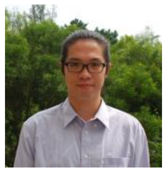
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Street Geometry Design and its Effect on Mean Radiant Temperature: A Parametric Study based on Numerical Modelling

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1. Introduction

The role of urban design parameters in outdoor thermal comfort has been widely discussed in recent decades (Mayer and Höppe,1987; Pearlmutter *et al.*, 1999; Nikolopoulou and Steemers, 2003; Johansson and Emmanuel, 2006). In general, the conditions of outdoor thermal comfort in urban environment are controlled by street canyon geometry and their orientations as they affect the radiative balance within street canyons (Masmoudi and Mazouz, 2004; Emmanuel and Johansson, 2006; Johansson, 2006; Thorsson *et al.*, 2011; Lindberg *et al.*, 2014). Surface albedo also affects the amount of radiation absorbed by building and ground surfaces (Erell *et al.*, 2014). It therefore implies that climate-sensitive urban planning and design, particularly at street level, can contribute to better outdoor thermal comfort in urban environment.

Shading is one of the counteracting measures to thermal stress since it reduces the convective heat transfer from sunlit building and ground surfaces (Spronken-Smith and Oke, 1999). It also reduces direct shortwave radiation reaching building and ground surfaces as well as humans. The level of the effect by shading is generally determined by street orientation and canyon geometry in terms of sky view factor and height-to-width (H/W) ratio (Johansson and Emmanuel, 2006; Oliveira *et al.*, 2011; Shashua-Bar *et al.*, 2012). In previous studies, it was found that daytime maximum physiological equivalent temperature decreases with increasing H/W ratio (Johansson, 2006; Ali-Toudert and Mayer, 2006; Abreu-Harbich *et al.*, 2014). In terms of mean radiant temperature (T_{mrt}), it can be up to 30 °C higher in sunlit places than areas under shading (Mayer and Höppe, 1987; Thorsson *et al.*, 2011). These studies confirmed that shading is effective to alleviate thermal discomfort in urban environment.

This study presents a parametric model of simulating T_{mrt}, as an indicator of heat stress, in three European cities using a regular street layout. Different H/W ratios and street orientations are examined for their effect on the spatial distribution of T_{mrt}. T_{mrt} is simulated by using the Solar and LongWave Environmental Irradiance Geometry (SOLWEIG) model (Lindberg *et al.*, 2008; Lindberg and Grimmond, 2011). In this parametric study, the focus is on the effect of street geometry on the spatial variation and magnitude of hotspots, which are identified for the application of potential mitigation measures. Findings will contribute to the development of design recommendations for more climate-sensitive urban design from European perspective.

2. Methodology

2.1 Meteorological Data and Experimental Design

Three cities, namely Gothenburg, Frankfurt and Porto, are selected to examine the spatial pattern of outdoor heat stress in northern, central and southern European climates in this study. In each city, hourly meteorological data, including air temperature, solar radiation (global and diffuse components) and relative humidity, are obtained from local meteorological stations. The observation periods are 1998-2005 for Gothenburg and 2003-2010 for Frankfurt and Porto. These records are used to simulate the spatial variation of T_{mrt} under different regional climatic conditions. It is noted that the earlier period for Gothenburg is due to the closing down of the meteorological station in Gothenburg, which leads to the lack of solar radiation data from 2005 onwards. These data are served as the inputs of the SOLWEIG model. Spatial information in the form of digital surface model (DSM) at a spatial resolution of 1 m, and a geographical location (i.e. latitude, longitude, and altitude) is also required to model the three-dimensional radiation fluxes and T_{mrt} within complex urban settings.

The present parametric study is based on a regular grid of 323x323 m (Fig. 1). Street canyons are 20 m wide and five H/W ratios (0.5, 1, 2, 3 and 4) were analyzed. The study domain was rotated by three different angles (0°, 22.5° and 45°) in order to examine the effect of street orientation on the spatial variation of T_{mrt}. The spatial variation of three-dimensional radiation fluxes and T_{mrt} was simulated by the SOLWEIG model (version 2014a). The model was previously evaluated with a number of independent observed datasets acquired in Gothenburg, Sweden as well as Freiburg and Kassel, Germany (Lindberg *et al.*, 2008; Lindberg and Grimmond, 2011).

2.2 Numerical modelling of mean radiant temperature

T_{mrt} is calculated for a standing person where the angular factors (proportion of radiation received by the human body in each direction) are set to 0.22 for radiation fluxes from the four cardinal points (east, west, north and south) and 0.06 for radiation fluxes from above and below. Standard values of absorption coefficients for shortwave and longwave radiation are set to 0.7 and 0.97, respectively (Höppe, 1992; VDI, 1998). Values for albedo and emissivity for buildings are set to 0.2 and 0.95, respectively according to Oke (1989). Wind field and variations in materials on ground and building walls are not considered in the current version of the model. A detailed description of the SOLWEIG model is documented in Lindberg *et al.* (2008) and Lindberg and Grimmond (2011).

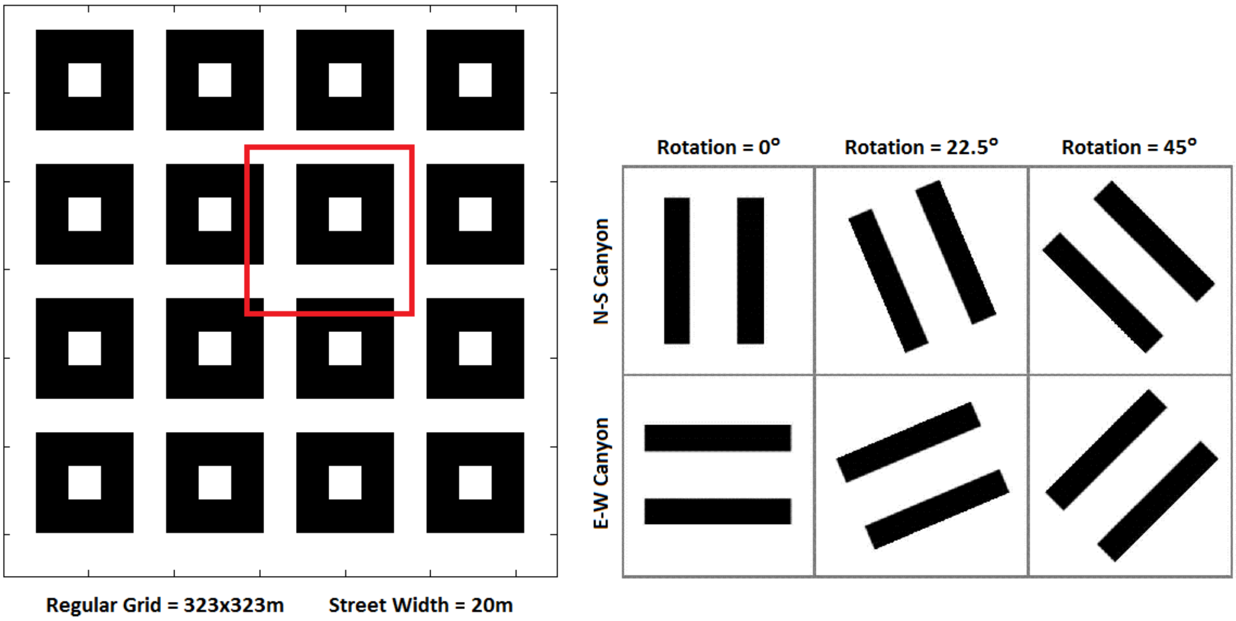

Fig. 1 Various schemes of the street canyons for the simulation.

Areas affected by heat stress are identified by calculating the frequency of occurrence (in hours) of different T_{mrt} levels (from 50 °C to 65 °C) for individual ground pixels. Outdoor heat stress is then examined by using a threshold of 30 hours per year. The highest T_{mrt} experienced by each ground pixel is then recorded in a spatial map to indicate the extent of potential heat stress areas (hotspots). The purpose of using these maximum T_{mrt} values is to determine the spatial variation of hotspots (areas of high radiant load).

In order to examine T_{mrt} for a non-specific (generic) urban location, a simplified version of SOLWEIG called SOLWEIG1D [32] is used to calculate radiation fluxes and T_{mrt}. Unlike the full SOLWEIG simulations discussed above, where SVF and shadow patterns are determined for each pixel in a DSM, SOLWEIG1D has a single, fixed, user-specified SVF and the location is assumed to be sunlit during the daytime hours. The latter would not be the case in a real world situation, where surrounding objects would block the sun at specific times of the day and year when SVF < 1. Otherwise, the same settings are used as presented. For these calculations, SVF is set to 0.60 which is supposed to represent a typical urban environment. In this study, the threshold of $T_{mrt\text{-}generic}$ is set to 60 °C in order to represent severe heat stress conditions. When $T_{mrt\text{-}generic}$ > 60 °C, the corresponding spatial maps of these hours are averaged and used for investigating the effect of street geometry and street trees on outdoor heat stress.

3. Results and Discussion

3.1 The effect of H/W ratio on the spatial characteristics of hotspots

Fig. 2 shows the spatial variation of the highest T_{mrt} observed within the non-rotated study grid. The highest T_{mrt} level is generally found along sunlit south-facing façades at H/W = 0.5 in all three cities due to the high level of direct and reflected shortwave radiation as well as longwave radiation emitted from surrounding sunlit surfaces. High T_{mrt} is also observed in the northeastern corner of courtyards. Although the spatial pattern is the same in all three cities, the levels are much higher in Frankfurt and Porto than in Gothenburg due to higher sun altitude, resulting in longer period of sun exposure. High T_{mrt} is also observed along west-facing façades which is due to the higher air temperature in the afternoon. Along north-facing façades, T_{mrt} levels are found to be lower than 50 °C due to constant shading of the buildings, indicating that heat stress is not experienced in these areas.

Spatial pattern remains the same when H/W ratio increases to 1 despite of the smaller extent and reduced magnitude observed in the northern part of courtyards in all three cities. In Gothenburg, the southwestern corner of buildings appears to be the hottest place as it is the most frequently sun exposed place due to the more open settings. Within the E-W canyon, high T_{mrt} levels are more confined to the south-facing façades. Increasing H/W ratio to 2 greatly reduces the extent of high T_{mrt} areas which are only found in front of the southwestern corner of building in Frankfurt. It is due to the high H/W ratio which only allows incoming shortwave radiation reaching ground and building surface for a short period of time at noon in Frankfurt. The hottest area is at the immediate front of the south-facing façades in Porto. There is no observable heat stress in Gothenburg since only limited area of moderate T_{mrt} are found in the N-S canyon. In addition, heat stress is absent in the courtyards in Gothenburg and Frankfurt while a very small area of T_{mrt} below 55 ºC is found in front of the south-facing façade within the courtyard in Porto.

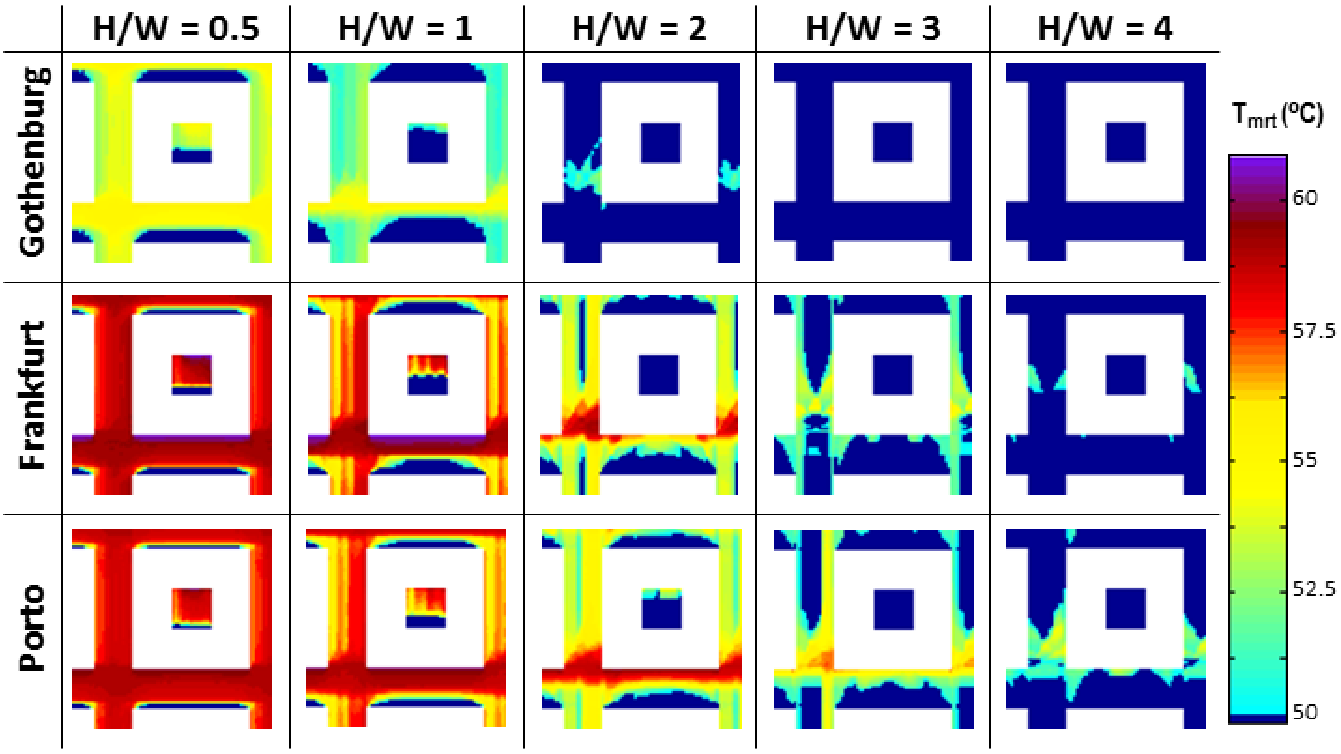

Fig. 2. Spatial variation of the maximum T_{mrt} level (with a threshold of 30 hours per year) observed at individual pixels for different H/W ratios.

The hottest place is shifted from the southern part of buildings to the west-facing façades as H/W ratio increases to 3 although the magnitude is greatly reduced (except a small area at the southwestern corner of buildings in Porto). It is because incoming shortwave radiation can only reach the canyon surface through the gaps between tall buildings. High T_{mrt} level is still observed in the N-S canyon in Porto, particularly at the southwestern corners of buildings but at a lower magnitude. For H/W = 4, hotspots are virtually absent in all three cities despite of the moderate level of T_{mrt} found in front of the west-facing façades in Porto. It implies that dense structure is generally effective in reducing radiant heat load and mitigating heat stress and additional shading strategies such as arcades and overhanging facades may be needed at lower latitudes.

3.2 Street orientations

The street grid is rotated anti-clockwise by 22.5º and 45º in order to examine the effect of street orientations on the spatial variation and magnitude of hotspots. Table 1 details the spatial average of average hourly T_{mrt} when $T_{mrt\text{-}generic}$ > 60 ºC for E-W and N-S canyons, as well as diagonal streets. It is shown that rotating E-W and N-S streets exhibits opposite effects on the spatial average of T_{mrt}. Rotating E-W canyons to the NE-SW orientation increase average T_{mrt} considerably with the highest increases generally observed at H/W = 2 (Gothenburg and Frankfurt) and 3 (Porto). Thus the effect of street orientations is rather limited at low H/W ratios due to the effect of sun exposure. On the other hand, the NW-SE orientation shows a reduction in average T_{mrt} compared to the N-S canyons and the magnitude of reduction decreases with latitudes. It is 15.5 ºC, 9.0 ºC and 5.5 ºC lower than the NE-SW orientation at H/W = 2 for Gothenburg, Frankfurt and Porto respectively. Due to the relatively fewer hours with such high $T_{mrt\text{-}generic}$ values in Gothenburg and the values are extremely high, the average in Gothenburg could be higher than those in the other two cities which have more hours with high $T_{mrt\text{-}generic}$ values (may not be as high as the average in Gothenburg). Nonetheless, the influence of street orientations is larger at higher latitudes since shading by buildings is able to reduce incoming shortwave radiation due to the lower sun altitude.

Similar spatial pattern of hotspots is found in the three cities and the spatial pattern does not change considerably at low H/W ratio. At H/W = 1, when the street grid is rotated by 22.5°, areas with T_{mrt} level over 50 °C (Gothenburg) and 55 °C (Frankfurt and Porto) increase in the NE-SW street canyon. At the same time, areas with low T_{mrt} levels along the north-facing façades are reduced. It is a result of the longer period of sun exposure experienced by the canyon surface in the afternoon (Fig. 3). It indicates that there is a redistribution of radiant heat load within the street canyons. The northern corner of the courtyard also appears as hotspots but it is more confined to building walls due to the reflected shortwave radiation.

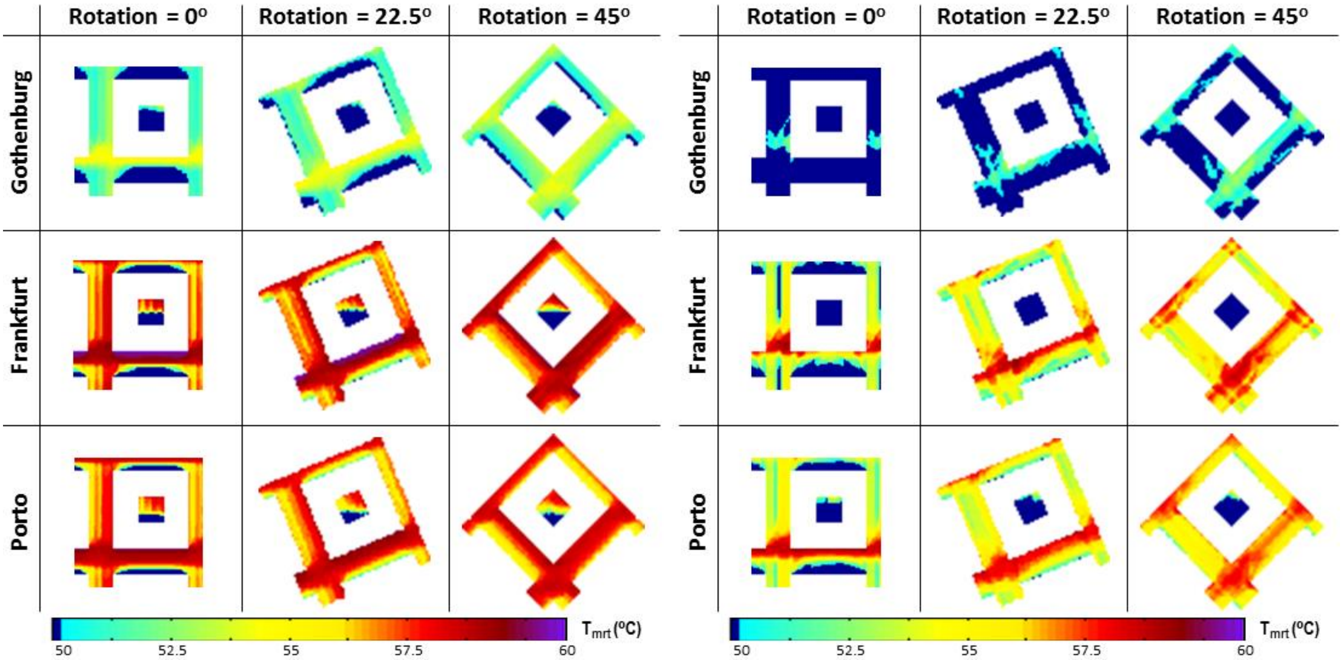

Fig. 3. Spatial variation of the maximum T_{mrt} level (with a threshold of 30 hours per year) observed at individual pixels for different rotation at H/W = 1 (left) and 2 (right).

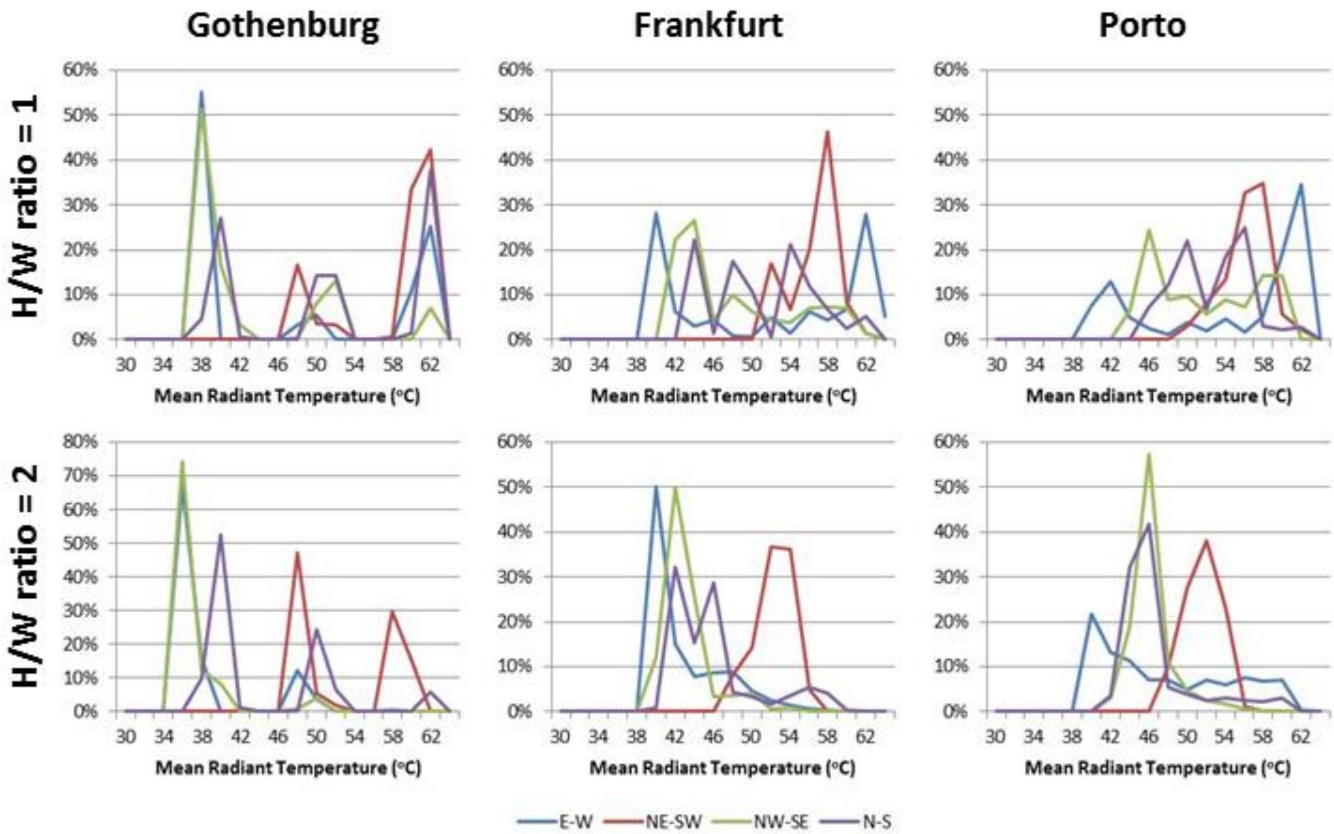

Fig. 4. Probability distribution of ground pixel in average hourly T_{mrt} when $T_{mrt\text{-}generic}$ above 60°C for all street orientations at H/W ratio = 1 (upper row) and 2 (lower row).

For 45°-rotation, high T_{mrt} levels are found along the entire NE-SW canyon due to the prolonged period of sun exposure. They also appear along the southwest-facing building walls in both NW-SE canyon and courtyard. It is a result of the reflected shortwave radiation and emitted longwave radiation from the building walls in the afternoon. The effect of street orientations on radiant heat load is also investigated by the probability distribution of ground pixels in the street canyons in average hourly T_{mrt} when $T_{mrt\text{-}generic}$ > 60 ºC (Fig. 4). Diagonal streets exhibit differently in terms of the average hourly T_{mrt}. 70% of the ground pixels have values over 55 ºC in the NE-SW canyon in Frankfurt and Porto due to a lack of shading during heat stress conditions. The reduction in pixels with severely high T_{mrt} (above 60 ºC) is offset by the considerable increase in the number of pixels with moderately high T_{mrt} (55 ºC). In contrast, the NW-SE canyon reduces the number of pixels with moderate to high T_{mrt} and the percentage of having low average hourly T_{mrt} is the highest among the four street orientations.

Table 1. Spatial average of the ground pixels within street canyons for the average hourly T_{mrt} when $T_{mrt\text{-}generic}$ above 60ºC for all H/W ratios and orientations.

	Gothenburg				*Frankfurt*				*Porto*			
H/W	**EW**	**NE-SW**	**NW-SE**	**NS**	**EW**	**NE-SW**	**NW-SE**	**NS**	**EW**	**NE-SW**	**NW-SE**	**NS**
0.5	53.8	58.1	52.0	55.6	55.6	57.8	53.8	55.2	57.0	57.7	55.6	56.0
1.0	46.1	56.8	41.8	50.5	51.0	55.6	47.4	50.5	53.6	55.3	50.9	51.7
2.0	37.7	52.2	36.7	43.3	41.7	51.2	42.2	45.3	46.9	50.7	45.2	46.0
3.0	36.1	48.4	36.2	38.1	39.1	48.0	41.0	41.5	41.9	48.0	43.3	43.5
4.0	34.9	44.2	35.5	36.7	38.0	45.8	39.9	39.4	39.8	46.1	42.1	41.1

At H/W = 2, when the street grid is rotated by 22.5º, high T_{mrt} levels are found at the southern corner and along the south-east facing façade of the buildings in Frankfurt and Porto due to the increased duration of sun exposure. Moderate T_{mrt} levels are found in the rotated NW-SE canyon where no heat stress is observed in the middle of the non-rotated N-S counterpart due to the increased reflected radiation from both sides of the street canyon. In addition, the extent of areas with T_{mrt} level of about 52 ºC increases in the NE-SW canyon, suggesting an increase in radiant heat load within the street canyon. Diagonal streets in the NE-SW orientations increase the extent of high T_{mrt} but the magnitude of such T_{mrt} level is generally decreased. It somewhat reduces the diversity of the level of radiant heat load. As shown in Fig. 4, areas with higher average hourly T_{mrt} (52 ºC) are considerably increased in Frankfurt and Porto. It is also observed that at H/W = 2, the NW-SE does not reduce average hourly T_{mrt} as much as it does at H/W = 1 since the NW-SE canyons are always sunlit at around noon and increasing H/W ratios only reduces the duration of sun exposure and the amount of sunlit building walls, which does not affect the calculation of average hourly T_{mrt} very much.

4. Discussion and Conclusion

The results of the numerical modelling show that T_{mrt}, as an indicator of heat stress, is predominantly affected by the exposure to incoming solar radiation, which is determined by H/W ratio and street orientation. The spatial distribution of hotspots, in terms of the highest T_{mrt} level observed at individual pixels, and their corresponding magnitude, which is defined by the average hourly T_{mrt} when $T_{mrt\text{-}generic}$ > 60ºC, are examined using a regular street layout. Hotspots are mainly found along the south-facing façades at low H/W ratios because of the reflected shortwave radiation and longwave radiation emitted from the sunlit surface. South-facing façades cannot be shaded by buildings and prolonged period of sun exposure increases the radiant heat load which affects outdoor as well as indoor thermal conditions. The effect of regional differences is observed in two aspects. Firstly, the higher sun altitude results in larger extent of sunlit areas in Frankfurt and Porto. The spatial pattern of hotspots observed in Gothenburg at low H/W ratios can still be found at higher H/W ratios in Porto. Secondly, although similar spatial pattern is found at low H/W ratios in all three cities, the magnitude of hotspots is much lower in Gothenburg due to the lower air temperature. It implies that mitigation measures to heat stress are subject to the influence of regional climatic differences (Ali-Toudert and Mayer, 2007; Paolini *et al.*, 2014).

Increasing H/W ratios changes the location of hotspots to the southwestern corner of buildings and street intersections since south-facing building walls are shaded by buildings and solar radiation can only penetrate to these locations through building gaps. It further reiterates the results of previous research that dense urban structure provides a solution to mitigate outdoor heat stress and potentially reduce indoor cooling demand by decreasing radiant heat load of building and ground surfaces (Thorsson *et al.*, 2011; Lau *et al.*, 2014). In addition, it is notable that, due to the higher sun altitude in Porto, such a pattern only occurs when H/W ≥ 3, suggesting that a denser urban structure is particularly important at lower latitudes.

The comparison of the influence of street orientations on T_{mrt} demonstrates that there are no considerable differences in the location of hotspots at high H/W ratios since they are generally found in open locations like street intersections. For low H/W ratios, hotspots are more commonly found on the south-facing side of the E-W canyons. It agrees with previous studies that, at low H/W ratios, N-S canyons are more favourable to mitigating outdoor heat stress and reducing radiant heat load of buildings since they provide shading on either side of the canyons throughout the day (Johansson, 2006; Andreou, 2013). They also provide a better thermal environment for higher H/W ratios at lower latitudes (Ali-Toudert and Mayer, 2006). Diagonal streets with 22.5º deviation are less favourable since hotspots exhibit larger extent and magnitude in both orientations. Similar results were obtained in previous studies that the southwest-facing side of diagonal streets exhibits considerable heat stress (Mayer *et al.*, 2008). The 45º-rotated streets are found to exhibit larger areas of moderately high T_{mrt} in the NE-SW street canyons, indicating that heat stress is likely to occur during the hottest time of the day. Shading by either artificial devices or vegetation is therefore recommended to these areas in order to minimize prolonged sun exposure during daytime (Emmanuel et al., 2007). In contrast, NW-SE orientated streets are able to reduce radiant heat load during heat stress conditions. In addition, diagonal streets somewhat affect the diversity of thermal environment, which reduces the possibility for pedestrians to choose to walk within the street canyons according to their needs for thermal comfort.

The present study provides information about how street geometry design helps to mitigate daytime heat stress in urban environment through identifying areas with potential heat stress. Regional climatic conditions influence the radiant heat load within urban environment, which has implications on outdoor thermal comfort. It is shown that dense urban structures are capable of reducing radiant heat load within complex urban environment as high H/W ratios generally mitigate the high T_{mrt} levels observed in the study grid. Street orientations affect the spatial pattern of high T_{mrt} levels (hotspots) and somewhat reduce the diversity of thermal environment. Findings of the present study would contribute to subsequent formulation of design guidelines for mitigating outdoor heat stress in urban environment. The effect of street trees will also be investigated since it is one of the most effective measures in terms of mitigating outdoor heat stress.

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