# Analyzing the Relationship between Local Urban Morphology and Predicted Thermal Perception
## Using the Universal Thermal Climate Index UTCI

EDUARDO L. KRÜGER[1], PETER BRÖDE[2]

[1]Department of Civil Construction, Universidade Tecnologica Federal do Parana (UTFPR), Curitiba, Brazil
[2]Leibniz Research Centre for Working Environment and Human Factors (IfADo), Dortmund, Germany

*ABSTRACT: Recognizing that urban morphology attributes can promote improvements in outdoor thermal conditions, thus positively affecting both the use of public spaces and indirectly the energy demand of buildings located in urban areas, it is paramount to develop tools which can quantify the effect of changes in morphology on the outdoor thermal environment and consequently on human thermal responses. The present paper is concerned with the understanding of urban morphology features which most likely affect human thermal perception in outdoor spaces, focussing on pedestrian streets in two different climate regions. From field measurements carried out in pedestrian areas in Curitiba, Brazil (subtropical climate in elevation) and in Glasgow, UK (maritime temperate climate), comparisons were made between observed human thermal perception against predictions with the Universal Thermal Climate Index (UTCI) for the two sets of data. In both cities, large scale surveys throughout seasons ($N_{(Curitiba)}$=1685, $N_{(Glasgow)}$=567) combining comfort questionnaire administration with concurrent monitoring campaigns were conducted. In the context of urban planning an analysis was carried out showing that UTCI is able to capture the influence of the urban design characteristics on urban microclimate and thus its impact on pedestrian thermal comfort.*

*Keywords: human biometeorology, urban microclimate monitoring, urban planning, outdoor thermal comfort, index UTCI*

### INTRODUCTION

Outdoor comfort indices can be important tools for urban planning, as they provide an integrated approach to the evaluation of thermal conditions in outdoor spaces. Once a set of site-specific climatic conditions are known (by means of in situ measurements or from predicted data from computer simulations), outdoor comfort/discomfort in cities can be more comprehensively assessed than by traditional UHI analyses or ambient temperature estimates, therefore facilitating the analysis of existing linkages between urban morphology and microclimate conditions.

The present paper shortly introduces the basics of the recently developed outdoor thermal comfort index UTCI (‘Universal Thermal Climate Index’) and is concerned with its effectiveness in predicting local thermal perception when accounting for urban morphology effects. For that, two locations with quite distinct climatic and socio-cultural patterns were evaluated. Data gathered from extensive campaigns conducted in both locations throughout outdoor comfort surveys are compared to UTCI predictions. Comparisons are drawn for the two data sets in terms of microclimatic data and predicted thermal sensation with UTCI for two groups of data, according to a simple categorization (‘open spaces’ and ‘street canyons’).

The purpose is to find out whether and to what degree UTCI would be able to reflect the impact on thermal comfort from changes in urban morphology defined by site characteristics like the sky view factor (SVF), which for a given site indicates the degree of sky obstruction by the surroundings [1], a factor known to have an influence on urban microclimate [2]. In this paper, SVF values are used as a surrogate for urban morphology. Our approach was to use data obtained from outdoor comfort surveys with pedestrians in Curitiba, Southern Brazil [3] and Glasgow, UK [4], and to extend earlier analyses [5] by considering the influence of urban morphology as characterised by the local SVF.

### UTCI Basics

UTCI aims at the assessment of the outdoor thermal conditions in the major fields of human biometeorology by a one-dimensional quantity summarising the interaction of environmental temperature, wind speed, humidity and of the long-wave and short-wave radiant fluxes. This assessment should be based on the physiological response of the human body, which in turn was to be simulated by a thermo-physiological model [6]. For this purpose, based on an advanced multi-node model of human thermoregulation [7] the ‘UTCI-Fiala’ model of thermo-physiological comfort was adopted [8] and coupled with a state-of-the-art clothing model [9]. This model considers (i) the behavioural adaptation of clothing insulation observed from European field studies for the general urban population in relation to the prevailing environmental temperature, (ii) the distribution of the clothing over different body parts, and (iii) the reduction of thermal and evaporative clothing resistances caused by wind and the movement of the wearer, who is assumed walking at 4 km/h on the level.

Similar to other indices employed to the assessment of outdoor thermal conditions, such as the commonly used PET index ('Physiologically Equivalent Temperature') [10], UTCI adopts the concept of an equivalent temperature. This involved the definition of a reference environment with 50% relative humidity (but vapour pressure not exceeding 20 hPa), with still air and radiant temperature equalling air temperature, to which all other climatic conditions are compared. Equal physiological conditions are based on the equivalence of the dynamic physiological response predicted by the model for the actual and the reference environment. As this dynamic response is multidimensional (body core temperature, sweat rate, skin wettedness etc. at different exposure times), a strain index was calculated by principal component analysis as single dimensional representation of the model response. The UTCI equivalent temperature for a given combination of wind, radiation, humidity and air temperature is then defined as the air temperature of the reference environment, which produces the same strain index value. In order to facilitate a widespread use, the operational procedure was completed by simplified routines, which allow to calculate UTCI from the input of ambient temperature, mean radiant temperature, wind speed, and water vapour pressure by an approximating regression function or by a table-lookup approach [11].

## RESEARCH METHODS

Field measurements with concurrent administration of comfort questionnaires were carried out in pedestrian areas in Curitiba, Brazil (25°26'S, 49°16'W, 917m amsl, subtropical climate in elevation) and in Glasgow, UK (55°51'N, 04°12'W, 0-100m amsl, maritime temperate climate). In both locations, surveys were carried out in pedestrian areas during daytime with 'portable' weather stations and according to a standard comfort questionnaire. The same team leader directed both field studies, thus ensuring compatibility of the employed procedures.

In Curitiba, measurements and field surveys were conducted between January and August 2009, over 14 days of sampling, spanning up to five hours each day (typically from 10am to 3pm local time). Two HOBO® weather stations (Onset Computer Corporation) were used (Fig. 1a), equipped with a three cup anemometer at approximately 2.1 m height, air temperature and relative humidity sensors at 1.1 m, a copper gray-coloured globe thermometer at 1.1 m (copper sphere with enclosed PT-100 sensor) and a silicon pyranometer measuring global solar radiation at 1.6 m.

In Glasgow, climate measurements and field surveys were carried out between March and July 2011, over 19 outdoor survey campaigns. Each measurement/survey campaign spanned up to three hours (from 10am to 1pm, local time). Climate measurements employed a Davis Vantage Pro2 weather station (Fig. 1b), equipped with a three-cup anemometer (at approximately 1.5 m above ground), air temperature and humidity sensors at 1.1 m above ground and a silicon pyranometer at 1.4 m. Additionally, a globe thermometer was prepared for assessing the mean radiant temperature, which consisted of a gray sphere with an enclosed temperature data logger (Tinytag-TGP-4500), attached to the tripod at 1.1 m above ground.

*a)* *b)*

*Figure 1: Equipment used for microclimatic measurements: a) in Curitiba, Brazil; b) in Glasgow, UK*

The mean radiant temperature ($T_{mrt}$ in °C) was calculated from globe temperature measurements (Tg in °C), and taking into account wind speed (v in m/s), air temperature ($T_a$ in °C), and the globe's emissivity (ε) and diameter (D in m), respectively, according to ISO 7726 [12] using the formula for forced convection. The exact times when surveys were conducted were subsequently matched to questionnaire responses. All data were averaged over five minutes.

The questionnaire used was designed from recommendations of ISO 10551 [13]. Thermal perceptions were assessed on a symmetrical 7-point twopole thermal sensation scale ranging from -3='cold' over 0='neutral' to +3='hot'.

Following the recommendations of ASHRAE Standard 55 [14], only data from respondents who had spent at least 15 minutes in the outdoor space were considered for analysis. Thus, in Curitiba, the resulting sample consists of 1685 thermal sensation votes (out of a total of 2024 responses). In Glasgow, the sample was significantly smaller: 567 thermal sensation votes (from a total of 763 responses). It should be stressed that the population size of Curitiba is about 3.2 Million people, whereas Glasgow has presently around 600,000 inhabitants.

### UTCI Calculations

Values of the UTCI equivalent temperature were obtained in both cases by means of the simplified regression approach provided by the operational procedure [11]. As UTCI requires the input of wind speed at 10 m above the ground, the wind speed values measured at 2.1 m and 1.5 m above ground (in Curitiba and in Glasgow, respectively) were scaled-up according a logarithmic formula as proposed by the operational procedure [11].

### Local Morphology and Data Grouping

In both studies, surveys were conducted at different locations within the pedestrian areas. In Curitiba, a total of 15 points were surveyed whereas in Glasgow the surveys covered 6 monitoring points. At each point, the sky view factor (SVF) was assessed from fisheye photographs, used in this study as a proxy for urban morphology. The images were post-processed in RayMan [15]. For the purpose of the present study, two urban morphology groups were defined: 'street canyons', where most of the surveys took place in both samples, characterised by lower SVF values; and 'open spaces or crossroads' with higher SVF (Table 1). Noticeable differences in SVF ranges were found for each category in both cities, as a result of a different history in urban planning.

### Data Analysis and Statistics

To describe the average course of microclimatic measurements and of thermal sensation considering the potentially non-linear relationships with environmental temperature and UTCI, respectively, general additive models with locally estimated smoothing functions (LOESS) and 95%-confidence bands were computed separately for open spaces and street canyons [16].

*Table 1: Range of sky view factors (SVF) and number of observations (n) – for Curitiba and for Glasgow*

| Site | Curitiba | | | Glasgow | | |
|---|---|---|---|---|---|---|
| | Example fisheye image | SVF range | n | Example fisheye image | SVF range | n |
| Open spaces / Cross-roads |  | 0.34-0.55 | 580 |  | 0.45-0.48 | 197 |
| Street canyons |  | 0.20-0.32 | 1105 |  | 0.38-0.41 | 370 |
| Total sample | | 0.20-0.55 | 1685 | | 0.38-0.48 | 567 |

## RESULTS AND DISCUSSION

Figures 2 & 3 compare separately for both locations Curitiba and Glasgow, respectively, the mean curves with 95%-confidence bands of the microclimatic recordings of humidity, wind speed and radiant heat load expressed as $\Delta T_{mrt}=T_{mrt}-T_a$ as well as of UTCI values in relation to air temperature that were obtained in open spaces and in street canyons.

Similarly, Figures 3 & 4 illustrate the mean curves of the thermal sensation votes related to air temperature and UTCI, respectively, for street canyons and open spaces in Curitiba and Glasgow. Table 2 provides an overview of the goodness-of-fit of the thermal sensation votes predicted by the UTCI-Fiala model [8] for open spaces and street canyons in Curitiba and Glasgow. The following subsections discuss the results obtained in both study locations.

### Curitiba

In open spaces with less sky obstruction i.e. with higher SVF, global radiation (short and long wave, incoming, outgoing and reflected measured on a horizontal plane) and consequently the mean radiant temperature were higher than in street canyons. Less discernible differences between both morphology groups occurred in other relevant variables such as humidity and wind parameters (Fig. 2). The higher mean radiant temperature had by its turn a sensible effect on UTCI values, for the whole spectrum of ambient temperatures.

The effects of morphology on microclimate are noticed by somewhat higher votes of thermal sensation as reported by the respondents in open spaces when plotting thermal sensation against air temperature (Fig. 4).

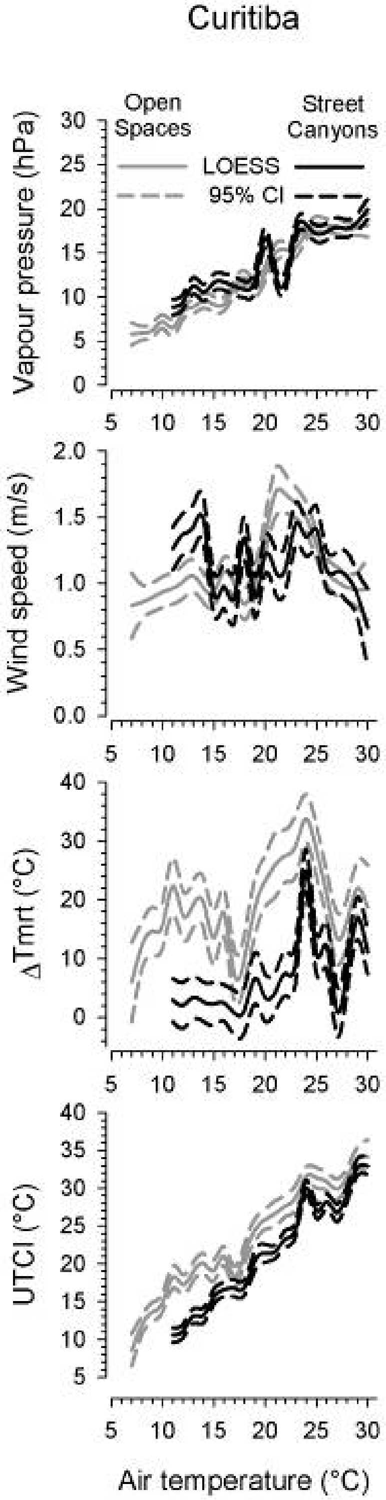


*Figure 2: Mean LOESS curves with 95% confidence bands of climate data and UTCI recorded for open spaces and street canyons in Curitiba.*

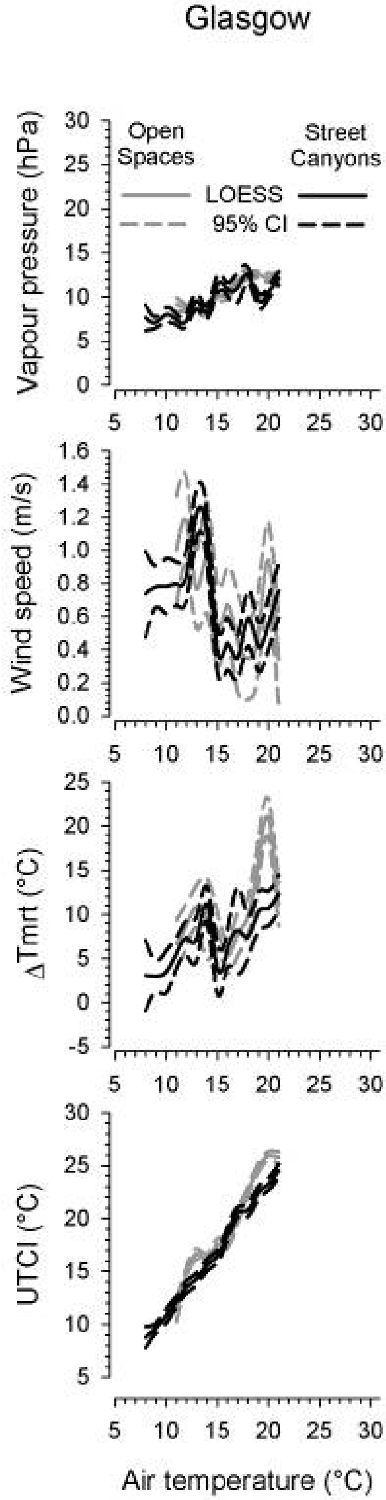


*Figure 3: Mean LOESS curves with 95% confidence bands of climate data and UTCI recorded for open spaces and street canyons in Glasgow.*

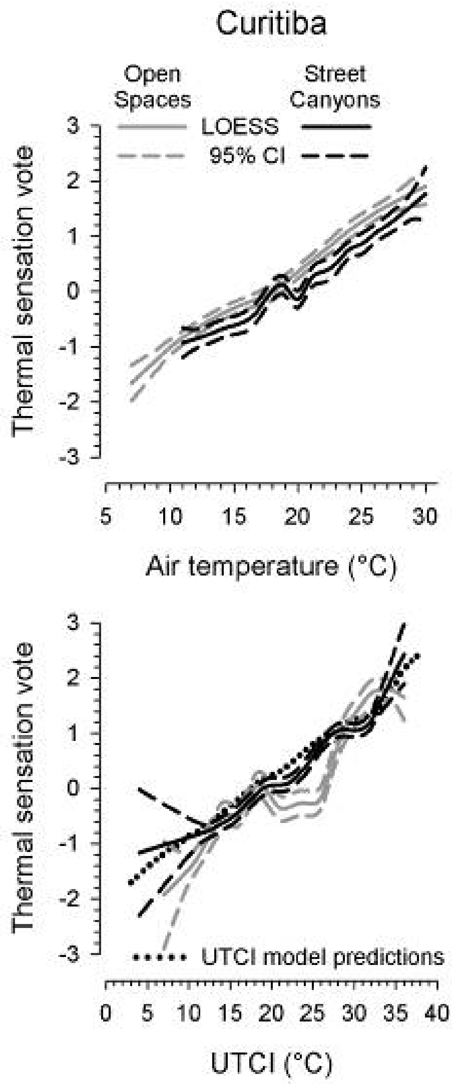


Figure 4: Mean LOESS curves with 95% confidence bands of thermal sensations votes recorded for open spaces and street canyons in Curitiba vs. air temperature (upper panel) and vs. UTCI (lower panel), respectively. The dotted line shows the sensations predicted by the UTCI model.

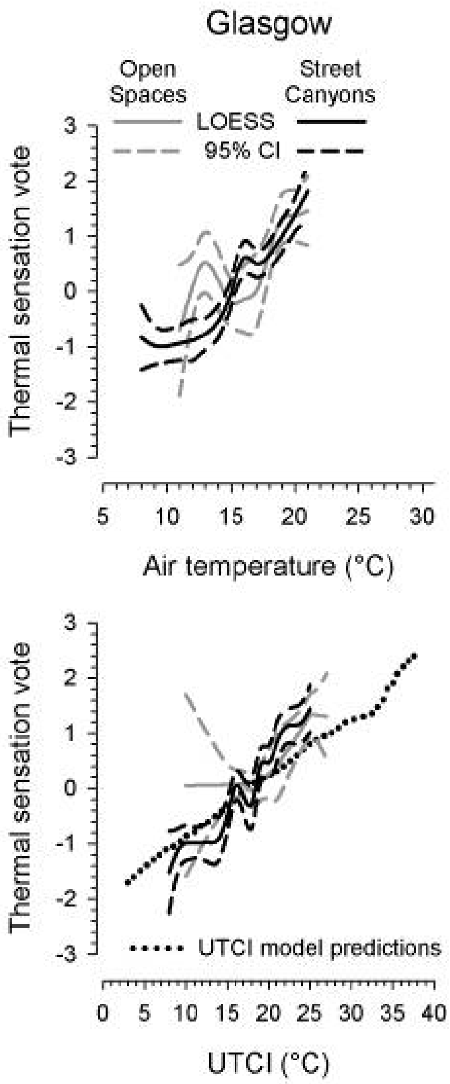


*Figure 5: Mean LOESS curves with 95% confidence bands of thermal sensations votes recorded for open spaces and street canyons in Glasgow vs. air temperature (upper panel) and vs. UTCI (lower panel), respectively. The dotted line shows the sensations predicted by the UTCI model.*

As identical index values of UTCI should represent identical physiological strain [6], it could be expected that differences in thermal sensation attributable to urban morphology disappeared when considered in relation to UTCI. This is confirmed in Figure 4 (bottom) no longer showing higher thermal sensations in open spaces and even a slight over-compensation between 20 to about 28°C UTCI. Nevertheless, the small differences between morphology groups in bias, RMSE and correlations of the goodness-of-fit analysis for the sensations predicted by UTCI (Table 2) were negligible and of similar magnitude as those previously found for different groups of age, gender or body composition [5].

**Glasgow**

Glasgow data were less differentiated and more uniform in respect of urban morphology attributes (Fig. 3). Differences were less pronounced in terms of all microclimatic variables including UTCI. This can be ascribed to a more uniform urban morphology, commonly observed in European cities. Mean radiant temperature changes were directly responsible for UTCI variations, particularly for higher ambient temperatures above 18°C.

With regard to urban morphology effects on thermal sensation, Glasgow data did not show straightforward trends and grouped data were confounded versus air temperature as well as versus UTCI (Fig. 5).

Analogously to Curitiba, mean bias, RMSE and Pearson correlations with UTCI predictions (Table 2), indicated a reasonable fit, though with smaller correlations. Again, both categories yield similar results, although a weaker correlation was found for open spaces, possibly due to fewer observations over a narrower temperature range.

*Table 2: Number of observations (n), averaged errors (bias), Root Mean Squared Errors (RMSE) and Pearson correlation coefficients (r) of the observed thermal sensation votes compared to the dynamic thermal sensation predicted by the UTCI-Fiala model in relation to the site characteristics*

| Sample | Site | n | bias | RMSE | r |
|---|---|---|---|---|---|
| Curitiba | Crossroads / Open Spaces | 580 | 0.38 | 1.07 | 0.65 |
| | Street Canyons | 1105 | 0.18 | 0.92 | 0.60 |
| Glasgow | Crossroads / Open Spaces | 197 | -0.24 | 1.36 | 0.35 |
| | Street Canyons | 370 | -0.19 | 1.20 | 0.52 |
| Total | Crossroads / Open Spaces | 777 | 0.23 | 1.15 | 0.55 |
| | Street Canyons | 1475 | 0.09 | 1.00 | 0.55 |

## CONCLUSIONS

Results suggest that UTCI was able to adequately capture the effects of urban design features on predicted thermal sensation, when expressed versus UTCI values. It was noticed that differences between calculated UTCI are more related to changes in relevant microclimatic variables than to variations in urban morphology, here grouped as a function of SVF categories. Mean bias was low for all cases, irrespective of urban morphology aspects or location.

Interestingly, UTCI values underestimated, though minimally, pedestrian thermal sensation in Curitiba and overestimated it in Glasgow. Both cities, despite being classified as 'Cfb' according to Koeppen-Geiger's Classification System, present quite different climatic conditions. Curitiba is greatly affected by its proximity to the Tropic of Capricorn and by its high elevation, whereas Glasgow has a mild temperate climate type, due to strong maritime influences (Gulf Stream). Indeed, a comparison of average ambient temperatures shows that winter conditions in Curitiba are comparable to those found in summer in Glasgow. Furthermore, other aspects (cultural and socio-economic) also play a role in defining to what levels of thermal comfort/discomfort local population is exposed to and will thus have an effect on UTCI's performance.

## REFERENCES


1. Grimmond, C.S.B., Potter, S.K., Zutter, H.N. and Souch, C., (2001). Rapid methods to estimate sky-view factors applied to urban areas, *International Journal of Climatology*, 21(7): 903-913.
2. Oke, T.R., (1981). Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations, *International Journal of Climatology*, 1(3): 237-254.
3. Krüger, E. and Rossi, F.A., (2011). Effect of personal and microclimatic variables on observed thermal sensation from a field study in southern Brazil. *Building and Environment*, 46: 690-697.
4. Krüger, E., Drach, P., Emmanuel, R. and Corbella, O., (2012). Urban heat island and differences in outdoor comfort levels in Glasgow, UK. *Theoretical and Applied Climatology*, 112 (1-2): 127-141.
5. Bröde, P., Krüger, E., Rossi, F.A. and Fiala, D., (2012). Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI - a case study in Southern Brazil. *International Journal of Biometeorology*, 56(3): 471-80.
6. Jendritzky, G., de Dear, R. and Havenith, G., (2012). UTCI-Why another thermal index? *International Journal of Biometeorology*, 56(3): 421-8.
7. Fiala, D., Lomas, K.J. and Stohrer, M., (1999). A Computer Model of Human Thermoregulation for a Wide Range of Environmental Conditions: the Passive System. *Journal of Applied Physiology*, 87(5): 1957-1972.
8. Fiala, D., Havenith, G., Bröde, P., Kampmann, B. and Jendritzky, G., (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International Journal of Biometeorology*, 56 (3): 429-41.
9. Havenith, G., Fiala, D., Błażejczyk, K., Richards, M., Bröde, P., Holmér, I., Rintamäki, H., Benshabat, Y. and Jendritzky, G., (2012). The UTCI-clothing model, *International Journal of Biometeorology*, 56(3): 461-70.
10. Höppe, P., (1999). The Physiological Equivalent Temperature - a Universal Index for the Biometeorological Assessment of the Thermal Environment. *International Journal of Biometeorology*, 43(2): 71-75.
11. Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., Tinz, B. and Havenith, G., (2012). Deriving the Operational Procedure for the Universal Thermal Climate Index UTCI, *International Journal of Biometeorology*, 56(3): 481-94.
12. ISO 7726, (1998). Ergonomics of the Thermal Environment - Instruments for Measuring Physical Quantities. Geneva, International Organisation for Standardisation.
13. ISO 10551, (1995). Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. Geneva, International Organisation for Standardisation.
14. ASHRAE, (2004). Standard 55 - Thermal Environmental Conditions for Human Occupancy. ASHRAE Inc., Atlanta.
15. Matzarakis, A., Rutz, F. and Mayer, H., (2010). Modelling radiation fluxes in simple and complex environments: basics of the RayMan model, *International Journal of Biometeorology*, 54(2): 131-139.
16. Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A. and Smith, G.M., (2009). Things are not Always Linear; Additive Modelling. In: Zuur, A.F. et al. (eds.), *Mixed effects models and extensions in ecology with R*, Springer, New York, 35-69.