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MODELING BUILDING ENERGY PERFORMANCE IN URBAN CONTEXT

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ABSTRACT

Many buildings already exist in an urban context, in close proximity to many other buildings of similar or larger size and in micro-climates (e.g., urban canyons and heat islands) created by this environment. As the world's population increasingly flows into cities, many more buildings will fit this description.

Cities are collecting new data on basic building features, mutual shading, and microclimate and synthesizing it in GIS platforms and in 3D city models like CityGML. This new data in the urban context impacts building energy performance. Taking advantage of this information to improve urban building energy modeling requires simulation engines to incorporate it into calculations and do so in a scalable way that achieves acceptable computing performance and accuracy for urban scale modeling applications.

This paper presents several new features recently implemented in EnergyPlus version 8.8 to improve its accuracy in the urban context and expand its applicability to urban scale building energy modeling. These features include (1) import and export of exterior shading schedules, (2) calculation of long-wave radiant exchange between buildings, and (3) use of urban microclimate conditions. We discuss these features along with simulation examples to demonstrate their use and impact on urban scale building energy modeling.

INTRODUCTION

Buildings consume up to 70% of the primary energy used in cities. Cities are paying greater attention to building energy efficiency in urban planning, and in meeting city goals for reduction of greenhouse gas (GHG) emissions.

The urban context—surrounding buildings and their direct individual effects on the building and their collective effects on the urban climate and microclimate (e.g., urban heat island effect) can strongly influence building energy use. The various effects include (i) local air velocity, temperature and humidity; (ii) solar irradiation and specular and diffuse reflections; (iii) surface temperatures of buildings, the ground and the sky, with the respective long-wave radiant exchange between surfaces. As more data related to building features, shading, and microclimate is collected and synthesized in GIS platforms and 3D city models like CityGML, traditional building energy modeling can be both improved and scaled up from individual buildings to districts or the entire cities. However, this requires simulation engines to evolve to incorporate this new information into calculations and to do in a scalable way that achieves feasible computing performance and accuracy for urban scale applications.

Past studies have developed algorithms and tools to address the need of modeling building energy in an urban context, taking the surrounding buildings into consideration. Jones and Greenberg have introduced the method of pixel counting combined with B-spline surface interpolation for calculating direct solar gains on architectural CAD models (Jones and Greenberg, 2011). Hoover and Dogan have also presented the pixel counting algorithm for external solar shading calculation, addressing its weakness of high comuptational costs in existing simulation tools. Similarly (Hoover and Dogan, 2017), Jones et al. have presented the ray casting method of calculating view factors between two urban surfaces, which is faster than the commonly used geometric analogy way (Jones et al., 2013). The simulation engines, such as EnergyPlus, can take advantage of these advanced and robust algorithms by integrating the external calculation results into their simulation.

Several integrated urban building energy modeling (UBEM) programs have also been developed during the past few years (Keirstead et al. 2012, Reinhart and Davila 2016), including CitySim (Emmanuel and Jerome 2015), UrbanOpt (NREL 2018), the Urban Modeling Interface (UMI) (Reinhart et al. 2013), and the City Building Energy Saver (CityBES) (Hong et al. 2016, Chen et al. 2017). UMI is a Rhino-based design environment for architects and urban planners interested in modeling the environmental performance of neighborhoods and cities with respect to operational and embodied energy use, walkability and daylighting potential. UMI creates EnergyPlus models using simplified zoning and HVAC systems. CitySim uses its own XML schema to represent building information and reduced order energy models assuming simplified zoning and HVAC systems. UrbanOpt is an analytics platform for buildings and district energy systems collocated within a geographically contiguous area. It uses Openstudio and EnergyPlus. These UBEM tools are limited to specific applications and some do not use open standards, which are important for sharing and exchanging information across a wide array of urban modeling tools. A parallel effort to use the Modelica-based framework developed for open Integrated District Energy Assessment by Simulation (OpenIDEAS) by KU Leuven and 3E. This uses building load profiles to optimize district energy using Modelica libraries (Fuchs et al. 2015, Wetter et al. 2015), integrating physics-based modules of systems in a larger context such as district heating/cooling or shared energy infrastructures (Baetens et al. 2012, Baetens et al. 2015). CityBES is an open web platform for city building energy efficiency. It provides (1) GIS-based building performance visualization, (2) portfolio scale building energy benchmarking, and (3) urban scale building energy retrofit modeling. CityBES uses open datasets compiled in CityGML, an international OGC standard for representation and exchange of 3D city models. Some of these programs (CitySim and OpenIDEAS) use reduced order energy models, others (UMI, UrbanOpt and CityBES) use detailed physics-based models like EnergyPlus.

Modeling the energy use of a building in an urban context requires simulating interactions with other buildings and with the urban microclimate. Interactions with other buildings include shading, long-wave radiant exchange between exterior surfaces, and short-wave solar reflection. An urban microclimate, e.g., a heat island or an urban canyon, changes ambient weather conditions (temperature, humidity, wind) for surrounding buildings. In a dense urban setting, these effects can be large and can have a significant impact on building performance. Groups of buildings that are served by a shared district energy system add another layer of building interaction or coupling.

This paper presents several features implemented in EnergyPlus version 8.8 that improve its accuracy in an urban context and expand its applicability to urban scale building energy simulation. These features are discussed along with simulation examples to demonstrate their use and impact.

URBAN MODELING FEATURES IN ENERGYPLUS

Import and export of shading results

Accurate calculation of solar shading on building exterior surfaces is of great importance in whole building energy simulation. Modeling a building in an urban context may involve many shading surfaces from adjacent buildings, which can significantly slow down EnergyPlus simulations using currently implemented shading algorithms. For urban scale simulation—which involves many buildings—there are ways to calculate shading that are more efficient than doing so one building at a time within EnergyPlus. There is also the potential of using GPUs and other parallel computing platforms for shading calculations. Various simulation tools, such as Radiance and Daysim, employing state-of-the-art ray-tracing simulation techniques, can be used to pre-calculate shading fractions for each exterior building surface.

We enhanced EnergyPlus to optionally turn off the internal calculation of shading and import pre-calculated shading fractions as schedules for exterior walls. The new feature enables a significant speed up in urban-scale simulations. It also benefits individual building simulations by allowing reuse of shading results from previous simulation runs. This reuse could benefit conventional workflows but also large parametric studies (e.g., HVAC systems related simulations) which usually do not change external shading. This feature also allows OpenStudio and other EnergyPlus clients to use Radiance for shading calculations.

Long-wave radiant exchange between buildings

Radiant heat exchange between buildings is a key factor in understanding energy flows in an urban context. In older versions of EnergyPlus, calculations for long-wave radiant heat exchange between exterior surfaces and between exterior surfaces and shading surfaces were over-simplified in EnergyPlus, causing potential under or over-estimate of exterior surface temperatures. Specifically, EnergyPlus assumed that the temperatures of exterior surfaces of *different* buildings are essentially uniform and that long-wave radiant exchange between them is negligible. In many urban contexts, specifically in the presence of urban canyons - relatively narrow streets with tall, continuous buildings on both sides of the roads - this assumption is invalid. We enhanced EnergyPlus to calculate long-wave radiant heat exchange for exterior surfaces to and from nearby buildings in addition to long-wave radiation from sky and ground currently considered (Figure 1).

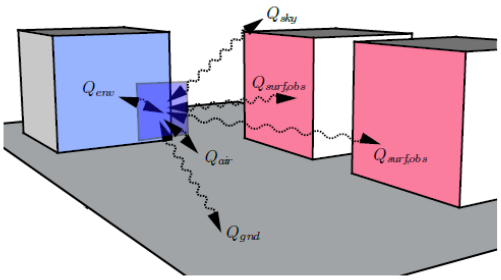

Figure 1 Long-wave radiation calculation considering surrounding surfaces

In the updated model, the energy balance of an exterior building surface from the sky, ground, and surrounding surfaces is written as:

$$q_{LWR} = \varepsilon\sigma[F_{sky}(T_{sky}^4 - T_{surf}^4) + F_{s1}(T_{s1}^4 - T_{surf}^4) + F_{s2}(T_{s2}^4 - T_{surf}^4) + \cdots + F_{sn}(T_{sn}^4 - T_{surf}^4) + F_g(T_g^4 - T_{surf}^4)]$$

Where:

$\varepsilon = long - wave\ emittance\ of\ the\ surface,$

$\sigma = Stefan - Boltzmann\ constant,$

$T_{surf} = Outside\ temperature\ of\ the\ surface,$

$T_{sky} = Sky\ temperature,$

$F_{sky} = View\ factor\ of\ the\ sky,$

$T_g = Ground\ temperature,$

$F_g = View\ factor\ of\ the\ ground,$

$T_{si} = Outside\ temperature\ of\ surrounding\ surface\ \boldsymbol{i},$

$F_{si} = View\ factor\ of\ surrounding\ surface\ \boldsymbol{i}\ to\ the\ surface.$

Note that the sum of all view factors must equal 1, i.e., $F_{sky} + F_{s1} + \cdots + F_{sn} + F_g = 1$.

Heat-balance equations are solved iteratively *within each time step*; resulting in small updates to surface and air temperatures until convergence criteria are met. Because the number of surfaces from other buildings can be large, an iterative solution method can add significant runtime. To avoid this complexity, for surrounding surfaces, we use a fixed temperature T_{si}, specifically the one calculated by the previous time step. Effectively, we assume one timestep worth of "lag" for exterior surface temperatures. This simplification may sacrifice some accuracy but significantly improves computing performance. To each exterior surface, we assign a "surrounding surfaces" object. The object declares a list of surrounding surfaces, and each surface has a name, a constant view factor, and a reference to a temperature schedule. If EnergyPlus is used in "co-simulation" or "urban-scale" mode to simulate multiple buildings in parallel, the schedule can be overwritten at each time step via the co-simulation interface.

Used in an urban-scale modeling application, this new feature enables modeling the urban canyon effect, which also influences the building's energy demand and indoor occupant thermal comfort.

Computational Fluid Dynamic (CFD) tools used to simulate urban micro-climate also need exterior building surface temperatures as boundary conditions. This new feature also allows EnergyPlus to be coupled with CFD-based urban climate tools for an integrated urban energy simulation.

Urban microclimate

The microclimate that surrounds urban buildings can be quite different than "standard" weather data which is collected at airports, essentially flat open fields. The energy consumption of urban buildings is affected by their surrounding microclimate conditions in various scenarios. For example, the air temperature can be higher due to the urban heat island (UHI) effect, or lower mitigating by the presence of water bodies. The local wind speed can be lower due to wind sheltering in a dense area, or higher introduced by high-rise buildings. . Conversely, the building itself affects the outdoor microclimate. As Figure 2 shows, the building model in EnergyPlus serves as the boundary between the interior and exterior (urban) atmosphere model, and the building exchanges mass (air) and heat with the surrounding environment, including exhaust air from fans, DX condensing units, cooling towers, boilers, etc.

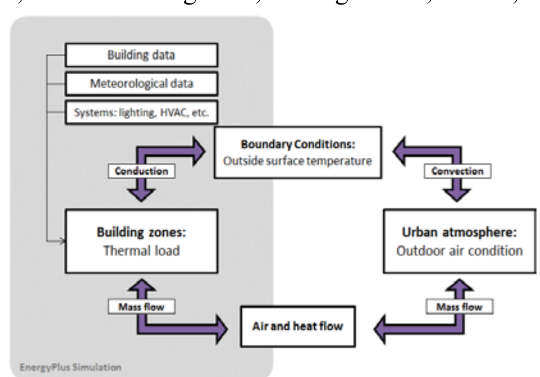

Figure 2 EnergyPlus data exchange with the urban microclimate model

EnergyPlus version 8.7 and older assumes a perfectly elastic outdoor environment that cannot be influenced by the building itself. We enhanced the Outdoor Air Node object in EnergyPlus to allow input and output for outdoor dry-bulb and wet-bulb temperatures and wind speed and direction. The implementation can accept inputs as schedules, allowing EnergyPlus to leverage this information to either simulate a single building using a pre-simulated micro-climate or to co-simulate a collection of buildings. EnergyPlus uses these values in calculations for:

(1) Convection coefficients used in the exterior surface heat balance;
(2) Zone air infiltration and simple ventilation;
(3) External air condition used in the airflow network calculation.

This new feature enables the use of local outdoor air conditions for the calculations of heat and mass balances at the exterior surfaces and zones levels, as well as for air system calculations (e.g., outdoor air entering the AHUs). Since each surface and zone can be linked to a local outdoor air node, this implementation enables the use of local ambient air conditions at arbitrary nodes or coordinates for co-simulation (Figure 3).

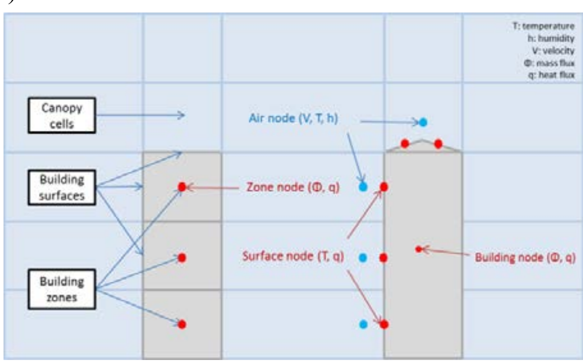

Figure 3 Local outdoor air conditions at the zone and surface levels

SIMULATION EXAMPLES

Simulation Settings

We chose a city block in the Chicago North Region along the Michigan River to conduct a case study, as shown in Figure 4. The block contains 20 buildings, of which 14 are office buildings and six are retail buildings. The total floor area of the buildings ranges from 150 to 24,219 m^2.

Figure 4 A sample city block in Chicago North Region

Figure 4 also maps out the locations of the 15 local Air Nodes used as ambient air conditions for the simulation. Each Air Node has an absolute physical coordinate with a latitude, longitude and height in meters (x, y, z). The 15 nodes are selected based on the layout of streets and the flow of the river. As most of the buildings have only one or two floors and the height of the tallest building is less than 20m, we use a single Z layer (z = 3.0 m) to represent local weather conditions. Figure 5 shows the coordinate of Air Node 4. During simulation, all surfaces at the east façade of Buildings 1 and 2, and the west façades of Buildings 5 and 6 use the microclimate condition at Air Node 4. The environmental data stored at each Air Node is generated from local canopy simulation models.

Figure 5 A sample local air node in the urban context

Figure 6 shows how a single building model takes inputs from the exterior surfaces of other building models and from external local Air Nodes. A surface object gets it local weather condition from the linked Air Node and provides mass and heat flux rate to the Air Node. CFD tools simulating urban micro-climate provide the data for the Air Nodes.

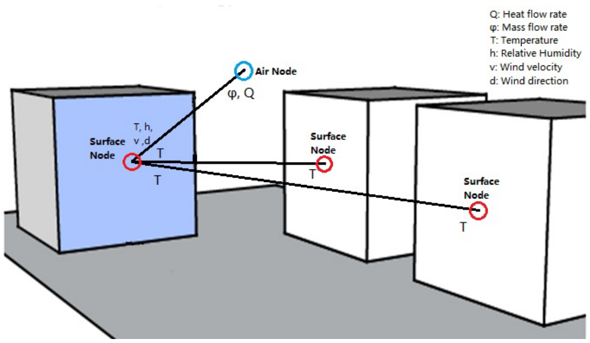

Figure 6 External inputs for a building model in an urban context

For each exterior surface, we calculated the view factor and temperature schedule of every surrounding surface, and linked it to the properties of its surrounding surfaces. For each exterior surface and exterior zone, we calculated its absolute physical coordinates and mapped it to its nearest air node out of the 15 pre-defined ones by distance.

Table 1 Input variables for data exchange to an EnergyPlus model from urban context

VARIABLE	RESOLUTION
Local air dry-bulb temperature	Nearest Air node
Local air wet-bulb temperature	Nearest Air node
Local wind speed	Nearest Air node
Local wind direction	Nearest Air node
Surrounding exterior surface temperature	Surrounding Surface Node

For each time step of the simulation, outputs are generated at each Zone, Surface and System object.

Table 2 Output variables for data exchange from an EnergyPlus model to urban context

VARIABLE	RESOLUTION
Surface convective heat flux rate	Surface object
Surface radiative heat flux rate	Surface object
Exterior surface temperature	Surface object
Zone exfiltration air flow rate	Zone object
Zone exhaust air flow rate	Zone object
Heat rejection from HVAC systems including exhaust/relief air, cooling towers and condensers	System node object

Simulation Results

To analyze the results, we compared the following simulation scenarios.

Scenario 1 runs each EnergyPlus building model individually and independently without considering input from other buildings or the microclimate.

Scenario 2 runs each EnergyPlus building model taking input data generated from other building models. The inputs include a weighted surrounding surface temperature and the corresponding view factor for each exterior surface. For this case, every exterior surface for every building requires an external temperature schedule.

Scenario 3 runs each EnergyPlus building model taking input data generated from external urban canopy models. The inputs include the local conditions at the 15 Air Nodes. For this case, every building requires importing external data from one to four Air Nodes.

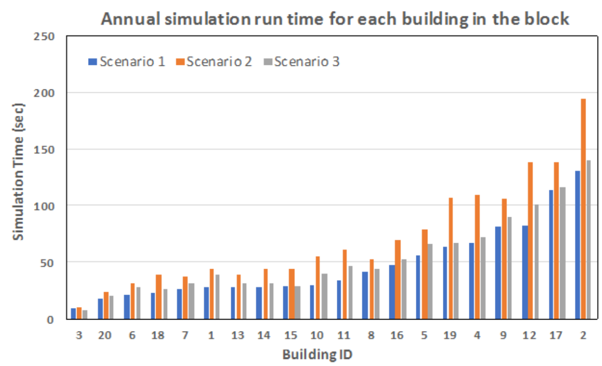

Figure 7 Simulation run-time of the 20 buildings models

Figure 7 summarizes the simulation run-time of 20 building in the sample building block. For Scenario 2 the annual simulation run-time is 50.4% longer than Scenario 1 on average. For Scenarios 3 the run-time is 14.8% longer than Scenario 1 on average. However, if we require a denser data exchange resolution for Scenario 3, such as one air node per zone or per exterior surface, the required run-time and I/O burden can increase.

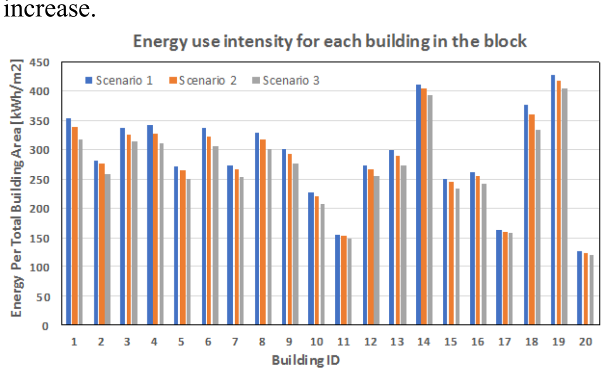

Figure 8 Energy Usage Intensity of the 20 buildings

To evaluate the sensitivity of the energy use to the local environmental data, Figure 8 summarizes the energy use intensity (EUI) of the 20 buildings. Heating dominates for the sampled buildings in Chicago. In Scenario 2, as we account for heat gain from surrounding surfaces with temperatures that are usually higher than the ground and sky temperature, EUI is slightly lower (by 1%-5%) than in Scenario 1. For Scenario 3, as the local temperature is generally higher than the climate data from weather station due to the urban heat island effect, the EUI is 2%-11% lower than the EUI of Scenarios 1. In this experiment, the buildings with larger surface to volume ratios, such as Building 18 in Figure 4, are more sensitive to local microclimate conditions.

For blocks in the downtown area, which generally have a much larger building density and average building height, the energy sensitivity to the urban context can be larger. A variety of experiments can be performed to demonstrate this using the new features of EnergyPlus.

CONCLUSION

This paper presents several new features recently implemented in EnergyPlus version 8.8 to improve its use for urban context and urban scale building energy modeling. Simulation examples demonstrate their use and impact on runtime and energy use calculations. Future studies include effective techniques to couple building energy modeling and urban climate modeling considering their vast differences in spatial and temporary resolutions. More detailed simulation and quantification of the effects of building interactions and coupling between buildings and urban microclimate at a larger scale is also needed.

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REFERENCES

Baetens, D., De Coninck, R., Jorissen, R., Picard, F., Helsen, D., Saelens, L. 2015. OpenIDEAS - An Open Framework for Integrated District Energy Simulations. International Buildings Performance Simulation Association.

Baetens, R., De Coninck, R., Van Roy, J., Verbruggen, B., Driesen, J., Helsen, L. and Saelens, D. 2012. Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation. Applied Energy, 96:74–83.

Chen, Y., Hong, T., Piette, M.A. 2017. Automatic Generation and Simulation of Urban Building Energy Models Based on City Datasets for City-Scale Building Retrofit Analysis. Applied Energy, 205:323-335.

Emmanuel, W. and Jérôme, K. 2015. A verification of CitySim results using the BESTEST and monitored consumption values. Building Simulation Applications Conference.

Fuchs, M., Teichmann, J., Lauster, M., Streblow, R. and Müller, D. 2015. Approach for simulation-based scenario analyses of district energy systems. 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.

Hong, T., Chen, Y., Lee, S., Piette, M.A. 2016. CityBES: A Web-based Platform to Support City-Scale Building Energy Efficiency, Urban Computing 2016.

Hoover, J., & Dogan, T. (2017). Fast and Robust External Solar Shading Calculations using the Pixel Counting Algorithm with Transparency. Building Simulation, (August), 1083–1091.

Jones, N. L. ., & .Greenberg, D. P. (2011). Fast computation of incident solar radiation from preliminary to final building design. In 12th Conference of International Building Performance Simulation Association.

Jones, N. L., McCrone, C. J., Walter, B. J., Pratt, K. B., & Greenberg, D. P. (2013). Automated translation and thermal zoning of digital building models for energy analysis. 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28, 202–209.

Keirstead, J., Jennings, M. and Sivakumar, A. 2012. A review of urban energy system models: Approaches, challenges and opportunities. Renewable and Sustainable Energy Reviews, 16(6):3847–3866.

MIT Sustainable Design Group. 2016. Boston Citywide Energy Model. Available: http://web.mit.edu/sustainabledesignlab/projects/BostonEnergyModel/. [Accessed: 15-May-2016].

NREL. UrbanOpt, https://www.nrel.gov/buildings/urbanopt.html, accessed January 8, 2018.

Reinhart, C.F. and Davila, C.C. 2016. Urban Building Energy Modeling – A Review of a Nascent Field. Building and Environment, 97:196-202.

Reinhart, C.F., Dogan, T., Jakubiec, J.A., Rakha, T. and Sang, A. 2013. Umi - an Urban Simulation Environment for Building Energy Use, Daylighting and Walkability. Proceedings of BS 2013: 13th Conference of International Building Performance Simulation Association.

Wetter, M., Fuchs, M., Grozman, M., Helsen, P., Jorissen, L., Müller, F., Nytsch-Geusen, D., Picard, C., Sahlin, D., and Thorade, P. 2015. IEA EBC Annex 60 Modelica Library - An international collaboration to develop a free open-source model library for buildings and community energy systems. International Buildings Performance Simulation Association.