HOW TO PREVENT A PASSIVE HOUSE FROM OVERHEATING

An industry case study using parametric design to propose compliance strategies

MAX MARSCHALL[1] and PABLO SEPULVEDA[2]
[1,2]Aurecon, 850 Collins St, Melbourne VIC 3008, AUSTRALIA
[1]max.marschall@aurecongroup.com
[2]pablo.sepulveda@aurecongroup.com

Abstract. The airtight, well-insulated building fabric of a Passive House can reduce operational energy consumption but can also present a risk of overheating during summer. PHPP, the Excel tool used to model Passive Houses, considers the whole building as a single thermal zone; a simplification that might be partly responsible for the tool's limited ability to predict overheating risk. The current study on a real-world project provides insights on two topics. First, we compare PHPP's overheating assessment with that of CIBSE's TM59 standard that requires dynamic energy modelling at a room level. Our results support the claim that PHPP underestimates overheating; in our case, glazing SHGC and air change rate were some of the most important parameters affecting compliance, as were some other, rarely analysed factors like ratio of external wall to room volume. Second, we report on the effectiveness of using parametric design for compliance modelling of this kind, and found that parameter studies, coupled with appropriate data visualisation, are an effective way to build intuition on a design problem of this kind.

Keywords. Passive House; Social Housing; EnergyPlus Modelling; PHPP Modelling; Overheating Risk; Parametric Data Visualisation; SDG3; SDG13.

1. Introduction

A warming climate, heightened expectations for indoor air quality, embodied and operational carbon reductions, housing affordability; these are some of the new global challenges that face the building sector. To solve them requires new approaches; one such approach is the Passive House standard. This standard was developed in Germany and focuses on the following principles to reduce operational energy consumption while increasing occupant thermal comfort: increased thermal insulation; construction practices that result in a continuous, airtight thermal envelope; mechanical heat recovery ventilation; high-performance windows; and thermal bridge-free construction.

This paper addresses the United Nations Sustainable Development Goal 3 "Good

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Health and Well-Being", by highlighting a thermal comfort risk inherent in Passive House buildings, and by documenting an approach to mitigate it. The well-insulated airtight building envelope of a Passive House keeps the building warm in winter and can reduce external heat gain in summer (Truong and Garvie, 2017). However, the design of the building requires careful consideration to prevent overheating during warm periods, when heat loss through the envelope would in fact be beneficial, but where an airtight, highly insulated façade may prevent this. Several studies have shown a tendency of Passive House buildings to overheat during warm periods (e.g. Kang et al., 2021; Sameni et al., 2015).

A requirement for Passive House compliance is to use the Passive House Institute's Excel tool “Passive House Planning Package” (PHPP) to predict whether a building design will meet the standard’s requirement of not exceeding heating and cooling demands of 15kWh/m2/a each. Part of the reason for why PHPP may sometimes underestimate overheating risk, is that it considers the heat balance of the building as a whole; the building is simplified to a single space, without considering internal partitions of walls and floors. This resolution may not always account for individual rooms overheating due to their specific conditions.

While there are many examples in literature where researchers have conducted parametric modelling for sustainable building design in general, there are very few such studies related to Passive Houses specifically. Commonly, Passive House Designers will exclusively use PHPP from within Excel to run analyses, making iterative changes manually based on their expert knowledge until they find a feasible solution that meets the performance requirements. There appears to be a missed opportunity to leverage parametric modelling to provide more holistic advice for achieving compliance.

While PHPP allows comparing options, this feature is currently limited in a way that restricts more largescale parameter studies. The few researchers who have run this type of analysis do so using other software like MATLAB (e.g. Mengyuan et al., 2020), IES-VE (e.g. McLeod et al., 2016) or Python and EnergyPlus (e.g. Chiesa et al., 2019) to automate the simulation of many design options, and sometimes use algorithms to optimise parameter settings (e.g. Chen et el., 2020; Li et al., 2021) or conduct sensitivity analyses (e.g. McLeod et al., 2016). The outcomes of these studies are generally used to form insights on how to achieve Passive House compliance most efficiently within a certain context, e.g. related to a specific building type or climate zone. While many of the existing studies are very thorough, their methods lack evidence of being helpful in communicating simulation outcomes to clients in real-world consulting scenarios.

The studies that specifically analyse overheating risk in Passive House buildings tend to conclude that glazing fractions and shading are the most important factors (e.g. Lavafpour and Sharples, 2015; McLeod et al., 2016). However, this is based on a very small number of studies; more research is required to shed light on this complex issue.

1.1. PROJECT BACKGROUND

Above Kāinga Ora, a government agency that provides rental housing for New Zealanders in need, is aiming to achieve high levels of comfort and sustainability for their social housing project 'Ngā Kāinga Anamata' (Māori for ‘homes of the future’). The project is therefore designed for Passive House certification. It involves five almost identical three-level walk-up buildings in Auckland, New Zealand.

Each building will be constructed using a different structural system (precast concrete, light timber frame, cross-laminated timber (CLT), light gauge steel frame, hybrid light timber and CLT. The purpose of this is to compare the ease of planning and construction, cost, and other challenges, as a case study for future reference. Aurecon was engaged as a Passive House design consultant and services engineer for the project.

1.2. AIM

The aim of this study was to complement the PHPP modelling for the 'Ngā Kāinga Anamata' project through high-resolution dynamic building performance modelling, to test the current building design for the risk of overheating, and to recommend design and operational strategies to reduce this risk.

2. Methodology

2.1. APPROACH

In order to provide holistic design advice with several potential pathways towards compliance, we decided to employ a parametric modelling approach. We used the Ladybug Tools Grasshopper plug-in to conduct energy dynamic energy simulations through EnergyPlus. To visually analyse the results from the parametric modelling, we used the interactive web dashboard Design Explorer.

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2.2. SITE AND BUILDING GEOMETRY

All five buildings on site have the same orientation; their longitudinal axis is rotated about 11° clockwise away from a true east-west orientation. Since overshadowing from neighbouring buildings was determined a rare occurrence, and the study followed a worst-case scenario approach, we decided to not include the neighbouring buildings in the simulations at all. TM59 recommends using CIBSE design summer year (DSY) weather files, however no such file exists for Auckland; instead, we used the NIWA EPW file for current conditions, and the C875 weather file to account for increased risks due to future climate change.

Since all five buildings have identical geometries, we only modelled one of them, namely the one with the light-gauge steel (LGS) construction since this was the one deemed most likely at risk of thermal performance issues. The buildings each have two apartments per floor with a north-facing balcony and separated by a core zone with a communal staircase (see Figure 1). The assumed number of occupants per apartment is five; two adults occupying the northern bedroom and three children occupying the southern bedroom.

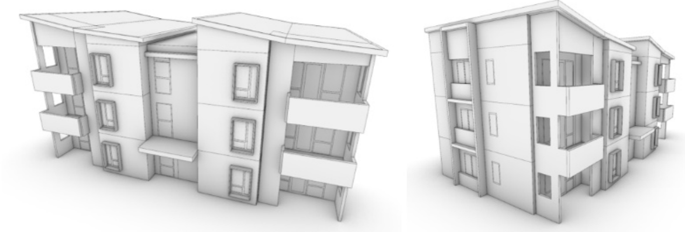


Figure 1. 3D model generated for the analysis

2.3. CONSTRUCTIONS

Where available, constructions were extracted from the project's PHPP model; unspecified constructions (e.g. interior floors and walls) were obtained from the architectural plans available at the time of planning. EnergyPlus requires entering materials on a layer-by-layer basis per construction. In cases where several materials occupy a single layer (e.g. studs and insulation), we applied a cross-section area-weighted average to all properties of the materials found in the layer.

From the PHPP model, we extracted all building-wide thermal bridges that were not related to window constructions and accounted for them in EnergyPlus by converting them to an exterior wall construction U-value degradation. The EnergyPlus U-value was matched with the PHPP U-values that consider the linear (e.g. slab-wall junction) and punctual (e.g. cladding fixation points) thermal bridges. We determined that the external U-value had to be increased from 0.191 to 0.296 in order to account for thermal bridging; this was achieved by reducing the wall insulation layer thickness from 100mm to 78mm.

We calibrated the individual glazing layer properties, such that the resulting U-values and SHGCs of the constructions matched the glazing systems found in a glazing specification document that had been shared with the project team.

Window frames were modelled as separate wall sections with simplified 'no mass' materials. This allowed us to incorporate the window-related thermal bridges into the frame definitions. Corresponding values were calculated using the thermal bridge modelling software FLIXO PRO 7.1. We extracted average thermal bridges from the PHPP model, which we converted to equivalent U-value degradations that we added to the frame U-value specifications.

2.4. LOADS AND SCHEDULES

We used the load and schedule assumption recommendations from TM59, but specified additional, continuous loads from the domestic hot water (DHW) piping to the affected rooms (cores, stairwell, lobbies, hallways, bathrooms) from the pipe lengths and level of insulation specified in the PHPP model.

We specified an outdoor air supply with 80% sensible heat recovery, operable at all times in all rooms. As per TM59, we assumed that operable windows were open whenever the indoor temperature exceeded 22 °C. However, since the staircase windows will be operated mechanically based on indoor and outdoor temperature sensors, we set these windows to be open when the indoor ambient temperature exceeded 21 °C, but only if the outdoor ambient temperature was at least 1 °C cooler than the indoor temperature. All doors, including balcony sliding doors, were modelled as closed at all times.

2.5. METRICS FOR THERMAL COMFORT

TM59 defines the following compliance criteria:

- HE ('Hours of Exceedance') for living rooms, kitchens, and bedrooms: the number of hours during which ΔT is greater than or equal to 1K during the warmer months may not be more than 3% of occupied hours. ΔT is the difference between the indoor operative temperature and the upper adaptive thermal comfort temperature threshold, rounded to the nearest integer. The warmer months are defined in TM59 as May to September inclusive which applies to the northern hemisphere; we therefore changed this to November to March inclusive.
- NT ("Nigh-time Threshold") for bedrooms only: to guarantee comfort during the sleeping hours, the operative temperature in the bedroom from 10pm to 7am may not exceed 26 °C for more than 1% of annual hours.

While not mandatory, we included the additional metric recommended in TM59:

- HE ("Hours of Exceedance") for communal corridors (in this case, the staircase): if an operative temperature of 28 °C is exceeded for more than 3% of the total annual hours, then this should be identified as a significant risk within the project.

Furthermore, in order to gain an understanding of the extent to which different rooms fail or comply with the above criteria, we also logged the average number of yearly hours during which rooms exceeded an operative temperature of 26 °C:

- Ke: Kids' bedrooms
- Pe: Parents' bedrooms
- Se: Staircase

2.6. DESIGN PARAMETERS

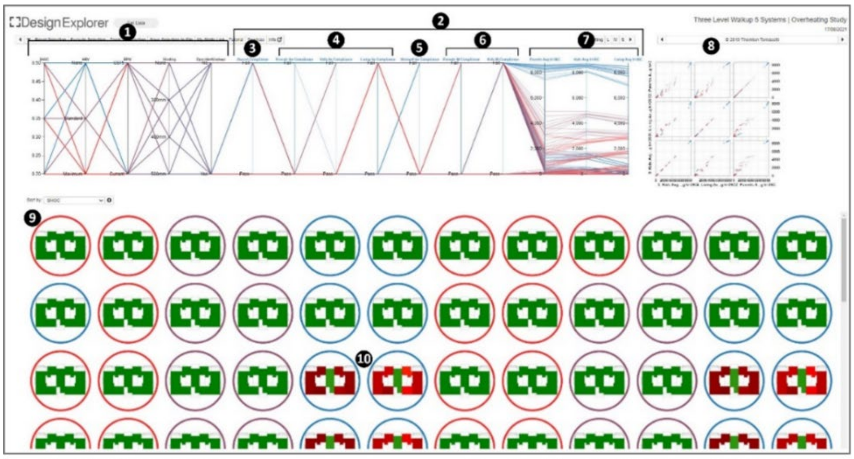
The parametric study consisted of energy simulations for all 144 combinations of the following parameter settings:

- Weather file: current (NIWA) and future (C875)
- Glazing solar heat gain coefficient (SHGC): 0.50, 0.35, and 0.20
- Heat recovery ventilation air changes per hour (ACH): none (0 ACH), standard (0.64 ACH), and maximum (0.83 ACH)
- Depth of 'shading aprons' for the parents' bedroom windows: none, 300mm, 400mm, 500mm. A shading apron is an exterior shading device; geometrically, it is an outward extrusion of the outline of a window.
- Operable windows: with and without

3. Results

3.1. DASHBOARD

The elements of the dashboard created in Design Explorer are shown in Figure 2.



1. Inputs (design parameters)
2. Outputs (compliance & performance metrics)
3. Overall compliance to TM59
4. Compliance to TM59 criterion "hours of exceedance" (separately for parents' bedrooms, children's bedrooms, and living rooms)
5. Non-mandatory TM59 criterion "hours of exceedance" for staircase
6. Compliance to TM59 criterion "night-time threshold" (separately for parents' bedrooms and children's bedrooms)
7. Additional performance metric "hours over 26 °C operative temperature" (separately for parents' bedrooms, children's bedrooms, and living rooms)
8. Correlation matrix between parents' bedrooms, children's bedrooms, and living rooms in terms of the additional performance metric "hours over 26 °C operative temperature"
9. Thumbnails for each design variation showing the "hours of exceedance" compliance for the top floor rooms
10. Non-compliant design variations have rooms coloured in yellow or red

Figure 2. Parametric data visualisation dashboard created using Design Explorer

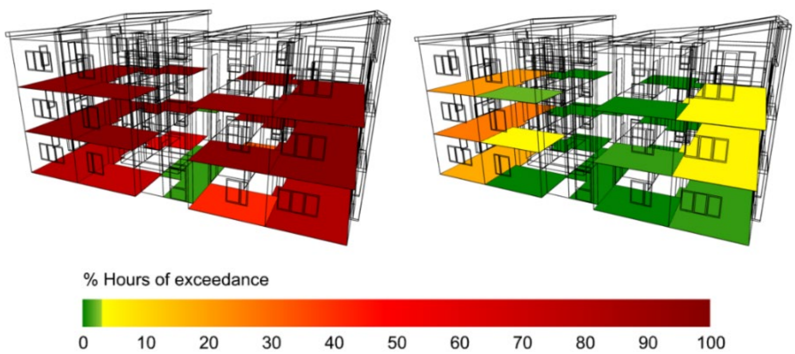


Figure 3. Examples of the 3D visualisation of the 'Hours of exceedance' metric

3.2. SENSITIVITY OF METRICS

Several patterns emerged when exploring the 3D visualisations (see Figure 3) of the Hours of Exceedance metric in the dashboard. Different parts of the building tend to have different levels of risk in terms of meeting this criterion:

- The top floor is at higher risk than the other floors. This was to be expected since heat rises, and because the top floor is adjacent to the roof space which has a high solar exposure.
- The western rooms are at higher risk than the eastern rooms. This was also to be expected since temperatures after midday tend to be higher than those before midday, and the western spaces receive more direct solar radiation during this time.
- The kids' rooms are at higher risk than parents' rooms. This was somewhat unexpected since in the southern hemisphere north-facing rooms are commonly at higher risk of overheating than south-facing rooms. However, it is explained on the one hand by the increased internal gains due to the fact that the southern bedroom is occupied by three people instead of two, and on the other hand due to the fact that shading elements were included to the northern bedroom windows for most of the analysed design variations.
- The living rooms are at higher risk than the kids' rooms. This is explained through the TM59 assumptions on schedules and loads, as well as the rooms' boundary conditions and geometry. TM59 assumes living rooms to be fully occupied (in this case by 5 occupants) for most of the day. Their assumed peak equipment load is almost 6 times higher than that of the bedrooms. Furthermore, the living rooms have a higher glazing fraction (25% compared to 11%) as well as a higher ratio of exposed façade area to room volume (0.46 compared to 0.37).

The abovementioned indicator "ratio of exposed façade area to room volume" appears to be a factor that is rarely explicitly analysed in other research. This may be because dynamic energy simulation programs consider interior room partitions; the effect of the indicator is therefore accounted for in the simulation and reflected in the results. The importance of this indicator in our study exposes a shortcoming of the PHPP methodology, which is to model the building volume as a whole and discount interior room partitions.

Which of the individual criteria outlined in Section 2.5 are most difficult to fulfil? To gain insight on this question, we counted how many of the 144 analysed design variations failed on each of the individual criteria (see Figure 4). Assuming that the number of failed design variations is an indicator of the how difficult the different TM59 criteria are to fulfil, we made the following observations:

- The Night-time Threshold (NT) criterion is more critical than the Hours of Exceedance (HE) criterion. There is a natural tendency to assume that overheating is more of a risk during daytime than night-time. However, 95 design variations failed the NT criterion for the kids' bedrooms while only 32 design variations failed the HE criterion for the kids' bedrooms. This is because the HE criterion is more forgiving of high temperatures since it follows the adaptive comfort model, thereby allowing indoor operative temperature of up to 29 °C during hot periods, while the

NT criterion has a hard cut-off at 26 °C.

- The living rooms and staircase are more critical than bedrooms in terms of HE. The reasons for why the living rooms performed worse than the bedrooms are explained in the section above. The fact that the staircase runs a higher risk of failing its criterion may have several reasons. One reason is the fact that the threshold temperature defined for overheating is constant at 28 °C, whereas the threshold for the other rooms is dynamic. Other reasons for the poor performance of the staircase is its high glazing fraction of 35%, as well as the continuous DHW loads.
- The kids' rooms are more critical than the parents' rooms. The reasons for this are explained in the section above.

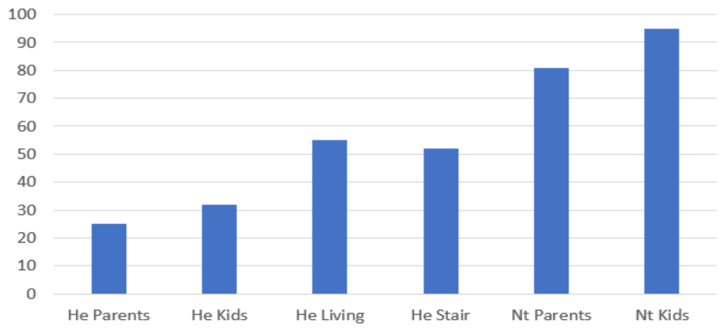


Figure 4. Number of failed design variations by criterion. "HE" stands for Hours of Exceedance, "NT" for Night-time Threshold, see Section 2.5

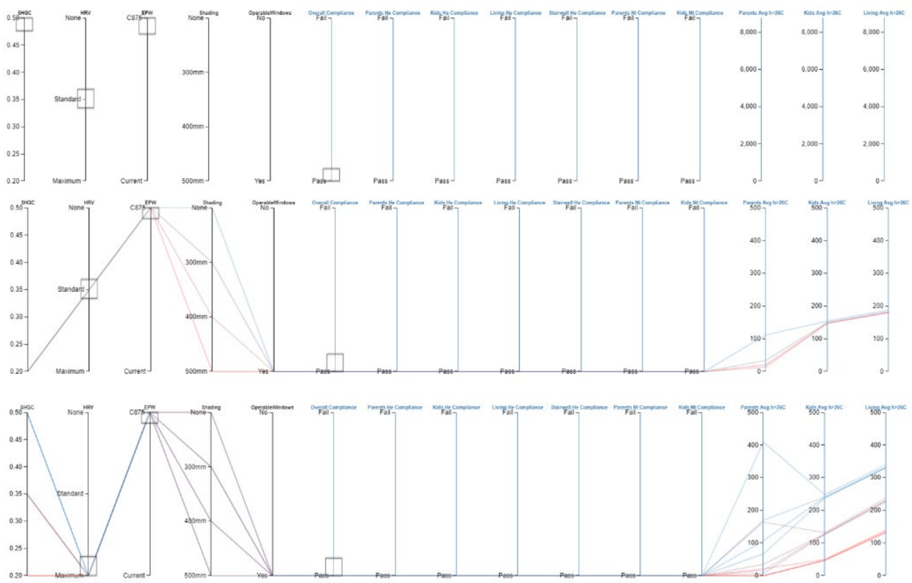


Figure 5. Top: For the baseline design parameters, the modelling could not produce a design that passes TM59. Middle: TM59 compliance could be achieved by decreasing the glazing SHGC Bottom: TM59 compliance could also be achieved by increasing the air change rate of the HRV

3.3. COMPLIANCE

Figure 5 shows that, based on our modelling, we found that the current design did not comply with TM59, despite PHPP indicating no overheating risk. To meet compliance, we found two options. The first was to lower the SHGC. Specifically, we tested SHGCs of 0.20 and 0.35; 0.20 complied while 0.35 did not. This means that the required maximum SHGC is somewhere between 0.20 and 0.35. While the choice of shading for the parents' bedrooms did not affect the compliance, it did substantially reduce the predicted number of hours where these bedrooms had high temperatures, from 122 hours to between 14 and 34 hours, depending on shading depth.

The second option to meet compliance was to increase the HRV air changes to "Maximum". While this technically allows SHGCs of up to 0.50, it performs worse than the previous solution on the latter metrics. Without shading, the predicted number of hours where the parents' bedrooms have high temperatures is 402, and between 67 and 170 with shading, depending on shading depth.

4. Conclusions

Similar to other studies (e.g. Li et al, 2021), we found that glazing SHGC had the largest impact on overheating risk; this was followed by HRV air changes. Shading had a lesser impact in our study than in other studies (e.g. Lavafpour and Sharples, 2015), however in our case the project constraints limited the use of shading which limited its potential to combat overheating; furthermore the dense occupancy assumed for the current project increases the importance of internal loads over external ones. While the window dimensions were fixed, we noticed that rooms with higher glazing fractions had a higher overheating risk. A similarly impactful factor, and one that we have yet to find mentioned in the literature, was the ratio of exposed façade to room volume.

Both latter parameters are of particular interest for Passive House design, since they relate to room-level characteristics that PHPP does not consider. While we understand that PHPP has been carefully developed with the intention of striking a reasonable balance between accuracy and simplicity, our study points out its risk of underestimating overheating as an argument for increasing the PHPP modelling complexity to include room partitions in future. Our study supports the claim that PHPP underestimates overheating, since the predicted overheating was much higher when following the more detailed modelling procedure laid out in TM59, a standard specifically focused on assessing this risk. Following TM59, we were still able to advise the client on omitting active cooling for the project - a win in terms of operational energy and emission reduction. For future research, the TM59 standard should be further validated regarding its assumptions on occupant behaviour, which has a significant impact on energy consumption and overheating (Sameni et al., 2015), especially occupancy (Chiesa et al., 2019) and window operation (Robinson and Haldi, 2011; Truong and Garvie, 2017).

We found that a parameter study, combined with interactive dashboarding, is an efficient way to assess to what extent different design factors impact compliance, and to be able to propose multiple compliance pathways. Our method of counting how many of the analysed design variations pass along each compliance criteria helped assess which of the individual criteria are most critical. Including additional continuous metrics instead of just binary compliance metrics furthermore helped determine the extent to which individual designs complied. However, a parameter study is limited by the 'curse of dimensionality'; since all parameter combinations are assessed, the simulation runtime limits the number of parameters that can be included, as well as the number of options along each parameter. Such studies are useful for gaining intuition on a design problem and determining parameter ranges that meet performance criteria, but assessing a specific parameter combination usually requires additional simulation runs.

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