Urban building energy modelling and urban design for sustainable neighbourhood development-A China perspective

Feng Yang and Zhidian Jiang
College of Architecture and Urban Planning, Tongji University, 1239, Siping Road, Shanghai, 200092, China

yangfeng@tongji.edu.cn

Abstract. Urban design at the neighbourhood scale has profound effects on urban microclimate, and thus on urban buildings energy consumption (in particular heating, cooling and lighting), extent of applicability of passive heating/cooling strategies, indoor/outdoor thermal comfort and street vehicle emissions dispersal (air quality). Previous studies, especially recent explorations in the emerging field of urban building energy modelling (UBEM), suggest clear neighbourhood-scale energy impact from building type, density, layout/orientation and facade/fenestration treatment. The purpose of research is to inform design, but how the research findings in urban building energy inform urban design practice is not straight-forward, in that real-world urban development involves all stakeholders and needs to take environmental, social and economical factors into account, in addition to energy and urban climate. If to support more healthy, comfortable and energy-efficient urban district/ neighbourhood is one goal of green neighbourhood development (ND) rating tools, we should investigate possibilities to further and more efficiently integrate findings of UBEM into guidelines and credits system that inform climate-responsive urban design. This paper, based on a review on recent advancement in UBEM, investigates a more comprehensive and systematic prescriptive approach in ND to optimizing urban building energy performance by moderating urban form, fabric and land cover. Although UBEM as a scientific tool is diagnostic in evaluating urban design scenarios on a case basis, prescriptive design guidelines based on good science are suitable and useful for architects in integrating urban building energy issues in practice.

1. Introduction
Energy consumption in the building sector of China currently accounts for ~25% of the overall national energy consumption (not included is the energy used for construction material, which is included in the industrial sector). However, due to continuous urbanization and improvement on living standards, this component is increasing rapidly, closing the gap between China and developed countries.

While energy conservation for individual buildings has been (relatively) well studied and codes and standards for low-energy design has been issued and implemented in China, urban building energy conservation has been receiving increasing research interests. Because it has been increasingly aware that urban form of contemporary large cities, through affecting sun and wind, has clear effects on urban building operational energy usage. Although the effect on a single building may be small, the aggregation of effects at district/urban scale can be significant. For low-energy urban design and urban energy management, it is important to develop useful tools for modelling urban building energy.
Aimed at urban building energy efficiency and passive and climate-responsive urban design, this paper tries to examine the technical advancement in urban building energy modeling (UBEM) and the potentials it has in supporting more effective application of sustainable neighborhood development (ND) rating tools.

2. Urban building energy modelling

Urban design works on tens to thousands buildings. Accordingly, the energy modelling on the scale, i.e., urban district, neighborhood down to street block level, is considered urban building energy modelling (UBEM) [1].

Generally, UBEM can be divided into physics-based modeling and data-driven modeling (black or grey box) modeling. Below is a brief review on some of the published tools developed either specifically or with a clear and strong focus on UBEM.

2.1. A brief review of UBEM tools

2.1.1. Light and thermal (LT) method [2]: Developed by Nick Baker et al. Cambridge, LT method is innovative in association of building form/fabric (passive zone, orientation, w/w/ratio, obstruction angle etc.) with heating/cooling/lighting energy demand firstly through a set of correlations (visualized as a set of energy curves) and was later embedded in DEM-based image processing extension of GIS platform to estimate urban energy demand [3]. LT uses stationary modelling based on a set of assumptions. It may not work very well for warm/hot climates under which cooling is important building energy demand.

2.1.2. CitySIM [4]: developed by Robinson from his previous integrated urban sustainability early-stage assessment model SUNtool [5], and focuses on urban building energy.

2.1.3. Urban modelling interface (UMI)[6]: developed by Reinhart et al., at MIT, UMI is a Rhino plug-in to connect the CAD software with EnergyPlus simulation engine. It models operational energy, transportation (walkability/bikability) and daylight availability at the neighborhood scale. Essentially a multi-zone dynamic model, it quantifies solar/daylight effect of urban building adjacency based on a series of technical innovations such as a “shoe boxer” algorithm[7] an “AutoZoner” algorithm [8], to extrapolate for the energy use intensity (EUI) of all buildings in a district/neighborhood.

2.1.4. Building block energy estimation (BBEE) [9]: developed by Yanda et al. from Tsinghua University, BBEE is inspired by the idea of Shoeboxer, and has two components-a BBEE algorithm and an energy database. Suitable for heating-dominated climate, the application would have considerable error when modelling under warm/hot climate, e.g., 27% biases can occur for Guangzhou.

2.1.5. EEP model [10]: The EEP and the followed two tools are all based on GIS platform and aimed as city-scale energy auditing tools. EEP aims for the whole city and uses GIS for compiling and organizing surveyed urban data and estimating building stock energy usage by stationary model SAP. GIS platform greatly facilitate the workflows of urban and building attributes information needed to carry out segmentation and characterization (archetyping) [11].

2.1.6. City energy analyst (CEA) [12], built as an extension of a GIS platform. It allows analysing the energy, carbon and financial benefits of urban design scenarios.

2.1.7. City building energy saver (CityBES) [13] is also GIS-based, and aims to support urban energy management.

2.1.8. Urban energy index for buildings (UEIB) [14]: The UEIB uses a unique form-based methodology, to abstract urban form while retaining its essential characteristics of energy demand.
According to the author it provide an innovative approach in addition to the extrapolation of thermal-physics modelling and statistical inference. It reduces actual urban districts into a representative notional grid by key morphological parameters e.g. building density, compactness index and floor area ratio, and calculates energy use intensity of the grid model.

There are many other UBEM tools not listed above, that adopt similar analytical structure and have been validated by various approaches. In addition, the urban effect indirectly associated with form factor but more with general urbanization such as UHI effect has counter-impact on heating and cooling energy. UWG is a set of algorithms intended to estimate UHI [15], it uses the EPW format weather file as input and output. It has been used by other research on context-dependency of urban buildings for instance the UHI and mutual-shading effects on high-rise commercial building in compact urban context in hot-humid climate of Brazil [16].

3. UBEM tools for low energy neighbourhood design

3.1. UBEM to inform low energy urban design?

Urban management on energy and carbon emission reduction seems to be one of the major field of application for UBEM tools. This is understandable for developed countries/regions where urbanization progression has mainly on renovation and redevelopment. But in developing countries e.g., China, new urban districts or even an entire new city are being constructed to accommodate the increasing urbanized population. Towards the common goal for emission reduction towards the 2030 mission, can UEBM tools support low carbon urban design for new build? Architects in large cities of China e.g. Shanghai always work overload at fast pace, for them an added step of (iterative) urban energy simulation to feedback design improvement seems rather difficult to accept. So is it possible to develop for them the prescriptive provisions in the form of diagrammatic design guide, regarding urban building density, layout, orientation, spacing and aspect ratio, window/wall ratio, etc.?

3.2. Towards mixed-use walkable living circles

Mixed-use neighborhood as an urban functional unit is considered a sustainable and pedestrian-friendly typology, and the mixed functionality and flexible block layout require deeper understanding on function/form and energy demand.

Urban housing developments in Chinese cities used to be barrack-like apartment slabs with main façade orientated towards South, with building spacing regulated by winter irradiation requirement. It is a common belief particularly among Southern Chinese citizens that this is the best layout for indoor/outdoor comfort and building energy saving. This overly-simplified layout pattern, despite its merits in utilizing passive solar and cross-ventilation, tends to cause many problems such as dull and faceless street, gated communities, and highly homogeneous urban space landscape.

This belief is in fact not well-grounded in a holistic perspective of sustainable neighborhood development, and our design research indicates that a more thoughtful urban design may improve the urban landscape, street walkability, indoor/outdoor microclimate as well as building energy demand. In the QianJiang NewTown (Hangzhou, ~160km away from Shanghai) planning scheme, an urban structure with smaller street block and denser street grids is developed (Fig.1. Research design team: Sun, Xu, Yang, et al.). Numerical simulation on the environmental performances of three urban form indicates that the new urban grid 1 and 2, which are smaller and denser while more diverse in orientation/height variation, show improved spatial microclimate and thermal comfort: percentages of strong and very strong thermal stress area (quantified by the universal thermal climate index UTCI) in the grid 1 and 2 are lower than that of grid 3, i.e. traditional urban form. The building energy demand simulation indicates a descending order of EUI (kwh/m².yr) of grid 3 (89), grid 1 (87) and grid 2(83). The improvement may be due to the mutual shading effect by adjacent buildings in the (semi-) enclosed layout. Note that the advantages in energy and comfort of grid 2 and grid 1 over grid 3 are marginal. Nevertheless, the results support that the enclosed and semi-enclosed neighborhood patterns
are no inferior to the linear layout with respect to building energy demand and outdoor thermal comfort.

Figure 1: The Qianjiang NT urban design (a) and comparative analysis on microclimate and EUI (b)
Today new policy and design code in China are being issued to promote development based on unit of neighborhood (the so-called “5-10-15 min walk living circle” is in fact residential neighborhoods at different scales). Neighborhood embraces street life, walkable/bikable streets with commercial/retail street shops, and flexible building layout creates more diverse microclimate. The new Planning standard for urban residential area [17] allows higher density (footprint), lower green space whereas imposes stricter building height limit. The impact of urban form on UBE can be higher, and UBEM can be more meaningful and important in future low-carbon urban design.

4. UBEM and its integration with ND rating tools
The neighborhood development (ND) rating tools publicized in a number of countries/regions invariably include microclimate& energy-related credits, these include BREEAM Communities, LEED-ND; Bioclimatic Design Section in HKBEAM; CASBEE-UD and CASBEE-HI, etc. Some provisions are performance-targeted (i.e., what results to be achieved, 1°C or 2°C?), some are prescriptive (i.e., what design should do to achieve that 2°C reduction?). As for China, the Green Eco-District Evaluation Standard (GB/T51255-2017) includes credits regarding district-scale energy efficiency, such as solar orientation, wind corridor, greenery ratio and quality, heat island reduction, renewable energy and certified green buildings.

The two neighborhood development (ND) rating tools from the US and China, i.e., the LEED ND (V4, 2018) [18] and China Evaluation Standard of Green and Eco Urban District (GB/T-51255-2017) [19], or China green building label system, are compared as below regarding the provisions of code compliances that are associated with urban building energy:

4.1. Building orientation (for passive and active solar):

- LEED US: Two options. Opt 1-block orientation; Opt 2-building orientation. 75% of building main façade towards within plus/minus15° off due south, awarded 1 pt (Green infrastructure and building GIB, LEED-ND V4, 2018).
- GBL China: Building orientation that benefits UBE saving: 80%, 85%, 90% of all the ND residential buildings orient the main façade towards the direction that is deemed benefit building thermal energy saving under the local climate. (The beneficial direction is unclear, in terms of passive/active solar, or natural ventilation? Probably South?), awarded 6,8,10 pts. (4.2.8, GB 51255-2017).

4.2. Site ventilation:

- LEED US: No provisions for site ventilation is identified.
- GBL China: Provision of wind corridor wider than 50m in accordance with prevailing (which season?) wind direction, awarded 10 pts (4.2.9, GB 51255-2017).

4.3. UHI mitigation:

- LEED US: Three options. Opt 1 - nonroof, 50% shaded or high solar reflectance (SRI, three-year aged value at least 0.28) or open grid pavement (at least 50% unbound); Opt 2 – Roof, 75% of high SRI roof material, or vegetated (green) roof, or combination; Opt 3 – Mixed roof and nonroof). GIB credit, 1 pt (LEED-ND V4).
- GBL China: UHI intensity lower than 3°C, 2.5°C, awarded 3 or 5 pts. (Detailed specification is not provided, e.g., summer or winter, day or night, instrumented experiment or numerical simulation?) (5.2.10, GB 51255-2017).

4.4. Percentages of certified green buildings:

- LEED US: Percentage of certified GB areas meets 10%-20%, 20%-30%, 30%-40%, 40%-50%, >50%, awarded 1-5 pts (LEED-ND V4).
Towards SBE: from Policy to Practice

IOP Conf. Series: Earth and Environmental Science 329 (2019) 012016
doi:10.1088/1755-1315/329/1/012016

• GBL China: percentage of GB certified New builds with 2-start Label or higher, 35%-40%, >40%, awarded 10, 15 pts. Percentage of certified GB renovation areas 10-20%, >20%, awarded 5, 10 pts (6.6.1, 6.2.2. GB 51255-2017)

4.5. Renewable energy:
• LEED US: Percentages of RE-5%, 12.5%, 20%, awarded 1, 2, 3 pts (LEED-ND V4).
• GBL China: Percentages of RE-2.5%, 5%, 7.5%, awarded 5, 8, 10 pts (7.2.2, GB 51255-2017).

4.6. Building energy saving:
• LEED US: 90% building floor area meets Opt1- Energy performance simulation. Percentage improvement new builds of 12% (1 pt) or 20% (2 pts) over ANSI/ASHRAE/IESNA Standard 90.1–2010; Opt2-prescriptive compliance ASHRAE 50% Advanced Energy Design Guide (2 pts) (LEED-ND V4).
• GBL China: Percentage of new builds with design energy use intensity (EUI) 10% or lower than national standard (GB/T 51161) - 25%, 50%, 75%, awarded 5,7,10 pts (A detailed simulation setting-up is lacking as compared to LEED) (7.2.4, GB 51255-2017).

5. Challenges and suggestions for code compliance with some ND rating tools

5.1. Prescriptive vs. performative
In terms of time-saving and design support, prescriptive provisions seems better than performance indices provisions. Also, the performance indices compliance without detailed regulation on simulation setting-up (e.g., software and model chosen, boundary and initial conditions, workflow and protocol, etc.), for instance, the UHI mitigation provision in GB51255-2017, would allow large room of manipulation on simulation results.

5.2. Need for benchmarking
For case-based performance assessment, there is lack of a benchmarking procedure for ND rating tools, i.e. a proper base-case with which a proposed urban neighborhood scenario (new design or renovation) under energy modeling can be compared with. The urban base-case model is analogous to the base-case model for energy efficiency simulation of individual building rating, e.g., Energy credits in LEED for BD+C as per required by Appendix G, ASHRAE 90.1.

6. Potentials of UBEM tools in support ND rating

6.1. Support prescriptive code-compliance provisions
As discussed before, prescriptive urban design guides would better suit the needs and workflow of architects. At its present state, some prescriptive provisions of ND tools are qualitative instead of quantitative, e.g., the air ventilation assessment (AVA) in Chapter 11 of the Hong Kong Planning and Design Guidelines. Some are quantitative, but how the threshold values are determined is unclear: is it scientifically tested, or just based on limited expert judgement? For that, well-developed and validated UBEM tools can be applied in a systemic way in supporting better-grounded prescriptive provisions.

6.2. Support base-case urban building energy model
While urban physicists and building scientists focus on technical improvement of their UBEM tools, architects and planners are (or should be) interested in possible implication of these tools in their practice. One such possibility would be to help build the base-case urban building energy models, depending on geography, climate, and typology (e.g., commercial, residential, or mixed). In new town building, key urban parameters are predetermined before urban design such as volumetric density FAR, footprint density BCR, green space ratio, land use and building functions, etc. A base-case urban
model will comply with all the parameter setting, probably in an idealized grid setting to minimize manipulation on space and form (which is what architects are for). Design scenarios can be modelled by UBEM and the energy performance compared with the base-case.

A base-case urban model may help benchmarking the energy assessment workflow in ND rating and clearing out ambiguities and uncertainties. One interesting case is the UEIB that is introduced previously, which manages to “average” complex urban morphology into standardized “grid” with predefined key morphological parameters. The model, when used in assessing real urban areas, may risk averaging out the problematic spots where bad urban form/fabric adversely affect nearby building energy demand. UEIB however demonstrates the association of real-world urban areas, especially regarding the mean energy use intensity (EUI) and carbon emission rate, with a carefully-defined ideal urban grid model by a given set of planning indices. For the model itself, further validation using authoritative, thermo-dynamic energy modelling tools may be needed, as the UEIB results were compared with simulation results by Climatelite[14], a tool developed by BRE in 2013 and seems not accessible for the time being.

Acknowledgments
Authors acknowledge financial support from the National Natural Science Foundation of China (NSFC) Project (No.: 51678413), the Fundamental Research Funds for the Central Universities and the National Key R&D Program of China (No.: 2016YFC0700200).

References
[1] Reinhart CF, Cerezo Davila C. Urban building energy modeling – A review of a nascent field. Building and Environment 2016; 97: 196-202.
[2] Baker N, Guedes MC, Shaikh N, Calixto L, Aguiar R. The LT-Portugal software: A design tool for architects. Renewable Energy 2013; 49: 156-160.
[3] Ratti C, Baker N, Steemers K. Energy consumption and urban texture. Energy and Buildings 2005; 37: 762-776.
[4] Robinson D. Computer Modelling for Sustainable Urban Design: Physical Principles, Methods and Applications. Earthscan, 2012.
[5] Robinson D, N. Campbell, W. Gaiser, K. Kabel, A. Le-Mouel, N. Morel, et al. SUNtool – A new modelling paradigm for simulating and optimising urban sustainability. Solar Energy 2007; 81 (9): 1196-1211.
[6] Reinhart CF, Timur Dogan, J Alstan Jakubiec, Rakha T, Sang A. Umi-an urban simulation environment for building energy use, daylighting and walkability. 13th Conference of International Building Performance Simulation Association. Chambéry, France, 2013.
[7] Dogan T, Reinhart C. Shoeboxer: An algorithm for abstracted rapid multi-zone urban building energy model generation and simulation. Energy and Buildings 2017; 140: 140-153.
[8] Dogan T, Reinhart C, Michalatos P. Autozoner: an algorithm for automatic thermal zoning of buildings with unknown interior space definitions. Journal of Building Performance Simulation 2016; 9 (2): 176-189.
[9] Zhu P, Yan D, Sun H, An J, Huang Y. Building Blocks Energy Estimation (BBEE): A method for building energy estimation on district level. Energy and Buildings 2019; 185: 137-147.
[10] Jones P, Patterson J, Lannon S. Modelling the built environment at an urban scale—Energy and health impacts in relation to housing. Landscape and Urban Planning 2007; 83 (1): 39-49.
[11] Caputo P, Costa G, Ferrari S. A supporting method for defining energy strategies in the building sector at urban scale. Energy Policy 2013; 55: 261-270.
[12] Fonseca JA, Nguyen T-A, Schlueter A, Marechal F. City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. Energy and Buildings 2016; 112: 234-253.
[13] Chen Y, Hong T. Impacts of building geometry modeling methods on the simulation results of urban building energy models. *Applied Energy* 2018; **215**: 717-735.

[14] Rodríguez-Álvarez J. Urban Energy Index for Buildings (UEIB) : A new method to evaluate the effect of urban form on buildings’ energy demand. *Landscape and Urban Planning* 2016; **148**: 170-187.

[15] Bueno B, Roth M, Norford L, Li R. Computationally efficient prediction of canopy level urban air temperature at the neighbourhood scale. *Urban Climate* 2014; **9**: 35-53.

[16] Lima I, Scalco V, Lamberts R. Estimating the impact of urban densification on high-rise office building cooling loads in a hot and humid climate. *Energy and Buildings* 2019; **182**: 30-44.

[17] MOHURD (Ministry of Housing and Urban-Rural Development). *GB50180-2018-Standard for urban residential area planning and design GB50180-2018*. 2018.

[18] USGBC. *LEED v4 for Neighborhood development*. U.S. Green Building Council, 2018.

[19] MOHURD (Ministry of Housing and Urban-Rural Development). *GB/T-51255-2017 Evaluation Standard of Green and Eco Urban District*. 2017.