



Addressing the Need for Microclimate Considerations in DOE Reference Building Prototypes for Urban Energy Simulation with a Focus on The Urban Shadow Effects

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Abstract

The U.S. Department of Energy (DOE) offers building reference prototypes for energy use modeling in commercial and residential buildings. However, these reference prototypes have traditionally been treated in isolation, neglecting the impact of neighboring objects on local microclimate. In urban energy models, where the intricate interaction of urban elements significantly shapes environmental conditions, it becomes more important to reconsider the conventional treatment of building reference prototypes. In this paper we aim to discern potential disparities in energy consumption estimations using DOE prototypes at an urban scale. The Urban Modeling Interface (UMI) was chosen as the simulation platform to incorporate the shadow effect from neighboring objects on building energy use across six scenarios with different shadow coverage by neighboring objects. We found that trees as neighboring structures can decrease cooling load by up to 29%. These results highlight the importance of considering the urban context in energy use estimation of buildings.

Keywords: Energy use modeling, DOE, Building reference prototypes, Residential buildings, Microclimates, Shadow effect.

Introduction

Background and Significance

DOE's Pacific Northwest National Laboratory (PNNL) developed reference building prototypes for commercial and residential buildings in the United States as baseline models for energy use modeling. Structures are divided into two groups by PNNL: Single-family detached houses and multi-family low-rise apartments. Additionally, each configuration is associated with the applicable year of the International Energy Conservation Code (IECC). For residential buildings, there are 3,552 models for 18 climate locations, and for commercial buildings 3,952 models across 19 climate locations have been developed (Prototype Building Models | Building Energy Codes Program, n.d.). The DOE reference

prototypes serve as a basis for researchers to estimate building energy use (Field et al., 2010). These reference prototypes come with their associated EnergyPlus model input data files (IDF) to estimate building energy use.

DOE offers a set of 18 typical meteorological year version 3 (TMY3) weather files for energy use estimation of residential buildings and 19 weather files for commercial buildings. A TMY3 dataset is representative of the climate conditions at the location over an extended period of 30 years (Wilcox & Marion, 2008). Users can choose weather files suggested by DOE or a weather file aligned with their research site. DOE reference prototypes are a baseline for many studies in different fields. For instance, a city-level building energy consumption model was developed in a study by Li et al. (2018). This model allowed for estimating energy usage at the individual building level on an hourly basis across an entire city. In that study, the U.S. DOE reference buildings played a pivotal role in determining the baseline energy usage (Li et al., 2018). In another recent project Chen et al. (2022) employed the U.S. DOE reference prototype as a reference point for their investigation into the temporal variations of anthropogenic heat emissions from buildings.

The DOE reference prototypes serve as a benchmark for building performance assessment. However, it is essential to acknowledge that while these building prototypes offer valuable insights, they often treat buildings as isolated entities and overlook the intricate interaction of neighboring objects which can affect the local microclimate. Numerous studies in urban-scale energy management have demonstrated the significant impact of microclimates on building energy usage. For instance, in Trondheim, Norway, a study by Brozovsky et al. (2022) assessed the impact of urban surface composition on microclimate and building energy demand. Using Computational Fluid Dynamics and Building Performance Simulation, four scenarios were analyzed for a 13-floor office building. During a heatwave, the absence of vegetation increased cooling energy demand by 28.5%. In autumn and winter, a no-

vegetation scenario lowered heating energy demands by 3.5% and 0.9%. (Brozovsky et al., 2022). This study highlights the crucial role of microclimate considerations in accurate energy performance assessments.

Mosteiro-Romero et al. (2020) employed the microclimate model ENVI-met and the district-scale energy simulation tool City Energy Analyst for a study of Zurich, Switzerland. The simulation demonstrated a 5% increase in space cooling load on hot summer days when considering the local microclimate at the district scale (Mosteiro-Romero et al., 2020). These results underscore the importance of expanding understanding beyond conventional building codes to incorporate microclimatic dynamics. This knowledge enhances the precision of energy models and paves the way for more sustainable and resilient building practices.

Research Objectives and Questions

Microclimate refers to specific climate conditions on a localized scale close to the Earth's surface (Naiman et al., 2005). Trees can regulate a microclimate by creating shadows and through evapotranspiration. In the context of this paper, our primary focus is on understanding the significance of considering the influence of trees and neighboring buildings on energy consumption when using DOE reference buildings. The outcome of this paper provides a preliminary understanding of how shadows from nearby objects influence energy performance and efficiency, ultimately contributing to more accurate and context-aware energy simulations. This investigation seeks to bridge the gap between standardized reference prototypes and the dynamic real-world conditions that buildings operate within, offering insights into the importance of adapting building design and energy strategies to local microclimates.

The parameters utilized in prototype development, rooted in isolated building scenarios, lack consideration for the intricate factors shaping the urban microclimate. As highlighted by Javanroodi and Nik (2019), the microclimate is notably influenced by factors like building size and shape, surface albedo, vegetation and water bodies, giving rise to localized variations in temperature, humidity, wind patterns and other weather conditions. Trees are one element that can significantly regulate the microclimate surrounding buildings. Dong et al. (2023) evaluated urban trees' cooling effects and energy-saving potential during the summer season in a severely cold region of China. They found that the energy savings due to trees varied across local climate zones in the study area, ranging from 0.9% to 8.0%. Another study by Tsoka et al. (2021) proved that optimized trees placement could reduce cooling demand by up to 54%. The primary objective of this research is

to evaluate the significance of neighboring structures on building energy consumption, a factor not included in DOE reference prototypes.

Methodology

To account for the influence of neighboring objects, this study utilizes the Urban Modeling Interface (UMI), a Rhinoceros-based tool specifically designed for urban modeling developed at the Sustainable Design Lab at Massachusetts Institute of Technology (Reinhart et al., 2013). This tool has demonstrated its ability to capture intricate urban shadows, as highlighted in the work of Dogan and Reinhart (2014). UMI employs EnergyPlus as a simulation engine for building thermal simulations (Reinhart et al., 2013).

This study was initiated by choosing a specific prototype from the comprehensive list of building prototypes provided by DOE. The selected prototype is a single-family residential building with a gas furnace heating system and a slab foundation, situated in climate zone 5A, representing Des Moines, Iowa, USA. This study is part of a larger, comprehensive project in which Des Moines serves as the study area. The results obtained from this residential prototype will be integrated into the main study by aligning the chosen prototype with the specific needs of the broader study. Following DOE guidelines, users are authorized to customize the provided IDF files to suit the precise geographical context of their study area.

We made modifications to the longitude, latitude, time zone, and elevation values in the selected prototype to accurately reflect the geographical attributes of our study area. DOE established some assumptions for the geometry of the building, such as a 220 m² conditioned area and 110 m² unconditioned area above the conditioned area and eight windows with specific dimensions on each side (Figure 1).

A 3D model was developed based on the selected DOE prototype in UMI to investigate the influence of neighboring structures on energy use. In DOE prototypes, eight windows are specified, each positioned 0.9 meters above the floor, measuring 1.5 meters in height and 2.7 meters in width. Conversely, the UMI approach introduces a modification by preserving the proportionality of window area on each wall—10 percent on the north and east sides and 20 percent on the south and west sides of the building (Figure 2). This adaptation in the UMI approach arises due to modeling constraints, as UMI does not support the precise representation of windows with specific dimensions; instead, it relies on window-to-wall ratios for design.

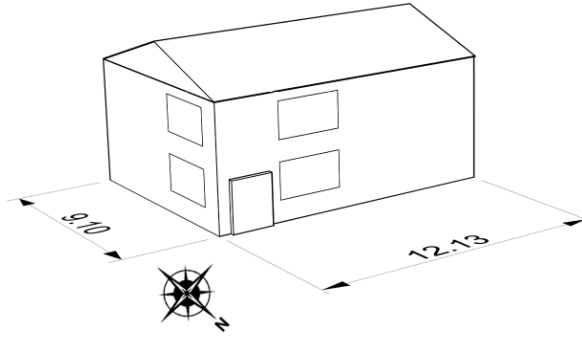


Figure 1-Geometry of the DOE residential building prototype.

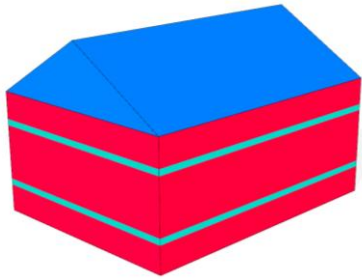


Figure 2- The 3D model generated in UMI based on the geometry of the DOE building prototype.

In line with the inherent thermal attributes of the chosen prototype, a corresponding Template Library File (TLF) was created to be utilized in UMI. The TLF, configured as an XML file, includes the thermal and environmental characteristics of all buildings and spaces within the UMI model and serves as a comprehensive repository for energy use estimation. The TLF includes building material, construction, heating/cooling set point, occupancy schedule, ventilation schedule, and heating/cooling schedule inherited from the DOE prototype. Following the preparation of the UMI template library and the establishment of the building's geometry, the model was executed in UMI to compare outcomes with the original DOE cooling and heating load. The objective was to verify the accurate transfer of the modeled file from EnergyPlus to UMI. This file serves as the baseline scenario for the subsequent steps in the analysis. Subsequently, neighboring objects were added to the model to explore the influence of shadows on energy consumption (Figure 3).

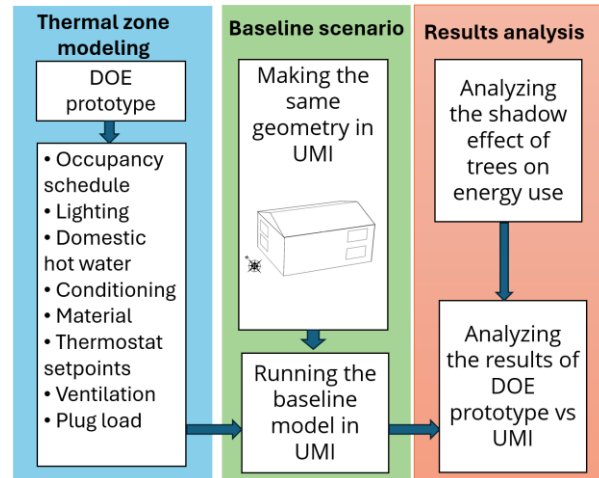


Figure 3- The workflow used to investigate the importance of shadows on building energy consumption using DOE reference building prototypes.

Six scenarios were developed to investigate the shadow effect of neighboring objects on building energy use in an urban context that is not included in DOE building prototypes. The baseline scenario involves estimating the annual cooling load of the selected DOE prototype using UMI instead of EnergyPlus. The purpose of the baseline scenario was to ensure a seamless file transfer to UMI. In Scenario 1, a single tree with a crown diameter of 6 meters and a trunk height of 1.5 meters is positioned on the South side, 3.5 meters from the wall. In Scenario 2, an additional tree of the exact dimensions is added, maintaining the same distance. Scenario 3 involves the placement of a third tree on the East side, with the prescribed distance from the wall. Similarly, in Scenario 4, a second tree is added to the East side. In Scenario 5, a neighboring building of equal height to the target building is added to the West side. Adhering to real-world conditions, the North side of the building is intentionally left open without any shading objects, mirroring practical considerations. This design choice is influenced by the sun path, as the impact of sunlight is more pronounced on the South, East, and West sides (Figure 4).

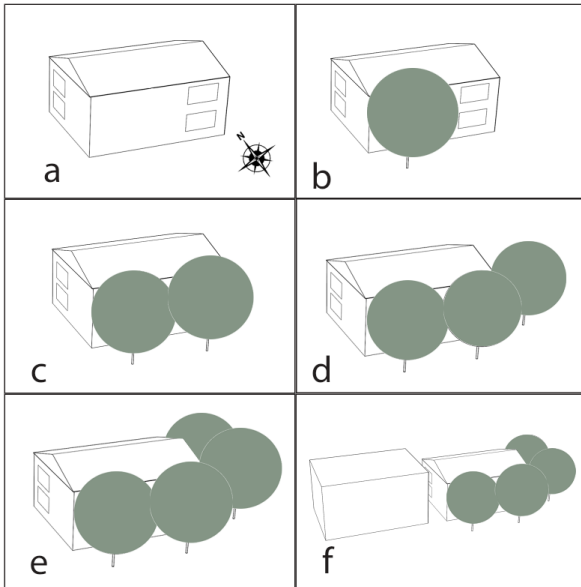


Figure 4- Scenarios to investigate the importance of the shadow effect of neighboring objects in DOE prototypes. a) the baseline scenario, b) scenario 1, c) scenario 2, d) scenario3, e) scenario 4, f) scenario 5.

Similarities and differences between UMI and the EnergyPlus files associated with the DOE prototypes

UMI and the DOE prototypes are distinct in their approaches for generating thermal zones. DOE prototypes employ single-zone thermal zoning, simplifying the whole building as a box. This method has been shown to provide less accurate results, especially for cold days (Johari et al., 2022). In contrast, UMI uses core/perimeter zoning. This method segments the floor plan into a "core" and "perimeter" area. The perimeter refers to the space adjacent to the facade. This outer area is further divided based on orientation, and if sections possess glazed exterior surfaces with multiple orientations the subdivision is carried out proportionally. The central portion of the floor plate is identified as the "core." (Dogan, et al.,2014). Spaces are categorized into core and perimeter zones, based on ASHRAE 90.1–2016, Appendix G (ASHRAE 90.1 Section 11 and Appendix G Submittal Review Manual, 2021), one of the most reliable methods for achieving precise results in the initial phase of building energy modeling (Manav et al. et al., 2020), (Shin & Haberl, 2019). Thus, UMI employs a more refined approach by dividing spaces into core and perimeter zones, enhancing the accuracy of thermal simulations.

The second difference is the Heating, Ventilation, and Air Conditioning (HVAC) system setting. UMI adopts the EnergyPlus "IdealLoadsAirSystem" component,

allowing for assessment of building performance without the need to model a complete HVAC system. On the other hand, the DOE prototype incorporates the "Zone HVAC Energy Recovery Ventilator (ERV)" for its ventilation needs, a different strategy to optimize energy efficiency and indoor air quality. It is also worth mentioning that the DOE prototype's IDF files include sizing calculations for design days, a feature absent in UMI. Design days include Summer Design Day (for cooling) and Winter Design Day (for heating), allowing users to customize the schedules for design conditions. In this study, the design days for Des Moines were obtained from the ASHRAE handbook (ASHRAE Sequences of Operation 1.0, n.d.). Additionally, UMI utilizes the DOE2 algorithm for outside surface convection, contributing to a more robust heat transfer simulation. This contrasts with the DOE approach, which accounts for the outdoor convection algorithm in its simulations explicitly.

Moreover, UMI incorporates the conjunction transfer function in its heat balance algorithm, a feature not considered in the DOE prototypes. Thus, there are differences between UMI modeling and IDF files provided by DOE (Table 1). Based on the 2015, 2018, and 2021 versions of the IECC, the DOE prototypes implement the airflow network for duct leakage modeling in the context of single-family prototypes. The multi-family prototypes have duct leakage specifications in later updates. Preventing duct leakage is essential for building energy savings (Makawi et al., 2023); even well-insulated ducts will lose heat (Minimizing Energy Losses in Ducts, n.d.).

Table 1- Similarities and differences between UMI files and IDF files provided by DOE.

Input	DOE Prototype	UMI model
Thermal zone	Single zone for whole building (conditioned and unconditioned)	Core and perimeter zones
HVAC system	Energy Recovery Ventilator (ERV)	Ideal Loads Air System
Sizing calculations	Design days	NA
Outside surface convection	NA	DOE2 algorithm
Heat balance	NA	Conjunction transfer function
Duct leakage specifications	Varies based on IECC	NA

Results

In this study we focused exclusively on comparing the cooling effects of neighbouring objects, including trees and nearby buildings, for two reasons. Firstly, the investigation concentrated on the impact of tree shadows on the cooling load of buildings, recognizing the significant influence of tree shading on the thermal dynamics of structures. Secondly, a detailed examination of heating and cooling loads due to adjustments in leakage ratio and various sub-settings within EnergyPlus indicated the heating load exhibited more significant fluctuations than the cooling load across different IECC standards from 2006 to 2021 (Table 2).

Table 2-Comparison of cooling and heating loads of single-family prototypes for different IECC codes.

IECC	Heating (kWh)	Cooling (kWh)	Supply Leak	Return Leak
2021	20,089	2,184	0.0396	0.0396
2018	20,230	2,409	0.0396	0.0396
2015	20,575	2,409	0.0396	0.0396
2012	20,737	2,410	0.0396	0.0396
2009	34,192	2,656	0.099	0.099
2006	39,607	2,821	0.1485	0.1485

Among the IECC standards spanning from 2006 to 2021, IECC 2006 was chosen as the benchmark. This decision was motivated by the higher duct leakage ratio associated with IECC 2006, aligning more closely with the characteristics of the UMI model, which does not incorporate considerations for duct leakage.

As outlined in the workflow, the initial phase focused on a seamless transition from simulating DOE prototypes in EnergyPlus to UMI. Cooling loads for the IDF file associated with the DOE prototype revealed a marginal difference (Table 3). The cooling load for the IDF file is 2821 kWh, while the UMI model for the same file indicates a closely aligned value of 2782 kWh, suggesting a negligible variance between the two models.

Table 3- Cooling loads of the models simulated based on the selected DOE prototype in UMI compared to results of the IDF file for the selected DOE prototype.

Model	Cooling Load (kWh)
IDF file associated with the DOE prototype	2821
UMI model	2782

Under identical geometry, thermal characteristics, and environmental conditions, the cooling loads for both models remain consistent (Table 3). This finding reaffirms the reliability and accuracy of the baseline scenario on the UMI simulation platform. The successful integration of the baseline ensures a stable foundation for

comparative analyses to assess the impact of different scenarios on cooling load.

In order to investigate the importance of considering the shadow effect of the neighbouring objects on energy use based on DOE building prototypes, six scenarios were compared in terms of cooling load using UMI.

We then compared the cooling load of the six developed scenarios that varied based on the shadow coverage of the targeted building (Table 4).

Table 4- Overview of the parameters and differences in annual cooling load for the scenarios used in UMI.

Scenario	Annual Cooling Load (kWh)	Scenario Impact (%)
Baseline	2782	0.00
Scenario 1	2652	4.67
Scenario 2	2538	8.77
Scenario 3	2531	9.03
Scenario 4	2493	10.4
Scenario 5	1984	28.67

Adding objects around the buildings resulted in a decrease in cooling effect by 4.67 % when adding one tree on the south side of the building and in scenario 2 with adding one more tree of the same size and distance from the building on the south side of the building drops the cooling load by 8.77 % (Table 4). This change decreased by 9.03% when considering another tree on the east side of the building. Adding the second tree on the east side decreases the cooling load by 10.4 %, and finally, with all trees present adding one neighbouring building on the west side reduces the cooling load by 28.67 %.

Discussion

This investigation into trees and nearby buildings' shadows revealed their influence on the cooling load of buildings. Trees, with their ability to cast shadows and mitigate solar heat gain, emerge as crucial contributors to the overall energy efficiency of buildings. The disparities observed across the various scenarios (Table 4) underscore the pivotal role of nearby objects' shading effects in shaping energy consumption patterns. Without additional objects, the baseline scenario served as a reference point against which the subsequent scenarios were evaluated.

Scenario 1, involving the addition of a single tree on the south side of the building, resulted in a 4.67% decrease in the cooling load. This reduction is attributed to the shading effect provided by the tree, mitigating the solar heat gain on the building's southern facade.

Scenario 2 included another tree of the same size and distance from the building on the south side. This adjustment led to a more substantial 8.77% decrease in

the cooling load. The cumulative effect of multiple trees further contributed to shading and reduced solar exposure.

Scenario 3 introduced a tree on the east side of the building, leading to a 9.03% decrease in the cooling load. This variation highlights the impact of orienting shading elements strategically, considering the sun's path throughout the day.

In Scenario 4, adding a second tree on the east side resulted in a 10.4% reduction in the cooling load. The cumulative effect of shading from multiple trees on different sides of the building demonstrates the potential for optimizing energy performance through thoughtful landscape design.

In traditional building energy simulations, the absence of trees often corresponds to higher energy use for cooling, as exemplified by the DOE reference prototype. The DOE prototypes designed to treat buildings in isolation tend to yield higher energy use since they do not account for shading effects from nearby objects. Our results underscore the substantial influence of surrounding objects on energy performance.

Conclusion

In conclusion, our study examined six scenarios for estimating building energy use, each with distinct outcomes. The baseline scenario uses DOE Prototypes that treat buildings as isolated entities, focusing on minimal consideration of microclimate factors. In contrast, the other scenarios employing UMI incorporated the influence of trees and other buildings through shading effects, representing more realistic urban conditions.

The results from the six scenarios further elucidate the influence of shadow coverage on annual cooling load. Notably, the progressive addition of objects around the building led to a decreased cooling load. This decrease ranged from 4.67% with the addition of a single tree on the south side to a significant 28.67% when all trees and a neighbouring building on the west side were incorporated.

The difference between these scenarios highlighted the pivotal role of local microclimate effects in shaping energy consumption patterns. This observation emphasizes the critical need for nuanced and localized energy modelling, considering microclimate influences to yield more accurate and relevant energy assessments.

The significance of understanding and incorporating local microclimate effects in shaping energy consumption patterns extends far beyond individual building models; it is crucial for the development of comprehensive and effective urban energy models.

In urban settings, where diverse microclimates and varied architectural landscapes coexist, considering buildings as isolated objects leads to inaccurate energy use estimation. As demonstrated in this study, local microclimate effects can play a pivotal role in optimizing energy efficiency at the building level. Recognizing and accounting for these influences is essential for creating urban energy models that accurately reflect the intricacies of energy usage within the context of specific environmental conditions.

In addition, we note that this study did not incorporate evapotranspiration effects, crown size, and species of trees which can impact energy use to an even greater degree. The exclusion of these factors in many earlier urban energy models represents an avenue for further exploration and an opportunity to enhance the precision of future energy assessments.

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