Opportunities and Challenges for Multi-Scale Modeling of Sustainable Buildings

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Existing urban settlements are comprised of buildings that use approximately 40% of the total primary energy in the U.S., and as a result are the major contributors to green house gas emissions based on the International Energy Agency (IEA) reports. In fact, buildings use more energy than either the transportation or industry sectors. This intense energy demand is projected to increase in the next couple of decades based on IEA projections through the year 2030. As a result, building infrastructure has became an important research area and funding agencies have launched new initiatives such as: (1) Department of Energy's (DOE) Energy Innovation HUB on Building Energy Efficiency; and (2) National Science Foundation's (NSF) Emerging Frontiers in Research and Innovation (EFRI) on Science in Energy and Environmental Design (SEED) in 2010. Furthermore, the issue of energy-efficient and environmentally-friendly buildings was also addressed in the National Academy of Engineering's (NAE) report entitled "The Grand Challenges for Engineering" in the chapter on "Restore and Improve Urban Infrastructure." A technology that can support addressing this grand challenge in engineering is the predictive multi-scale modeling of transport processes in and around buildings.

Contemporary approaches to multi-scale modeling of buildings in urban settlements are limited to isolated case studies on energy consumption of building systems and resultant projected CO_2 emissions. The full integration of results into a comprehensive understanding of system behavior does not exist or is based on simplified, linear approximations of various system components. Only recently has there been the emergence of models and simulation platforms that implement comprehensive modeling of buildings in urban settlements. At present, novel approaches to addressing simulation challenges are derived from two disciplinary domains, each informed by their own respective fields of expertise:

1. Meteorologists and climatologists have introduced constraining anthropogenic sources in prognostic weather and climate models, to better understand urban heat islands, as well as outdoor air quality and contaminant dispersion in cities
2. Building scientists have explored weather and climate forcing for airflow, energy and contaminate simulations in and around buildings to understand building energy consumption, ventilation/infiltration, and contaminant dispersion

The connection among all of these disparate fields of study is the universal system of transport equations solved numerically for appropriate temporal and spatial scales. The solution of transport equations typically includes mass and momentum equations to solve the airflow field, while the addition of partial differential equations to represent scalars, such as temperature and contaminant concentrations, or solid phase for particles are problem specific. The required computational power to directly solve these partial differential equations is enormous. For example, the fastest petaflops super-computers allow up to approximately 10^{12} grid resolution that is only sufficient to solve simple indoor airflows in a single room, where a typical Reynolds number is 10^{5}. Directly solving an outdoor airflow problem is impossible as Reynolds numbers are on the order of 10^{7}. Therefore, the required grid resolution for a simple outdoor airflow problem would be close to 10^{16}. As a compromise, building simulations have to be based on accurate physical models that can be successfully implemented and solved with the available computational power.

For the past couple of decades, modeling of buildings was accomplished using several approximations that were quite important for understanding physical transport processes in and around buildings even as we are gaining access to unprecedented computational power. More recently, those models are being coupled in unifying simulation platforms and novel methods for leveraging different models are being discovered. For example, Multi-zone Modeling (MZ), Energy Simulations (ES), and Computational Fluid Dynamics (CFD) based on Reynolds Average Navier Stokes equations all have their strengths and weaknesses in modeling building transport processes. MZ can predict infiltration rates, bulk flow and contaminant transport; ES can predict building energy consumption; while CFD can predict detailed airflow, temperature and contaminant concentrations. For the same simulation domain of a single building, MZ typically requires seconds, ES takes minutes, and CFD needs hours to run a model on a PC. This is due to different levels of model complexity, which corresponds to the level of details that each model provides. No matter how simple or complex, each of these models has supported development of sustainable building solutions, such as natural and hybrid ventilation, advanced building enclosure materials and unconventional mechanical systems.

The initial approaches to sustainable building solutions have focused on simulation models of a single building and the environmental impacts at the occupancy and building scales based on past climatic conditions. This historic overlay was partially due to both the limited computational capacity and our limited understanding of driving transport processes for buildings. The simulations at the single building scale are now widely used even though there are still important issues to be resolved with the accuracy of these models. Contemporary work is focused on improving the accuracy of existing single building models via *in situ* validation studies and assimilation of *in situ* measured data into simulation platforms. Energy simulation models can produce results that closely track measured data or can produce errors as large as an order of magnitude when compared to the actual building energy consumption. During recent validation efforts, it was found that the one of the largest sources of error in physical models was due to modulating factors driven by human behavior. Those factors include building systems management and maintenance, occupancy rates, and how occupant use building systems. In our recent study, we have also found that human behavior factors can become insignificant for building energy consumption when the outdoor and indoor air temperatures are very different, such as during typical winter days in the north east US. Overall, as our understanding of physical transport processes and their modulating factors improve, so should model accuracy.

In the next couple of decades, it is expected that with ever increasing numbers of buildings and renovations of existing structures, the impact on augmenting local micro-climates will be on the order of 10^3 meter radius, which will also amplify large scale transport processes in the boundary layer and lower troposphere. Therefore, buildings should not be simulated based on past climatic conditions and sustainable building design concepts have to be conceptualized on much larger spatial and temporal scales than the comparatively miniscule footprint of a single building and its associated annual energy consumption. This presents a unique opportunity for unprecedented synthesis of simulation models from meteorology and engineering, where a range of scales encapsulating relevant processes should be integrated, including: (1) mesoscale predictions at a scale of $\sim 10^5$ m; (2) weather forecasting ($\sim 10^3$ m); (3) microscale outdoor transport processes ($\sim 10^0$ m); and (4) indoor transport processes ($\sim 10^{-1}$ m). The range of relevant spatial and temporal scales is substantial, but this challenge represents a profound opportunity for innovations in simulation technology that will enable progress in the development of sustainable urban settlements. There are several outstanding efforts that are attempting to address this exciting and daunting research problem globally, including scientist from Japan (Yamaguchi and Shimoda 2010), Europe (Rasheed et al. 2011), U.S. (Chen et al. 2011) as well as the building science research group lead by the author. If successful, these efforts can be extended from performance predictions to sustainable engineering of urban settlements at an unprecedented scale.

References

Chen, F.; Kusaka, H.; Bornstein, R.; Ching, J.; Grimmond, C.S.B.; Grossman-Clarke, S.; Loridan, T.; Manning, K. W.; Martilli, A.; Miao, S.; Sailor, D.; Salamanca, F. P.; Taha, H.; Tewari, M.; Wang, X.; Wyszogrodzki, A. A.; and Zhang, C. 2011. "The integrated WRF/urban modelling system: Development, evaluation, and applications to urban environmental problems," International Journal of Climatology, v 31, n 2, p 273-288.

Rasheed, A.; Robinson, D.; Clappier, A.; Narayanan, C.; and Lakehal, D. 2011. "Representing complex urban geometries in mesoscale modeling," International Journal of Climatology, v 31, n 2, p 289-301.

Yamaguchi, Y.; and Shimoda, Y. 2010. "District-scale simulation for multi-purpose evaluation of urban energy systems," Journal of Building Performance Simulation, v 3, n 4, p 289-305.