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Building neighborhood emerging properties and their impacts on multi-scale modeling of building energy and airflows

Jelena Srebric [a, *], Mohammad Heidarinejad [a], Jiying Liu [b]

[a] Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA
[b] School of Thermal Engineering, Shandong Jianzhu University, Jinan 250101, China

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ABSTRACT

This paper provides a critical review on the building neighborhood properties influencing the energy and airflows in urban neighborhoods. Specifically, the review focus is on the multi-scale modeling required to quantify this influence of the building neighborhood properties on the energy consumption in buildings. The energy consumption patterns of buildings located in dense city centers are highly dependent on the surrounding urban neighborhood, compared to the low density, suburban/rural regions, where the building energy consumption patterns are similar to an isolated building energy consumption patterns. Due to the complex nature of the outdoor airflow around the buildings in urban neighborhoods, a practical modeling approach utilizes multi-scale modeling to account for different spatial and temporal scales for the relevant transport processes. Specifically, this modeling approach aims to identify the most important neighborhood properties influencing building energy consumption. The urban morphology parameters, such as the urban plan area density, frontal area density, and mean height of the buildings represent successful examples of emerging properties suitable for development of generalized solutions and physical models at the neighborhood scale. This paper also reviews different modeling approaches that account for the impacts of the urban neighborhood properties on the thermo-fluid property of the air, surfaces, and sky in the built environment as the required inputs for accurate assessment of building energy consumption. Furthermore, these emerging properties of urban neighborhoods directly affect (1) the mitigation strategies for a better adaptation, (2) design performance metrics of neighborhoods for the green building rating systems, and (3) socio-environmental factors.

1. University campuses as urban neighborhoods

The aim of this paper is to conduct a critical literature review on the influence of the building neighborhood properties on the energy and airflows in buildings, focusing on the multi-scale modeling required to quantify this influence. This critical literature review summarizes the commonly used methodologies to model energy and airflows at the urban neighborhood scale and define research visions to develop more generalized solutions and physical models rather than relying on the case study approach. The selection of the urban neighborhood as a study focus in this paper is due to the rapid migration of people from rural to urban areas and the fact that urban neighborhoods represent building blocks of cities.

Migration of people from rural to urban areas known as urbanization has accelerated since the era of industrialization [1]. While at the beginning of the 20th century, 13 percent of the world's population lived in urban areas, today, over 50 percent of the population resides in urban areas [2,3]. This trend is expected to continue at least through 2030 [4], including an unprecedented increase in the size of cities that has resulted in megacities with populations of more than 10 million people [3]. The rapid urbanization of the world is causing changes to the global energy use patterns and building-related Greenhouse Gas (GHG) emissions [5], leading to an increased dependency on fossil fuels. In fact, the building sector is the largest contributor to the primary energy consumption in most countries, including the U.S., when compared to the industry and transportation sectors [6]. It is estimated that urbanization and changes in the land coverage account for an increase in mean air temperature of 0.27 °C in the continental United States during the past century [7]. Therefore, one of the primary areas of research for the federal agencies is to restore urban

* Corresponding author. Tel.: +1 (301) 405 7276; fax: +1 (301) 314 9477.
E-mail address: jsrebric@umd.edu (J. Srebric).

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communities with sustainable neighborhoods, requiring theoretical and applied research to address this grand challenge in engineering [8,9].

The design of sustainable neighborhoods and restoring communities require a full scale modeling of urban neighborhoods that is not consistently replicable with the current computational approaches [10]. The urban modeling of the neighborhoods requires solving numerically universal systems of equations for suitable temporal and spatial scales. The simulation of the airflow field requires solving mass and momentum equations, while scalars such as the temperature and concentration of contaminants could be solved coupled or uncoupled to derive the temperature and concentration fields. At present, using supercomputers only allows direct numerical solutions of a simple indoor airflow in a single room where the Reynolds number is about 10^5 with a grid resolution of 10^{12} [11]. For the outdoor simulations where the airflow Reynolds number is in the order of 10^7, the grid resolution for a simple outdoor simulation would be 10^{16}, suggesting that the direct numerical solution of outdoor airflow is not feasible. Even relying on less intense airflow modeling approaches, such as Large Eddy Simulations (LES), for a city scale seems impractical with the current computational power and data storage capacity. At present, outdoor airflow simulations assume steady state simulation with simplified building geometries and models to tackle the complexity of simulations, especially close to the solid surfaces of the buildings/ground. These restrictions do not include considerations for coupling the energy, airflow, radiative, and evapotranspiration models in the built environment. The coupling requires careful consideration of the spatial and temporal time steps for the two directional dynamic exchange of the data from different modeling approaches. In the next couple of decades, it is expected that the impacts of urban neighborhoods on the buildings and associated modeling approaches need to be resolved within 1 km [11], suggesting that an integrated modeling simulation of the built environment should start from the neighborhood scale rather than the a city scale.

In addition to the computational and storage limitations for the airflow modeling around buildings and their implications of the energy use patterns of buildings in urban neighborhoods, there are inherent restrictions with the availability of reliable and public building energy data for the validation of the simulated building energy consumption in a large scale for a cluster of buildings [12]. In the U.S., recent city building benchmarking data and data from the Commercial Building Energy Consumption Survey (CBECS) are two major, public, and large-scale building energy consumption data sources [13]. However, there are intrinsic restrictions, such as granularity of building energy data, lack on detailed information about the building internal and external characteristics, and reliability of the collected building energy data [14,15]. The lack of a large-scale, reliable, and public building energy data for a cluster of buildings with different urban neighborhood configurations render the coupling and/or co-simulation of the energy and airflows in an urban neighborhood at the city scale not feasible at present. A solution to model the built environment is to consider urban neighborhoods in a smaller scale comprised of different terrain configurations with existing sustainability programs to monitor and store reliable building energy consumption data. University campuses are usually orders of magnitude smaller than the city scale and due to the sustainability programs, they typically have detailed and reliable building energy consumption data [16]. The selection of the urban neighborhood located in the university campuses allows development of new physical models to study energy and airflows in the built environment and develop/integrate simulation tools to simulate the energy consumption of the buildings and airflows around the buildings. These efforts will create building blocks for reliable modeling of the energy and airflows at the city scale.

2. Neighborhood morphology, emerging properties, and energy budget

2.1. Neighborhood morphology and emerging properties

A practical approach uses the similarities in different morphological representations of the neighborhoods to develop more general physical models and solutions. Existing studies have shown that cities are comprised of neighborhoods with different morphological representations [17,18], enabling the building science research community to develop quantitative assessments of the energy and airflows based on the first principles for urban neighborhoods. In general, each urban neighborhood has features that render them unique from each other. However, among the unique features, there are similar properties that can be used to model urban neighborhoods. Emerging properties of urban neighborhoods enable the researches to develop generalized assessments of urban neighborhood. As an example, an emerging property of an urban neighborhood relevant to the outdoor airflow modeling is the context area. Specifically, in the simulation domain, the "area (or building) of interest" is known as the "primary area (building)" and the "surrounding area to the primary area (building)" is known as the "context area (buildings)". Fig. 1 illustrates the building of interest and context buildings for a campus neighborhood comprised of different building types. This definition of the primary and context buildings allows the modeler to include an additional focus to the area where the most important energy and airflow exchanges, such as the convective heat transfer, infiltration, and conductive heat transfer, occur. The reminder of the neighborhood outside of the context area represents roughness elements that define the inlet properties in the simulation domain, such as wind, temperature, and turbulence property distributions.

Another useful approach to represent urban neighborhoods is to model urban neighborhoods with indefinitely long canopies or regular arrays of buildings with simplified shapes [19–21]. These modeling simplifications enable researchers to consider new emerging properties of urban neighborhoods, including the urban plan area density (λ_p), frontal area density (λ_f), and mean height of the buildings to successfully classify the urban neighborhood and develop generalized modeling approaches. As an example, roughness height z_o in cities is primarily a function of urban plan area density and frontal area density [22,23]. Specifically, Washington DC is a city comprised of different urban neighborhoods with buildings of similar heights, suggesting that simplifications of the urban morphology could enable accurate modeling of its homogeneous urban neighborhoods. For heterogonous urban neighborhoods, this approach requires further consideration [24]. Fig. 2 illustrates these examples of emerging properties in urban neighborhoods. Fig. 2(a) and (b) depict the urban plan area density and frontal area density that are non-dimensional parameters. The urban plan area density is the area that the buildings in the context area occupy in the horizontal cross section divided by the underlying overall context area of the urban neighborhood in the horizontal cross section [23]. Furthermore, the frontal area density is the area of each building facing the incoming wind in the vertical cross section divided by the underlying overall context area of the urban neighborhood in the horizontal cross section [23]. Fig. 2(c) and (d) provide examples of two different urban plan area densities that represent a dense city center with urban plan area density of 0.44, and a low dense suburban/rural urban neighborhood with urban plan area density of 0.0625.