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

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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

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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.

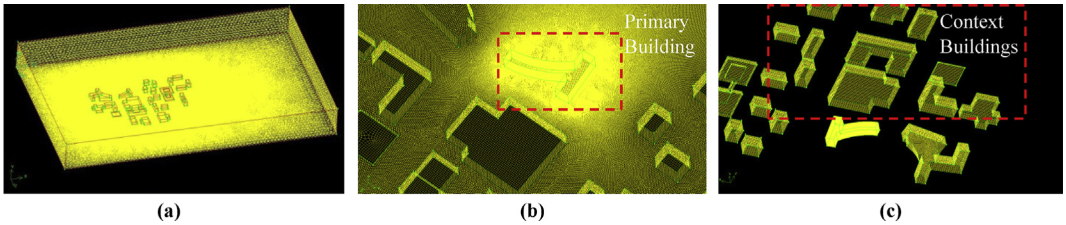

Fig. 1. Representation of a campus urban neighborhood with the focus on the primary building and context buildings for the airflow simulations: (a) The entire domain, (b) Primary building, and (c) Context buildings.

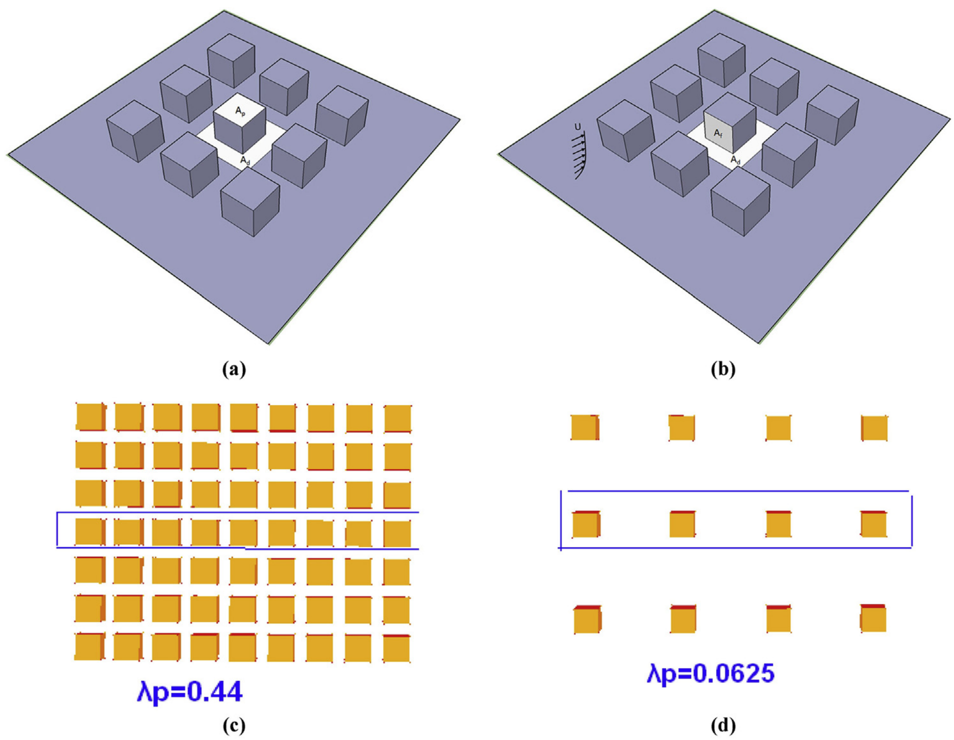

Fig. 2. Representation of (a) The urban plan area density and (b) Frontal area density, (c) An example of urban plan area density of 0.44, (d) An example of urban plan area density of 0.0625.

Existing studies mainly focus on urban neighborhoods with specified a range of urban plan area densities of: 0.11 [25], 0.25 [26], 0.25 and 0.4 [27], 0.16 to 0.37 [28], 0.0625 to 0.44 [29], 0.04 to 0.44 [20], and 0.0625 to 0.69 [30]. For the most densely populated cities, such as the Hong Kong or Manhattan in New York City, it is more practical to use frontal area density to classify the urban neighborhood since the urban frontal area density accounts for the height blockage of the selected area. While typical frontal area densities in urban areas vary from 0.12 to 0.33 [31], the urban areas with high variation of the building heights such as Hong Kong has the common frontal area density value of more than 0.4 [32–35], with up to 1.07 [27,36]. A frontal area density higher than 1 indicates the surrounding buildings mostly block the wind from the building of interest [35]. A combination of the urban plan area and frontal area densities could define an emerging urban morphology that represents the ability of wind to penetrate the urban neighborhood and to flush out contaminants effectively in the urban canopy layer [36,37]. These configurations of the urban morphology are extremely important for pollutant removal especially if the source of the pollutant is inside the urban area for cities with high-rise urban structures. Mean age of air ($\overline{\tau}_p$) and the air exchange efficiency (ε_a) are defined similar to the indoor spaces to quantify theses influences [37,38]. The shape of the urban neighborhood (e.g. round, rectangle, and cubic shapes), width and length of the streets, and wind direction are among the variables that have influence on the mean age of the air and the air exchange efficiency [39–42].

The emerging neighborhood property of the urban plan area density enabled development of new urban physical models for the Convective Heat Transfer Coefficients (CHTCs) and Coefficient of Performance (COP) of Heating, Ventilation, and Air-Conditioning (HVAC) cooling systems [17,18,20,28]. Recently, new CHTCs were developed, validated, and demonstrated to account for the influence of urban neighborhoods on the CHTCs [20,43,44]. The new CHTCs expand from the general representation of the CHTCs specified in Equation (1) as a function of the incoming wind velocity at the 10 m elevation (U^c_{10}) [45]. Equation (2) shows the new representation of the CHTCs as a function of urban plan area density where a, b, and c are two coefficients and an exponent, respectively. Table 1 provides the values of correlation coefficients for different λ_p and U_{10}, where λ_p varies from 0.04 to 0.25 and the Reynolds number ranges from 7×10^5 to 5×10^6 [20].

Table 1
Convective heat transfer coefficients (h_c) corrections combined λ_p and U_{10} for arrays of buildings [20].

Surface	h_c for $\lambda_p = 0.04$	h_c for $0.063 \le \lambda_p \le 0.25$
Windward	$4.61U_{10}^{0.80}$	$(4.56 + 1.86\lambda_p)U_{10}^{0.78}$
Leeward	$2.48U_{10}^{0.81}$	$(2.38 + 1.59\lambda_p)U_{10}^{0.79}$
Lateral	$4.15U_{10}^{0.80}$	$(4.52 - 3.96\lambda_p)U_{10}^{0.78}$
Top	$4.44U_{10}^{0.81}$	$(4.41 + 1.42\lambda_p)U_{10}^{0.79}$

$$h_c = aU_{10}^c \tag{1}$$

$$h_c = (a + b\lambda_p)U_{10}^c \tag{2}$$

Another example of a successful use of the emerging neighborhood properties is the use of urban plan area density to account for the variation of the operational COPs for HVAC cooling systems [46,47]. Operational COP ($COP_{operational}$) is defined as a COP that accounts for the influence of the urban neighborhood on the reduction of the rated COP that manufactures usually provide, known as rated COP (COP_{rated}), to the user of the HVAC cooling systems. Since there is limited number of peer reviewed studies that derived the rated COP correlations as a function of outdoor air temperature based on the manufacture data [48–53], there is a need to define an averaged operational COP to weigh the influence of different rated COP correlations that exist in the literature [46,47]. To emphasize on the degradation of the COP of the cooling systems with the increase in the urban plan area density, a non-dimensional averaged COP ($COP_{averaged\ normalized\ operational\ at\ \lambda_p}$) can be defined. This non-dimensional averaged normalized operational COP is defined as the ratio of the operational COP calculated for each urban plan area density ($COP_{averaged\ operational\ COP\ at\ \lambda_p}$) divided by the operational COP at urban plan area density of 0.04 ($COP_{averaged\ operational\ COP\ at\ \lambda_p=0.04}$) where this COP represents an urban plan area density of a rural area. Equation (3) illustrates the definition of the normalized averaged operational COP. Fig. 3 shows the variation of the operational COP for cooling systems installed on the windward and leeward building walls, as well as the roofs with different urban plan area densities. The results show that for the dense urban plan area densities, there could be up to 10% and 6% cooling system COP reduction for the roofs and windward walls, respectively. It is important to note that these findings are derived for specific conditions [46,47]; additional configurations of the urban neighborhoods and weather conditions could provide further insights to the effects of the urban plan area density on the degradation of the operational COP of HVAC cooling systems.

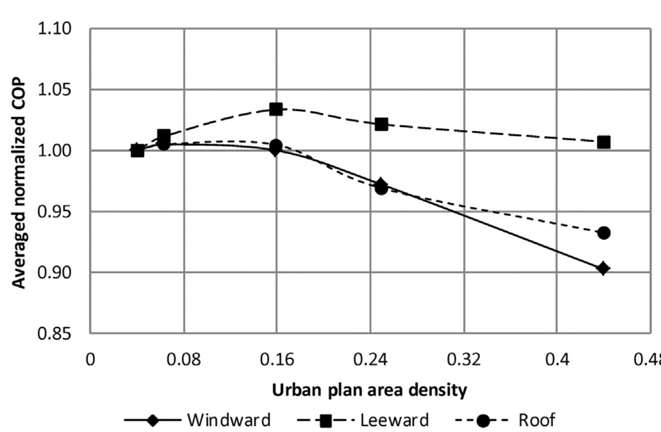

Fig. 3. Variation of the averaged normalized operational COP of the cooling HVAC systems for the windward and leeward walls as well as the roofs [47].

$$COP_{averaged\ normalized\ operational\ at\ \lambda_p} = \frac{COP_{averaged\ operational\ COP\ at\ \lambda_p}}{COP_{averaged\ operational\ COP\ at\ \lambda_p=0.04}} \tag{3}$$

To further quantify the influence of the urban neighborhood and placement of the HVAC systems for the high-rise buildings, a follow up study could include additional inputs, such as heat rejection from the individual units, location of the units, and location of the urban neighborhood, in addition to the assumptions used in the previous reviewed studies [46,47,54]. This follow up study could provide insights for the installation of HVAC systems in dense urban neighborhoods, especially Asian cities such as Hong Kong and Singapore, that tend to install window packaged units at each floor [49,50,53]. This kind of installation allows the heat rejection from the lower floor unit to increase the local re-entrant temperature to the upper level units and effect the performance of the condenser of the HVAC systems in the upper floors [49]. Consideration of the heat rejection for the installation of the packaged units at each floor for the high-rise buildings and the increase in the urban plan area density could result in additional reduction to the operational COP of the HVAC cooling systems [47] beyond the reduction that was quantified in the previous studies [47,54]. Therefore, there is a need for future studies to consider the placement of the HVAC systems at different locations within the buildings (e.g. rooftop units or packaged units) in various urban plan area densities, taking into consideration the locations of the urban neighborhood and the configuration of the urban neighborhood morphology. This could enable a better quantification of the HAVC system cooling COP for the buildings in urban neighborhoods. These results have an implication on the design of HVAC systems, including their size and location. Overall, developed CHTCs and COPs show how the emerging neighborhood properties could be used to develop generalized modeling approaches of the urban neighborhoods, rather than modeling a specific case study.

Campus buildings as the test beds provide opportunities to develop, validate, and demonstrate the urban physical models for

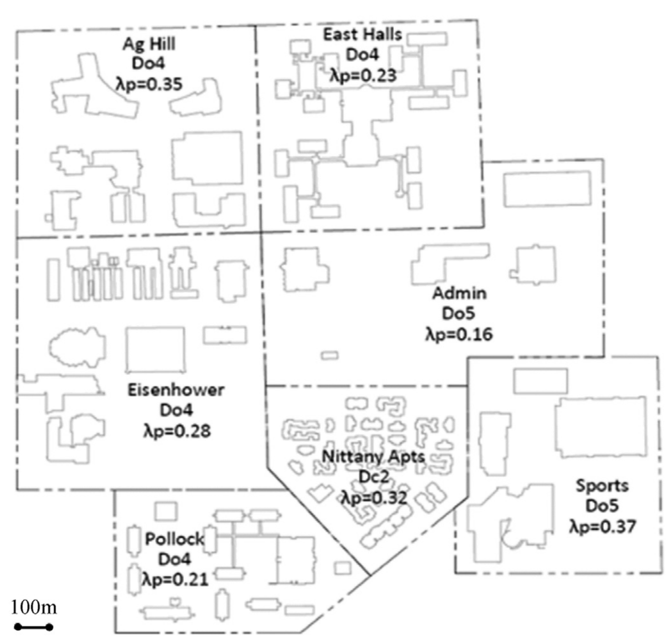

Fig. 4. Urban terrain zones for part of the Penn State's campus (Dc2, Do4, and Do5 represent three shelter types found in this neighborhoods) [28].

different configurations of urban neighborhoods. Fig. 4 illustrates how an urban neighborhood can be comprised of different urban plan area densities [28]. This figure shows that within an urban neighborhood of approximately 1 km × 1 km, there are at least seven different urban plan area densities with different types of buildings. For example, the energy consumption of the buildings using the new CHTCs or the averaged normalized operational COP were assessed for the East Halls neighborhood, illustrated in Fig. 4 [44,46,47,54,55]. Typically, roads can represent natural breaks between buildings of similar scale, purpose, and architecture to determine the scope of the urban neighborhood [56]. The determination of different urban plan area densities for the urban neighborhoods in the campuses enable the research community to consider the area of the interest and surrounding areas (including the sheltering areas) with different urban plan area densities for the energy and airflows modeling. This methodology has implications on the assessment of the energy and airflows in the urban neighborhood.

A more generalized representation of the urban plan area density is to define the Urban Terrain Zone (UTZ) classification, including the ground elevation. The UTZ was originally defined to divide the city into distinctive parts [18], where people in this zone react similarly to economic conditions or problems, with an attempt to identify the varying patterns of urban terrain for the military uses. This classification of UTZs has implications for the characterization of homogeneous units of urban terrain within the city scale environment, specifically aiming to support the urban planners and scientists engaged in planning developments. An update for UTZ types was presented for urban meteorological use, and proposed that a city scale is comprised of seven typical terrain zones, from a city core to fairly isolated terrain zones where buildings are sparsely dispersed [17]. Each of the seven terrain zones can represent suburban terrain zones. This classification has a wide variety of morphological features, including the building type, building density, street patterns, and building surface construction materials. Table 2 provides the definition of the suburban terrain zones at the city scale. Therefore, the UTZ can be used to characterize terrain type combined with the urban plan area density [28]. The UTZ is highly dependent on the selection of the spatial scales. The spatial scales for an urban neighborhood typically include a 1 km–5 km radius, while the spatial scales for a city are much larger.

2.2. Energy budget

An effective energy budget for urban neighborhood requires the consideration of the interactions between different heat and mass transfer mechanisms. Usually, a simplified energy budget, along with the potential flow, is used to calculate the boundary conditions for the temperature, heat flux, and airflow in the models. In general, urban canopy models usually define the energy budget for an urban neighborhood as represented by Equation (4), with consideration of different models to account for the variation of each heat flux component [57–60].

Table 2
Urban terrain zone classifications for a city scale modeling [17].

Type	Urban terrain zone	Typical location within city
I	Attached and closely spaced inner-city buildings	City core
II	Widely spaced high-rise office buildings	City core and edge of built-up city (e.g. near airports)
III	Attached houses	Near city core
IV	Closely spaced industrial/ storage buildings	Along railroads near core and on docks
V	Widely spaced apartment buildings	Edge of city
VI	Detached houses	Near core and in suburbs
VII	Widely spaced industrial/ storage building	At city edge near highways

$$Q^* + Q_A = Q_{Sen} + Q_{Lat} + \Delta Q_S + \Delta Q_{Adv} \quad (4)$$

This equation shows that net radiation (Q^*) and anthropogenic energy release within the urban neighborhood (Q_A) are a function of the sensible heat transfer (Q_{Sen}), latent heat transfer (Q_{Lat}), energy stored in the urban neighborhood (ΔQ_S), and advection heat transfer (ΔQ_{Adv}). The full-scale modeling of the built environment with the energy budget is more complex than Equation (4) since the different components in Equation (4) are coupled, and, therefore, require an iterative modeling approach. For example, the net solar radiation term is a function of the short-wave and long-wave radiations, where the long-wave radiation is highly correlated with the ground, wall, pervious surfaces, and sky temperature differences that require relying on the other equation terms. In addition, the short-wave and long-wave radiation have downward and upward components that needs to be considered. Overall, the models that focus on the neighborhoods or at the larger scale consider simplifications to represent different terms in Equation (4) [58]. One emerging area of interest is to consider the detailed representations of the building shapes and dynamic representation of the buildings energy models instead of considering canyon hypothesis to assume modeling only roofs, walls, and roads.

Assessment of the order of magnitude of each component in Equation (4) depends on the location and morphology of the urban neighborhood. Therefore, it is not possible to provide a general quantification on the significance of each term. The short-wave component of the net solar radiation is a function of the urban neighborhood location, cloud cover, and the degree of air pollution [61]. A combination of the net radiation and land coverage could support a methodology to assess the order of magnitude of the terms. Therefore, existing studies try to limit the influence of the terms to simplify modeling different terms in Equation (4). For example, selection of urban neighborhoods or cities with low vegetation cover (less than 5%) could consider energy flows without modeling the latent heat transfer due to the existence of the vegetation surfaces [59]. This simplification with the location of the city may lead to high radiation and based on the existing of the impervious surfaces, 2/3 of the net radiation energy could go to storage heat flux during day and large sensible heat flux during night. Land coverage is an important factor that influences the biochemical and biogeophysical on a global scale that also affect the distribution of the latent and sensible heat transfers [62]. While the soil heat flux in rural areas take 5% of the all radiation, in the urban areas, this radiation could take up to 40–50 percent [61]. Larger scale studies that are beyond the scope of this paper used Community Land Model Urban (CLMU) or Community Climate System Model (CCSM) models to connect the mesoscale atmospheric models with the surface with the consideration of the land covers [63–67]. Therefore, one of the important factors that could determine distribution of the order of magnitude orders is the land coverage.

Another parameter that could have significant influence on the distribution of each term in Equation (4) is the anthropogenic term. The anthropogenic term has contributions not only from the building sector, associated building heat dissipation, and associated heat rejection form the HVAC systems, but also from the other industry sectors, including transportation and manufacturing [57,61,68]. The models could estimate the anthropogenic term from 10 W/m^2 to 1000 W/m^2 [61]. For example, the anthropogenic heat flux in a university campus neighborhood is a function of the heat dissipations from the buildings. This influences the (Q_A) term, and consequently the total balance of the energy heat transfer processes in Equation (4). Similarly, the sensible, latent, storage, and advection equation terms require a careful consideration to account for the interactions with other physical phenomenon. Overall, there is a need to consider a comprehensive set of models, which include heat and mass transfer, hydrology, and future climate predictions, to resolve the physical phenomena of the energy and airflow transport at the urban scale. The reviewed emerging morphology, such as the urban plan area density, the frontal area density [20], the street aspect ratio [60], building arrangements [69], and orientation of the urban neighborhood and streets [37] are among the influential emerging properties that could affect the distribution of the heat transfer processes in Equation (4) and ultimately quantification of order of magnitude of each term in Equation (4).

3. Modeling methods

One of the challenges in the multi-scale modeling of the built environment is associated with the lack of detailed on-site measured data or simulated results. This section provides an overview of the existing modeling methods and the existing studies to provide the thermo-fluid properties dependent on the urban neighborhood emerging properties.

3.1. Overview of existing functional models

Integrated approaches for the multi-scale modeling of buildings located in urban neighborhoods are limited to individual case studies to analyze energy consumption of buildings and/or airflow around buildings. The full integration of energy, airflows, and transport equations into a comprehensive understanding does not exist yet. Traditionally, detailed models of each system or a simplified set of equations are considered for the co-simulations. Recently, urban modeling simulation platforms and newly developed physical models are developed to integrate energy and airflows for the buildings located in urban neighborhoods [20,57,70–74].

3.2. Limitations and benefits of different modeling methods

Four different methods, including (1) observations, (2) on-site urban-scale measurements, (3) experiments at laboratory scales, and (4) numerical simulations, are used to quantify the impact of urban neighborhoods on local variables [75–79]. There are inherent limitations, such as reliability and cost, as well as benefits, such as detailed distribution of results, associated with different modeling methods. Observations usually rely on short-term measurements, meaning the results of the observations provide limited information about the temporal and spatial distribution of the observed phenomena. On-site measurements could be reliable with the use of accurate sensors; however, the on-site measurements could be costly. Examples of on-site field experiments include measurements of the temperature on the building surfaces, outdoor air temperature around the buildings, infrared (IR) measurements, wind speed around the buildings using anemometers, and portable weather stations [55,79–81]. Fig. 5 provides examples of four different installations of the sensors to enable measurements of on-site variables at the neighborhood scale. The results of the thermography from the IR measurements usually provide a good spatial distribution of the temperature readings over the exterior surfaces [44,55,82]; however, the accuracy of the measurements and the duration of the measurements are two inherent setbacks associated with the results of the thermography [44,55]. Compared to commonly used thermistors, the temperature readings from the thermography are less accurate; in addition, typically IR measurements are conducted through handheld devices that do not allow long-term measurements [55]. Recent advances in the unmanned thermography vehicle do not only enable long-term measurements, but also provide access to the surfaces that are not easily accessible (e.g. roofs) to the user due to the safety codes [83,84]. Therefore, thermography can provide promising opportunities to validate the exterior surface temperature values.

Installation of portable weather stations has recently become very prevalent due to the reduction in their costs. One challenge with the installation of the portable weather stations is associated with accuracy of the sensors and careful installation of the sensors on the portable tripod to ensure accurate readings of the sensors. For example, in airport weather stations usually the reference wind speed and direction readings happen at 10 m from the ground to ensure that the flow is not blocked by the surrounding objects. In addition, the temperature sensors may fall into the thermal boundary layer originating from the building roof, which may lead to the measurement of sensor temperature readings being affected by the heat dissipation from the building roof.

Experiments, including prototype modeling, of the built environment also have limitations and benefits. Wind tunnel measurements of the airflow and temperature distributions around buildings are an example of experiments at the laboratory scale. The results of the wind tunnel measurements are a reliable source of data for the validation of numerical Computational Fluid Dynamics (CFD) results. The limitations associated with the experiments could be cost and the inherent limitations for the small scale modeling, such as thermal similarities between the model and the prototype. Simulations can provide detailed distributions of the simulated variables, which enables the validation of the simulation results with the on-site measured data, and extends the applicability of the simulation results for the situations where there are limitations associated with the other methods. However, the simulations also could have inherent limitations and simplifications associated with simulation models that render the simulation model different from the actual physical phenomena. In general, the choice of the modeling methods depends on the desired outcome of designed experiments.

3.3. Overview of the CFD modeling challenges for neighborhood environments

CFD is extensively used to evaluate the pedestrian thermal comfort and pollutant dispersion in an urban environment [85]. Furthermore, when looking at energy consumption in building neighborhoods, wind and thermal environment parameters are important for investigating the heat transfer adjacent to the building enclosure and airflow. Due to the large domain size of neighborhoods, the requirement of detailed geometries and finer computational grids are fairly difficult, resulting in a large number of simplifications for neighborhood configurations. Current modeling approaches usually consider tradeoffs between the finer grids and computational resources to establish the computational domain size.

Reynolds Averaged Navier Stokes (RANS) models tend to have slightly inferior performance with respect to accuracy, but reasonable computational time compared to the Large Eddy Simulation (LES) performance. LES can provide relatively more accurate results, but with a longer computational time because of finer mesh adjacent to the building surfaces. Another approach to benefit from the accuracy of the LES models and the computational time of the RANS models is to use the Detached Eddy Simulation (DES) or Delayed Detached Eddy Simulations (DDES) [86]. These

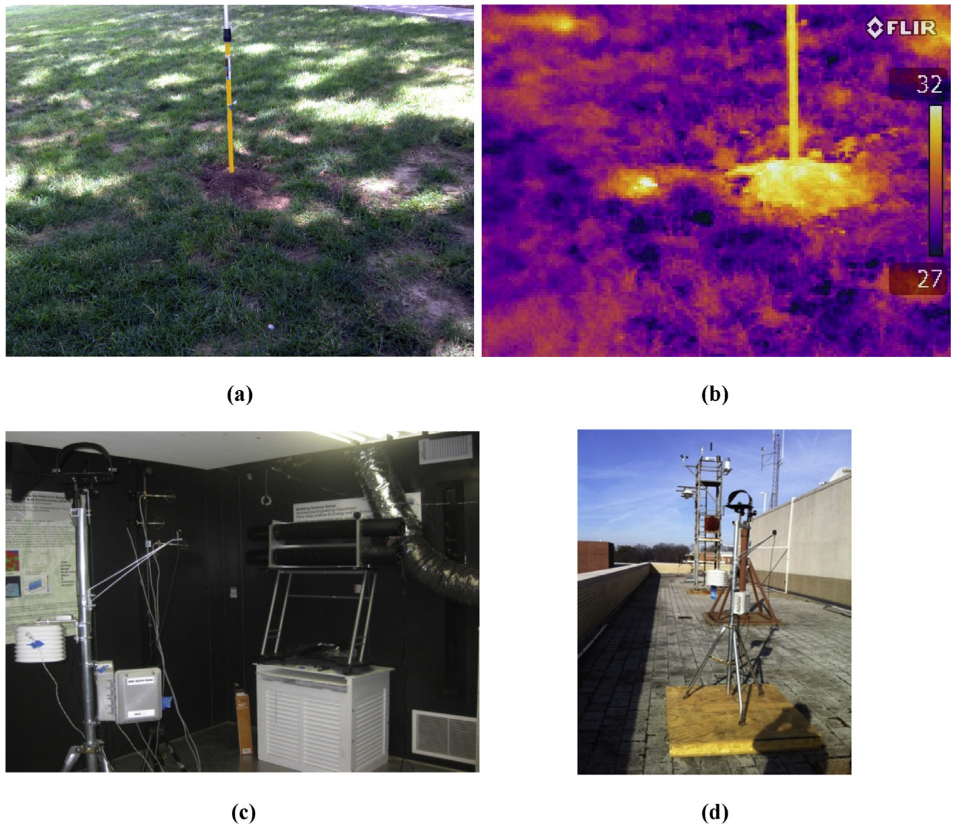

Fig. 5. Examples of instrumentation used to measure to the local thermo-fluid properties: (a) iButton sensors and (b) IR camera to measure local temperature close to a vegetated surfaces, (c) calibration of a portable weather station at the laboratory, and (d) installation of a portable weather station on a building rooftop.

models benefit from different spatial and temporal scales in the flow field to account for a variety of proximities from the buildings, using a close proximity to the buildings (or within the boundary layer) for RANS equations, and solving LES equations for the separated regions [87]. For the large scale simulations of the urban neighborhoods, especially for urban neighborhoods with complex geometries compared to the cubic urban canyon models, due to the challenges associated with computational time, storage, and convergence, RANS models are widely used to model outdoor airflow around buildings located in an urban neighborhood [20,44].

There are challenges associated with the neighborhood scale modeling of the airflows. The number of computational cells, boundary conditions, and domain size are examples of the challenges with the outdoor airflow simulations. For example, one important parameter during the decision making of the number of cells is the distance between the wall surfaces and the center of the first adjacent cell to the wall, known as y^+ [70,71]. Depending on the turbulence model and available computational/storage resources, the variation of the y^+ could be significant. Low-Reynolds wall functions, typically suitable for the y^+ around 1, can provide accurate representation of the y^+ values close to the wall. However, $y^+ = 1$ means a wall-adjacent cell size of approximately 0.0004 m for a domain size of 1000 m $\times$ 1000 m $\times$ 200 m, resulting in approximately billion cells in the simulation domain. To reduce the number of required cells, existing studies typically use the standard "logarithmic wall function", allowing for the y^+ values to vary from 30 to 300. Studies showed that for the coupled simulations of the airflow and temperature fields, there is an inherent over-estimation of the heart fluxes, especially for the prediction of the natural convective heat transfer [88,89]. There are other categories of studies that have utilized the standard logarithmic wall function for the modeling of the urban thermal environments [76–78,90–92]. One possible solution might be to determine significance of the turbulence close to the wall using μ_t/μ as the non-dimensional indicator and the influence of the forced/free convection using the Richardson (Ri) number. With $\mu_t/\mu > 30$ and Ri << 1 allow to use y^+ in the range of 1–30 [93,94], suggesting a fairly fine mesh close to the building, including a fine first cell size closest to the building surfaces. However, the number of cells in the simulation domain would still reach several hundred millions, which is not possible to simulate without computational clusters. This is a solution that seems feasible in the near future with advances in the widely available computational resources. Another setback associated with the values of the y^+ is due to the significant variation of the velocities from the bottom to the top of a building or even from the front to the back of a building's roof. This velocity gradient could be up to two orders of magnitude. This significant gradient cannot be compensated with variable grid sizes, causing finer grid sizes for the places where the y^+ needs to be very low. Therefore, for the simulations of a fairly large, outdoor domain size while taking into consideration the outlined setbacks, it would be possible to rely on wall functions. This would allow the y^+ values to vary from 30 to 200 around the zone of interest, while the maximum allowable value of y^+ for surface locations on surrounding buildings could potentially exceed 300 in the high velocity region around the edges at the top of the buildings. Existing studies modeled the urban microclimate with the high resolution grid in the range of 0.5 m–1.0 m for the zone of interest, while using a coarse resolution grid in the range of 3.0 m–8.0 m for the surrounding zone [76,92]. The comparison for the case of the urban microclimate in Rotterdam was conducted through comparing the CFD simulation results with experimental data, which presented the fairly reliable prediction with an average deviation of 7.9% [92]. However, due to limited studies that specifically discuss the grid resolution in neighborhood scale and provide the sufficient validation, further researcher should focus on expanding the topic. Overall, there is a need to consider the tradeoffs of modeling the adjacent cell on the building walls, including mesh size, and the accuracy of the simulations based on the availability of the computational and storage resources.

3.4. Overview of the energy and airflow modeling for neighborhoods

Energy modeling of the buildings located in the urban neighborhoods is currently not fully understood. The prediction of building energy consumption for a large number of buildings requires relying on different procedures to (1) build large-scale building energy models, (2) include the influence of the urban neighborhood in the energy models, (3) include on-site data from the energy audits into the building energy models, (4) perform sensitivity analysis on the uncertainties associated with the inputs of the building energy models [95–97], and (5) calibrate the building energy models with the metered energy data. All of these different procedures require substantial experience and resources to accomplish accurate predictions of the building's energy consumption.

The integration of the airflow and energy for the coupling or co-simulation of these two approaches requires data exchange at the common surfaces of the airflow and energy domains that are the building exterior surfaces. Key variables in the decision-making for the coupling/co-simulation are accuracy, stability, computational time, and temporal and spatial scales. Due to the variety of the heat transfer rates in the building energy and airflow models as well as computational time, there is a need to perform the energy and airflow simulations separately and enable data exchange at certain time steps [93]. An example of different time scales in the airflow and energy simulations is the time required for building walls to respond and reach a steady-state condition compared to the air temperature response. While the response time for building walls may take from hours to days, this response time for the surrounding air could be within minutes [93,98]. These different response times suggest that the time steps required to solve the energy and airflow equations differ in their orders of magnitude, suggesting the time step required to solve the transient energy flow is one order of magnitude larger than the airflow simulation time step. Therefore, the importance of the transient term in the momentum equations becomes less significant compared to the convection and diffusion terms. Overall, one practical solution is to consider steady state transient airflow simulations at different snapshots through time when there are significant changes to the airflow and perform transient energy simulations. Traditionally, coupled or co-simulation of the energy and airflows are performed in indoor spaces [94,98–101] that could provide insights for the outdoor coupling energy, radiative, and airflow simulations. Existing outdoor coupling studies have utilized the recommendations for the indoor coupling and co-simulations to pair the energy and airflows in the building environment with the consideration of the intensity required to perform outdoor energy and airflow coupling [102–105].

One practical approach to couple or co-simulate the energy and airflows in the urban neighborhood utilizes the proposed workflow. Fig. 6 shows the steps for modeling buildings located in urban neighborhoods. Step 1 of the modeling requires analyzing the urban neighborhood and developing UTZs for the neighborhood of interest as well as the context neighborhoods. In Step 2, aerial snapshots are used to develop the airflow and energy model inputs. Finally, one can create reduced-order energy and airflow models in Step 3. One practical approach to model this neighborhood recommend using (1) outdoor solar radiation simulations to identify heat fluxes at the building surfaces and the ground, (2) airflow simulations to predict the local outdoor conditions and record the emerging properties such as CHTC, COP, and (3) heat fluxes and local thermo-fluid properties at the building surfaces to perform energy simulations. With a full scale modeling of the energy in the built environment, integrated models should be considered to allow data exchange between the airflow, radiative, and energy flows.

3.5. Existing simulation tools and used field measurements

Emerging molding approaches for neighborhoods typically use existing individual software tools to simulate airflow, energy, and solar irradiance in the built environment. For example, for the CFD simulations traditionally PHOENICS [28], Fluent [20,21], CFX, and OpenFOAM [46,86] are used to calculate the flow and temperature fields. Building energy models such as EnergyPlus, TRNSYS, DOE-2, eQuest, and HAP are used [106–108]. Overall, the use of different tools requires considerations of different spatial and temporal scales during the modeling procedure. In the past decade, interest has been expressed in the coupling, integration, and co-simulations of the existing simulation tools. Recently, the advances in the computational resources enabled different studies to develop a suite of simulations for the modeling of the built environments. Examples of the recently-developed simulation tools include (1) SOLENE and SOLENE-Microcimat [24,109,110], (2) CitySim [111,112], (3) ENVI-Met [113,114], (4) Virtual PULSE [115], and (5) Honeybee [116]. These tools have used an integrated approach to model the urban neighborhood and quantify the energy consumption of buildings in the neighborhood.

4. An overview of modified thermo-fluid properties for urban neighborhood modeling

The influence of the urban neighborhood on the local variables includes local wind speeds, local air temperatures, CHTCs, infiltration rates, solar irradiation, and evapotranspiration.

4.1. Local wind speeds

Urban microclimate has a significant influence on the local wind speeds around the buildings located in an urban neighborhood. The meteorological wind speed from the weather file at the height of 10 m plays a significant role in the external surface heat balance equation, as well as the convective heat transfer coefficient correlations, infiltration rates, and HVAC system efficiencies [117]. However, the majority of wind speed values employed in the energy simulation programs are the local wind speed (U_{loc}), obtained from meteorological stations. Currently, the conversion from the meteoroidal wind speed to the local wind speed is mainly obtained according to the urban terrain types as it is specified in Equation (5), characterizing by the wind speed profile exponent (α) at the site with the ranges from 0.14 for flat and open country to 0.33 for towns and cities [21,118–120]. In the existing literature, the relation between the meteorological wind speed and the local wind speed is presented as a coefficient value of 0.852, instead of using the typical wind profile exponent, in order to derive the convective heat transfer coefficient correlations accounting for the neighborhood effect [21]. As an important element of actual on-site weather data file for building energy simulation, the local wind speed represents the characteristic of the actual environment. Therefore, it is crucial to account for the influence of the urban neighborhood on the local

Fig. 6. Representation of a modeling approach for buildings in the urban neighborhoods.

wind speed in the multi-scale modeling of the airflows and energy simulations.

$$V_z = V_{met}\left(\frac{\delta_{met}}{z_{met}}\right)^{\alpha_{met}}\left(\frac{z}{\delta}\right)^{\alpha} \tag{5}$$

In Equation (5), V_z, V_{met}, δ_{met}, z_{met},α_{met}, and δ are wind speed at altitude z, wind speed at profile boundary layer thickness at the meteorological station, height above ground of the wind speed sensor at the meteorological station, altitude (the elevation above ground), and wind speed at profile boundary layer thickness at the site [119,120].

4.2. Local air temperatures

Similar to the local wind speeds, the effects of local air temperature gradients induced by the surrounding building densities, green plot ratios, and urban terrain types was thoroughly investigated in the last decade [121,122]. Current studies usually consider the influence of the urban neighborhoods on the biogeochemical cycles and regional effects in the cities typically represented by Urban Heat Island (UHI) [3]. Existing studies reviewed the influence of increased ambient temperatures on the cooling loads/energy of the buildings and found an increase of up to 17% in the energy consumption of buildings for the reviewed case studies [95,123].

Energy and airflow simulations typically rely on weather data from the airport weather stations to define model inputs. These airport weather stations could be far from the building of interest where the local weather data is highly affected by the local environment. Therefore, it is important to assess the influence of the urban neighborhood on the local air temperature variation around the buildings. Due to the local ambient temperature gradients, the impact of the urban climate on the building energy sector could be categorized as the influence on thermal loads, energy consumption, and HVAC system performances. A study found that the city of Athens in Greece, when local mean temperatures increase by 10 °C in summer, the cooling load of neighborhood building doubled, while for the same mean temperature change, heating loads in winter reduced up to 30% [124]. For energy consumption, the variable urban temperatures at the local environment and the meteorological station have a significant impact on the energy consumption varying by ±5% [125] and ±7% [126]. These differences are mainly due to the influence of local environmental temperatures, where the local site is far from the weather station. A review indicated that with the increase of 1 °C for outdoor temperature, the electricity consumption increases by 9.2% and 3.0% for residential and commercial building, respectively [127]. Another study showed that the local air temperatures in urban environments approximately increased by 2.0 °C due to the exhaust of air-conditioning waste heat in summer [128]. Therefore, local air temperatures usually increase the energy consumption of the buildings located in an urban neighborhood. For building energy simulations, real-time meteorological data needs to be measured as close to the actual site as possible when the meteorological station is not close, and the local weather file is not available. One practical approach to estimate the temperature at the building site for the urban canopy is to utilize the Canyon Air Temperature (CAT) or Urban Weather Generator (UWG) models [129–131]. These models usually rely on a reference weather station outside of the urban canopy, such as an airport weather station, and solve an energy balance for a control volume inside the urban boundary [130]. This approach enables integrating mesoscale models to predict the outdoor air temperature with the microscale models to consider building energy models and airflow simulations. Although these models could provide inputs for the building energy models, the simplifications and assumptions applied to the model prevent them from capturing detailed, site-specific microclimate effects that require robust solutions of the momentum equations through outdoor CFD simulations [131]. Another factor to consider when using this model is associated with the selection of the reference weather station that is not affected by the microclimate of the site-specific that may not exist in other places since the majority of the reliable weather stations are located in airports. Recent advances in the use of the satellite based data also could allow partial accessibility to the on-site weather data. This satellite based data is not usually publically available in real-time to the building science community, which also does not allow the widespread availability of the satellite based data. Further studies are necessary to consider the publically available satellite based data for the use of the on-site, real-time weather data, and provide recommendations on the significance and shortcoming of this data for the energy and airflows multi-scale modeling of the urban neighborhood. In summary, the accurate estimation of energy consumption within the neighborhood is important, especially when accounting for the impact of surrounding buildings on the local thermal environment, such as shading the incoming solar radiation or the shielding and channeling of the incoming wind.

4.3. Convective Heat Transfer Coefficients (CHTCs)

CHTCs were previously studied by researching the airflow simulations around bluff bodies. In the recent years, there is a renewed interest in studying CHTCs for the buildings located in urban neighborhoods. Existing studies showed that CHTCs can play a significant role in the building's energy consumption, and more specifically in the exterior building surface temperatures. A literature review found that these energy consumption variations are up to 30% [72] for isolated building and up to 80% [132] for buildings in urban environments. These fairly large variations are due to the use of different exterior CHTC correlations that considered the CHTC values due to the effect of urban neighborhood configuration. Another study demonstrated that the influence of exterior CHTC correlations on the annual cooling energy consumption was less impactful, with difference of up to ±10% [43]. Recently, new CHTCs are being developed, validated, and demonstrated for the buildings located in actual urban neighborhoods [20,21,43]. Specifically, a study found that with the changes of plan area densities from 0.04, indicating almost isolated buildings, to 0.44, indicating significantly denser neighborhoods, the total cooling and heating energy consumption increased by 4% and decreased by 1.3% due to the exterior surface CHTC correlations, respectively [21]. It is important to notice that these variations only accounted for the CHTC effect, and do not consider the effect of wind sheltering and solar shading effect.

The influence of the exterior surface CHTCs not only directly impacts the energy consumption of the buildings, but also it directly impacts the exterior surface temperature of the buildings. The exterior surface temperature of the buildings play an important role in the radiant temperature in the urban neighborhood, due to long-wave heat flux exchanges between the pervious and impervious surfaces, as well as the sky. The results of the implementation of the new urban scale CHTCs shows that the building's actual surrounding environment has more influence on the building exterior surface temperatures, rather than the energy consumption of the building due to the building insulation types [43,44]. The location of the building also plays an important role in the quantification of the influence of the building exterior surface temperatures and energy consumptions. For new construction buildings that are built based on the recent ASHRAE Standard 90.1 or 189.1, the CHTCs have less impact on the building energy consumption and surface temperatures due to higher conductive resistance compared to the convective resistance [21].

4.4. Infiltration rates

Empirical, single-zone, and multi-zone models are used in the literature to model infiltration rates that are elaborated in details in the literature [28,45,120,133–135]. Influence of the urban neighborhood on the infiltration rates is also an important variable affecting building energy consumption in neighborhoods due to changes in the local air temperatures and wind speeds [28]. To benefit from the capability of the outdoor CFD simulations, studies have performed co-simulation/coupled studies of outdoor CFD simulations with the multi-zone models in CONTAM [134,135] or airflow networks in EnergyPlus [98]. The pressure coefficient (C_p) is one of the most important parameters that is usually is exchanged between the CFD and the infiltration models. The pressure coefficient is usually derived from databases of analytical models or measurements (e.g. wind tunnels), and there may be significant variations between the modeled pressure coefficients and the measured pressure coefficient. In general, the building energy simulation engines do not usually accept custom pressure coefficients as inputs [133]. Therefore, an interest in modeling the modified infiltration rates based on the urban neighborhood coupled CFD simulations and multi-zone airflow simulations could increase the accuracy of the building energy simulations. Equation (6) shows an example of one of the basic methods in EnergyPlus to calculate the infiltration rate. In this model, the schedule coefficients cannot represent actual neighborhood morphology. The existing coefficients in the energy simulation models, such as EnergyPlus, are usually developed for the residential buildings, and simplified coefficients are considered [136]. Another practical approach is to calculate the coefficients in Equation (6) with outdoor airflow simulations to account for the variation of the urban neighborhood. There are more models that can be used to account for the infiltration rates in the building energy simulation program especially EnergyPlus [45,120].

$$Infiltration = I_{Design} + F_{Schedule} \times \left(A + B \times |\Delta T| + C \times W + D \times W^2\right) \quad (6)$$

Existing studies showed that the implementation of the time-dependent infiltration rates derived from coupled CFD and airflow multi-zone models into the building energy simulations could have significant effect, which is dominated by local climate conditions and neighborhood morphology [137,138]. Accounting for the variation of actual infiltration rates depending on the wind direction, wind speed, sheltering, and building layout, integrated simulation of CFD and building energy simulations were developed to investigate the effect of infiltration surrounded by neighboring buildings on the energy consumption [138]. In this integrated approach, CFD provided airflow simulations around the building neighborhood with detailed wind pressure distributions on building surfaces. The results indicated that the changes in the urban neighborhood morphology provided an additional 14% to the infiltration loads to the building of interest [138]. Overall, it is important to note that changes in local air temperatures and wind speeds below the roof level are highly affected by the neighborhood orientation, the heights of surrounding buildings, solar gain of exterior building surfaces, and wind pressure. These driving mechanisms of infiltration are directly influenced by the neighborhood morphology. There is a need for future studies to develop new physical models based on the emerging properties to account for the infiltration rates for buildings built in the urban neighborhoods.

4.5. Solar irradiation

Solar radiation in the built environment plays an important role in terms of the incoming energy delivered to the urban neighborhood, and the interactions of the urban neighborhood's pervious and impervious surfaces with the sky. Usually, the influence of the urban neighborhood on the solar radiation shows up as short-wave and long-wave radiation components, due to the thermal storage in the built environment. In addition to the location of the urban neighborhood and configuration of the urban neighborhood, various building-related parameters, including the building wall and roof U-values, U-values and Solar Heat Gain Coefficient (SHGC) of the building fenestration systems, and Solar Reflectance Index (SRI), a measure of reflectivity for the surfaces, determine the impacts of the surface temperature and heat flux exchanges in the urban neighborhood.

The boundary conditions indicating the utmost importance of neighborhood CFD simulation, including constantly changing surface temperatures or heat fluxes. Empirical models, such as the Objective Hysteresis Model [139], the building wall heat balance equation [91], on-site measurements [20,55], solving one dimensional heat conduction in the building walls/ground, or coupling with outdoor solar radiation and CFD simulations [140] are among the methods to derive the boundary conditions for the wall/ground heat fluxes and temperatures. The modeling of the ground surface becomes more difficult in the presence of snow that affects the reflectivity of the ground [96]. Another method to predict building surface temperatures is the whole building energy modeling [46], which integrates the indoor/outdoor surface heat balance equations and thermal conduction of building envelope, as well as thermal loading calculations.

4.6. Evapotranspiration

Influence of the latent heat transfer in the neighborhoods usually appears in the evapotranspiration of the vegetated surfaces. The evapotranspiration modeling requires local thermo-fluid variables that are difficult to account for in the urban environments. Several studies modeled vegetated surfaces, especially green roofs, including the laboratory scale and on-site measurements on the rooftops of actual buildings [141–145]. An important input that affects the evapotranspiration in the built environment could be the plant area coverage and the Volumetric Water Content (VWC). However, the influence of the evapotranspiration for the urban scale airflow and energy consumptions is not fully considered in the existing studies. Only recently did studies that quantify the influence of the evapotranspiration on building energy consumption appear. Specifically, a study incorporated a green wall model into TRNSYS [146] and another one incorporated a green roof model into EnergyPlus [147] to understand the influence of different vegetation types on the total energy balance at the building enclosure. There are studies that identified details of the land use for the building footprints from the satellite images [131]. Image processing is a practical method to identify the building footprints, vegetation and pervious surfaces (e.g. ponds, trees, and lawns), and the impervious surfaces (e.g. streets). Another approach to understanding the urban neighborhood and distribution of spatial and temporal variables may use unmanned thermography vehicles to obtain the surface temperature values, and ultimately the configuration of the urban neighborhood [82]. Overall, future studies would need to expand to the scale of a neighborhood to account for evapotranspiration effects of pervious and impervious surfaces in the total energy balance of a neighborhood.

4.7. Summary

It is important to note that there is a need for future studies to consider the impacts of the reviewed properties present in urban neighborhoods with different morphologies. Existing studies modeled the urban neighborhoods with the consideration of selected variables, and do not consider the full scope of the variables, such as local air temperature, local air velocity and direction, CHTCs, infiltration rates, solar radiation (including short-wave and long-wave), and evapotranspiration (including the influence of the land coverage). In addition, there is a need to assess the influence of these variables under different circumstances, and how they cause the energy budget to vary based on the net solar radiation, anthropogenic, sensible heat flux, latent heat flux, storage of the heat flux, and the advection heat flux specified in Equation (2). Future studies could build upon the reviewed emerging properties and thermo-fluid properties selected in this study, and quantify the significance of each thermo-fluid variable under various urban neighborhood morphologies.

5. University campus case studies

In the reviewed studies, different configurations of the urban neighborhoods are reviewed. Due to the complex nature of the multi-scale modeling of the urban neighborhoods, researchers have selected various configurations depending on the accessibility and availability of the data and computational resources. The aim of the case studies in this section is to provide a summary of different approaches used in the existing studies that selected university campuses as case studies. Primary reasons to select campus are (1) the accessibility to the energy consumption data for the buildings that usually are monitored with the sustainability programs on campuses, and (2) the availability and willingness of the campus facility managers to support the research by installing new sensors and instruments to measure the energy and airflows in the urban neighborhood. For example, the installation of the temperature sensors at different elevations to measure airflow temperatures require following the instructions specified by the university campus policies [44,55]. The university facility managers at the campuses usually help building science researchers with the installation of the sensors in and around buildings, and share the energy consumption data of buildings [44,55]. Therefore, this study reviewed the studies that have used campuses to partially support

Table 3
A summary of the case studies for the multi-scale modeling of the urban neighborhoods.

Study	Case study	Approach	Main focus
Srivanit and Hokao [80]	A university campus, Saga, Japan	Airflow simulations with validation of the results with on-site measured data	Emphasize on the importance of the greening as a potential method for passive cooling and for use in reducing ambient air temperatures
Jadidi and Heidarinejad [86]	A university campus, Tehran, Iran	Airflow simulations using Detached Eddy Simulation	Predict outdoor thermal comfort of pedestrians
Liu et al. [21,44]	A university campus, University Park, PA, USA	Airflow simulations with validation of the results with on-site measured data	Develop, validate, and demonstrate CHTCs based on different urban neighborhoods
Taleghani et al. [148,149]	Two university campuses in Portland, USA and Delft, the Netherlands	Field measurements using thermography and portable weather stations	Effects of vegetation and water in summer and winter conditions
Takahashi et al. [140]	Comparison of a city case study with a campus case study	Measurements of temperature and validation with the outdoor CFD simulation	Quantify the influence of the vegetation on the UHI and provide implications to mitigate the UHI
Wong et al. [125]	A campus case study in Singapore	Field measurement of temperature and validation with the outdoor CFD simulation	Assess implication of the vegetation on the potential energy consumption of rooftop units
Gracik et al. [47]	A university campus, University Park, PA, USA	Field measurement of temperature and validation with the outdoor CFD simulation	Quantify the operational COP degradation due to the influence of the urban plan area density
Zhao [138]	A university campus, University Park, PA, USA	Perform outdoor CFD simulations without on-site validation and co-simulate CFD with multi-zone models	Quantify the impacts of the urban morphology change with the addition of a new building

the idea of the emerging neighborhood properties reviewed in this study.

Table 3 shows an overview of the existing studies with the defined approach and study areas. The results of Table 3 show that the studies have used the selected case studies to strengthen the reliability of their findings, using both simulations and on-site measurements. For the outdoor CFD simulations, the primary reason to select both the simulations and measurements was to assess the impacts of different turbulence models, and validate the simulations with the on-site measurements of the air temperature and velocity [44,47,54,55,80,140]. Then, the results of the CFD simulations were used to provide recommendations about the design of the campus urban neighborhood and outdoor thermal comfort in the urban neighborhood [86]. Another implication of the outdoor CFD simulations was to use the outdoor CFD simulation results to (1) develop a new CHTC design for the urban neighborhoods as one of the emerging properties [44,55], (2) quantify impacts of the urban neighborhoods on the COP of the HVAC systems [47,54], or (3) assess the influence of the infiltration rate with the changes in the urban morphology [138]. One of the emerging properties that was reviewed in the literature is the influence of the land covering and greenery on rooftops in order to quantify the influence of vegetation, and provide recommendations for the UHI mitigation strategies [125,140,148,149]. Overall, university campuses have served as case studies to support the development of new physical models, and quantify the significance of the emerging properties. Further studies are required to support the use of the university campuses as urban neighborhoods.

6. Discussions

This study identified several commonly used mitigation and adaptation strategies to alleviate the side effects of the urbanization. In addition, the results of this study provide new performance characteristics for the influence of the urban neighborhoods on the energy and airflows in the built environment which are directly relevant to the design of sustainable and energy efficient communities. Finally, this discussion section briefly summarizes the implications of the urban neighborhoods on the social and environmental factors.

6.1. *Mitigation and adaptation strategies*

Various mitigation strategies are suggested throughout the literature to reduce the side effects of the urban neighborhoods. For example, one practical solution is to decrease the coverage of impervious surfaces (e.g. concrete and conventional roofs) and increase the coverage of pervious surfaces, including vegetated surfaces (e.g. lawns, trees, and green roofs) and water surfaces (e.g. ponds and restoration of water streams) [150–153]. The impervious surfaces typically have lower albedo (reflectiveness) and higher heat transfer capacity compared to the pervious surfaces. An increase in the vegetation surfaces typically (1) cool the air due to the evapotranspiration, (2) reduce the heat gain of surfaces due to the higher albedo, (3) lessen the long-wave radiation between the surfaces and sky, or (4) in some cases, such as trees, provide additional shading of the incoming solar radiation [154]. However, there are certain limitations associated with mitigation strategies that require the application of the vegetated surfaces based on the climate and type of the vegetation. For example, vegetated surfaces require greater water use, rendering this mitigation strategy impractical for arid regions. The type of the vegetated surfaces usually determine the evapotranspiration rate, transmission, albedo, and permeability [154]. Therefore, a practical, sustainable community design considers the tradeoffs of different mitigation strategies to reduce the energy dissipation in the built environment, while it simultaneously providing a better adaptation strategy for the people who reside in the built environment.

Among the impervious surfaces, green roofs are one of the most widely used mitigation strategies that have numerically and experimentally been studied in the past two decades, quantifying the influence of the green roofs on the building energy use pattern and indoor/outdoor thermal comfort of the building's occupants [74,141–145]. Among the building energy simulation programs, EnergyPlus has a green roof model that can represent a building roof, constructed in layers, for the simulated buildings [45,74]. A recent study incorporated another extensively validated green roof model into the EnergyPlus to account for the influence of the plant coverage [147]. Overall, comparisons between the green roofs and conventional roofs show that there can be 2–5 °C air temperature difference between a green roof and a conventional roof. This temperature reduction has a direct impact on the energy consumption of the HVAC systems since the intake air for HVAC systems and air around the condensing units enables a higher, nominal, and local COP for the HVAC systems. Therefore, the HVAC system installed on a green roof consumes less energy compared to the HVAC system installed on a conventional roof. Another usage of the vegetated surfaces is green walls, that also reduce the temperature in the urban canyons [109,155,156]. Overall, incorporation of vegetated surfaces, especially green roofs, has become an important measure in the design of sustainable communities.

6.2. *Applicability of the multi-scale modeling*

Understanding the urban neighborhood provides a clearer picture of the built environment for the urban planners/designers, so they can design energy efficient and sustainable communities [108,157]. The emerging morphology is among the properties that have direct implications on the understanding of urban neighborhoods. Urban plan area density from 0.04, a rural neighborhood, to 0.44, a city center neighborhood, could affect the reviewed thermo-fluid variables such as CHTCs, operational COP of HVAC systems, and infiltration rates. For example, for the reviewed case studies [47,54], urban planners/designers could account for a reduction of up to 6% and 10% in the operational COP for the dense city centers, compared to the rated COP for the roofs and windward walls installed in the rural neighborhoods, respectively. As another example, in the design of the urban neighborhoods, if the height of the buildings increases, e.g. Hong Kong and Manhattan, New York City, an improvement to the ventilation of these cities could benefit from designing a wider and shorter length of building arrays [37,158]. In addition, it is recommended to use taller buildings with wider streets instead of shorter buildings with narrower streets and utilize large open spaces (e.g. gardens and waterways) to separate the cities into different urban neighborhoods of 1 km [158]. Overall, these recommendations could support the initial design of urban neighborhoods. After the initial design phase of the neighborhood, more robust methods, such as numerical multi-scale modeling, could facilitate the design of the urban neighborhood.

One solution uses reliable and rapid numerical, multi-scale modeling of urban neighborhoods for airflow around buildings to provide influential recommendations for the urban planners/designers. These urban planners/designers usually seek rapid and accurate energy and airflow models to assess different urban neighborhood designs with limited accessibility to high computational resources. In the multi-scale modeling of an urban neighborhood, the airflow and radiative components are usually more computationally intense compared to building energy simulations. While the building energy simulation of the buildings at urban neighborhood scale could take hours to assess different design scenarios, co-simulation of the energy models with the airflow and radiative models may require days of simulation. One practical solution to reduce intensity of the simulations suggests reducing the accuracy of the airflow and radiative simulations using reasonable assumptions at the early stage of the urban neighborhood design. Then, for the limited number of viable urban neighborhood designs, perform full-scale simulations with the required complexity to finalize the urban neighborhood design.

This development of multi-scale models of urban neighborhoods could also have direct implications on the assessment of the fast growth of megacities, especially cities associated with significant air pollution, like in Asia [3,159]. Specifically, these modeling efforts could provide opportunities to design more environmental friendly urban neighborhoods. The multi-scale modeling of the energy and airflows in the built environment could significantly benefit from new physical models, including but not limited to zero equation turbulence models and urban neighborhood CHTCs [20,21,44,160], developed specifically for the transport processes in the urban neighborhoods. This study identified existing and potential new emerging areas for the development of the physical models for the buildings located in the urban neighborhoods. Furthermore, it is important to validate the models with the on-site field measured data or wind tunnel experimental data, and to demonstrate the applicability of the models for actual urban neighborhoods. With such a comprehensive approach to model development from its inception to a validation in an actual neighborhood, different studies can quantify the influence of the newly developed physical models on the accuracy of the energy and airflow simulations.

Overall, the results of reliable, multi-scale modeling could provide opportunities to model an urban neighborhood based on the first principles, and further provide opportunities to recommend mitigation strategies to alleviate the side effects of urban neighborhoods on the environment. The mitigation strategies need to include better design practices for both buildings and urban neighborhoods to (1) minimize the influence of the urban canopy, (2) reduce anthropogenic heat transfer, (3) enhance walkability in the urban neighborhood, and (4) substitute existing urban impervious surfaces with pervious surfaces to reduce the overall impacts of the UHI on the built environment. It is important to note that these strategies have implications for the green building rating systems, such as Leadership in Energy & Environmental Design (LEED) for Neighborhood Development (ND), Building Research Establishment Environmental Assessment Methodology (BREEAM) Communities, and Comprehensive Assessment System for Built Environment Efficiency (CASBEE) for Urban Development that focuses on the design of urban neighborhoods [161]. These green building rating systems for urban communities are fairly new, and they could be used as neighborhood scale case studies to collect on-site measured data to quantify the influence of the urban neighborhoods on the socio-environmental factors, as well as the changes in the energy and airflows in/around buildings. Therefore, the results of multi-scale modeling methods need to extend the applicability of these research methods to be disseminated as urban design metrics.

6.3. Environmental factors

Generally, building neighborhood effects can be identified as different eminent aspects, including pedestrian wind comfort, pedestrian thermal comfort, building energy demand, pollutant dispersion, and wind-driven rain [162]. Therefore, theoretically the influence of the built environment not only affects the thermo-fluid properties in/around buildings, but it also has significant impacts on the socio-environmental factors. This section briefly summarizes the several major social and environmental factors.

The pollutant concentration dispersion in the built environment is strongly associated with the urban plan area density, frontal area, and arrangement of the buildings [163–165]. One important consideration in the modeling of pollutant dispersion in the built environment is not only the mean value of the pollutant concentration, but also the probability of the high pollutant concentrations [166]. The high pollutant concentrations may pass the acceptable threshold values of the pollutant concentrations for the people who reside in the urban neighborhoods. The urban neighborhood's emerging properties could affect the concentration of the pollutant near the buildings, leading to a higher concentration of pollutants in the air intake of the HVAC systems for the conditioned spaces, or incoming air to the building from naturally ventilated buildings [167]. Similar to the indoor space studies, the outdoor airflow studies define breathability as a parameter that specifies how the airflow in the urban neighborhood flows around the buildings located in the urban neighborhoods [30,168]. For the dense urban neighborhoods, e.g. urban neighborhoods with urban plan area density of 0.44 or higher, the accumulation of the pollutants emitted from the buildings, transportation, and industrial activates creates environmental side effects for the occupants who reside in these urban neighborhoods. In another example, the rate of ozone formation increases with the UHI [169]. Overall, the urban neighborhood and interactions among its buildings significantly change the distribution of the pollutants in the built environment.

Another important consequence of the urban neighborhood's emerging properties is the temperature increase due to the built environment. A study found that future energy demand by current buildings in the U.S. will decline for heating, and will increase for cooling, and the increased air temperature poses a new challenge of increased humidity levels that will cause uncomfortable interior conditions for occupants [170]. The increase in the temperature for a location that is not resistant to the heat waves, such as the East Coast cities in the U.S. or European cities such as Basel in Switzerland, could have severe effects on the mortality of the people who reside in the built environment [171–175]. It is projected that the associated effects of the urban neighborhood will manifest in a higher rate of heat waves in the 21st century [172,176]. Reviewed mitigation and adaptation strategies could reduce the risk of exposure to extreme heat waves. Outdoor thermal comfort of the people recently attracted significant interest in order to design sustainable communities [85]. Not only have the heat waves had a significant impact on the health of the people who reside in the urban neighborhood, but also for the large institutions, depending on the their energy contracts, the cost of their energy is significantly increased when the consumption reaches to a certain level. This has implications for the policy makers and urban developers.

6.4. Social factors

Building occupants are not only passive subjects experiencing environmental conditions, but they are also active participants that define the energy use in urban neighborhoods. This realization inspired numerous research studies and incentive programs to target the behavior of residential building occupants in the aftermath of the first energy crises in the 1970s [177,178]. These first sets of studies successfully demonstrated that feedback and engagement of social networks can play a significant role in energy saving initiatives. Specifically, the measured reduction in the eclectic energy consumption was anywhere between 10% and 15%, depending on the type of the feedback those occupants received. More importantly, these early studies established the foundation for successful active engagements of building occupants in the energy conservation efforts. These principles include marketing strategies such as visualization, personalized information, and market segmentation, as well as delivery methods properties such as convenience, financial incentives, and regular consumption data monitoring. Numerous recent studies deploy these principles in the context of individual buildings and urban neighborhoods.

Recent studies deployed (1) social energy monitoring, (2) competitions, and (3) behavior modeling to understand the impact of social networks and their interactions with energy use in individual buildings and urban neighborhoods [179–181]. The social energy monitoring is the first step in the building occupant engagements to promote energy saving behavior. A series of research studies demonstrated that the social peer pressure through electric energy consumption monitoring, along with direct comparisons of participant performance, is an effective tool in reducing the electric energy consumption [182–184]. Interestingly, the structures of the social networks, including network degree and Eigenvector centrality, have positive correlations with reduction in electricity consumption. In addition, different types of social networks lend themselves to different methods of comparisons, defined as normative, one-on-one, and ranking. Another group of studies extended the social energy monitoring into the social competitions with different types of rewards and incentives [179,185]. Unfortunately, the existing studies do not report the quantitative electric energy savings resulting directly from these occupant engagements, as these studies primarily managed to pilot the methods and tools.

Similar to the scale issues for building energy and airflow modeling, the social networks are studied and modeled at different temporal and spatial scales. Due to recent developments in the instrumentation for data collection and computational capacity, state-of-the-art studies use real-time data for the temporal scale, while the special scales are expanding from a building to a neighborhood, for both experimental and modeling studies [180,181]. It is also important to notice that all of the reviewed studies are opening novel areas of research, so they typically utilize a relatively small sample with relatively homogenous populations, such as students in dormitory rooms or building residents dominated by a similar market segment. Therefore, the presented results could be biased with respect to specific findings, but they all found that social network engagements can save electric energy with at least 10% or even higher savings, depending on how well-designed and executed the engagement of social network is.

7. Conclusions

This study provides a critical review of the literature to summarize the commonly used methodologies to model the energy and airflows at the urban neighborhood scale. In addition, supporting evidences are included in this paper to define a research direction to develop more generalized solutions, physical models, and results for the urban scale modeling of the neighborhoods, rather than relying on the case study approach. The urban morphology parameters, such as the urban plan area density, frontal area density, and mean height of the buildings represent successful examples of the urban morphology variables as suitable emerging properties for development of generalized solutions and physical models at the neighborhood scale. A critical literature review of the local thermo-fluid properties influenced by the outdoor urban neighborhood shows that full scale modeling of the urban neighborhoods requires relying on the consideration of different spatial/temporal scales and models to account for the interactions of different heat, mass, momentum, and concentration scalars, which require substantial computational and storage resources. This full scale modeling of the urban neighborhoods cannot be widely used at present. Therefore, a practical solution to the widespread use of these predictive models relies on using justifiable simplifications to model the energy and airflows at the urban neighborhood scale. Finally, this study identifies that the multi-scale modeling of the urban neighborhoods has implications on (1) the mitigation strategies for a better adaptation of people who reside in the built environment, (2) design performance metrics of the neighborhoods for the green building rating systems, and (3) socio-environmental factors.

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