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The microclimate performance of urban form: A quantitative morphological approach

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Abstract

Understanding how urban form influences the urban microclimate is crucial to inform urban planning and design in the challenge of adapting cities to climate change. The complex relation between the spatial and the thermal performance of the urban environment has been proven in previous climatological studies. However, the understanding of the interaction between morphological characteristics and the thermal behaviour of urban spaces has been limited by the systemic differences between the disciplines involved, such as the use of spatial units, scale systems and classification methods. Climatological studies mainly employ morphological approaches based on qualitative classification of 'generic' urban patterns or supervised classification of homogeneous zones with course resolution. Both approaches have limited applicability to analyse heterogeneous urban environments, which can be overcome by using multi-variable and inter-scalar characterization approaches from the field of urban morphology. This paper addresses this potential by developing a quantitative method to identify morphological types based on climate-related form attributes of buildings and their immediate context. Application of the method in the case of Rotterdam allows to identify 5 buildings and 5 context types. Finally, a microclimate performance assessment on the resulting 25 archetypes is carried out, by using the ENVI-met microclimate model.

Keyword: *microclimate, ENVI-met, cluster analysis, building type, context type*

1. Introduction

Climate change increasingly poses challenges in urban planning and design. The overall increase in temperatures and frequency of heatwaves events (Founda et al., 2019; Guerreiro et al., 2018) are expected to exacerbate the magnitude of Urban Heat Island phenomena and heat stress in cities (Ward et al., 2016). In this context the construction of climate resilient cities urges for the development of conceptual and methodological frameworks that can support the understanding of local spatial conditions that either increase or reduce overheating mechanisms.

Climatological studies have demonstrated that urban form characteristics significantly influence the magnitude of the Urban Heat Island effect by shaping thermal and turbulent processes (Oke et al., 1991). However, few studies investigate the impacts of urban form on climate phenomena with a high level of resolution in existing cities (Chatzipoulka & Nikolopoulou, 2018). For the majority of the studies, two main morphological approaches can be recognised. The first approach is characterised by an analytical focus on the relation between single form characteristics and climate processes. Usually, these studies are based on modelling, and attempt to quantify the impacts of form on thermal comfort (Ali-Toudert & Mayer, 2006; Perini & Magliocco, 2014) or single climate components such as wind speed (Allegrini, Dorer, & Carmeliet, 2015; Javanroodi, Mahdavinejad, & Nik, 2018), short- and long-wave radiation (Morganti, Salvati, Coch, & Cecere, 2017; Van Esch, Looman, & De Bruin-Hordijk, 2012), and air temperature (Salvati, Monti, Coch Roura, & Cecere, 2019; Wong et al., 2011). In this morphological approach, quantitative parameters are employed as a means to describe form characteristics of e.g. density, compactness, aspect ratio and green density. However, methods to identify representative samples of urban areas rely on qualitative selection of homogeneous urban fabrics or in the artificial creation of 'generic' form patterns by multiplying a specific building type in a regular array to normalize the computational results (Toparlar, Blocken, Maiheu, & van Heijst, 2017; Zhang et al., 2012).

The second morphological approach is characterized by the linking of multiple form attributes and climate characteristics through quantitative and qualitative classification techniques. This approach has been widely used in meteorological studies for different purposes (e.g. Chandler 1965; Ellefsen 1991), and is applied to Urban Heat Island studies to address the inadequacies of a (too) simple urban rural division (Stewart and Oke 2006). An example of this approach is the Local Climate Zone classification method (Stewart & Oke, 2012) that defines typical thermal behaviours of urban areas based on the compactness level of the built agglomeration and the building types classified in high-, medium and low-rise. Quantitative parameters such as Sky View Factor, aspect ratio of the street canyon and average height of the roughness elements are used for the description of the classes. However, these methods are limited by their mapping accuracy (Verdonck et al., 2019) and low spatial resolution that does not allow to fully understand the microclimate trade-offs (and potential amplifications) between single buildings and their surroundings.

To overcome the limitations of the two approaches in capturing the complexity of the urban environment, and to tackle the microspatial dimensions of climate phenomena, a data-driven typo-morphological approach is developed and tested in the city of Rotterdam, The Netherlands. The proposed classification approach enhances the identification of both buildings and context types, based on quantitative descriptors of: (i) building geometry, (ii) compactness, (iii) density, and (iv) land cover. Additionally, it enables the identification of UHI intensity related to spatial conditions by combining statistical, morphological and modelling techniques to increase the spatial resolution of climate mapping.

The article firstly presents the methodological framework to obtain and assess types based on climate-related morphological parameters. Secondly, the results of morphological and microclimate characterization are analysed. Finally, the influence of form attributes on indoor and outdoor temperatures is assessed through a sensitivity analysis and discussed.

2. Methodology

This study builds on previous development (Berghauser Pont et al., 2019; Hausleitner & Berghauser Pont, 2017; Serra, Psarra, & O'Brien, 2018) of multi-variable inter-scalar characterization of urban form with data-driven morphological classification techniques. A typo-morphology classification is carried out on the city of Rotterdam. For each resulting archetype, outdoor air temperature values are simulated through ENVI-met. Statistical analysis on the results is carried out to identify correlations between urban form parameters and air temperatures.

2.1 Data driven classification and archetype characterization

A hierarchical cluster analysis was used to classify building types and context types, in order to separate microclimate processes dependent on building characteristics and context conditions. For this purpose, morphological parameters were selected based on climatology literature, and computed for the Rotterdam dataset. As shown in Table 1, these eight variables describe size and compactness of building units, roughness, density and green coverage of the urban fabric. For the context characterization, parameters were calculated in buffer areas of 25m and 50m radius. After the hierarchical clustering, the optimal number of types was selected based on resulting dendrograms.

Table 1. Climate-related morphological variables

Variables	Description	Type of parameter
B_Height (m)	Measure of the building height	Building geometry
B_Footprint (m2)	Area of the building footprint	Building geometry
B_StoV (m2/m3)	Building envelope to volume ratio	Building geometry
GSI	Ground Space Index	Context in buffer 25m
T_{area} (m2)	Tree crown area in buffer	Context in buffer 25m
FSI	Floor Space Index	Context in buffer 50m
MeanH (m2)	Average building height in buffer	Context in buffer 50m
G_{area} (m2)	Total grass coverage area in buffer	Context in buffer 50m

2.2. Microclimate simulation of building and context types

In order to perform microclimate simulations on cases that well represent the cluster characteristics, archetypes were identified. The cases closest to the cluster's centroid of building types were selected, one for each context type. For these cases outdoor and indoor temperature values were simulated in ENVI-met 4.4. Spatial models were created through ENVI-Monde with equal grid resolution (x,y,z = 3 m) and material characteristics. Simulations were carried out for two consecutive hot days with clear sky (June 29-30 2018) by full forcing KNMI weather data from Rotterdam Airport station. After the simulations indoor and outdoor temperature values at façade were retrieved for each archetype under analysis.

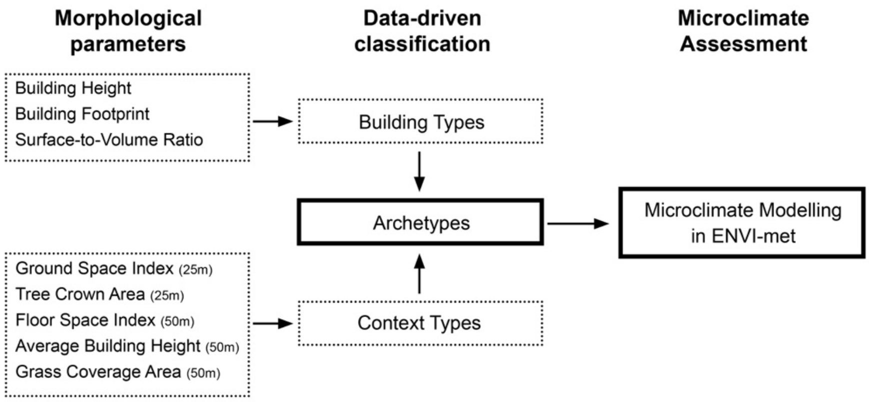

Figure 1. *Scheme of the methodological framework*

3. Results

3.1 Morphological characterization of building and context types

Five building types (B_Type) and five context types (C_Type) were identified through the hierarchical clustering analysis of form parameters. Figure 2 shows the numerical thresholds used for types description. Building types classification is based on height, ground coverage and compactness parameters. B_Type1 is characterized by low compact and low-rise buildings with small footprint. The latter characteristics apply also to B_Type3 that differently from the previous group comprises highly compact buildings. B_Type2 and B_Type5 are composed by mid-rise buildings with high compactness. The discriminant between the two is the footprint area, small in the first and large in the second group. Finally, B_Type4 comprises high-rise buildings with medium size footprint.

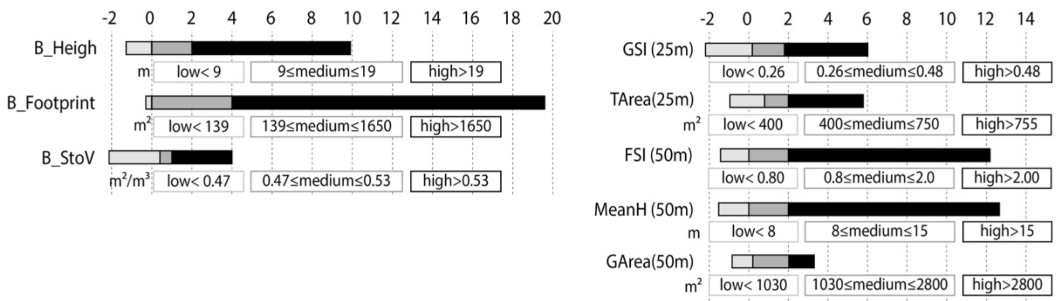

Figure 2. *Parameters standardised values and descriptive threshold*

Context types are characterized based on density, green coverage and roughness parameters. C_Type1 groups urban tissues defined by low density and low to medium-rise buildings, with high tree coverage and medium grass coverage. C_Type2 is characterized by mid-rise and medium density, while C_Type5 by high-rise and high density of the urban fabric. In both types, the presence of grass and trees is scarce. C_Type3 and C_Type4 consist of low-rise and low-density urban fabrics with low presence of trees. However, grass coverage low in C_Type3, reaches a medium level in C_Type4.

Based on the numerical profiles of the types, 25 archetypes were selected (Figure 3) to analyse the microclimate behaviour of the five building types in each context condition (see Appendix).

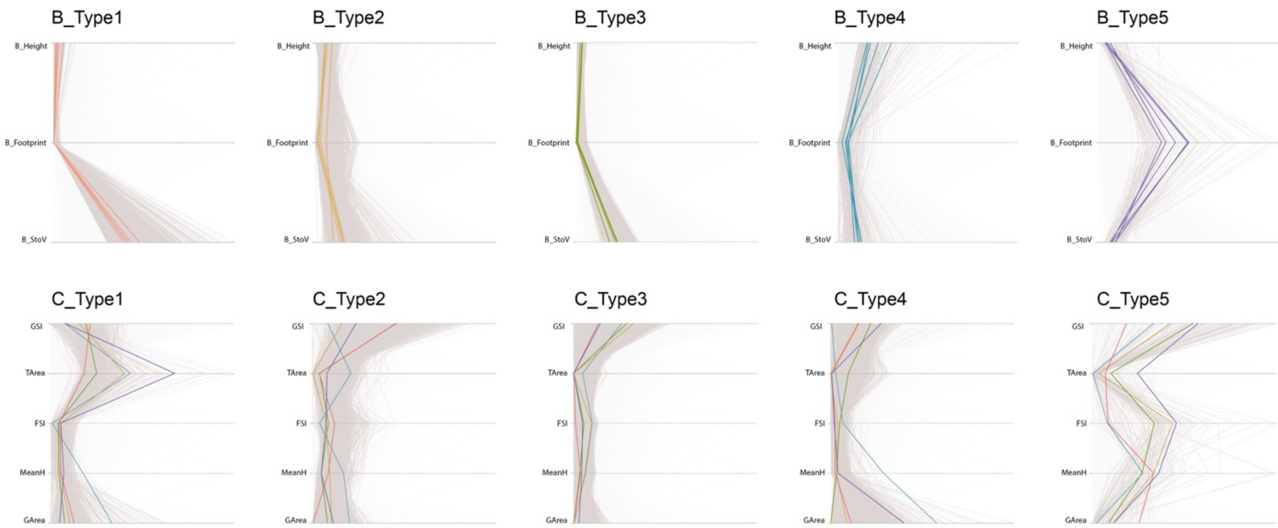

Figure 3. *Numerical description of building (B_Type) and context (C_Type) types, and selected archetypes.*

3.2 Microclimate characterization of types

Outdoor air temperatures resulting from ENVI-met simulations of the 25 archetypes were retrieved in the air layer near the facades, and indoor air temperatures were averaged for the whole building volume. The data indicates a high magnitude of UHI in Rotterdam (between 0.6 and 3 °C). In fact, outdoor temperatures (OutAT) in all urban cases are higher compared to the rural environment. Maximum daytime OutAT at the KNMI weather station is 25 °C the first day and 28.2°C the second day, while, as shown in Figure 4 (left), all urban cases reach maximum OutAT between 25.6°C and 28°C the first day, and between 28.7°C and 31°C the second day.

Additionally, the analysis indicates that the microclimate performance of the archetypes depends upon both building and context characteristics. Low and medium density contexts have similar thermal behaviours (C_Type1,2,3,4), while high-rise high-density contexts (C_Type5) clearly yield lower temperatures in the period under study. Similarly, it can be noticed that high-rise buildings (B4) are the less sensitive to temperature increase in all the contexts. It is also observed that the change in vegetation cover doesn't produce relevant temperature variations among types.

Figure 4 (right) shows that outdoor temperature increases during the second day, leading up to 1.5 °C increase in daytime average indoor temperatures (IndAT). Additionally, clear thermal patterns for each building type can be observed. Low-rise buildings (B_Type1, B_Type3) have the largest difference range in indoor temperature (1.4 – 3.2 °C), as they are sensibly affected by their context characteristics. In particular when these building types are surrounded by highly dense contexts, IndAT drops substantially. Mid-rise buildings characterised by small footprints follow (B_Type2), having IndAT difference ranging between 0.7°C and 1 °C. Differently, high building footprint in B_Type5 leads to more similar and very high IndAT values among the five cases, suggesting that variations in the contextual conditions hardly affect the balance between thermal gains and losses. Finally, high-rise buildings (B_Type4) show lower IndAT values and minor differences between cases. This observation suggests that towers and skyscrapers are less affected by urban warming mechanisms and the influence of their urban form surrounding.

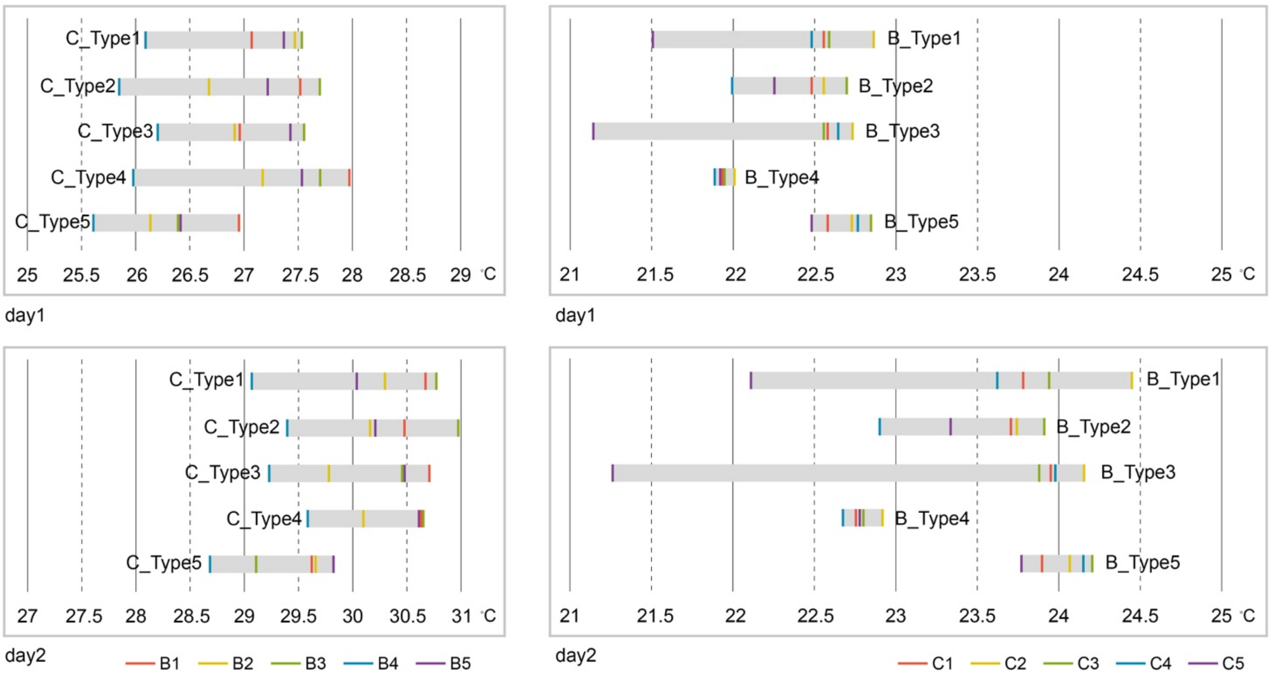

Figure 4. *Maximum daytime outdoor temperature aggregated for context types (left), and average daytime indoor temperature aggregated for building types (right)*

3.3 Sensitivity analysis

A multiple linear regression analysis, applied to the ENVI-met simulation results, allowed to examine the significant correlations between average IndAT, average OutAT and the urban form variables employed in this study. During daytime hours building height and Floor Area Ratio are highly correlated to OutAT, together explaining between 85% (day 1) to 77% (day2) of the temperature patterns. This result thus confirms that decreasing built intensity and height, the urban environment becomes warmer, probably due to the reduced shadow density. During nigh-hours, a significant relationship is found between OutAT and the morphological variables of tree area and Ground Space Index that together explain 39% of urban temperatures. The positive sign of the relation indicates that high building and tree coverage leads to an increase in air temperature during night-time. The possible reason is that compactness and roughness elements inhibit radiative heat loss and ventilation. Finally, a consistent strong correlation (R^2= 0.50) is found between IndAT and two morphological variables: footprint of the building types and mean building heigh of the context types. Thus, this finding suggests that height of the context and size of the footprint (also corresponding to the roof area in these models), are the main factors governing the losses through convection and solar gains at the building façade.

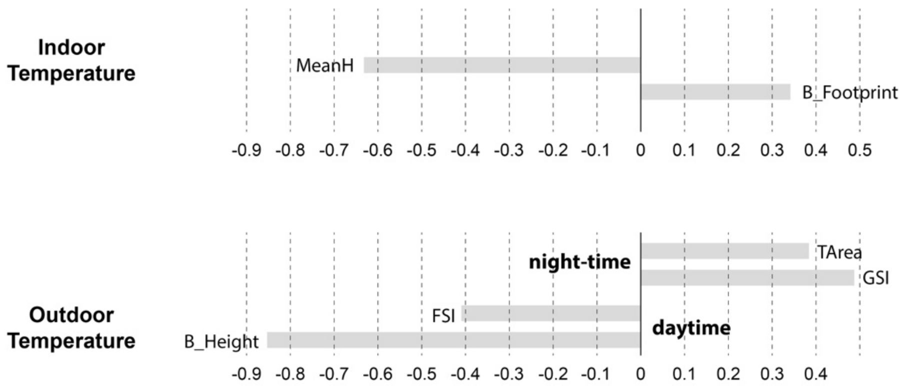

Figure 5. *Standardized coefficient of the relation between temperatures and form parameters.*

4. Conclusions

The study proposes a novel application of a data-driven morphological approach for urban climate classifications in order to increase climate mapping accuracy. The approach enhances the identification and the microclimate assessment of buildings and context types in the case study of Rotterdam, The Netherlands. The employed hierarchical clustering analysis based on quantitative morphological descriptors of building geometry, density and land cover enabled to classify five building types and five context types. Additionally, the microclimate modelling through ENVI-met 4.4 allowed to simulate outdoor and indoor temperatures for the resulting 25 archetypes and analyse the thermal behaviours of types.

The results highlight that temperature patterns depends on the synergic interaction between geometrical characteristics of buildings and their context. Generally, high-rise buildings are less sensitive to temperature change and high-rise, high-density building contexts tend to reduce overheating mechanisms during daytime.

Finally, a statistical analysis verified the relationships between form variables and urban temperatures. During daytime, FSI and building height are the major factors influencing outdoor temperatures. Differently, at night, compactness of the context and presence of trees are related with overheating mechanisms. A significant relationship is also found between indoor temperature and two other form factors that govern buildings' thermal gains and losses: Building footprint and mean height of the context.

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