building and its systems. In addition, Energy Plus is a well-recognised open-source simulation tool developed by the US Department of Energy (Crawley et al., 2001). In this regard, open-source tools can be very useful, since one can check the model (how it is mathematically represented by the software) and adapt it to represent reality more accurately. In addition, both of them have been tested under the comparative Standard Method IEA HVAC BESTEST E100-E200 test suit (Henninger et al., 2004, Szewczuk and Conradie, 2014).

Furthermore, EnergyPlus considers humidity production from the occupants (latent/sensible heat production, from specified metabolic rate) and offers several options for the heat and moisture balance calculations (DOE, 2021). It is both flexible (EMS controls) and transparent, modelling only what is explicitly described. Besides, it offers comprehensive surface temperature calculations, with a heat balance for all surfaces and time-dependent conduction, allowing the consideration of both heat storage and thermal lag. This in turn makes it suitable for passive solar design (thermal mass), radiant heating/cooling and thermal comfort studies. Then, it offers an integrated solution where the systems, loads and geometry are coupled together so that changes in those get reflected automatically on comfort.

**Conventional approach**

We modelled the whole building (Figure 1) but considered only the results from the 2nd floor as an *open office* with some internal zones (corresponding to the toilets, elevator, stairs and services) that provide extra thermal mass and help distribute the space (airflow).

The simulations were carried out for a *whole year*, with the default warm-up period in EnergyPlus (4 weeks). Then, the calculation method for thermal loads was *Conduction Transfer Function* (CTF), which is also the default one. Also, the *schedules* considered for the different internal loads and systems (occupancy, equipment, lighting, natural ventilation) were the default ones in DesignBuilder/EnergyPlus.

Both nominal values for *internal loads and materiality* for different construction elements followed project specifications for BE2226 (Eberle et al., 2016).

The indoor values of temperature and humidity obtained from the simulations have been presented in two different ways. *In relation to time*, to show seasonal and daily fluctuations, the amplitude of its variations, and the proximity to the targeted comfort range of 22-26°C (Eberle et al., 2016). *On the psychrometric chart*, to reflect the total scattering of climatic values, thermal comfort zones for summer and winter with the percentage of hours of discomfort, and potential for extending these comfort zones using passive strategies.

The *psychrometric charts* (Figure 2) show the effect of envelope, internal gains and natural ventilation on indoor climate, with respect to the original outdoor climate. There can be appreciated an increase in *temperature*, bringing more climatic values inside the comfort range (from the original 8.6% to 21.7%), but also leading to some overheating problems in the warmer periods.

As for the *relative humidity*, it becomes much lower than outdoor values, mainly as a result of the increase in temperature. With most of the values in the range of 20-40%, indoor RH appears to be somewhat lower than the 40-60% recommended for health and comfort in the literature (Arundel et al., 1986, Hinds, 1999, Wolkoff and Kjærgaard, 2007).

![Figure 2: Psychrometric chart for the outdoor and indoor climates obtained with the conventional approach to BPS. Images from Climate Consultant.](https://doi.org/10.26868/25222708.2023.1614)
to bring many of the remaining values to comfort by applying different passive strategies.

On annual temperature distribution (Figure 3) we can see how thanks to the stabilizing effect of the envelope, daily fluctuations in outdoor climate do not have such pronounced effect indoors, while changes in occupation become very relevant. The operational schedule for internal gains appears at least as important as their thermal load.

The mean for the indoor temperature follows a similar curve as the outdoor conditions, but warmer thanks to the effect of the internal gains. It also becomes apparent both the cumulative effect of internal gains, as well as the cooling effect of the ventilation in the working days.

To conclude, the annual distribution of the indoor temperature and relative humidity clearly show that the values obtained are not similar enough to those measured in the BE2226 (Junghans and Widerin, 2017). There is much higher variability in the temperature, not staying in the range of 22 to 26°C. Also, the relative humidity is too low, compared to the average of around 45% that has been measured, and also with too high variability. This challenges us to try and improve the BPS model settings to get closer to the measurements and find out the main reason for the differences between them.

Even though the relative humidity is not usually the focus of a BPS calibration, we feel the need to include it because of the nature of this study, using the representation in the psychrometric chart for the application of both thermal comfort and passive strategies. Humidity is not usually considered, since the standards tend to focus on temperature (thermal comfort) or energy use (energy supply). In addition, the effect of humidity is not so easy to quantify (the human body does not have dedicated sensors for humidity) or control (an excess of moisture indoors can easily end up causing health problems).

Tailored approach
For the configuration of the model, we studied all the publications we could find about the building (Junghans, 2015b, Junghans, 2015a, Hugentobler et al., 2016, Eberle et al., 2016, Junghans and Widerin, 2017), interviewed the architect, Dietmar Eberle, visited the building with Willem Bruijn, managing partner and architect at Baumschlager Eberle, and obtained on-site measurements from Lars Junghans, the engineer behind its energy concept.

It has been a real challenge to model such a special building to a level of detail and accuracy appropriate for calibration. From the definition of the materials to the windows and their opaque opening flaps, to the automation controls for the natural ventilation and lighting system, to the heat transfer calculation models, everything had to be reflected upon and tailored. On the other hand, the learning potential was also great.

The control algorithm for the window opening to provide natural ventilation, for instance, has to respond to CO2 concentration, indoor air temperature and outdoor air temperature. The one for the lighting, in turn, reacts to the time of the day (night-OFF to not disturb the neighbours), indoor air temperature (backup heating) and illuminance (only when occupied).

![Figure 5](https://doi.org/10.26868/25222708.2023.1614)
The building has an automated window opening with a hysteresis controller, and with the possibility for personal override, for natural ventilation.

In addition, the artificial lighting system is used as backup heating, besides ensuring a minimum of 500 lux in occupied working spaces.

The most challenging aspect of BPS is the uncertainty generated due to occupancy (density, distribution, operation), complexity of physical environment, and climate (daily and seasonal variability, climate change).

In addition, there are more levels of uncertainty brought by the BPS tool itself, with its choice of algorithms, approximations, simplifications, and default settings.

Besides, and above all other sources of uncertainty, there is the influence of the modeller, who decides on the geometry, parameters, settings, schedules and calculation models and methods to be applied in the simulation. These need to be considered.

It would be interesting to make a more detailed uncertainty analysis in a future paper, to offer a better overview of the reliability of our results.

Since this analysis is performed on an existing building and not a new one, some of the parameters have a limited variability around the base case, while others have already been fixed. By identifying the most significant input parameters in terms of their influence on the output variability, we can apply a crude OAT local sensitivity analysis around the base case. This way, we might be able to capture a relatively large fraction of the total variance of outputs (Cattarin et al., 2018) and at the same time, get a clearer idea of how to alter the BPS model to improve our results.

If the objective were the design of a new building, where most parameters could still be changed, then a global sensitivity analysis might be preferable.

**run period (warmup with internal gains)**

Performed to check the time needed for heat and moisture load into the materials. Most relevant for the winter design week, with the lowest outdoor temperature and no occupancy.

![Figure 6: Indoor air temperature for the winter design week, with different warmup periods with internal gains.](image)

We can appreciate in Figure 6 similar results for indoor temperature, independently from the length of the run period, showing that the thermal load into the materials is a relatively fast process.

**heat and moisture transport calculation method (CTF/FD/EMPD/HAMT)**

Conduction Transfer Function / Finite Difference / Effective Moisture Penetration Depth

The moisture buffering properties of the different construction elements were introduced, so that we could use the EMPD (effective moisture penetration depth) calculation method for heat and mass transfer. This was necessary to produce a more accurate approximation to the indoor relative humidity. We chose the EMPD method over the more detailed HAMT because it produces very close results to those from HAMT but with much shorter simulation time and fewer errors (Woods et al., 2013).

Winter design week is again the most relevant (coldest, empty, lowest airspeed).

![Figure 8: Indoor air temperature for the winter design week, with different heat and moisture transfer calculation methods.](image)

Figure 8 shows similar results for the indoor air temperature, independently from the thermal model.
In contrast, the choice of thermal calculation model is fundamental for obtaining a more realistic representation of the relative humidity in the zone (Figure 9), showing the relevance of the moisture buffer from the materials. While both CTF and FD focus solely on temperature, EMPD does consider moisture penetration into the materials, so that they can act as a buffer to help maintain more constant values in the relative humidity, closer to those measured.

The attempt to apply the HAMT heat and mass transfer calculation method produced a terminal error and could not be carried further. The problem was that in DesignBuilder the open internal doors were modelled by creating holes in the partitions, to ensure that they would always be open. Then DesignBuilder would internally create an object in EnergyPlus named “holes & vents_0.2” which could not be changed to include HAMT properties (all the materials had to include these properties so that the calculation method could be applied). However, in the same way, CTF offers a simplified approach to FD, providing somewhat similar results in much shorter time, EMPD was created as an approximation to HAMT (Woods et al., 2013), avoiding the error in our case.

**Cd, hc, Ta distribution model**

The results for different values of these parameters and models were not substantially different. This might be due to the lower ventilation rates in this building, making it more dependent on the materials reaction to the indoor environment and less so on parameters related to air movement.

**Results**

In order to account for the slow but significant moisture buffering effect of the building materials, some of the default simulation settings had to be changed (run period, HAMT calculation method). Others (Cd, hc, Ta distribution model) were not so relevant to this case and could be left as default.

- run period: from 4-week warmup without internal gains + annual simulation with internal gains (default), to bi-annual simulation with internal gains (1-year warmup)
- HAMT calculation method: from CTF (default) focusing only on thermal loads, to EMPD (tailored) to allow for moisture load into the materials.
- mixed air temperature distribution model (default)
- dynamic calculation of convective coefficient - hc (default)
- default value of discharge coefficient - Cd (6.5)

The high-performance envelope increases the relative importance of the internal gains, compared to the outdoor climate. This in turn emphasizes the relevance of selecting the right operational settings. In the conventional approach, we used the default schedules from DesignBuilder for natural ventilation and lighting. By contrast, in the tailored approach we tried to recreate the automation control algorithms for the automated window opening and the artificial lighting system, making use of EMS coding possibilities in DesignBuilder/EnergyPlus.

As a consequence of changing the BPS model settings to tailor them to this kind of building, the climatic points appear tighter to each other and closer to the comfort zone on the psychrometric chart (Figure 10). This helps increase the number of comfortable hours from the 21.7% that we obtained with the conventional approach, to 29.3%. It will also make it easier to bring most of the remaining hours to comfort through the application of passive strategies.

The operational schedule for internal gains still appears at least as important as their thermal load. The mean for the indoor temperature follows a similar curve as the outdoor conditions, but warmer thanks to the effect of the internal gains, which creates some overheating problems in the warm season. It also becomes apparent both the cumulative effect of internal gains, as well as the cooling effect of the ventilation in the working days.
While the relative humidity outdoors is generally high throughout the year, with significant variability, we can appreciate indoors as an important restriction in this daily variability, thanks to the effect of the building envelope (Figure 12). Again, we can appreciate the effect of occupancy schedule, with very clear daily and weekly rhythm and important change in amplitude as consequence.

After the activation of the automation controls, more than 90% of the hours fall already into the comfort zone, and the rest can be easily brought to comfort by applying passive strategies. By introducing the resulting indoor climate in Climate Consultant (Figure 13), we can get an idea of how to improve the indoor climate further by passive/active means, to get 100% of the hours into the comfort zone.

The annual temperature distribution shows in Figure 14 that most of the curve falls inside the comfort area, as expected. There are just a few cases in summer with overheating, and a few more in the winter with slightly cold nights. It is easy to appreciate the summer period with higher ventilation levels and a more irregular curve. In the winter months in contrast, since there is not so much ventilation, it becomes clearer the operation schedules of the internal loads.

Thanks to the automation controls, now relative humidity is most of the time inside the recommended 40-60% (Figure 15). As in the graph for the temperature, it is easy to appreciate the summer period with higher ventilation.
levels and a more irregular curve. In the winter months in contrast, since there is not so much ventilation, it becomes clearer the operation schedules of the internal loads.

Even though the results from the tailored BPS analysis are much closer to the on-site measurements, they still show too high variability throughout the year, in comparison. A more detailed model calibration might throw some light on the cause and how to improve our results.

**Findings**

- relevance of considering the effect of air moisture, both for the BPS and BCBD analysis (including thermal comfort)
- space conditioning approach: materials-based (lower ach) vs. air-based (higher ach)
- relevant parameters: thermal mass, moisture buffering, air changes [vs.] convective coefficient, discharge coefficient, air temperature distribution model (since lower ventilation rates)
- warm-up period: relevance of thermal & moisture load in the materials (the higher the load, the longer the loading period)
- ventilation concept: from higher air changes for CO₂ control, to lower values for moisture and comfort (allow thermal/moisture load into the materials)
- relatively higher importance of internal gains (schedules/EMS) than outdoor climate, since high-performance envelope: tailored operational schedules
- importance of tailoring the BPS analysis approach to the specific needs of the building in its climate, function and operation

**Discussion**

The most challenging aspect of Building Performance Simulation is the uncertainty generated due to occupancy (density, distribution, operation), complexity of physical environment, and climate (daily and seasonal variability, climate change). In addition, there are more levels of uncertainty brought by the BPS tool itself, with its choice of algorithms, approximations, simplifications, and default settings. Besides, and above all other sources of uncertainty, there is the influence of the modeller, who decides on the geometry, parameters, settings, schedules and calculation models and methods to be applied in the simulation. These need to be considered.

Increased awareness of the potential and limitations of BPS and its tools can help us make better-informed decisions, be less wrong. We can then improve our approximation to a complex reality and minimize misinterpretations. We should also consider the effect of design and modelling decisions, and the relevance of understanding the fundamentals that underlay this analysis approach. Only then we can tailor our models to better respond to the problem at hand. The results of our analysis can only be as good as the data we feed into the program.

Even so, despite uncertainties and difficulties, it is important to acknowledge and utilize the potential within BPS and BCBD, to improve the design and operation of buildings, and to better understand and apply different passive strategies for climate adaptation.

**Acknowledgements**

We are grateful for the expert advice received from Tommy Kleiven, Inger Andresen and Laurent Georges. This research has been financed by the Department of Architecture and Technology at NTNU and The Research Centre on Zero Emission Neighbourhoods in Smart Cities.

**References**


GUYON, G. 1997. Role of the model user in results obtained from simulation software program. *International Building*.

HENNINGER, R. H., WITTE, M. J. & CRAWLEY, D. B. 2004. Analytical and comparative testing of...


