Chapter 18
Spatial Metrics to Investigate the Impact of Urban Form on Microclimate and Building Energy Performance: An Essential Overview

Michele Morganti

18.1 Introduction

In recent years, the topic of cities and climate change has drawn the attention of media, experts as well as researchers from different fields. The increasing frequency of natural disasters raises the question of how to adapt cities and counteract to these challenging conditions in the short-term period. The IPCC recalls for the urgency of urban adaptation and energy transition and determines spatial configuration of cities as a driver of high importance in these issues (IPCC 2014, 2018).

It has been widely demonstrated in the past 50 years that urban form has relevant effects on the urban microclimate, thermal comfort—both indoor and outdoor—and building energy performance (Emmanuel and Steemers 2018). A huge amount of information has been developed in the field of geography, climate, urban ecology, urban physics and resilient design. The characterization of these effects in every field has grown remarkably in the last years. However, the complex nature of the issue produces a rich but intricate body of theoretical knowledge making use of hundreds of spatial metrics that depend on the aim, perspective and tools of each study.

A broad set of urban form attributes and associated metrics with relevance for urban climate and energy performance is available today, but the proposed approaches are often partitioned and limited to few attributes. Moreover, the use in practice made by professionals in regenerative design is very limited. Architects, urban designers, planners and policymakers are generally aware of the importance of the issue, but they often turn out to be frustrating to include this knowledge when making decisions. Multiple metrics, sometimes conflicting, are available and which are the most important with the design objectives is not easy to define. The unintended interaction among urban form, microclimate and energy and the associated

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variables together with the difficulties to isolate the urban form from other drivers of microclimate and energy performance requires a more holistic comprehension of the relevance, suitability and effectiveness of metrics in the description of cities' functioning (Silva et al. 2017) (Fig. 18.1).

18.2 A Cross-Disciplinary Framework

This chapter provides an essential overview on spatial attributes of cities with relevance on microclimate and energy efficiency: a general framework on the most appropriate spatial metrics in quantitative design research method concerning urban form is introduced and discussed. On the one side, the overview wants to clarify the existing scientific "babble" on the metrics and promote an effective and suitable use. On the other side, it wants to foster the application of the metrics to climate-responsive regenerative design and planning. Quoting Jacobson, the most urgent challenge in this field is to enable architects and planners to easily understand, control and assess cumulative impacts and effects of their design decisions (Jacobson 2019). Metrics represent a powerful tool, especially for the possibility of integration into parametric design tools, nowadays widely used in professional practice as well as in scientific research.

The overview of the metrics is divided into three subsections. Each section describes the capability of existing methods to investigate the effects of urban form on microclimate and outdoor thermal comfort, solar irradiation and building energy performance, respectively. Recent relevant studies are analysed in terms of two additional factors—the scale of investigation and the climate of reference—as well as in terms of suitability and effectiveness of urban form attributes and the

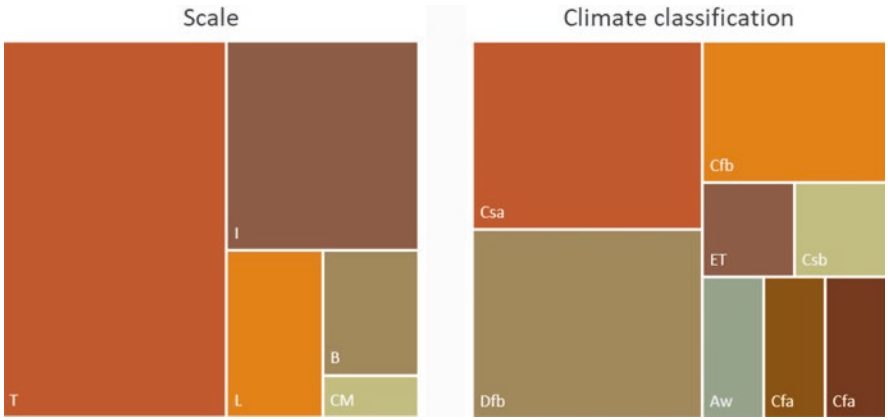

Fig. 18.1 Scale of analysis and Köppen climate classification of recent studies using spatial metrics to investigate urban microclimate and energy efficiency

associated metrics (Fig. 18.2). Taking advantage of metrics' neutrality to wave together three sectorial perspectives in a single framework is the main goal of this chapter.

18.2.1 Microclimate

The effect of physical characteristics of the urban environment on local microclimate is well known in the field. It has been a long time since we analysed and understood the main factors that affect this effect and possible solutions to counteract or mitigate it (Golany 1996; Oke 1982). Due to unprecedent climate change consequences on cities—temperature rise, extreme droughts and heatwaves in summer—recent advancements are focusing on outdoor thermal comfort and urban heat island effects. For this reason, most of the studies deal with warm and hot climates.

The most common metrics used in these research methods describe key morphology attributes of the urban fabric that are correlated with air temperature in the urban canopy layer: compactness, plot ratio, distance between buildings, vertical density and sky view factor—both of open space and façades (Table 18.1). Urban texture "porosity" and "building intensity" are the attributes of interest that play a crucial role in the urban heat energy balance. Both these attributes significantly affect most of the components of urban energy balance: wind flow, incident solar radiation, energy absorption and (re-)emission. The former expresses the amount of open space available in the urban area; the latter, conversely, expresses the amount of buildings that rise in the urban area. Several density metrics—such as porosity, compactness, plot ratio and vertical density—have been defined and used to measure these attributes and have proved to be indicators of outdoor comfort conditions and energy performance of buildings. For example, compactness, plot ratio and building volume density are directly related to summer air temperatures in the case of the Mediterranean climate (Petralli et al. 2014). Moreover, UHI intensity is strongly related to compactness in winter and to vertical density in summer (Salvati et al. 2019).

Stewart and Oke (2012) developed the local climate zones, a spatial metrics-based taxonomy of urban microclimates in order to overcome the inadequacy of simple urban-rural climate division and to determine different magnitudes of UHI in urban textures. The study characterizes built form types and land types using six urban form metrics out of eight. The idea of downscaling climate analysis in cities considering the effects of physical attributes—too often neglected by practitioners—is of interest concerning not only temperature studies but also the associated building energy demand. Through appropriate metrics—such as aspect ratio and compactness—consistency and accuracy of energy performance evaluation can be improved, including differences in UHI intensity (Vuckovic et al. 2017). This relation can be described even more effectively by using a combination of urban density metrics: compactness, vertical density and average building height show good correlation with energy demand for residential heating and cooling (Salvati et al. 2017).

Table 18.1 Urban form indicators investigated in recent studies

Main topic[a]	Ref.	Metric	Scale[b]	Climate[c]	Location	Main findings
E	Martins et al. (2019)	Plot ratio/ floor area ratio Compactness Aspect ratio Shape factor Courtyard/ patio aspect ratio Street width Standard deviation of building heights	T I B	Cfb	Toulouse, FR	For compact city blocks, the courtyard aspect ratio and the standard deviation of the built height account for almost 50% of the overall impact on heating demand of buildings. The relevance of certain factors was strongly linked to their typologies or to their urban environment.
E	Natanian et al. (2019)	Shape factor Plot ratio/ floor area ratio Window-to-wall ratio Distance between buildings	T	Csa	Tel Aviv, IL	The findings demonstrate the correlation between the shape factor and the energy load match index as well as the benefits of the courtyard typology in terms of energy balance, with its challenging daylight performance.
E	Nault et al. (2015)	Plot ratio/ floor area ratio	T I	ET Dfb Csb	Bern, CH Yverdon-les-Bains, CH San Francisco, USA	The study tests the role of simple metrics as performance indicators when applied to neighbourhoods. To do so, the selected metrics, including geometrical parameters (e.g. compactness) and solar exposure levels (e.g. annual irradiation), are compared with simulation results (e.g. heating need), taken as reference values.

(continued)

Table 18.1 (continued)

Main topic[a]	Ref.	Metric	Scale[b]	Climate[c]	Location	Main findings
E	Rodríguez-álvarez (2016)	Compactness Plot ratio/ floor area ratio Compactness ratio	T	Cfb Dfb Bsk Csa	London, UK Paris, FR Berlin, D Madrid, ES Barcelona, ES	The UEIB is a tool that has been specifically designed to assess the energy performance of buildings in large urban areas. It is based on the reduction of the urban geometry into a simpler national grid that retains critical information to perform meaningful estimations. Compactness, plot ratio and compactness ratio have been used to model urban form.
E	Rode et al. (2014)	Compactness Plot ratio/ floor area ratio Building height Shape factor Open space ratio	T I	Cfb Dfb Csa	London, UK Paris, FR Berlin, D Istanbul, TR	The average building height and building density were found to be good indicators for heat-energy efficiency, each correlating negatively with the heat-energy demand. The shape factor also correlates well but positively with heat-energy demand.

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Table 18.1 (continued)

Main topic[a]	Ref.	Metric	Scale[b]	Climate[c]	Location	Main findings
E	Steadman et al. (2014)	Building volume density Plan depth Exposed surface area	T I	Cfb	London, UK	A correlation of energy use with the exposed surface areas of buildings has been demonstrated, although the full significance of the correlation cannot be assigned to this parameter. Urban form-induced heat-energy efficiency is significant and can lead to a difference in heat-energy demand of up to a factor of six.
M	Salvati et al. (2017)	Compactness	T B	Csa	Rome, IT	Considering UHI intensity and solar obstruction determined by different urban texture, compact urban textures, with compactness above 0.5, contribute to reduced energy consumption in a Mediterranean climate.
M	Chatzidimitriou and Yannas (2016)	Aspect ratio Shading factor	T	Csa	Thessaloniki, GR	Aspect ratio has a strong effect on PET in summer season.
M	Leo et al. (2018)	Compactness Frontal area density Average building height	T I	Cfa	Oklahoma City, USA	The use of morphometric parameters based on scale-adaptive methods provides better agreement with measured data than those in which scales for their calculations are arbitrarily chosen.

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Table 18.1 (continued)

Main topic[a]	Ref.	Metric	Scale[b]	Climate[c]	Location	Main findings
M	Perini and Magliocco (2014)	Compactness Building height	T	Cfa Csa	Milan, IT Rome and Genova, IT	Compactness and height of buildings in a city area influence potential temperature and mean radiant temperature. Higher density causes higher potential temperatures. The height of buildings plays an important role in determining potential temperatures at 1.6 m from the ground level: with taller buildings temperatures are lower due to their shading effect.
M	Petralli et al. (2014)	Plot ratio/ floor area ratio Compactness Street surface Building volume density	T	Csa	Florence, IT	The minimum night temperature in summer is positively affected by an increase of street and building indicators.
M	Salvati et al. (2019)	Compactness Vertical density Average building height	T I	Csa	Rome, IT Barcelona, ES	In the Mediterranean climate, an increase of horizontal density of urban textures determines an increase of the UHI intensity in winter, while an increase of vertical density entails an increase of UHI intensity in summer.

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Table 18.1 (continued)

Main topic[a]	Ref.	Metric	Scale[b]	Climate[c]	Location	Main findings
M	Stewart and Oke (2012)	Sky view factor/sky factor Aspect ratio Compactness Average building height Impervious/pervious surface fraction	L	–	–	The proposed metrics are the basis for the classification of the LCZ as a comprehensive climate-based classification of urban and rural sites for temperature studies.
M	Tsitoura et al. (2016, 2017)	Aspect ratio Sky view factor/sky factor	T	Csa	Crete, GR	During summer, the effects of the aspect ratio on microclimate depend on the orientation of the urban canyon; SVF is used as an indicator of shading but orientation is crucial in thermal comfort (radiant temperature).
M	Vuckovic et al. (2017)	Aspect ratio of urban canyon Compactness Impervious/pervious surface fraction	T I B	Dfb	Wien, AU	A higher impervious surface fraction is noticeably correlated with higher night-time air temperature in the urban canyon. Significant deviations are noted in computed heating and cooling loads, as well as in overheating levels, with regard to standardized climate input data.
S	Martins et al. (2014, 2016)	Porosity Shape factor Aspect ratio Plot ratio/floor area ratio Contiguity Distance between buildings	T I B	Aw	Maceiò, BR	Results indicate a significant impact of the aspect ratio and the distance between buildings.

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Table 18.1 (continued)

Main topic[a]	Ref.	Metric	Scale[b]	Climate[c]	Location	Main findings
S	Chatzipoulka et al. (2016)	Mean outdoor distance Compactness Directionality Vertical density Standard deviation of building height	T	Cfb	London, UK	Mean outdoor distance, compactness, directionality and complexity were the most influential for the solar performance of open spaces, while building façades were mostly affected by standard deviation of building height and directionality (among others). Direct solar irradiance on ground and façades was found to be influenced by different variables in January and July.
S	Lee et al. (2016)	Compactness Plot ratio/floor area ratio Number of storeys	T I	Dfb Dfa	Copenhagen, DK NYC, USA	The lower the density, the higher the solar potential. Density has less effect on the active solar potential of roofs, where climate plays a more influential role. Solar accessibility appears to be less a function of density than of building layout and configuration.
S	Morganti et al. (2017)	Compactness Vertical density Sky view factor/sky factor	T I	Csa	Rome, IT Barcelona, ES	Compactness, vertical density and sky factor show very good correlation with solar irradiation and could be used to develop a comparative assessment tool of solar performance at fabric scale.

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Table 18.1 (continued)

Main topic[a]	Ref.	Metric	Scale[b]	Climate[c]	Location	Main findings
S	Mohajeri et al. (2019)	Street orientation Street width Street length Sky view factor/sky factor	L T	Dfb	Geneve, CH	Street orientation has a strong effect on received annual solar radiation by street surfaces and façades. Received solar radiation, both for street surfaces and façades, shows only moderate correlations with the other measured geometric parameters, namely street width, street length, asymmetric aspect ratio and SVF, the highest coefficient of determination being between received street-surface radiation and SVF.
S	Mohajeri et al. (2016)	Compactness Plot ratio/floor area ratio Volume-area ratio	L T	Dfb	Geneve, CH	Compactness, plot ratio and volume-area ratio are the most effective in describing the solar performance of roofs and façades.
S	Sarralde et al. (2015)	Average building height Compactness Average building perimeter Standard deviation of building heights Plot ratio/floor area ratio Distance between buildings	L T	Cfb	London, UK	Results show that by optimizing combinations of up to eight metrics of urban form the renewable energy potential of solar irradiation of roofs could be increased by ca. 9%, while that of façades could be increased by up to 45%.

[a](M) Microclimate, UHI and outdoor thermal comfort; (E) urban building energy performance; (S) solar irradiation
[b](L) Local > (T) urban texture > (I) urban island > (B) building
[c]Köppen-Geiger climate classification

In addition, spatial metrics have been positively applied to design-oriented research, with special attention to outdoor thermal comfort. Aspect ratio and sky view factor can be used in combination with orientation of the urban texture to predict temperature variation even in the warm climate, where the direct radiation plays a major role in comfort conditions (Chatzidimitriou and Yannas 2016; Tsitoura et al. 2016, 2017).

18.2.2 Solar Energy

Urban solar energy studies investigate and assess passive and active solar energy, and the solar potential of buildings to produce renewable energy, as well as their effects on the thermal gains on building façades and heat in open spaces, the desirability of which differs from winter to summer and depends on the local climate. Based on the latter and the research method, it must be noted that the same metric can be highlighted as relevant or not to solar performance. For example, at tropical latitudes, plot ratio has a minor impact on façade solar radiation, while at continental latitude it is one of the most effective in describing the same performance (Lee et al. 2016; Martins et al. 2016; Mohajeri et al. 2016). Another crucial aspect concerning the research method is the modelling of case studies. In this regard, two main approaches have been developed: dealing with real urban forms or using theoretical archetypes. When solar analyses on façades are conducted on homogeneous urban fabrics, rather than cells of fixed dimension, the relation between form archetypes and solar performance can be investigated. Through a combination of compactness, vertical density and sky factor, a clear trend can be fitted (Morganti et al. 2017). Moreover, the combination of spatial metrics can be easily applied in statistical model aiming at optimizing renewable energy potential of roof and façade. It has been demonstrated that it is possible to increase this potential up to 45% (Sarralde et al. 2015).

Several studies confirm the validity of two additional spatial metrics: sky factor and sky view factor. Considerable insights can be derived by the use of these metrics in investigating the solar performance of open spaces (Chatzipoulka et al. 2016; Chatzipoulka and Nikolopoulou 2018). Moreover, among several physical attributes of our city at the neighbourhood scale, the sky view factor has been effectively used for characterizing the solar access of street pattern and façades of adjacent buildings (Mohajeri et al. 2019).

18.2.3 Building Energy Performance

In recent years, due to the urgent need to meet the energy efficiency target established at international and national policy levels, the evaluation of energy performance has been upscaled from building to the urban environment. Firstly, building

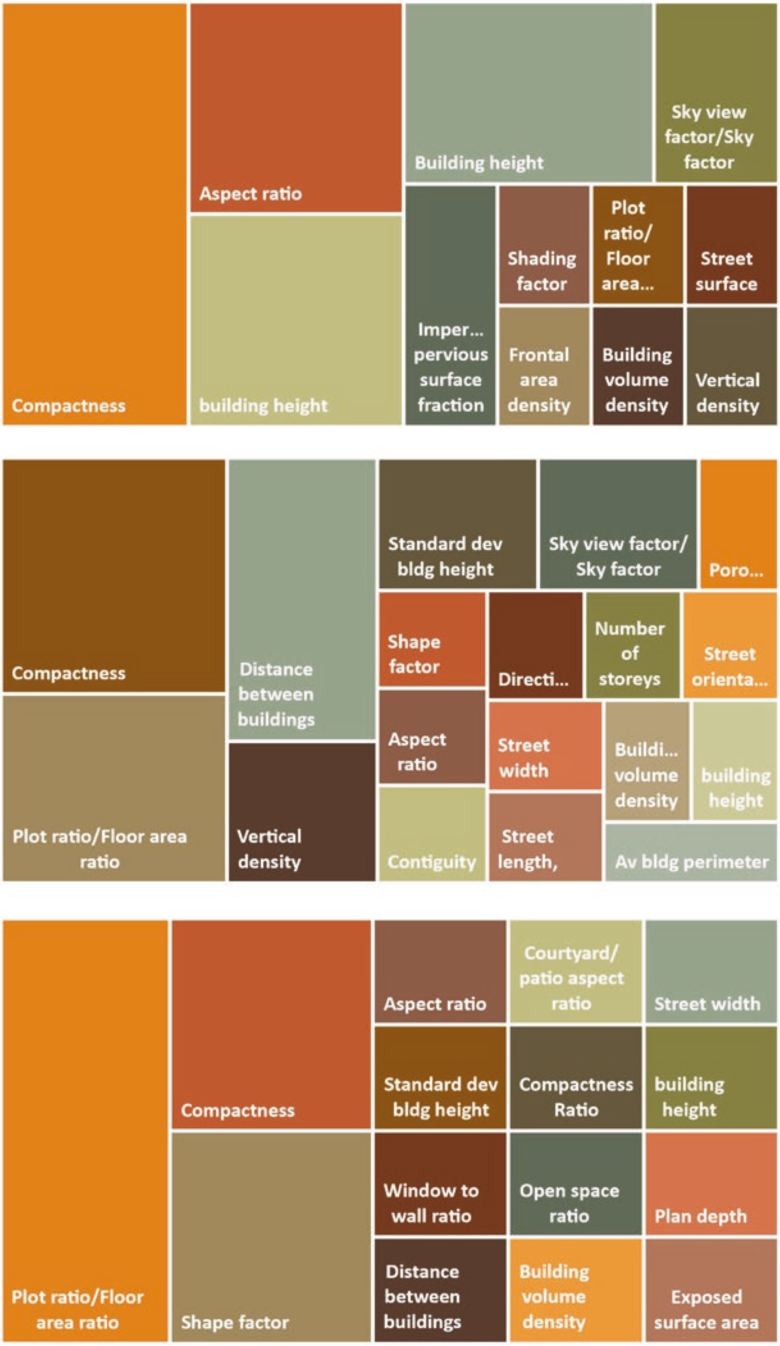

Fig. 18.2 Predominant metrics found in recent studies to correlate urban form attributes with microclimate and energy performance: (**a**) microclimate, and (**b**) solar and (**c**) energy performance

energy efficiency actions and regulations have found very limited application in the renovation process of the building stock. Secondly, researchers point out the importance of addressing the interactions among the building, the urban context and the microclimate to develop reliable building energy performance assessments. Thirdly, the need for analysing this performance for thousands of buildings at once, in order to develop efficient urban energy system, has emerged.

Therefore, new hybrid methods have been developed, merging statistical analysis of the building stock and building energy modelling (Allegrini et al. 2015; Reinhart and Davila 2016). Among these research methods, bottom-up approaches make use of spatial metrics as well as other building variables to generate archetypes for energy analysis of the building stock.

A difference of a factor up to six of the heating demand induced by urban form has been demonstrated (Steadman et al. 2014). In addition, the authors established a correlation between exposed surface area and energy use. Similar findings have been proposed by Rode et al. (2014): they demonstrate that urban density metrics and shape factor are good indicators of heating demand in European compact city model. Besides, spatial metrics related to urban form have been recently used in the development of urban building energy tools, such as Urban Energy Index for Buildings, in which the urban geometry is retained in a national grid through compactness, plot ratio and compactness ratio (Rodríguez-álvarez 2016).

As in the case of solar radiation, different energy demands and climates require different metrics: in the Oceanic climate, standard deviation of building height accounts for almost half of the overall impact on heating, while for cooling its effect is reduced due to the prevalence of other building indicators (Martins et al. 2019). In the Mediterranean climate, shape factor of urban form directly affects the energy load of buildings, demonstrating the effect of courtyard and patio morphology on the global performance (Natanian et al. 2019).

18.3 Reliability and Role of Spatial Metrics in Urban and Building Studies

This chapter presents an essential overview of the relevance and role of spatial metrics in recent research methods on microclimate and building energy performance. We report about the ongoing debate on the most relevant metrics associated with urban form attributes that produces important advancements.

Due to the use made by authors this world of metrics can be a "muddy terrain" for several reasons, especially for professionals without specific knowledge in the field. On the one side, different definitions for the same name have been used. For example, the plot ratio that is one of the most common density indicators has no unique definition: it is calculated by using the total footprint area of a building as well as the total floor area. On the other side, different names are used for the same definition. Intending to overcome this barrier and share knowledge on urban form

Table 18.2 Relevant and reliable metrics for urban microclimate and energy studies

Metric	Units	Definition
Aspect ratio	–	Ratio of building height to the width of the distance between buildings (street width + building setbacks)
Average building perimeter	m	The mean value of the building perimeters included in the urban site area
Building height	m	The value of the building heights included in the urban site area
Building volume density	m	The total volume of buildings in the urban site area
Compactness	–	The ratio of the building footprint to the urban site area
Compactness ratio	–	The proportion of exposed building envelope area (roof and external walls) to the floor area
Contiguity	–	The ratio of total vertical surface adjacent with other building envelopes to the total envelope surface that is exposed to the outside environment within the urban site area
Courtyard/patio aspect ratio	–	The ratio of the building height to the patio width
Directionality	–	The standard deviation of ground's permeability in 36 directions weighted by compactness
Distance between buildings	m	The minimum spacing between adjacent buildings
Exposed surface area	m^2	The total surface of the buildings' envelope in the urban site area
Impervious/pervious surface fraction	–	The ratio of the impervious surface coverage to the urban site area
Number of storeys	–	The mean value of the building storeys included in the urban site area
Plot ratio/floor area ratio	–	The ratio of the total built floor area to the urban site area where the buildings are located
Porosity	–	The ratio of the useful open volume to the total volume of the urban site area
Shape factor	–	The ratio of the non-contiguous building envelope to their built volume, over the urban site area
Sky view factor/sky factor	–	SF: The ratio of the solid angle of visible sky from each point of the considered urban components to the sky vaultSVF: The cosine-weighted ratio of the solid angle of visible sky from each point of the considered urban components to the sky vault
Standard deviation of building height	–	A quantity expressing by how much the building heights included in the urban site area differ from the mean value for the group
Vertical density	–	The ratio of the building façade area to the urban site area
Window-to-wall ratio	–	Average wall-to-window ratio in all the elevations of the urban site area

metrics the proposed overview draws a general framework on 20 essential metrics for microclimate and energy studies (Table 18.2). These metrics can be easily derived or calculated by means of GIS maps and open data set, and therefore are available for the great majority of cities. It is worth to underline that, due to their definitions and indirect correlations among basic variables, some metrics are equivalent indicators of urban form performances, as exemplified by the relation of sky view factor with compactness and mean outdoor distance variables (Chatzipoulka and Nikolopoulou 2018). Moreover, care should be taken in the selection of metrics in relation to the scale of analysis. Most of these metrics are not suitable to act as reliable performance indicators at all the scales, as highlighted in Table 18.1. Since they measure specific urban attributes, to consider their variation within the study area is crucial.

The most important insights are the following.

- Within the recent studies in the field, we can assume that the most successful metrics are density-based parameters, both for relevance and effectiveness: compactness and plot ratio, as well as shape factor, aspect ratio and building height.
- It should be highlighted that in microclimate studies the main focus of analysis is the relation among physical description and macroclimate of the cities: in particular, warm and hot climates are the most critical due to discomfort, health issues and increasing cooling demand during the summer season.
- When focusing on both the passive and the active performance of solar energy it is important to notice that, depending on the specific built element (ground, façade, roof) and on the season of the year, different metrics will result to be the most reliable to describe the solar performance. Therefore, attention must be reserved in the use of metrics within the research method and the associated design process.
- The characterization of urban form attributes in the definition of different building stock archetypes through urban metrics in building energy performance has the potential to easily control the effect of the urban texture at neighbourhood level on microclimate (UHI intensity) and energy demand of buildings.
- The full significance of the correlation between urban metrics and performance cannot be assigned to one single metric, as the complex interaction of climate-form-energy occurring in the urban environment cannot be represented by one single variable. For this reason, most of the studies discussed in this overview make use of a combination of urban metrics, both for describing the urban textures and testing the effectiveness in the description of a specific urban phenomenon, both for defining trends among metrics and performance, e.g. energy demand, urban heat island intensity and passive solar irradiation. Such kind of approach has proved to be more effective in the description of microclimate and energy performance and can be easily integrated into digital design tools for architects and urban planners. In addition, the approach helps the assessment of cumulative impacts of decisions on regenerative design process. However, attention must be paid to unintended conflicts and redundancies among metrics when used in combination for prediction or design purposes.
- To prioritize certain urban form variables widespread in urban design and architecture is crucial to support design strategies and to help architects understand the above-mentioned impacts. These metrics include plot ratio, compactness, shape factor and aspect ratio that can easily be included in urban climate and energy planning or policies.

The description through metrics of the effects of urban form on microclimate and energy performance is of primary importance for cities' adaptation to climate change and energy transition. In order to distinguish urban form metrics as a reliable indicator and to foster climate-sensitive design, several challenges remain. Nowadays theoretical knowledge and associated research methods are sectorial, confused, dispersed and too often complicated. A systematization of this knowledge on physical characteristics and spatial metrics relevant for urban microclimate and energy efficiency makes it possible to overcome current limitations. Firstly, to investigate unexplored connections among different urban phenomena is needed for climate change and energy transition agenda. Secondly, this is important because discussion on this issue would promote cross-disciplinary approach. Thirdly, a guidance on relevant metrics would allow urban designers and architects to control the impacts of design choices during the entire creative process. The diffusion of such kind of approach is crucial in the regenerative design of cities that plays a big part in the SDG for the near future.

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