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Robustness Assessment Method for Future Climate Uncertainties

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Abstract

Energy-efficient buildings tend to cause thermal discomfort due to overheating during summers. With the advent of climate change and increasing outdoor temperatures, the risk of overheating will be exacerbated. Henceforth, the building design must be future proof or robust for climate change. Passive design strategies applied to the building envelope are crucial in reducing the energy demand and provide thermal comfort. However, it is essential to determine their performance in the presence of climate uncertainties, especially in the early design stage. Therefore, the paper illustrates an assessment method for investigating the robustness of the building envelope in curbing the risk of overheating in future climate change scenarios of 2050 and 2085. The study focused on educational buildings as thermal discomfort due to overheating affects students' productivity. The study analysed the performance of different passive design strategies applicable at building envelope in reducing overheating risk and evaluated the robustness using the statistical method of *"best-case and worst-case scenario"*. The robustness assessment method found fixed or dynamic shading, reduced window to wall ratios, albedo effect of the building envelope, and mixed-mode ventilation strategy with P.C.M. panels as the most robust design solutions. However, ventilative cooling would have limited application towards the latter part of the century.

Keywords: Passive Design Strategies, Building Envelope, Educational Buildings, Thermal comfort, Overheating.

1 Introduction

The constant rise in external temperature due to global greenhouse gas emissions (GHG) is a critical factor for climate change. The building sector has a significant contribution to these emissions due to extensive energy consumption. To mitigate climate change, the Netherlands aims to achieve 45-80 % of energy reduction in their built environment with an 80% reduction in heating consumption (Hermelink et al., 2013, p. 100). For achieving these stringent goals, the focus is on the deep renovation of existing buildings and the new buildings to be nearly zero-energy or highly energy efficient from 2020 onwards. The building design thus focuses on passive solar gain and minimising the heat loss through the building envelope to reduce the heating energy consumption. Although these strategies can significantly reduce the heat consumption in winter, it creates thermal comfort problems in summer by increasing the risk of overheating (Attia, 2018; Barbosa et al., 2015; Kazanci and Olesen, 2016).

Overheating is one of the fundamental causes of thermal discomfort and dissatisfaction among the occupants, leading to illness or death (Hamdy et al., 2017). The risk of overheating will increase with outdoor temperature rise due to climate change (Attia, 2018; Kotireddy, 2018). Therefore, it is important to consider the effects of changing climate in our built environment. Numerous assumptions are made concerning energy performance and indoor comfort in current design methods to determine building performance in its lifespan. However, in practice, the buildings do not perform as expected, resulting in a performance gap (Juricic, 2011; Kotireddy et al., 2017a). According to (Moazami et al., 2019), one of the primary reasons for the performance gap of energy-efficient design is the exclusion of future climate uncertainties. Therefore, a building that can ensure its performance regarding low energy consumption and thermal comfort even in the presence of uncertainties such as climate change are defined as *robust* (Juricic, 2011; Kotireddy et al., 2017b; van den Ham et al., 2007).

The building characteristics and strategies that can adapt to climate change effects while maintaining the energy balance of the energy-efficient buildings can make designs tolerant and adaptive for future climates. Therefore, it is essential to include robustness assessment of different design choices in an early design stage.

2 Aim of the study

The study's main aim is to develop a robustness assessment method for evaluating the potential of design options in maintaining thermal comfort by reducing the risk of overheating in the climate change scenario of 2050 and 2085. Reducing overheating of interior spaces would require either active or passive measures to cool the building. The active measures can account for extensive cooling loads; therefore, passive design strategies must be promoted. As climate change is a moving target, it requires passive design strategies that are adaptive or climate responsive. The passive design strategies apply to various levels of design such as site, building, spatial or component level. However, the building envelope acts as a barrier between the exterior and interior and will significantly reduce or accentuate the risk of overheating. Therefore, it is essential to evaluate the performance of passive design measures applicable at building envelope in future climate scenarios.

3 Boundary Conditions

The study only focuses on the thermal comfort aspects of energy-efficient buildings. There are numerous indicators of climate change, like temperature rise, water, soil, and so forth. For this study, temperature as an indicator of climate change was considered. The passive design strategies were narrowed to be applicable for temperate climate only. The study is limited to the context of educational buildings.

4 Methodology

The study used a simulation-based methodology using Energy plus and Design-Builder simulation software. Firstly, two education buildings as case studies were identified, followed by data collection, based on input parameters needed for building performance simulation and assessment of overheating. After data collection, the Temperature Overrun (TOjuly) analytical method was used to identify the spaces with the highest potential to overheat. The TOjuly method as per Dutch Technical Agreement NTA8800 (NEN, 2020, sec. 5.7) is a static heat balance model that indicates the probability of excess temperature in July. Further, calibrated simulation models using Design-Builder were created for the identified spaces (Wahi, 2020). These spaces were then simulated for 2050 and 2085 climate scenarios to determine the extent of the overheating problem compared to the baseline 2008 weather file. The weather files for 2050 and 2085 were created by transforming the 2008 TRY for 1% probability of temperature exceedance as specified by NEN 5060 (2008). The transformation was done according to the worst-case scenario of climate change as specified by the Dutch Meteorological Institute (KNMI, 2015; Wahi, 2020).

The overheating was estimated using the Dutch adaptive thermal comfort (ATG) model. The ATG thermal comfort model of 2014 (ISSO, 2014) is based on international standard EN15251. This model estimates overheating by calculating the percentage of occupied discomfort hours of indoor space in question. Indoor space is considered comfortable if the percentage of occupied discomfort hours are within the maximum limits according to comfort classes A, B, C (Boerstra et al., 2015; ISSO, 2014). The method is also advantageous due to the hybrid nature of its application; that is, the method can be applied for mechanically cooled buildings (Beta buildings) and Free-running buildings (Alpha buildings). According to ISSO74 (2014), EN 15251, and "fresh school" (RVO, 2015) guidelines, the classroom spaces have a comfort level of class B, where only 10% of the occupied discomfort hours are allowed. Therefore, the simulated indoor operative temperatures for 2008, 2050 and 2085 were plotted against the running mean outdoor temperature of the past seven days and the percentage of occupied hours exceeding class B as discomfort hours were determined (Wahi, 2020). It is to be noted that the percentage of discomfort hours is calculated for the exceedance of both upper (overheating) and lower (underheating) limits of class B. However, for the study, only the number of hours that exceeded the upper limit of class B was calculated as the percentage of occupied discomfort hours for indicating overheating. After identifying the extent of overheating in future climate scenarios, passive adaptive strategies were selected for the case studies. The strategies applicable at the building envelope were selected based on their potential to reduce overheating through preventing, controlling, and removing excess heat. These strategies were simulated in various combinations in the climate scenarios mentioned above to observe their combined impact on reduction in overheating.

4.1 Robustness Assessment Method

A robust design would be a design with minimum performance variation in the presence of any uncertainties (Wahi, 2020). For evaluating robustness, a framework was developed (Figure 1), where the identified passive design strategies and their performance in reducing overheating in 2050 and 2085 climate scenarios were subjected to the statistical method of "best-case and worst-case scenario" (Kotireddy, 2018; Kotireddy et al., 2019). Table 1 illustrates the statistical method used.

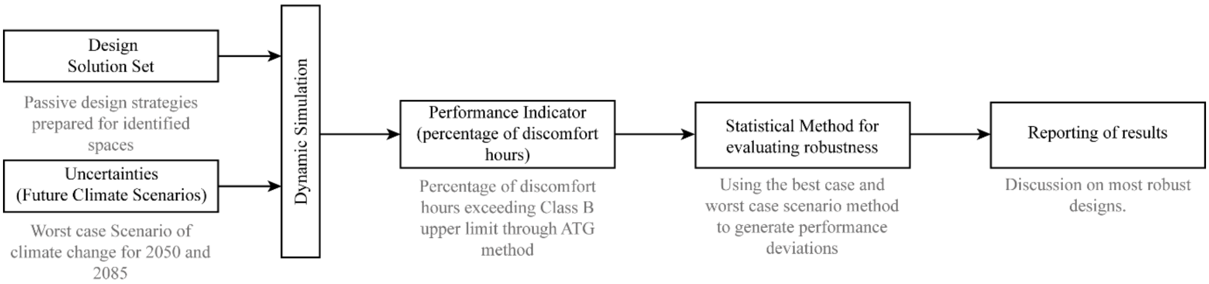

Figure 1 Framework for evaluating the robustness of design solution set against future climate and percentage of discomfort hours.

Table 1 Best-Case and Worst-Case Statistical model for evaluating robustness. Source: Adapted from the works of Kotireddy et al., 2019

Design Code	**Climate Scenario**		**Worst-Case Performance (WC)**	**Best Case Performance (BC)**	**Performance Deviation (WC-BC)**
	2050	2085			
C1	$P1_{2050}$	$P1_{2085}$	$Max(P1_{2050},P1_{2085})$	$Min(P1_{2050},P1_{2085}, ..., Pn_{2050},Pn_{2085})$	WC1-BC
…	…	…	…		...
Cn	Pn_{2050}	Pn_{2085}	$Max(Pn_{2050},Pn_{2085})$		WCn-BC
Most Robust Design					Min(WC-BC)

For each identified space, firstly, the design option (Cn), and their corresponding percentage of the discomfort hours in 2050 and 2085 climate scenario as their performance (Pn_{2050}, Pn_{2085}) were tabulated. For each design solution, the worst performance (WC) would be the maximum percentage of discomfort hours achieved by the solution in 2050 and 2085. Since the method compares the worst performance of a design solution with the best performing solution in the entire solution sample. Therefore, the best performing solution (BC) would be the design solution with a minimum percentage of discomfort hours. Finally, the most robust design would be the solution/s with a minimum performance deviation calculated as the difference between the best case of the entire design space (BC) and the worst-case from each climate scenario (WC).

5 Case Study: Educational buildings

Educational buildings are a vast typology of building stock; therefore, to cover more ground, two different cases of educational buildings were selected. A university building in the TU Delft campus (Pulse building) and a secondary school in Rotterdam (Melanchthon Kralingen) were investigated (Figure 2). The case studies set up under the bigger umbrella of educational buildings; however, they are different in terms of occupancy and activities. Table 2 illustrates the data collected for the two case studies regarding the building envelope properties, climate control systems, occupancy pattern and lighting. Hence, applying the strategies to these buildings would further help develop design guides that can be scaled for any educational building.

6 Discussion and Results

6.1 Identification of overheated spaces

The analytical method of TOjuly returns a dimensionless value where 0-2 is considered as low risk of overheating, 2-4 as moderate risk and above 4 indicates a high risk of overheating. From the result of TOjuly, two spaces with the highest risk of overheating were identified in each case study building. For the Pulse building, the identified spaces were Hall 8 and Hall 10, while for the school building, staffroom and class 31 were identified (Figure 3). Hall 8 and 10 are in the southwest and northeast direction, respectively. While class 31 and the staffroom located in the south direction. All the spaces are on the top floor of the building. The identified spaces coincide with the literature studies (Coley and Kershaw, 2010; Heracleous and Michael, 2018; Irulegi et al., 2017; Jenkins et al., 2009; Kamenský et al., 2014; Lykartsis et al., 2017; Teli et al., 2011; Zinzi et al., 2017) where it was observed that the teaching spaces like classrooms, seminar rooms are most likely to be overheated because of large occupant loads. Regarding the location of the spaces, it was found that the spaces on the south, south-east, north-east, and northwest are susceptible to overheating. Furthermore, the spaces on the top floors are at the risk of overheating, considering the external heat gain through the façade and roof.

Figure 2 Left: Pulse Building, TU Delft Campus. Source: qbiqwallsystems.com. Right: Melanchthon Kralingen School, Rotterdam. Source: KAW Architects

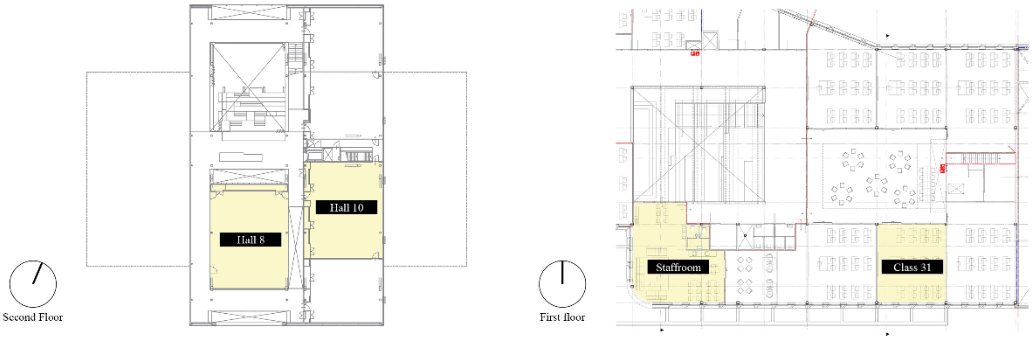

Figure 3 Identified spaces with high overheating risk. Left: Hall 8, 10 on the second floor of Pulse Building. Right: Staffroom and class 31 on the first floor of the Melanchthon School.

Table 2 Building envelope, climate control systems, occupancy pattern and lighting for the two case studies. Source: Campus and Real Estate, TU Delft; Wolf+Dikken Advisors

	Pulse, TU Delft	**Melanchthon School, Rotterdam**
Façade (opaque)	R-Value: 7m^2.K/W	R-Value: 4.5m^2.K/W
Roof		R-Value: 6m^2.K/W
Ground Floor	R-Value: 5m^2.K/W	R-Value: 3.5m^2.K/W
External floor		R-Value: 6m^2.K/W
WWR	0.75	0.6
Glazing	Triple IGU, U-Value: 0.8W/ m^2.K, VLT: ≤ 0.70	HR++, U-Value: 1.1 W/ m^2.K, VLT: ≤ 0.70
Infiltration	0.15 L/S per m^2 at 10Pa	0.42 L/S per m^2 at 10Pa
Shading	Internal blinds (NE), Textile External Shading (SW)	Overhangs, side fins, External Roller Blinds
Heating/Cooling Systems	ATES, Radiative Systems, Climate ceilings	District Heating, Natural Ventilation
Ventilation	Mechanical supply and exhaust	Mechanical ventilation heat recovery with summer bypass
Lighting	9 W/m^2	8 W/m^2
Occupancy	8:00 – 0:00 (all week)	9:00-16:00 (weekdays)

6.2 Identification of overheated spaces

As discussed in section 4, the percentage of discomfort hours are the occupied hours whose indoor operative temperature exceeds the upper temperature limit of Class B determined by Alpha or Beta case. For class B, 10% of the occupied hours can exceed the upper limit (Boerstra et al., 2015; ISSO, 2014). The results from the case studies in all three climate scenarios are summarised in Figure 4. From the figure, it was observed that the identified spaces in the Pulse building are comfortable in the baseline climate scenario, but eventually, as the outdoor climate changes in the future, the spaces become uncomfortable. Currently, there is no monitoring of free cooling by the mechanical ventilation system; therefore, it was not modelled. Nevertheless, the effect of summer bypass can be seen in the Melanchthon school, where it could reduce the discomfort due to overheated hours up to some extent in 2050.

Hall 10 in the Pulse building is possibly overheated in the future due to the lightweight construction of the façade. The surface temperature of the North East façade increases due to direct radiation from the morning sun. The surface temperature increases due to high outdoor air temperature in the future climate, resulting in heat gain in the lecture hall. Hall 8, on the other hand, has low insulation values of the partition walls. As a result, the partition wall on the southwest orientation receives direct solar radiation, contributing to overheating. Comparing the same observation with the Melanchthon School, the South façade is susceptible to high solar radiation throughout the day, curbed to a great extent by the sided fins and overhangs. The façade is also lightweight with timber frame construction. However, the unventilated side fins cavity add the necessary thermal mass to the façade to reduce heat gain. The window also has external blind control, which works better to reduce heat gain than internal blinds of Hall 10 in the Pulse building. Heat Removal through ventilation is an essential factor for reducing overheating. In the school building, the staffroom is comparatively comfortable from class 31 due to the possibility of cross ventilation, whereas class 31 uses single-sided ventilation through windows. However, the use of ventilation is greatly dependent on the context. The school also uses night-time ventilation through summer bypass, which helps reduce heat from the interior surfaces. However, night ventilation is not used in the Pulse building as the building is not in operation from 00:00 – 7:00. The radiative cooling starts at 4:00, which does not give enough time for the purge ventilation to cool the building.

6.3 Adaptive Solution Set

From evaluating Pulse and School building, it was found that Hall 10 provides maximum opportunity for testing different strategies out of all four identified spaces. Therefore, a first selection of strategies was made by considering only Hall 10. From the analysis, it was observed that for controlling heat, passive design strategies such as window-wall ratio (WWR) and fixed or moveable shading are most effective. In terms of heat control, increasing the albedo effect by adding white surfaces to the building envelope can be helpful, but it is more effective when the WWR is less than 75 %. For heat removal, ventilation strategies are promising, but it will depend on the system design for mixed-mode and outside air temperature at night to effectively cool the space. Adding PCM panels to increase thermal mass could be helpful for lightweight constructions but only in the presence of night ventilation. The individual assessment of strategies at Hall 10 represents the potential of passive design strategies in adapting to future climate to reduce overheating; however, when integrated with other strategies, the combined effect can further reduce the overheating. Therefore, different solutions set were prepared for each case study depending on the context of the building. The solution sets were analysed for the highest reduction in the percentage of discomfort hours according to the ATG method. These solutions set for all four identified spaces are illustrated in Table 3.

6.4 Robustness Evaluation

The solutions from Table 3 were evaluated for robustness using the steps discussed in section 4.1. Figure 5 illustrates the performance of the existing and proposed design solutions in reducing the percentage of discomfort hours in 2050, 2085 for hall 8 of the Pulse building. The "best-case" across all performances in 2050 and 2085 was design solution H8.3 with 6,6% of discomfort hours in 2050 compared to 18,2% of discomfort hours in existing situation. In contrast, each design strategy has its "worst performance" in 2085. From the performance deviation between the "best-case" H8.3 and "worst-case" of each design solution, it was observed that H8.3 has the minimum performance deviation. Design solution H8.3 with the combined effect of reducing WWR, increasing the insulation of opaque and transparent parts of the partition wall, PCM application, and mixed-mode ventilation has the most significant impact in maintaining thermal comfort in future climate change scenarios. Therefore, H8.3 is the most robust solution for hall 8.

Figure 6 illustrates the robustness analysis for hall 10. The strategies were applied to the existing façade with a WWR of 75% (H10.1-H10.4) and the façade with a WWR of 50% (H10.5-10.8). With the existing façade, the design solution H10.1, with the combined effect of external blinds as shading devices with white surfaces applied on building envelope, were found to have the highest reduction in percentage discomfort hours, in both the climate scenarios. When the actual performance of the design solutions was checked, it was found that strategies with mixed-mode ventilation (H10.3, H10.4) performed better in 2050, but in 2085 due to high outdoor temperature, the ventilative cooling will have limited application. From the robustness evaluation, the application of WWR of 50% was more effective in reducing overheating than the existing facade. The design solution H10.6 were found to be most robust. Although the WWR of 50% would significantly affect daylighting, a detailed daylighting analysis must be included in the robustness assessment in future research.

From the robustness assessment of different solutions for the school building, it was observed that the school building outperforms the Pulse building to reduce the percentage of discomfort hours. Although, it should not be ignored that the Pulse building has higher occupancy loads than the school building. From Figure 7, it can be seen that for both staffroom and class 31, the design solution S3 and C3 respectively were considered to be the most robust as they exhibit minimum performance deviations. The use of the albedo effect, application of PCM panels along with night ventilation can reduce overheating. However, an application of a 2m wide pergola can further reduce the risk of overheating in the future. Class 31 can be improved further by using a combination of openings along with the above strategies. The combination of high and low openings can facilitate cross ventilation for ventilative cooling. However, the possibility of ventilative cooling will reduce due to high outdoor temperatures in future. Therefore, in the latter part of the century, pre-cooling of air using low energy systems would become necessary.

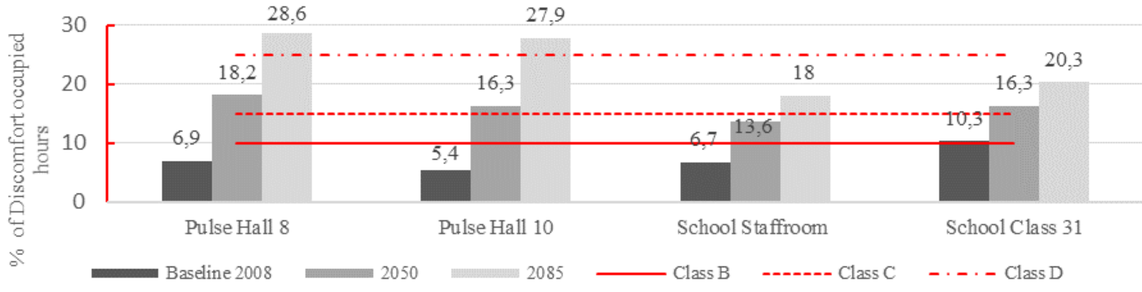

Figure 4 Comparison of percentage of discomfort hours due to overheating in baseline 2008, 2050 and 2085 climate scenarios.

Table 3 Selected design solutions with the highest impact on reducing overheating for case studies. Code H8 and H10 represent solutions for hall 8 and hall 10, respectively. Code S and C represent solutions for staffroom and classroom, respectively.

Code	Solution Set	Code	Solution Set
H8.1	Reduce U-Value of partition walls +White Surfaced Roof+WWR70%	**H10.7**	WWR 50% + White surface roof and facade+ mixed mode +PCM panels+ external blinds
H8.2	Reduce U-Value of partition walls +White Surfaced Roof+WWR70% +Mixed Mode	**H10.8**	WWR 50% + White surface roof and facade+ mixed mode +PCM panels+ external shutters
H8.3	Reduce U-Value of partition walls +White Surfaced Roof+WWR70% +Mixed Mode+ PCM panels	**S1**	White surface roof and façade +2 m width Pergola
H10.1	WWR 75% + White surface roof and façade+ External Roller blinds	**S2**	White surface roof and façade +PCM Panels
H10.2	WWR 75% + White surface roof and façade+ external shutters	**S3**	White surface roof and façade +2 m width Pergola + PCM Panels
H10.3	WWR 75% + White surface roof and facade+ mixed mode +PCM panels+ external blinds	**C1**	White surface roof and façade +2 m width Pergola
H10.4	WWR 75% + White surface roof and facade+ mixed mode +PCM panels+ external shutters	**C2**	White surface roof and façade +PCM Panels+ Combination of openings
H10.5	WWR 50% + White surface roof and façade+ External Roller blinds	**C3**	White surface roof and façade +PCM Panels+ Combination of openings+2m width Pergola
H10.6	WWR 50% + White surface roof and façade+ External Shutters		

6.5 Impact of robust design strategies

The robust design strategies identified from the assessment method significantly reduced the discomfort hours due to overheating in climate change scenarios. For example, at the building level, in the mechanically cooled Pulse building, the combination of robust design solutions can reduce the percentage of discomfort hours up to

54% in 2050 and 43% in 2085. While for the naturally cooled school building, the robust solutions can reduce the discomfort hours to 35% and 33% in 2050 and 2085, respectively.
The combination of white surfaces on the building envelope, reduction in WWR, careful application of shading strategies, and limited application of mixed-mode ventilation till 2050 are the most robust solutions applicable to the building envelope. Although, in 2085, we cannot avoid active cooling to support these strategies.

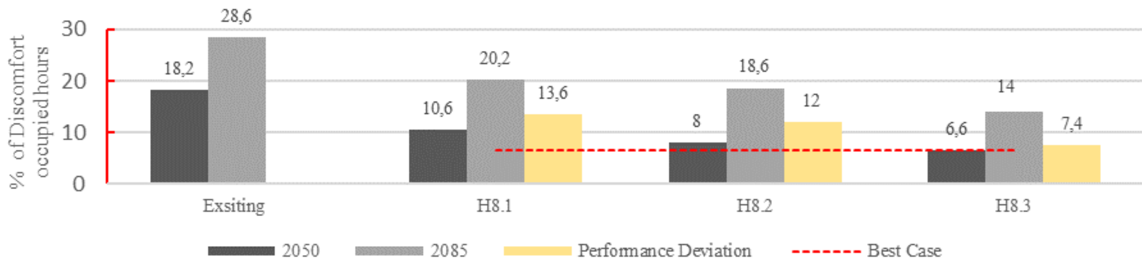

Figure 5 Robustness Evaluation of selected strategies for Hall 8 Pulse Building.

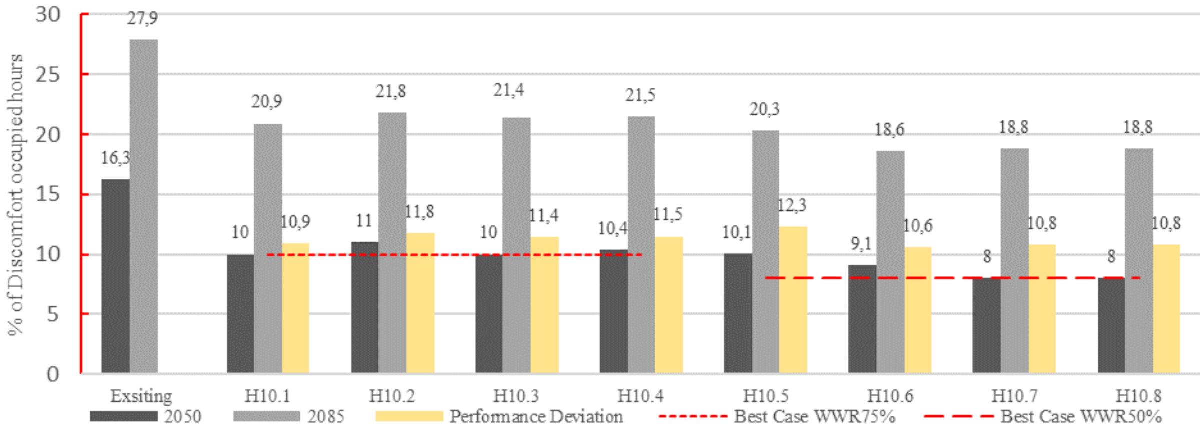

Figure 6 Robustness Evaluation of selected strategies for Hall 10 Pulse Building

Figure 7 Robustness evaluation of selected strategies for staffroom and class 31of Melanchthon School.

7 Conclusions

The study aimed at developing an assessment method for evaluating the robustness of different passive design solutions applicable to the building envelope. Furthermore, the assessment method was employed on educational case studies to identify design solutions that could maintain indoor thermal comfort by reducing the risk of overheating in future climate change scenarios. The assessment method used dynamic simulation methods to determine the performance of different strategies and evaluated the robustness using the statistical method of *"best-case and worst-case scenario*". From robustness evaluation, it was concluded that a combination of reduced WWR, white surface on the building envelope, careful application of shading devices on building envelopes, ventilative cooling with the application of PCM panels could very well make a building robust for a future scenario. From the study, it can also be concluded that the assessment method can be applied for both mechanically cooled and naturally ventilated buildings. The robust solutions identified from the assessment method could reduce about 54% in 2050 and 43% in 2085 for the Pulse building. While for the school building, the percentage of discomfort hours were reduced to 35% and 33% in 2050 and 2085. Currently, the evaluation method used only the criteria of thermal comfort. Therefore, the study suggests further research on the robustness assessment method to incorporate other aspects such as energy consumption, carbon emissions, and cost-efficiency to provide a holistic analysis of the most robust design solution.

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