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Psomas, Theofanis Ch.; Heiselberg, Per Kvols; Duer, Karsten; Bjørn, Eirik

ANALYSIS AND COMPARISON OF OVERHEATING INDICES IN ENERGY RENOVATED HOUSES

Theofanis Psomas[1], Per Heiselberg[1], Karsten Duer[2], Eirik Bjørn[3]
[1]Department of Civil Engineering, Aalborg University, Aalborg, Denmark
[2]VELUX A/S, Horsholm, Denmark
[3]DOVISTA A/S, Ringkøbing, Denmark

ABSTRACT

The scientific literature offers a number of methods for assessing the likelihood of overheating in buildings. The paper calculates eight well-documented indices for four representative family houses, from moderate and temperate climates, under different renovation processes (66 variants), with the use of multi-zone energy software. In two out of four cases, the calculation included passive cooling measures for optimization purposes (shading, ventilative cooling). The analysis shows strong correlations between different methods-indices originating from the same comfort model theory independently of the climate and the building geometry. Finally, many indices correlated highly with the annual building heat gains and losses.

INTRODUCTION

Energy efficient improvements of the existing European building stock are one of the most cost-effective ways to diminish energy use, fight climate change, decrease unemployment and achieve carbon emission targets (Paulou et al., 2014). Many post-occupancy comfort studies of energy renovated residential or nearly zero energy buildings have documented elevated temperatures above comfort levels, not only during the summer period but also during the shoulder months (Larsen, 2012). Evidence shows that high indoor temperatures, for long periods, cause serious impact on indoor quality and productivity (AECOM, 2012).

There is no rigorous or widely accepted definition of what constitutes overheating indoors for different type of buildings, climates or group of people (vulnerable, children and others). Most definitions are health, productivity or thermal comfort related (Carlucci et al., 2012). Literature and regulations have collected and analyzed more than seventy overheating indices over time (Epstein et al., 2006). Most of the indices relate and depend on the examined building type (office, residential and others), the calculation period (specific period or the total hours) and the occupation schedule (Psomas et al., 2015). New standards and regulations accept a minimum risk of overheating indoors (deviation from the comfort conditions; e.g. EN15251, 2007). The length of deviation (e.g. 3% or 5% of total hours) of every method-index varies (CIBSE, 2013; EN15251, 2007).

Overheating indices are widely used for operational assessment of comfort in existing buildings and optimization of the envelope and the control strategies in the design phase ("best solution"). Designers use different overheating indices and metrics for their cases, because they refer to different regulations and standards. As a consequence there is no common ground for intercomparison and generalization of their results.

The objective of this research is to compare and correlate the results of eight different well-documented and widely used overheating risk indices (overheating assessment). The analysis was conducted for four different single family houses and geometries (reference cases) in different climatic conditions (Denmark, United Kingdom, Austria and South of France), under different renovation processes and different applied passive cooling measures. Possible correlations of the indices (independent of the examined geometry and climatic conditions of the case studies) would diminish and simplify the amount of analysis (compliance to different regulations and standards) during the design phase. In addition, the researchers or designers' various design proposals ("best practices") calculated by different overheating metrics would be comparable on common ground. Compliance with the comfort regulations is out of the scopes of this research (length of deviation). A secondary output of the research is the representation of all the examined overheating results (different indices) with the annual losses and gains of the cases (66 variants). This analysis will use a new heat fraction, "annual ratio". The annual ratio equals the heat gains (HG) minus the heat losses (HL) divided by the heat losses (HL). This ratio is non-dimensional.

METHOD

Case studies

The case studies of the paper are representative single-family houses (the result of deep statistical analysis) as concerns the geometry, the energy performance and the materials for the specific examined periods. The houses are from 1960s, 70s and 80s and are one storey (Danish and French case

studies) two storeys (British and Austrian case studies) and detached or semi-detached buildings (British case study). The houses of these periods are heavy weight constructions made from brick and concrete block elements and have been constructed with no or the first elementary energy thermal regulations. These houses will be deeply retrofitted in the coming years (high market potential). The stock of these countries equates with one third of the European Union building stock (European Council, 2012), and these climates are representative of the temperate and moderate climates of Europe (Peel et al., 2007).

The houses are extracted from the TABULA project (Denmark, France; real buildings) and from the official reports of the countries to the European Commision (U.K., Austria; TABULA, 2014; OIB, 2013; DCLG, 2013). The TABULA project has a reference position regarding the definition of typical residences (single-family, terraced, apartments and multifamily) for 13 European countries (Ballarini et al., 2014).

Table 1

Thermal and technical characteristics (heat transfer coefficients (W/m^2K), g value, N50 (h^{-1}) of the elements, for all the case studies and renovation phases (1: base case, 2: national renovation regulations, 3: nearly zero energy target).

	WIND.	CEIL.	WALL	FLOOR	N50
AUSTRIA (144.4M^2, AFTER 1960)					
1	3/0.67	0.55	1.20	1.35	3.0
2	1.2/0.6	0.15	0.27	0.30	1.5
3	0.8/0.5	0.15	0.15	0.15	0.6
DENMARK (116.2M^2, 1973-1978)					
1	2.7/0.76	0.45	0.45	0.35	5.0
2	1.65/0.7	0.15	0.20	0.12	1.6
3	1.2/0.6	0.15	0.20	0.12	0.8
FRANCE (94.2M^2, 1982-1989)					
1	4.6/0.9	0.60	1.00	1.00	5.0
2	1.5/0.7	0.22	0.43	0.43	1.4
3	0.8/0.5	0.15	0.15	0.15	0.6
U.K. (60.3M^2, BEFORE 1978)					
1	3.2/0.8	0.85	2.25	1.35	8.0
2	1.6/0.7	0.18	0.30	0.20	4.0
3	0.8/0.5	0.15	0.15	0.15	0.6

Dynamic simulations and renovation steps

The analyses have covered various temperate climates: United Kingdom (London city), Denmark (Copenhagen), Austria (Vienna) and South France (Marseille), with the use of highly sophisticated and state of the art energy software DesignBuilder version 4.2. The examined weather data refer to the previous decade, and it is representative of the climatic conditions of these cities (Psomas et al., 2015; DOE, 2014). This software uses the calculation engine of Energy Plus v. 8.1 and complies with the state of the art European and ASHRAE energy guidelines and standards (DesignBuilder, 2014).

The study includes renovating and analysing the case studies in steps in three phases (Table 1). The first phase will contain analysis of the initial base case study as extracted from the reports (Psomas et al., 2015). The second phase will includes renovating the case studies according to the regulations of each country in steps (windows, ceiling, external wall, floor, airtightness). The third and final phase of the simulations will involve renovating the case studies (Table 1) to reach very efficient energy goals (2 to 4 variants; PassiveHouse, 2014, Danish Building Regulations, 2013). The main occupancy profile and internal loads reflect a 5-member working family, occupied the house 77.4% of the hours of the year (Psomas et al., 2015; Jensen, 2011, Grinden, 2008). The study simulated the case studies as free-floating buildings (transition and summer season) without mechanical cooling systems. The simulations were conducted with constant 0.5 air changes per hour all day for indoor air quality reasons. The heating set point was set to $20^{o}C$ (heating period). For the simulation of the heat conduction of the envelope, the study used the Conduction Transfer Function algorithm. The natural convection heat exchange was simulated internally the envelope with the use of the TARP method and externally the envelope with the DOE-2 method (Psomas et al., 2015).

Overheating indices

Eight overheating likelihood indices were examined in this research:

1. Percentage outside the range (POR), or the percentage of the occupied hours, with operative temperatures outside the upper range of the adaptive comfort model, adaptive method overheating index (category II-EN15251, 2007; Equation 1)

2. Degree hours outside the upper range of the adaptive comfort model (category II-Annex F, EN15251, 2007; Equation 1)

3. Exceedance of a fixed threshold, 25°C, measured during the occupied and non-occupied hours (% hours over the benchmark)

4. Exceedance of a fixed threshold, 25°C, measured only during the occupied hours, (CIBSE, 2013; % hours over the benchmark)

5. Exceedance of a fixed threshold, 26°C, measured only during the occupied hours, (CIBSE, 2013; % hours over the benchmark)

6. Exceedance of a fixed threshold, 28°C, measured only during the occupied hours, (CIBSE, 2013; % hours over the benchmark)

7. DT index, or the difference between peak indoor and annual average outdoor dry-bulb temperature (Carlucci et al., 2012)

8. Nicol's overheating risk index (NAOR; Nicol's et al., 2009; Equation 2)

For these assessments, the examination requires a calculation of the operative temperature of the building by weighing the temperatures of all the zones of the house in net volume terms (EN 15251, 2007). The overheating assessment was performed for the whole year, but the incidents outside the period of May to September are minimal.

The first two indices related with the European thermal adaptive comfort model. These indices were introduced by ISO 7730:2005 standard and were re-proposed by EN 15251:2007. These indices represent the percentage of the occupied hours and the degree hours where the operative temperature of the house is higher than the upper boundary of the adaptive comfort model range (Equation 1). These indices will be the core methodologies at the updated form of the standard, as far as the long-term evaluation of the thermal conditions of a building (expected publication in 2017). For renovation processes, category II is being used. There were no undercooling temperatures documented for the examined period in all cases and variants.

$$T_{i,op.max} = 0.33 * T_{rm} + 21.8 \qquad (1)$$

These indices are symmetric, dynamic, category based and widely used from the literature for the assessment of "free-running" buildings (no mechanical cooling) and especially residential houses where the options (e.g. access to operable windows) and possibilities of thermal adaptation of the occupants are many (EN 15251, 2007).

The next four indices calculate the percentages of hours (occupied or during the whole day; index 3) with temperatures above fixed thresholds. These indices-methods are *static*, simple and easily understandable for owners and designers. In addition, these are the most widely used indices for long-term assessment of overheating likelihood and occurrence in the literature and the regulation guidelines from various countries (Carlucci et al., 2014).

The calculation of the next index (DT) subtracts the annual average outdoor dry bulb temperature from the maximum indoor operative temperature (Carlucci et al., 2012). This index is simple, but it does not offer any information about the severity or the duration of the occurrence.

Finally, the last index developed by Nicol et al. (2009), as the result of a research project for thermal comfort analyses in office buildings. The concept advances the idea that thermal discomfort is not related to a specified temperature threshold but to the difference between the indoor operative temperature and the comfort temperature (EN 15251, 2007). The index is calculated by Equation 2 (regression analysis; CIBSE, 2013). The index is assymetric and is not based on categories. The index related with ASHRAE's thermal comfort scale (votes +2 and +3 for warm and hot).

$$P(\Delta T) = \frac{exp(0.4734 * \Delta T - 2,607)}{1 + exp(0.4734 * \Delta T - 2,607)} \qquad (2)$$

Passive cooling measures

The study applied two passive cooling measures the two most extreme climates of our case studies (Denmark and South France), for every phase of the analysis (base case, regulations and nearly zero energy target).

The first cooling measure is the increase of the ventilation rate from the basic value, for indoor air quality reasons, to higher constant values of 1 ach and 1.5 ach. The new rates were applied during all day and night for every zone of the case studies (Psomas et al., 2015).

The second cooling measure is the application of shading, with the use of three different shading systems (internal blinds, external blinds and fixed pergolas-awnings). The movable shadings were applied to all openings during the non-occupied hours. The reflectivity of the blinds was set to 0.8 and the projection of the fixed shading systems to 0.5m (Psomas et al., 2015).

All the overheating risk indices were decreased with the application of these passive cooling measures (30 out of the 66 variants).

Regression analysis

For the fulfillment of the objectives of the paper, linear and non linear regression analyses were performed using the generalized reduced gradient method (Carlucci et al., 2014). The linear or non linear equation (exponential or 2nd order polynomial), which fits better to the data, was chosen and the coefficient of determination (R^2) was calculated.

RESULTS AND DISCUSSION

Indices correlations

All the overheating risk indices were compared with each other, and regression analyses (linear or polynomial 2nd order) were performed. Table 2 presents all the results of the regression analysis of the indices with coefficient of determination over 0.6. This research extends the evidences and conclusions of previous research projects (Carlucci et al., 2014) as concerns the intercorrelation of the overheating risk indices, comparing results from different climatic conditions and building geometries (residential buildings).

Overheating likelihood indices originate from the same adaptive comfort model (POR method, degree hours method, Nicol's method) and highly correlate with each other with coefficients of determination from 0.86 to 0.98 (Figures 1, 2 and 3).

Table 2
Comparison and regression analysis (linear and non-linear equations and coefficients of determination) of pairs of overheating indices for all the case studies and variants.
(*Referred to the numbering at the method's section)

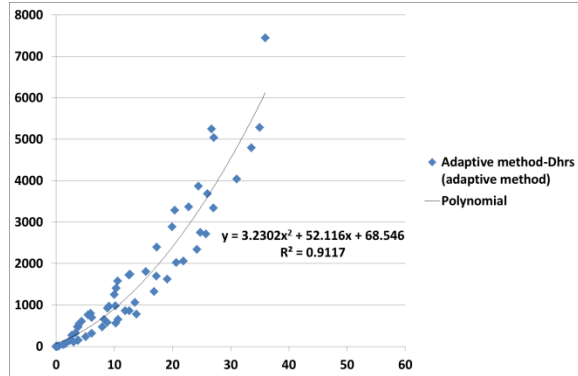| INDEX (X-Y)	REGRESSION	R^2
1-2*	$3.2302x^2-52.116x+68.546$	0.91
1-3*	$-0.0105x^2-1.1497x+14.139$	0.61
1-4*	$-0.0086x^2-1.0789x+14.769$	0.60
1-5*	$-0.0066x^2-1.0542x+10.086$	0.64
1-6*	$0.0045x^2+0.6627x+3.5009$	0.75
1-8*	$0.8297x+13.686$	0.86
2-8*	$3.8417x^2-29.365x-277.67$	0.98
3-4*	$0.9948x+0.375$	1.00
3-5*	$1.0006x-4.2775$	0.99
3-6*	$0.0224x^2-0.2844x+2.8487$	0.95
5-4*	$0.9826x+4.8736$	0.99
6-4*	$-0.0315x^2+2.0631x+7.3407$	0.96
6-5*	$-0.0251x^2+1.9006x+3.3161$	0.98

Figure 1 Comparison and regression analysis of the adaptive method POR overheating index (x-%) with the degree hours overheating index (y-°Chrs) for all the case studies and variants.
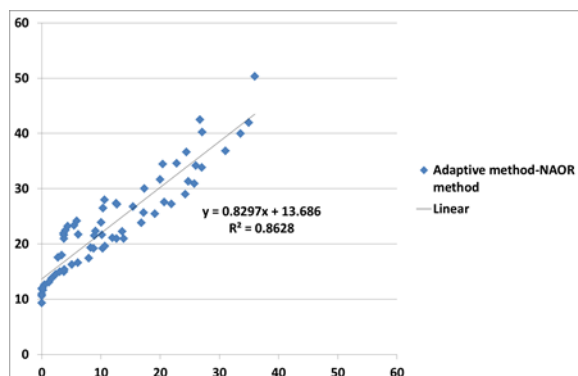

Figure 2 Comparison and regression analysis of the adaptive method POR overheating index (x-%) with the NAOR overheating index (y-%) for all the case studies and variants.

The correlation of the adaptive method with the indices using fixed benchmarks is medium to high with coefficients of determination from 0.60 to 0.75 (polynomial equations). There is no correlation (low R^2) between any index with DT index.
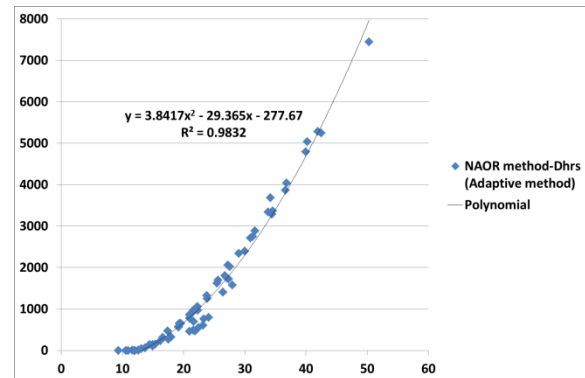

Figure 3 Comparison and regression analysis of the NAOR overheating index (x-%) with the degreehours overheating index (y-°Chrs) for all the case studies and variants.

The likelihood indices with fixed thresholds highly correlated with each other in most cases with polynomial equations and coefficients over 0.95 (Figures 4 and 5).
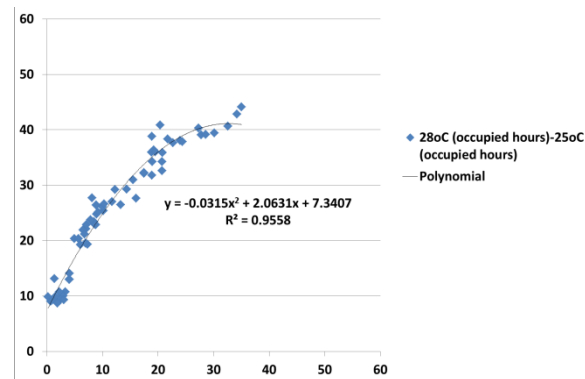

Figure 4 Comparison and regression analysis of the 28°C (fixed benchmark) overheating index (x-%) with the 25°C (fixed benchmark) overheating index (y-%) for all the case studies and variants.
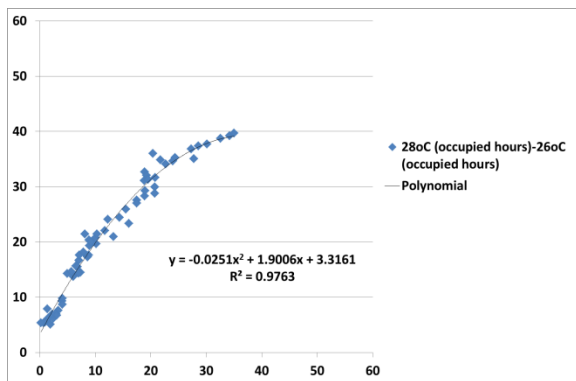
Figure 5 Comparison and regression analysis of the 28°C (fixed benchmark) overheating index (x-%) with the 26°C (fixed benchmark) overheating index (y-%) for all the case studies and variants.

Many regulations require the use of two or more continuous temperature benchmarks (e.g. 100 hours over 26°C and 25 hours over 27°C; Danish Building Regulations, 2013) for the assessment of overheating risk indoors. From the analysis, we may conclude that this double check is unnecessary because the benchmark indices (3, 4, 5, 6) highly statistically correlated with each other (e.g. if a dwelling overheated 20% (assessed by index 5-26°C) it will overheated 10% (assessed by index 6-28°C; Figure 5)).
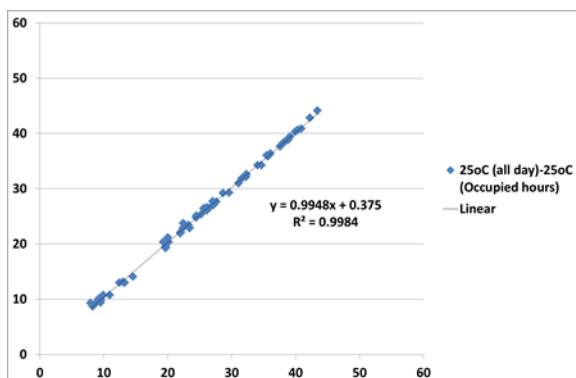

Figure 6 Comparison and regression analysis of the 25°C (fixed benchmark, measured all day) overheating index (x-%) with the 25°C (fixed benchmark, measured during the occupied hours) overheating index (y-%) for all the case studies and variants.

Many standards and regulations suggest different occupancy schedules for the overheating assessment of the various building types (offices, dwelling and others). From Figure 6 and Table 2, we may conclude that overheating indices, which refer to specific occupancy schedules, highly correlated (R^2 equals to one) with indices, which assess the risk all day, excluding this limitation. This research suggests the expulsion of the occupancy schedule "filter" (present guidelines) from the long-term assessments of the

overheating for simplicity and homogeneity reasons (intercomparison of the results in a common ground). More research with different occupancy schedules and building types (e.g. offices, schools and others) needs in the future for the confirmation of these proposals.

Correlation of indices with annual heating losses and gains

Table 3 presents the results of the nonlinear regression analyses of the indices with the annual ratio ((HL-HG)/HL). Figure 7 presents the indices with the highest coefficients of determination (R^2 over 0.60).

It is clear from the analysis that the overheating indices (%) decrease non-linearly with the increase of the annual ratio. Indices based on fixed benchmarks and thresholds are highly correlated with the ratio with coefficients of determination from 0.78 to 0.85. The relationships are described with 2nd order polynomial Equations (Table 3). The adaptive method also shows a clear tendency, but the coefficient of determination is medium. For the other indices there is not discrete relationship with the annual ratio (really low coefficients).
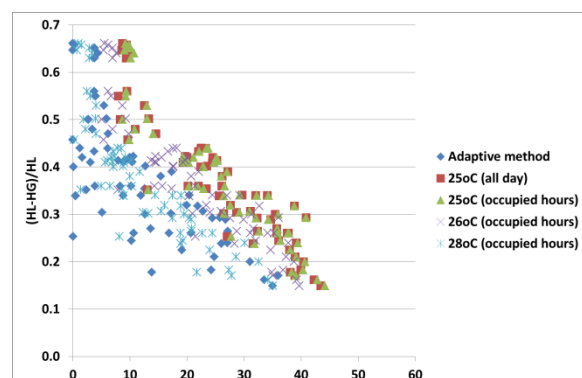

Figure 7 Comparison of overheating indices (x axis-%) with high coefficients of determination with the ratio of annual heating losses (HL) and gains (HG, kWh/m² per net floor area) for all the case studies and variants.

*Table 3
Regression analyses of all overheating indices with the annual heating losses (HL) and gains (HG, kWh/m² per net floor area) for all the case studies and variants.
(*Referred to the numbering at the method's section)*

X-INDEX	Y=(HL-HG)/HL	R^2
1*	$0.4905*exp(-0.028x)$	0.60
3*	$0.0001x^2-0.0168x+0.7161$	0.85
4*	$0.0001x^2-0.0168x+0.7199$	0.84
5*	$0.0002x^2-0.018x+0.6641$	0.83
6*	$0.0003x^2-0.0224x+0.5747$	0.78

The two-dimension (2D) contour graphs (Figure 8, Appendix) present the spatial distribution of the three variants (index, annual heating losses and gains) for all the 66 variants. The contour graph was created with the use of the software Surfer version 9.9.785 (Golden Software co.). The method used for gridding interpolation was the Kriging method. Kriging is one of the most flexible and accurate gridding methods (Surfer, 2015). Due to this method, each data point is weighted by its distance away from the neighbouring nodes. The linear variogram model of the Kriging method was used for the analyses (default options).

Many regulations, initiatives and standards (EN 15251, 2007, BR2010, 2013) for the assessment of the overheating likelihood use the fixed threshold of the 26°C (index 5). It is evident from Figure 8 in the Appendix that the percentage contours (10%, 20%, 30%) create almost linear relationships (between indices, annual heating losses and gains) and critical distinguished areas (colour scale). The annual heat losses have to be at least double when compared to the annual heat gains in order to have acceptable comfort indoor temperatures as concerns overheating indoors (e.g. less than 10%, assessed by this index).

The contour graph (also Figure 7) may be a very useful tool for the designers who examine e.g. the effect of a shading system (non-heated period; blue diagonal arrow) or the effect of envelope's improvements (insulation; red horizontal arrow; negative effects) to an existing dwelling with overheating indoors. The calculation of the heat gains (equipment, occupancy and solar gains) of an existing house per year is a well-defined procedure (EN 13790, 2008). The decrease of the annual heat gains due to the application of the shading system in the summer period would decrease the annual heat losses by the same amount (heating demand remains constant). The new position on the graph (x-y diagonal) would show the decrease of the overheating occurrence and the effectiveness of the shading measure.

Suggestions for further investigation include more analyses inside and outside the limits (heat losses and gains) of the graph and lower than the contour of 10% (also upper than the contour of 30%) of this graph. In addition, there should be more case studies from different climates, building types and with different occupancies analysed in the future.

CONCLUSION

From the analysis of this paper, we may conclude that:

Indices that originate from the same theoretic adaptive model are highly correlated with each other with coefficients of determination ranging from 0.86 to 0.98. The existence of both methods (adaptive and degree hours methods) at the new standards or regulations is an exaggeration. There is no correlation between the DT index and other indices.

The double check benchmark (static indices) of many regulations regarding the overheating assessment is unnecessary because the indices highly statistically correlate with each other.

Indices that measure overheating during the occupied and unoccupied hours (total hours; and refer to that period) highly correlate with indices that measure overheating solely during the occupied period (and refer to that period).

Static overheating indices highly statistically correlate with the annual heating gains and losses of the building, creating distinguished and critical areas in contour graphs. Overheating indices that refer to the adaptive comfort model (not only physical background) moderately correlate with the annual heating gains and losses of the building. The graph could function as an easy and fast tool for the effectiveness of a summer passive measure like the shading systems to the overheating indoors.

NOMENCLATURE

^oC = Celcius
DT = index, difference between peak indoor and annual average outdoor dry-bulb temperature (^oC)
g = solar heat gain coefficient
HL = annual heating losses (kWh/m^2), of net floor area
HG = annual heating gains (kWh/m^2), of net floor area
$N50$ = air change rate at 50Pa (pressure test)
R^2 = coefficient of determination
$T_{i.\ oper,max}$ = max value of indoor operative temperature due to the comfort model (^oC)
T_{rm} = running mean outdoor tempearture (^oC)
ΔT = difference between indoor and operative adaptive comfort temperature (^oC)

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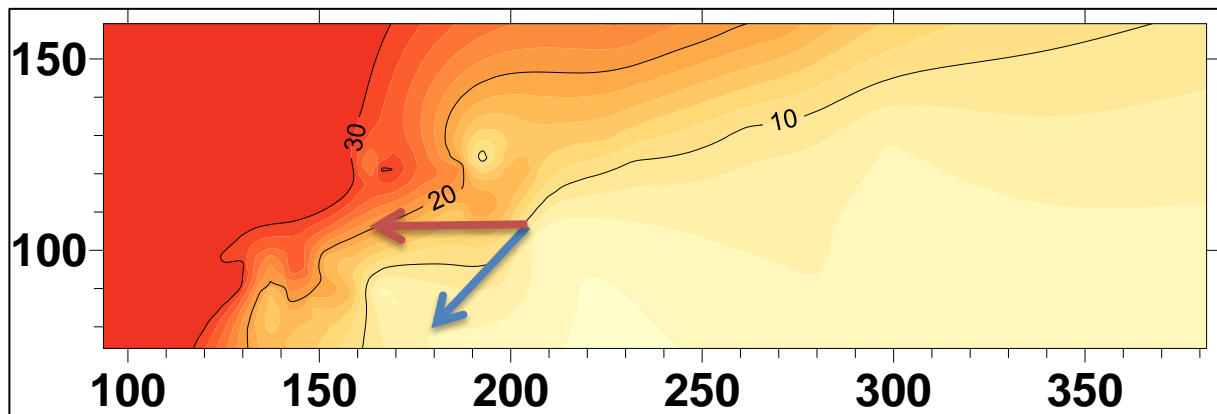
APPENDIX

Figure 8 2D contour representation of the fixed (occupied hours) 26°C overheating index (%), with the annual heat losses (x axis-kWh/m²) and the annual heat gains (y axis-kWh/m²), net floor area, for all case studies and variants (red arrow refers to the effect of envelope's improvements and blue arrow refers to the effects of shading systems).