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Climate Change Sensitive Overheating Assessment in Dwellings: A Case Study in Belgium

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Abstract

Due to the current rate of global warming, overheating in buildings is expected to be more frequent and intense in future climates. High indoor temperature affects occupant productivity, comfort, and health. Thus, it is necessary to predict the thermal performance of buildings concerning climate change. This paper applies a climate change sensitive overheating assessment method to a lightweight timber house in Eupen, Belgium. Three metrics are used, namely Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Building Climate Vulnerability Factor ($BCVF$). The overheating risk is assessed under four climate scenarios representing historical and future scenarios using dynamic simulation tool EnergyPlus v9.0. This method accounts for overheating severity and frequency, considering zonal occupancy profiles and thermal comfort models. The results indicate $BCVF$<1 for the Passive House case study showing its high potential in suppressing the outdoor thermal stress in the long-term. Finally, the increase in ventilation rate proves to be an adequate measure by decreasing the zonal peak temperatures up to 10°C and indoor overheating risk by ~60%.

Key Innovations

- Warm discomfort during the heating period is contained within the overheating analysis
- Lower base temperature for calculation of *AWD* is considered
- Climate change-sensitive overheating assessment is applied on a high-performance building in the Belgian context

Practical Implications

This paper provides a basis for the field experts in climate-resilient building design. It makes them aware of expected overheating risks in future climates and consider adaptation strategies in early-design stages.

Introduction

Overheating in buildings during sweltering weather conditions has become one of the main concerns in many countries (Eames, 2016; Laouadi et al., 2020). High indoor temperatures have significant impacts on occupant productivity, comfort, and health (Tanabe et al., 2013). During the extreme summer of 2003, more than 35,000 people died in Europe due to excessive heat stress (Brücker, 2005). This necessitates the definition of a reliable performance prediction methodology to indicate the vulnerability/resilience of buildings to high outdoor temperatures. Several studies assessed indoor overheating risk in residential buildings (Elsharkawy & Zahiri, 2020; Gamero-Salinas et al., 2020; Tian et al., 2020; Zukowska et al., 2019). Carlucci and Pagliano (2012) presented an overview of long-term thermal discomfort evaluation methods and grouped them into homogenous families. However, the thermal performance and overheating risk of buildings in relation to climate change are not appropriately addressed. Rahif and Attia (2021) investigated the overheating assessment methodologies to distinguish between short- and long-term methods. They found out that the only study that provides a climate change sensitive approach is the study of (Hamdy et al., 2017). In our paper, we apply this method to a Passive House (Attia & Gobin, 2020; Fani, 2020) in Belgium to predict its thermal performance in future climates.

Methodology

This study is a part of an ongoing project investigating the influence of climate change on occupant thermal comfort and overheating risk in Belgian residential building stock. Accordingly, a Passive House case study is simulated with minimum and maximum ventilation rates under four climate scenarios using dynamic simulation tool EnergyPlus v9.0. The monthly energy consumption and hourly indoor air temperature is calibrated by recorded data in 2015-2018 using ASHRAE 140 (2017) iterative method (Attia & Gobin, 2020). It is based on the calculation of Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of Root Square Mean Error (CV(RSME)). Finally, the potential of ventilative cooling is calculated as a mitigation strategy. The results of the simulations are then post-processed and visualized using MATLAB.

Case study description

The case study is located in Eupen (50°37′40″ N, 6°02′11″ E, 298 m) municipality with a temperate oceanic climate (Figure 1). The local climate can be characterized by 2678 HDD and 285 CDD for the period 1976-2004 (Ramon et al., 2019). The house is built in two levels (see Figure 2) and is a four-façade lightweight timber construction with a total area of 174 m^2. The building complies with the Belgian Passive House requirements where the annual net energy for heating should fall below 150 MJ/m^2.

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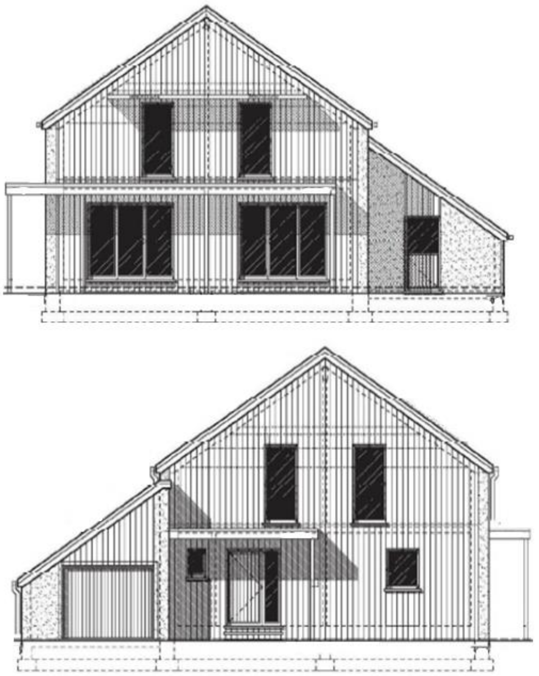

Figure 1: South-view (upper) and north-view (lower) of case study, Eupen, Belgium (derived from: http//energie.wallonie.be).

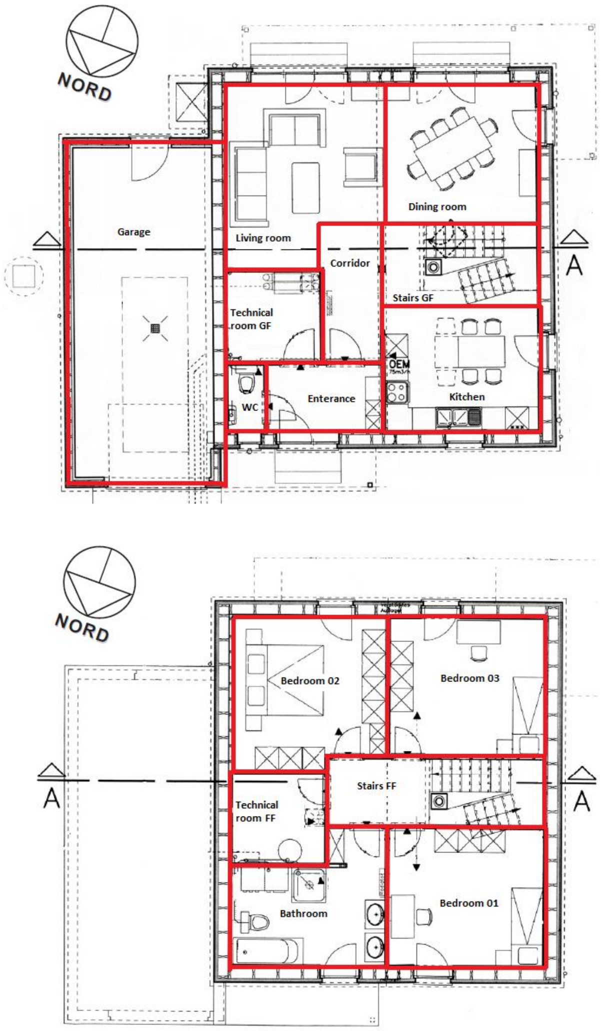

Figure 2: Case study plan: ground floor (upper), first floor (lower) (derived from: http//energie.wallonie.be).

The external wall conductivity is 0.132 W/m^{2}K insulated by mineral wool (6 cm) and cellulose (25 cm). Therefore, the thermal bridge caused by the mainframe in wood is eliminated. The building is heated by a pellet stove located in the stairs zone on the ground floor, and a gas water boiler supplies domestic hot water. The blower door test indicates the infiltration rate of 0.5 vol/h for a pressure difference of 50 Pa between the indoor and outdoor environments. South- and west-oriented ground floor zones (dining room, living room, and kitchen) and south-oriented bedrooms on the first floor are equipped with permanent solar shading devices.

The house is occupied by two adults and two children. Assumptions are made for the internal gains induced by equipment and the occupants considering weekdays and weekend occupancy scenarios.

Overheating assessment method

The overheating assessment method is based on three metrics called Indoor Overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*) and Building Climate Vulnerability Factor (*BCVF*) (Hamdy et al., 2017).

IOD is a multi-zonal indicator that quantifies the indoor overheating risk taking into account severity and frequency of high indoor temperatures,

$$IOD = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{op,i,z}-T_{op,i,z,comfort}\right)^{+}\times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}} \qquad (1)$$

Where i is occupied hour counter, z is building zone counter, Z is number of total building zones, N_{occ} is number of all occupied hours, $T_{op,i,z}$ is indoor operative temperature of time step i and zone z, and $T_{op,i,z,comfort}$ is the static or adaptive thermal comfort limit of time step i and zone z. *IOD* enables the implementation of multiple thermal comfort models in different building zones. We assumed a fixed temperature limit of 26°C based on the static comfort model CIBSE Guide A for the bedrooms. This selection is made since adaptation actions performed by occupants are limited during the sleeping period. For all other living areas, category II of the adaptive thermal comfort model EN 15251 is considered as one of the most commonly used comfort standards worldwide (Attia et al., 2019).

AWD indicates the severity and frequency of high outdoor temperatures according to a predefined base temperature,

$$AWD_{14°C} = \frac{\sum_{i=1}^{N}\left[\left(T_{a,i}-T_{b}\right)^{+}\times t_{i}\right]}{\sum_{i=1}^{N} t_{i}} \qquad (2)$$

Where N is total number of building occupied hours, $T_{a,i}$ is outdoor air temperature in time step i, and T_b is outdoor base temperature. T_b is determined based on building characteristics and is equal to an outdoor air temperature threshold, which above necessitates the operation of any means of passive or active cooling systems. Due to high insulation levels and overheating risk in Passive Houses, T_b of 14 °C is considered.

By assuming a linear correlation between *IOD* and *AWD*, *BCVF* is the slope of regression line that predicts the vulnerability of the building to overheating risk in relation to climate change,

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$$BCVF=\frac{IOD}{AWD_{18°C}} \quad (3)$$

$BCVF<1$ shows that the building can suppress the outdoor thermal stress, and $BCVF>1$ means that the building becomes overheated by increasing outdoor air temperature. The three above metrics help to estimate the ability of a building to maintain an acceptable indoor thermal environment in a warming climate.

Climate scenarios

The applied method requires two historical and two future weather datasets. For this aim, we used (i) average scenario representing historical climate using the weather data for the moderate year of 1965, (ii) extreme scenario that is the extreme data recorded in 2003, (iii) future normal scenario that is the normal climate projection of the year 1976 to 2100 with an increase of 2°C in average temperature due to global warming effect, (iv) future extreme scenario that is the extreme climate projection of the year 1976 to 2100 with an increase of 4°C in average temperature due to global warming effect and 1.4°C due to the urban heat island effect (Hamdy et al., 2017). The annual distribution of daily mean outdoor temperatures under four climate scenarios are shown in Figure 3.

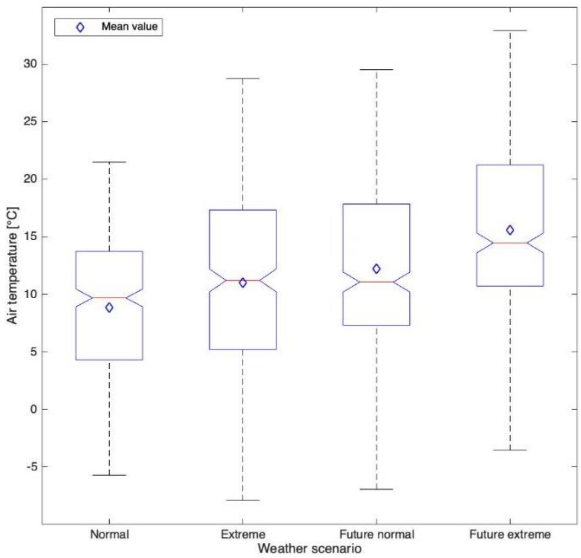

Figure 3: Annual distribution of daily mean outdoor air temperature under four climate scenarios.

Results

For each climate scenario, the case study with the minimum (0.9 $l/s.m^2$) and maximum (5 and 8 ac/h for bedrooms and living areas respectively) ventilation rates are simulated for annual periods (Hamdy et al., 2017). Therefore, the total number of simulations is 8. Figure 4 shows the trend of IOD in different climate scenarios represented by AWD. It is clear that the risk of indoor overheating increases as the average outdoor temperature increases. The slope of regression lines, 0.5269 for minimum ventilation rate, and 0.2443 for maximum ventilation rate, are the values of $BCVF$. It shows that the building with low ventilation rate has less potential to suppress the increased outdoor thermal stress in future climates. Figure 5 shows the annual distribution of hourly indoor operative temperature in different building zones under the future extreme scenario. Due to relatively higher solar gains through large glazing areas and orientation, the dining room, living room, and kitchen reach higher temperatures than the other zones. Figure 5 indicates that the maximum ventilation rate significantly decreases the upper margins of indoor operative temperature (up to ~10°C); however, high-temperature abnormalities emerge.

The potential of ventilative cooling is calculated based on the percentage of reduction in IOD. For this aim, the contribution of ventilative cooling $C_{\text{ventilation}}$ is defined as,

$$C_{\text{ventilation}}= IOD_{\text{min ventilation rate}} - IOD_{\text{max ventilation rate}} \quad (4)$$

The potential of ventilative cooling $P_{\text{ventilation}}$ is derived by normalizing the $C_{\text{ventilation}}$ over the $IOD_{\text{min ventilation rate}}$,

$$P_{\text{ventilation}}= \frac{C_{\text{ventilation}}}{IOD_{\text{min ventilation rate}}} \quad (5)$$

A new set of simulations are performed according to the minimum and maximum ventilation rates suggested by NBN D50-001 (1991) in Annex 4. All results regarding the potential of ventilative cooling (two sets of minimum and maximum ventilation rates) are depicted in Figure 6. The ventilative cooling potential decreases as global warming continues and it will be more challenging to mitigate the risk of overheating by only relying on ventilative cooling strategy.

Discussion

Findings and recommendations

More intense and frequent overheating events are expected as a result of climate change. This paper evaluates the thermal performance of a Passive House in a changing climate. Our study indicates that the buildings in compliance with the Passive House standard can suppress outdoor thermal stress. Figure 4 shows a substantial reduction in IOD in all scenarios for maximum ventilation rate. Higher ventilation rate decreases the vulnerability of the building to climate change by 53%. Figure 5 shows that in maximum ventilation rate, mean daily indoor operative temperature is reduced in the dining room, living room, and kitchen as high-risk zones by 7.5°C, 4°C, and 6°C, respectively. 5 ac/h for bedrooms and 8 ac/h for living areas has a significant potential of ~60% in overheating risk reduction (see Figure 6). However, Figure 6 shows that the effectiveness of ventilative cooling is predicted to be decreased by 3.74% in future extreme scenario compared to normal historical scenario. It means that although ventilative cooling is a resilient technology, its performance is expected to degrade with the continuation of global warming (Roetzel et al., 2010).

We recommend the Belgian government and experts in the field to take actions in defining accurate overheating calculation methods besides the requirements for active and passive mitigation strategies.

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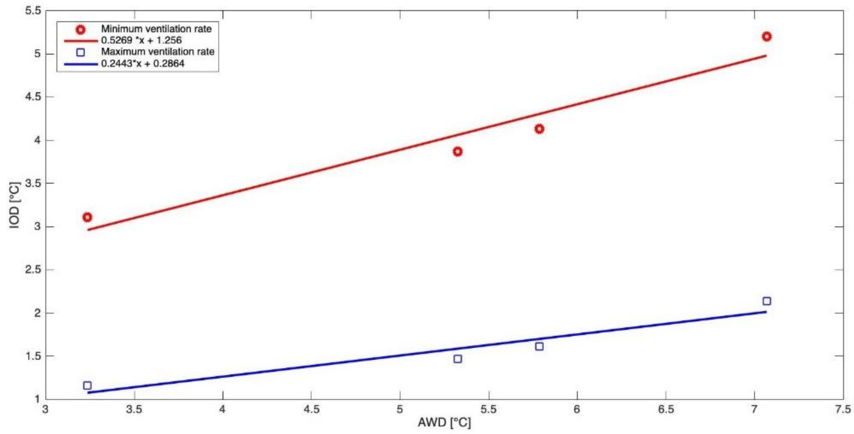

Figure 4. The Indoor Overheating Degree (IOD) presented by the Ambient Warmness Degree (AWD) under four climate scenarios for minimum (0.9 l/s.m^2) and maximum (5 and 8 ac/h for bedrooms and living areas) ventilation rates. The slope of the regression lines shows the Building Climate Vulnerability Factor (BCVF).

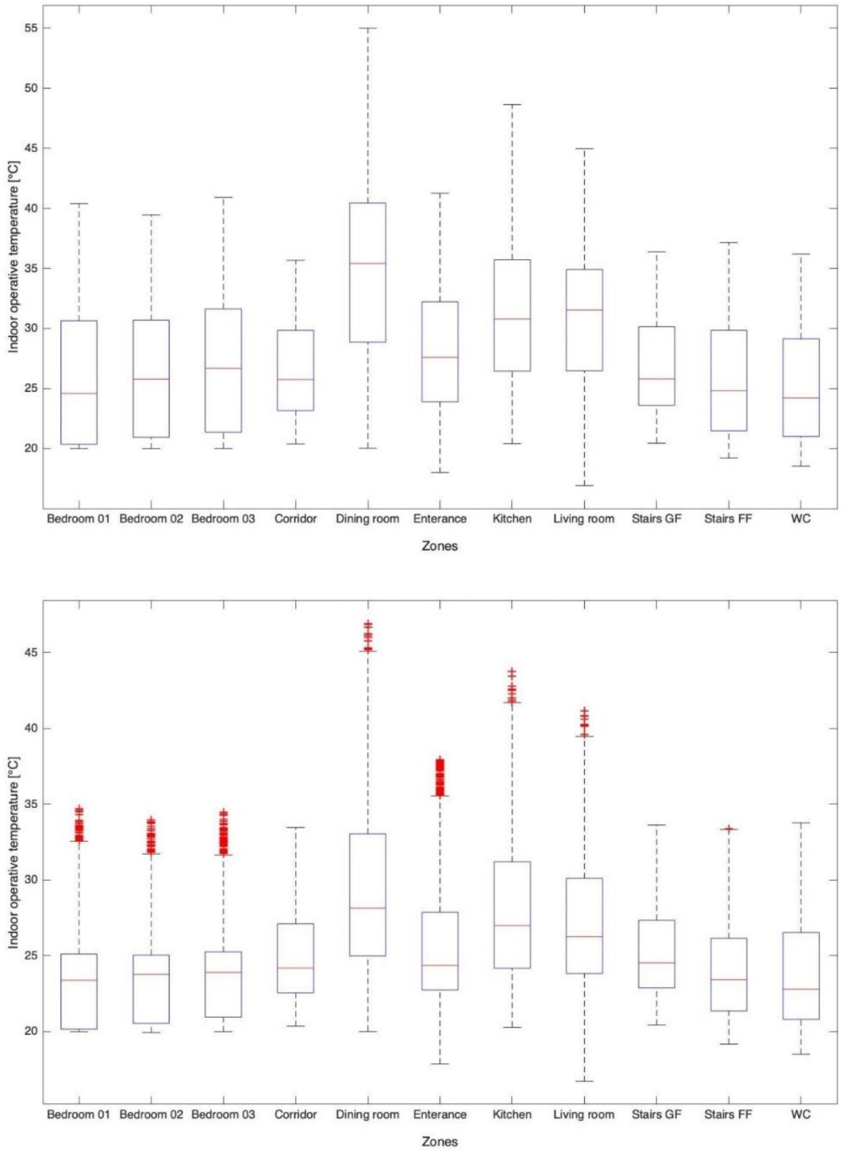

Figure 5. Annual distribution of hourly indoor operative temperature for minimum (top) and maximum (bottom) ventilation rates under future extreme scenarios for all living areas.

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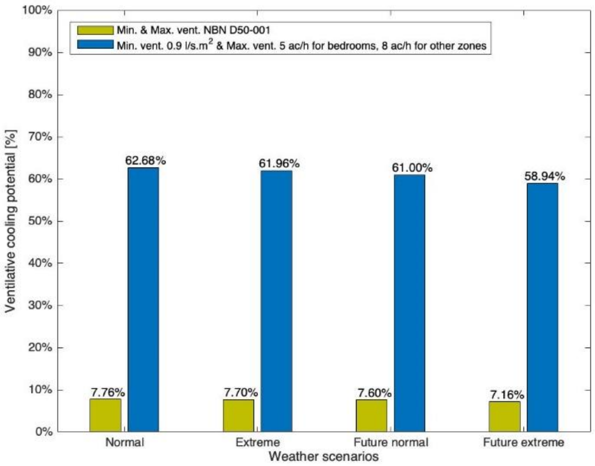

Figure 6. The potential of ventilative cooling to reduce the risk of overheating is expressed as a percentage of IOD for minimum and maximum ventilation rates.

We recommend exploring the potential of natural ventilation which is capable of 23-94% cooling demand reduction in future climates (Gilani & O'Brien, 2020). Mechanical ventilation increases building resiliency to climate change (Burman & Mumovic, 2018); however, it will increase energy consumption. Therefore, we recommend a full life-cycle assessment to balance energy efficiency and overheating resilience in the long-term. Also, we recommend the joint application of ventilative cooling with additional measures such as an increase in building thermal mass or solar shading devices.

Strengths and limitations

The first strength of our study relies on the validity of our simulation model due to the abundance and availability of data on the case study. Besides, we have implemented a novel method regarding climate change sensitive overheating assessment with some modifications. We extended the duration of our evaluation to the annual period. This enables us to consider the overheating risk during the winter season as well. Also, we defined a lower outdoor base temperature in the calculation of *AWD*. This is because the high-performance buildings with increased insulation levels are more prone to the risk of overheating (Attia, 2018) and needed to be cooled in lower outdoor temperatures.

The main limitation of the current study methodology is the neglect of solar radiation in the calculation of *AWD* which highly affects the results for *BCVF*. Besides, we only evaluate the potential of ventilative cooling. We hence do not account for the combined or individual effect of other measures such as an increase in thermal mass, glazing, solar shading devices, and building orientation. Also, we neglected the behavioral and spatial thermal adaptation in our assessments (Attia, 2020b).

Implication on practice and future research

One implication of our research is to include and address our modified methodology in future revisions of the national interpretation of the Energy Performance of Building Directive (EPBD). There is a need for major revisions in EPBD regulations to include and consider more precisely thermal comfort along with the energy calculation methods. The current rule for building stock in Belgium sets a static threshold of 23℃ as comfort criterion and ignores the occupant adaptation opportunities. This approach overestimates the discomfort hours and increases energy consumption by forcing the installation and operation of active cooling systems. Thus, there is a need for further investigation in developing accurate and distinct thermal comfort models (static, adaptive, and hybrid) for naturally ventilated, mechanically cooled, and mixed-mode buildings. We strongly recommend a multi-zonal approach for overheating assessment, which allows the designer to set zone-based comfort models (e.g., static model for bedrooms) and identify the zones at higher risk of overheating (Attia, 2020a). For future research, there is a need for future weather files with more accurate sky conditions and solar radiation factor. We also recommend developing national and regional benchmark models to test the suggested overheating method in different climatic conditions and building stock (Attia et al., 2020).

Conclusion

This paper applies a state-of-the-art overheating assessment methodology based on three metrics, namely Indoor overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), and Building Climate Vulnerability Factor (*BCVF*) on a case study in Eupen, Belgium. The lightweight timber construction Passive House shows its high potential to suppress annual overheating risk in future climates. However, provisions are required in the dining room, living room, and the kitchen as the most vulnerable zones due to the relatively high solar gains. The ventilation strategy proved to be an adequate measure in reducing the indoor overheating risk, but its potential will decrease with continuation of global warming.

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