

## Connecting the realms of urban form, density and microclimate

Emmanuel, Rohinton; Steemers, Koen

*Published in:*  
Building, Research & Information

*DOI:*  
[10.1080/09613218.2018.1507078](https://doi.org/10.1080/09613218.2018.1507078)

*Publication date:*  
2018

*Document Version*  
Peer reviewed version

[Link to publication in ResearchOnline](#)

*Citation for published version (Harvard):*  
Emmanuel, R & Steemers, K 2018, 'Connecting the realms of urban form, density and microclimate', *Building, Research & Information*, vol. 46, no. 8, pp. 804-808. <https://doi.org/10.1080/09613218.2018.1507078>

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

### Take down policy

If you believe that this document breaches copyright please view our takedown policy at <https://edshare.gcu.ac.uk/id/eprint/5179> for details of how to contact us.

# Connecting the realms of urban form, density and microclimate

Rohinton Emmanuel<sup>1</sup> and Koen Steemers<sup>2</sup>

<sup>1</sup> School of Engineering and the Built Environment, Glasgow Caledonian University, Glasgow, UK. ORCID: 0000-0002-3726-5892

<sup>2</sup> The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge, Cambridge, UK. ORCID: 0000-0001-8135-158X

The effects of urban form on local climate, thermal comfort and energy consumption have been well researched during the past 50 years. Starting with Olgyay's (1963) work on bio-regionalism, research in related areas have led to guidelines for climate sensitive urban design (Givoni, 1988); form optimisation for different climatic contexts – solar access rights in temperate climates (Knowles, 1981), solar shading in the tropics (Emmanuel, 1993), passive urban form for tropical cities (Martins et al., 2014), archetypical built forms for arid climates (Ratti et al., 2003); passive energy resource enhancement (Steemers et al., 2000) and urban energy management (Ratti et al., 2005; Fitcher et al., 2013). Tools for the analysis of energy performance of urban form – such the LT method (Baker and Steemers, 1994), Energy Index (Yannas, 1994) or Urban Energy Index for Buildings (UEIB, Rodríguez-Álvarez, 2016) have been demonstrated.

In parallel to these, work on 'sustainable urban form' has progressed in recent years to include the notion of urban resilience (ability to adapt to environmental stress without contributing to further acceleration of that stress; Anderies, 2014; Pickett et al. 2014; Hassler and Kohler, 2014) in the face of local and global climate change. Several authors have proposed urban parameters that are said to contribute to urban sustainability (e.g. compactness, mixed landuse – Breheny, 1992; compactness, sustainable transport, density, mixed land uses, passive solar design, and greening – Jabareen, 2006) while others contend that no universal relationships exist on the most desirable urban form in the context of sustainability (e.g. Frey, 1999; Williams et al., 2000). Nevertheless, and even accounting for the wide variations in the definition of 'urban form' (from two dimensional land-use patterns – Anderson, 1996 to three dimensional attributes such as size, density, clustering, evenness in size, edge density, and compactness – Schwarz, 2010) there appears to be a consensus towards 'compact' urban form as key to urban sustainability (e.g. Stone and Rogers; 2001, Yin et al., 2013).

Compact urban form raises significant questions about the impacts and consequences on local microclimates and what this means for energy demand, thermal comfort, air quality and health. These concerns are raised and addressed in this special issue and urgently need to be addressed. In addition, further questions are raised here for research, policy and practice. What effects does compactness have on climate sensitive urban design? Are there unintended energy, thermal comfort, air quality and ventilation consequences of compact urban form? What is known about the interactions between these effects? These are some of the issues explored in this special issue.

## To be cited as:

Emmanuel R, Steemers K. 2018. Connecting the realms of urban form, density and microclimate, *Building Research & Information*, doi: 10.1080/09613218.2018.1507078, <https://doi.org/10.1080/09613218.2018.1507078>

The effects of urban compactness on temperature and energy use are beginning to be appreciated (Ward and Grimmond, 2017). In the sub-tropical monsoon climate city of Wuhan, China, Lan and Zhan (2017) found that over half of the night-time air temperature variations could be explained by urban form (as defined by Floor Area Ratio, Building Density and Building Height, among others). Li et al (2018) found that in Ningbo, China (a sub-tropical coastal city) density is negatively correlated with residential energy consumption in the summer on account of the shading provided by urban form. However, tower-and-podium form buildings showed a positive correlation between density and residential electricity consumption for space conditioning needs. These studies highlight the importance of shading but also the unintentional negative consequences when the shading is of the 'wrong' type. While it may be tempting to dismiss such associations as irrelevant in temperate/cool climate cities, there is evidence that cities of cooler climates and cities with higher shares of urban green spaces were more affected by additional heat during warm episode (Ward et al., 2016). Thus, the urban effect on building energy consumption is a 'problem' in all parts of the world.

The interactions between urban form, shading, microclimate and energy consumption in buildings is particularly intriguing. While at local scales, strong correlations exist between exposed surface area and energy use, at district scale, a sharp increase in electricity use is seen in districts where buildings are deeper (and consequently typically require air-conditioning and permanent artificial lighting) (Steadman et al., 2014). Although compact cities may decrease the operational domestic heating energy consumption per household (Liu and Sweeney, 2012), they tend to have poor air quality; higher concentrations of NO<sub>2</sub> and PM<sub>10</sub> and densely populated cities suffer from higher SO<sub>2</sub> concentration (Rodríguez et al., 2016) – with a potential increase in the use of energy for air conditioning. Furthermore, compact cities with low surface-to-volume ratios minimize the building energy consumption for space heating/cooling, but maximize the outdoor heat stress (Martilli, 2014).

Building geometries in high density settings and their effects on solar absorptance due to shading (or lack thereof) lead to significant variations in the infrared temperatures over the urban areas. There is evidence that such variations will influence the performance of air conditioners in urban buildings (Levermore et al., 2018), which in turn requires careful consideration at the design stage – a task made difficult by the constant evolution of urban form. Additionally, increasing building height appears to have less of an impact on microclimate than increasing building fraction due to the important role of vegetated surfaces in moderating the urban climate (Ward and Grimmond, 2017).

This special issue brings together a collection of papers that explore the interactions between urban form and ventilation / shading, to highlight the unintended air temperature, building energy use and thermal comfort consequences in high density settings (Table 1). The focus is on shading and ventilation on account of both their potential as mitigation options but also the lack of knowledge of the interactions between them.

Table 1. Authors and titles of articles in this special issue 'Urban Form, Density and Microclimate', Building Research & Information (2018) vol. 46(8); guest editors: Rohinton Emmanuel and Koen Steemers.

Authors	Title	doi
R. Emmanuel and K. Steemers	Editorial: New challenges in urban form, density and microclimate	10.1080/09613218.2018.1507078
J. Song, S. Fan, W. Lin, L. Mottet, H. Woodward, M. Davies Wykes, R. Arcucci, D. Xiao, J. Debay, H. ApSimon, E. Aristodemou, D. Birch, M. Carpentieri, F. Fan, M. Herzog, G.R. Hunt, R.L. Jones, C. Pain, D. Pavlidis, A.G. Robins, C.A. Short and P.F. Linden	Natural ventilation in cities: the implications of fluid mechanics	10.1080/09613218.2018.1468158
J. Fitcher, G. Mills and E. Rohinton	Interdependent energy relationships between buildings at the street scale	10.1080/09613218.2018.1499995
D. Godoy-Shimizu, P. Steadman, I. Hamilton, M. Donn, S. Evans, G. Moreno and H. Shayesteh	Energy use and height in office buildings	10.1080/09613218.2018.1479927
M. Palme, L. Inostroza and A. Salvati	Technomass and cooling demand in South America: a superlinear relationship?	10.1080/09613218.2018.1483868
C. Chatzipoulka and M. Nikolopoulou	Urban geometry, SVF and insolation of open spaces: London and Paris	10.1080/09613218.2018.1463015
C.A. Short, J. Song, L. Mottet, S. Chen, J. Wu and J. Ge	Challenges in the low-carbon adaptation of China's apartment towers	10.1080/09613218.2018.1489465
L.S. Leo, R. Buccolieri and S. Di Sabatino	Scale-adaptive morphometric analysis for urban air quality and ventilation applications	10.1080/09613218.2018.1501797

Song et al. examine the effects of street layout and associated street canyons, of roof geometry and the wakes of nearby tall buildings. This paper shows the connection between internal ventilation (and pollution) conditions and the external conditions as influenced by the urban form, but also highlights the limits of our current knowledge to be able to correctly predict these indoor-outdoor relationships.

Several papers focus on the interaction between shading induced by urban form and building energy consumption. While the positive effects of shading on urban thermal comfort and energy

consumption are well known (see for example, Kantor et al., 2018), the street scale effects remain under-studied. Fitcher et al. attempts a corrective for 'commercial' buildings whose occupancy patterns coincide with peak solar insolation. They show that increasing the depths of a street canyon (as given by the ratio of height of buildings : width of street – H/W ratio) in areas dominated by commercial office space is beneficial as timing of its use (maximum internal energy use) and shading provided by built form (reduced external energy gain) correspond. However, this may not hold for other types of buildings whose occupancy may not coincide with peak insolation.

Godoy-Shimizu et al. empirically show a similar relationship as that pointed out by Fitcher et al. This paper empirically shows a substantial increase occurs in mean intensity of electricity and fossil fuel in taller buildings. The increase in height from 5 stories or less to 21 storeys and above results in 137% increase in energy intensity and 42% increase in fossil fuel use per unit of area). While the causes for such an association could not be determined by this statistical work, the increased weather exposure (e.g. sun, wind, rain, etc.) in the case of taller buildings (i.e. lack of shade) is cited as a potential contributor. This has profound consequences to the density vs. energy consumption debate.

The research by Palme et al. suggests that the consequences of urban density on cooling energy demand might have a threshold point of density, beyond which the urban cooling consumptions goes from a linear to superlinear relationship. The transition might be caused by the detrimental impact of the urban heat island (UHI) effect and the infrared environment in dense urban environments, highlighting the importance of shading.

Could the consequences of shading be positive for building energy consumption as well as in mitigating the urban heat island (UHI)? Fitcher et al. show that this may not be the case for streets that are dominated by daytime occupied buildings – wider streets would be useful to mitigate the UHI while this would lead to increased energy demand for office buildings. Given that the functions within buildings change faster than the 'street form' a further consideration is the potential lack of resiliency of urban form to climate adaptability in the medium to long term (Hassler and Kohler, 2014). For example, a more open-to-sky streetscape of residential buildings may not easily transform into climate-sensitive office buildings. This is so due to the variations in occupancy patterns – nighttime occupied buildings (such as residences) benefit from faster dissipation of trapped daytime heat while mutual shading is beneficial to daytime occupied buildings (such as offices). Fitcher et al. suggest that asymmetric streets, oriented East-West are the most adaptable in this regard.

In a comparison of the urban morphologies of London and Paris, Chatzipoulka and Nikolopoulou show that urban thermal comfort could be maximised by taller buildings (provided they are spaced widely apart). While this might appear to contradict the findings of Fitcher et al., the focus of these two papers are different (building energy consumption effects vs. urban thermal comfort), again highlighting the contradictions between these two end goals.

At this point, it might be appropriate to mention the need to define 'urban form' and 'density' in a heterogeneous urban context – the importance of distinguishing between 'horizontal' and 'vertical' density is emphasised by Chatzipoulka and Nikolopoulou. Their examination of ground-level Sky View Factor (mSVF) is shown to be affected by the quantity of the open space in a site, as expressed by site coverage and mean outdoor distance variables. This would mean a given level of density may be

achieved by the manipulation of either the horizontal (site coverage) or vertical (building height) density. They also show that the relationship between outdoor climate and urban form is context specific – in London, such relationship depends on site coverage, complexity and mean outdoor distance, whereas in Paris, complexity, mean outdoor distance and mean building volume influence the relationship.

The effect of isolated tall buildings on wind flow (and by association, pollution dispersal) is the focus of Song et al's work. Not only these cause a wide field of 'velocity deficit' but also make it impossible/meaningless to model the ventilation field of future buildings proposed in the vicinity problematic.

What are the implications of these works to the *practice* of climate-sensitive building design in urban contexts? Tools and protocols to facilitate city-based climate services that take into account the two-way interactions between urban form and local climate are emerging. One of the more promising recent approaches is the Urban Multi-scale Environmental Predictor (UMEP, Lindberg et al., 2018). The papers collected together in this special issue provide further local-scale (and a more nuanced) evidence of these interactions that could enhance the development and applicability of such tools.

Chatzipoulka and Nikolopolou advocate varied building heights, tall buildings freeing up more open space or 'simpler' form in tighter plan densities. This may form the basis of a practical compromise between density and local climate/energy consumption/comfort effects.

Short et al. provide low-energy, low-carbon retrofit options for tall buildings based on understanding and harnessing the microclimatic context of specific buildings. In the Hot Summer and Cold Winter (HSCW) zone in China they show that south-facing flats overheat significantly in summer largely due to solar radiation but external sun-shading structures could counter summer overheating. A 'modern' wind catcher and exhaust-stack natural ventilation system could enhance indoor thermal comfort using natural ventilation. Even in sections of tall buildings that are in shade such an approach might improve indoor thermal comfort. Cost neutrality of such options is also explored.

Leo et al.'s study is particularly relevant to high density cities that have an air pollution problem. Their work shows that the horizontal transport of pollutants within a city and among adjacent neighbourhoods mainly depends on the frontal area density, a morphometric variable that has received very little interests from planning practitioners. Those high density cities advocating air corridors may wish to consider the computation of frontal area densities at *intra-urban* scales to identify potential locations for such corridors as well as to avoid stagnant conditions.

What of the methodological complexities? Two papers in this special issue point to useful further directions. Leo et al. highlight the usefulness of morphometric parameters based on scale-adaptive methods and point to the determination of boundary conditions for modelling studies. Song et al. provide a way out of the current highly resource-intensive modelling approaches to urban ventilation studies that might point to key steps towards the use of a reduced order model for operational purposes.

The common theme in this special issue is the unintended consequences of decision-making at different scales of the built environment in urban areas. In particular, the interactions between

urban form and shading and ventilation highlight the need for decision making at different scales to be more integrated. There are significant implications here for planning but one of the more urgent needs is to be mindful of the interactions and feedback loops between these three attributes.

The papers thus demonstrate the need for a neighbourhood-scale assessment of climate. Comfort and building energy sustainability. The current fabric-first approach that treats the building as an isolated entity needs to be re-evaluated to include the interaction between buildings. Such an evaluation is amenable to planning control but this would call for a different approach to planning, one that systematically considers the interplay between sun and wind on building energy intensity especially in high density settings. The knowledge base is only beginning to evolve at present and appropriate guidelines for different climates and different density settings are urgently needed. It is only then that urban planning could be successfully deployed to create energy-efficient and thermally comfortable streets and buildings for a more holistic sustainability in high density cities.

## References

- Anderies, J M. 2014. Embedding built environments in social-ecological systems: resilience-based design principles. *Building Research & Information*, 42(2), 130-142
- Anderson W. 1996. Urban form, energy and the environment: A review of issues, evidence and policy. *Urban Studies*, 33, pp. 7–36
- Baker NV, Steemers KA. 1994. *LT Method version 2.0*. Cambridge, UK: Cambridge Architectural Research Ltd
- Breheny M, (ed.). 1992. *Sustainable Development and Urban Form*. London: Pion
- Emmanuel R. 1993. A hypothetical 'shadow umbrella' for thermal comfort enhancement in the Equatorial Tropical urban outdoors, *Architectural Science Review*, 36, pp. 173-184
- Frey H. 1999. *Designing the City: Towards a More Sustainable Urban Form*. London: E & FN Spon
- Futcher J, Kershaw T, Mills G. 2013. Urban form and function as building performance parameters, *Building and Environment*, 62, pp. 112-123
- Givoni B, 1998. *Climate Considerations in Building and Urban Design*, New York: Wiley
- Hassler, U. and Kohler, N. 2014. Resilience in the built environment, *Building Research & Information*, 42(2), 119-129
- Jabareen Y. 2006. Sustainable urban forms: Their typologies, models, and concepts. *Journal of Planning Education and Research*, 26, pp. 38-52
- Kántor N, Chen L, Gál CV, 2018. Human-biometeorological significance of shading in urban public spaces—Summertime measurements in Pécs, Hungary, *Landscape and Urban Planning*, 170, pp. 241-255
- Knowles RL, 1981. *Sun Rhythm Form*, MIT Press, Cambridge, MA, 1981
- Lan Y, Zhan Q. 2017. How do urban buildings impact summer air temperature? The effects of building configurations in space and time, *Building and Environment*, 125, pp 88-98
- Levermore L, Vandaele S, Parkinson J. 2018. Temperature adjustments for design data for urban air conditioning design, *Building Services Engineering Research and Technology*, 39(2), pp.211-218
- Li C, Song Y, Kaza N. 2018. Urban form and household electricity consumption: A multilevel study, *Energy and Buildings*, 158, pp 181-193

- Lindberg F, Grimmond CSB, Gabey A, Huang B, Kent CW, Sun T, Theeuwes NE, Järvi L, Ward HC, Capel-Timms I, hang Y, Jonsson P, Krave N, Liu D, Meyer D, Olofson KFG, Tan J, Wästberg D, Xue L, Zhang Z. 2018. Urban Multi-scale Environmental Predictor (UMEP): An integrated tool for city-based climate services, *Environmental Modelling & Software*, 99, pp. 70-87
- Liu X, Sweeney J, 2012. Modelling the impact of urban form on household energy demand and related CO2 emissions in the Greater Dublin Region, *Energy Policy*, 46, pp 359-369
- Martilli A. 2014. An idealized study of city structure, urban climate, energy consumption, and air quality, *Urban Climate*, 10, pp 430-446
- Martins TAL, Adolphe L, Bastos LEG, 2014. From solar constraints to urban design opportunities: Optimization of built form typologies in a Brazilian tropical city, *Energy and Buildings*, 76, pp. 43-56
- Olgay V. 1963. *Design With Climate: Bioclimatic Approach to Architectural Regionalism*, Princeton University Press
- Pickett, S, McGrath, B, Cadenasso, M L, Felson, A J. 2014. Ecological resilience and resilient cities. *Building Research & Information*. 42(2), 143-157.
- Ratti C, Raydan D, Steemers K. 2003. Building form and environmental performance: archetypes, analysis and an arid climate, *Energy and Buildings*, 35, pp. 49–59
- Ratti C, Baker N, Steemers K. 2005. Energy consumption and urban texture, *Energy and Buildings*, 37, pp 762–776
- Rodríguez MC, Dupont-Courtade L, Oueslati W. 2016. Air pollution and urban structure linkages: Evidence from European cities, *Renewable and Sustainable Energy Reviews*, 53, pp 1-9
- Rodríguez-Álvarez J, 2016. Urban Energy Index for Buildings (UEIB): A new method to evaluate the effect of urban form on buildings' energy demand, *Landscape and Urban Planning*, 148, pp 170-187
- Schwarz N, 2010. Urban form revisited – Selecting indicators for characterising European cities, *Landscape and Urban Planning*, 96, pp 29–47
- Steadman P, Hamilton I, Evans S. 2014. Energy and urban built form: an empirical and statistical approach, *Building Research & Information*, 42 (1), pp. 17-31
- Steemers K, Raydan D, Ratti C, Robinson CD, 2000. *PRECis: Assessing the Potential for Renewable Energy in Cities*. Final Report, Cambridge
- Stone Jr. B, Rodgers MO. 2001. Urban Form and Thermal Efficiency: How the Design of Cities Influences the Urban Heat Island Effect, *Journal of the American Planning Association*, 67, pp. 186-198
- Yannas S. 1994. *Solar Energy and Housing Design: Principles, Objectives, Guidelines* (Vol. 1) AA Publishing
- Yin Y, Mizokami S, Maruyama T, 2013. An analysis of the influence of urban form on energy consumption by individual consumption behaviours from a microeconomic viewpoint, *Energy Policy*, 61, pp 909-919
- Ward HC, Grimmond CSB, 2017. Assessing the impact of changes in surface cover, human behaviour and climate on energy partitioning across Greater London, *Landscape and Urban Planning*, 165, pp. 142-161
- Ward K, Lauf S, Kleinschmit B, Endlicher W. 2016. Heat waves and urban heat islands in Europe: A review of relevant drivers, *Science of The Total Environment*, 569–570, pp. 527-539

Williams K, Burton E, Jenks M. 2000. *Achieving Sustainable Urban Form*. London: E & FN Spon