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Developing a Workflow to Integrate Tree Inventory Data into Urban Energy Models

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Abstract

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Keywords

Urban building energy simulation, urban forest inventory, urban 3-D modeling, urban trees and shading, algorithmic modeling

Disciplines

Architectural Engineering | Computer-Aided Engineering and Design | Data Storage Systems | Environmental Design | Historic Preservation and Conservation | Natural Resources and Conservation | Urban, Community and Regional Planning

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ABSTRACT

Building energy simulation is of considerable interest and benefit for architects, engineers, and urban planners. Only recently has it become possible to develop integrated energy models for clusters of buildings in urban areas. Simulating energy consumption of the built environment on a relatively large scale (e.g., such as a neighborhood) will be necessary to obtain more reliable results, since building energy parameters are influenced by characteristics of the nearby environment. Therefore, the construction of a 3-D model of urban built areas with detail of the near-building environment should enhance simulation approaches and provide more accurate results. This paper describes the process of integrating urban forest inventory data into a 3-D energy model for a US Midwest neighborhood, including building footprint, parcel and tree data. This model was prepared for use in the Urban Modeling Interface (*umi*) tool to analyze the effect of tree shading on building energy performance. We used Grasshopper 3-D, the Meerkat plug-in, and GIS to integrate these datasets for model generation.

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ACM Classification Keywords

I.6.1 SIMULATION AND MODELING, I.6.5 MODEL DEVELOPMENT

1 INTRODUCTION

Advances in information technology have provided a wide array of new digital tools to support urban energy modeling. 3-D models of existing cityscapes, which can be updated, corrected, and augmented, allow for visualization of proposed and approved additions [1]. Although the effects of urban trees on building energy consumption have long been recognized [2, 3, 4, 5], integration of trees in dynamic energy modeling is a fairly recent endeavor [e.g., 6, 7] and examples of visualization are rare. Several tools are available to create 3-D models of urban environments, but for most of them it is not possible to rapidly integrate subsequent changes that alter the initial data set used for modeling. The model extensions

Grasshopper 3-D [8] and Meerkat [9] (both Rhinoceros-based plug-ins) provide an advanced method to update 3-D models according to changes in GIS shapefile data from site-based surveys. These tools can support decision and design processes in close to real time because it is possible to import contemporaneous GIS data. The workflow we created is useful for any location for which GIS data are available. This model can be incorporated into the urban building energy modeling platform *umi* (Urban Modeling Interface), which is a Rhinoceros-based design environment for architects, engineers, and urban planners interested in modeling the performance of neighborhoods and cities with respect to operational and embodied energy use, walkability and daylighting potential [10, 11]. The objective of this paper is to present a workflow to integrate building location and thermal-physical data with tree data to create a 3-D model of an urban environment with a dense tree canopy, and provide preliminary results describing the impact of the vegetation on building energy consumption. Energy consumption for residential cooling and heating is affected by tree placement, which can modify temperatures by casting shade [6]. The *umi* model is well suited to enable better understanding of the climatic and energy benefits of urban trees [12].

2 STUDY AREA

The Capitol East neighborhood in Des Moines, Iowa was the pilot study area for this urban energy simulation. It was chosen as a test case primarily because of social and economic characteristics that limit residents' capacity to regulate temperatures in their homes. This neighborhood is situated just east of the State of Iowa Capitol complex, near downtown Des Moines. In this paper, we integrate spatially explicit data from a complete inventory of existing trees in the neighborhood (both yard and street trees) to incorporate 1142 trees and 340 buildings in the simulation (Figure 1).

3 TREE INVENTORY

Tree data were collected in an inventory of a portion of the neighborhood during summer 2017: 1142 neighborhood trees were catalogued using a Trimble Geo 7X Handheld GNSS reciever. Data collected include tree species, trunk diameter, tree height, canopy shape/height, canopy width in two dimensions, and latitude/longitude coordinates.

Figure 1. Area of complete survey for trees and building data, Capitol East Neighborhood, Des Moines, IA. Map: Google 2017.

4 WORKFLOW

Grasshopper 3-D, the Meerkat plug-in, and GIS shapefiles were used to create the 3-D model of the buildings in the neighborhood. The first phase of model creation was the data collection process for the two major input sources for the model. Geographic Information System (GIS) files for building footprints and parcels (maintained by City of Des Moines' Assessor's office) and for urban trees.

4.1 GIS Shapefiles

A shapefile (.shp or .dbf) is a simple, non-topological format for storing the geometric location of geographic features. The workspace containing shapefiles may also contain dBASE tables, which store additional attributes joined to the shapefile features [13]. In our model development process, the GIS shapefile for Capitol East Neighborhood buildings (building footprints, elevation, and parcel) was obtained, and the tree data were subsequently integrated with it.

4.2 Meerkat

After preparing shapefiles for buildings and trees, which contained required information to create the model, we imported them into Rhinoceros 3-D. To do so, we used Meerkat (a GIS data-parsing plug-in) to import shapefile data into Rhinoceros 3-D. This plug-in allows selection and cropping of shapefile layers for a specific area of interest. The result is a layered collection of 2-D linework that can then be further manipulated in Grasshopper or Rhino [9].

First, to reference GIS shapefiles by Meerkat, the "Import Shapefile" module connected to a "Boolean Toggle" was chosen. By turning the Toggle to "True", the Meerkat interface was activated. After Meerkat was launched, the shapefiles created in the previous step (building footprints, parcel and tree inventory data) were added to the Meerkat map interface by selecting the "Add Shape File" menu item. We then used the "Crop Shape File" function in Meerkat to save the three .mkgis files.

We next linked the .mkgis files to the "Parse .mkgis" function through a "File Path" module. All information included in the shapefile was transferred to the Grasshopper interface under .mkgis format. By default, Meerkat locates the GIS information in a place far from the origin space of

Rhinoceros, so it is necessary to center the data at a 0.0.0 point. In order to work with all three shapefiles and create the entire model in one Grasshopper file, three "Parse .mkgis" modules were needed to address the files for building footprints, parcels and trees separately.

4.3 Grasshopper 3-D

After importing shapefiles through Meerkat to Grasshopper, the next steps of the process were performed in the Grasshopper interface. The "Area" module was used to create the center point of the bounds in point space using the "Construct Point" module. Using these two modules and a "Vector2 Point" module, we were able to move the center points of all geometries to an origin point in the Rhino canvas. The vector repositioned all points to a visible Rhino workstation via the "Move" module. After establishing center points of all geometries, the "Polyline" module was used to create line work from the points. These steps led to a similar base map for all necessary geometries (buildings and trees). The same process was used to locate building footprints, parcels, and trees.
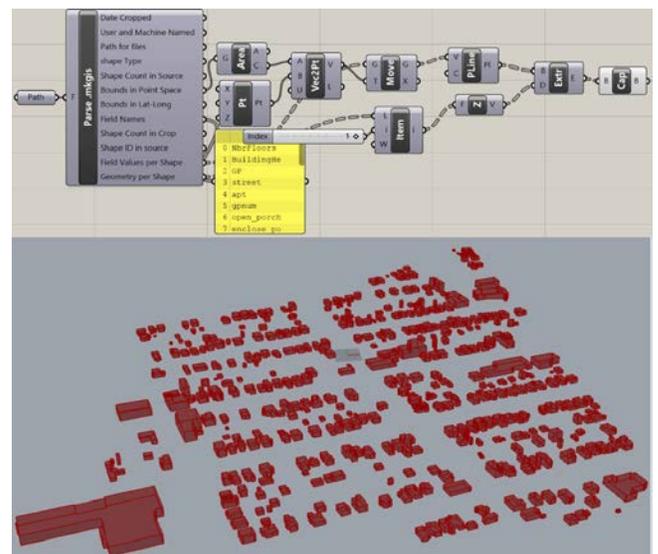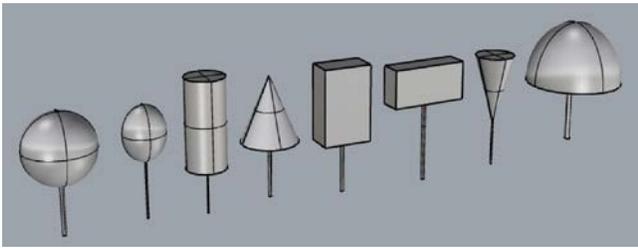
5 GEOMETRIES

5.1 Building Parcels

Building parcel 2-D outlines were created in polyline.

5.2 Buildings

To extrude single line segment data for the buildings at their correct elevation, building height was extracted from the .mkgis file connected to the "Parse .mkgis" module. In the "Panel" connected to "Field Names" building heights were saved using index number 1. The "List Item" from "Field Values per Shape" and index number 1 were used to collect building heights and a Z-vector was used to determine the direction for buildings to be elevated. The "Extrude" module containing the base of building footprints was combined with the Z-vector to create building heights. The "Cap" module was used to close the polysurfaces (Figure 2).

**Figure 2.** Workflow components for the creation of 3-D buildings.

Figure 3. Eight geometries were used to represent tree canopies.

5.3 Trees

The tree inventory included eight canopy shape categories: spheres, ellipsoids, cylinders, cones, horizontal rectangular cuboids, vertical rectangular cuboids, umbrella shapes, and paraboloids (Figure 3). The "Tree Shape" category in the tree shapefile was used to extract shape information using the "List Items" by index number 2 in the "Parse .mkgis" module. Here, workflow components for creation of tree trunks (cylinders) and paraboloid canopies (most common canopy type) are described in detail. Other shape categories follow the same process (see accompanying data set), with each shape category requiring their own creation "Module".

Trunks

Tree trunks were represented by cylinders. We created a cylinder module using three inputs, the base location (point data created in the "Move" module), trunk radius (based on data for tree diameter), and tree height. By looking at the "Panel" module connected to "Field Names", tree diameter and height were added in columns 3 and 5 inside the .mkgis file. As the "Cylinder" module is based on radius, we divided DBH (diameter at breast height) using a "Division" module after the "List Item" module. A Cap module was then used to close the polysurfaces (Figure 4).
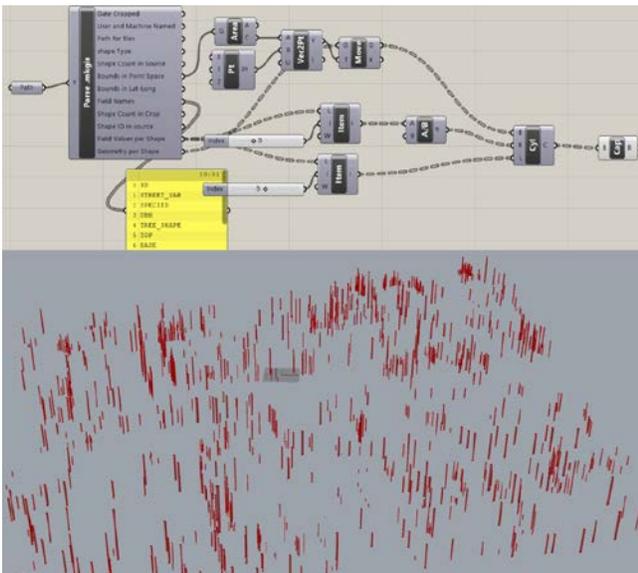
**Figure 4.** Components used to create cylindrical tree trunks.

Paraboloid Tree Canopy Template

Paraboloid canopies were created as semi-ellipsoid shapes. First, the process for creation of spherical canopies was used. To create trees with spherical canopies, two inputs - the base and the radius of the sphere - were needed. A "Match Text" ("TMatch") input command was used to choose only those trees with paraboloid canopies using the "List Item" from "Field Values per Shape" by index number 4 (tree shape) and panel letter Pa* (an abbreviation for paraboloid-shaped geometry). To include measurement of canopy radius for each tree, outputs of the "TMatch" module were multiplied by the outputs of the "List Item" module with index number 7, which included average N-S and E-W dimensions for each sphere diameter, and then divided by two to get the radius.

Then, using the "Surface Split" and "Deconstruct" modules we halved the spheres, and a "Dispatch" module was used to remove the bottom part of the spheres. Semi-spheres created in this step were converted to semi-ellipsoid shapes using a "Scale NU" module with a defined value (ranging between 1 and 1.5) to stretch each semi-sphere in the Z direction and create a semi-ellipsoid. Semi-ellipsoids had a bottom tangent line located at ground level, so they were adjusted such that their top tangent line fit to the top of the trunk using a "Multiplication" module to merge "TMatch" module output with the "List Item" index number 5 (containing tree heights).

We next used a "Subdivision" module to adjust the height of each paraboloid in the Z direction equal to its radius and fit the top tangent line of paraboloids to the top of the trunk. A "Cap" module was then used to close the polysurfaces (Figure 5).
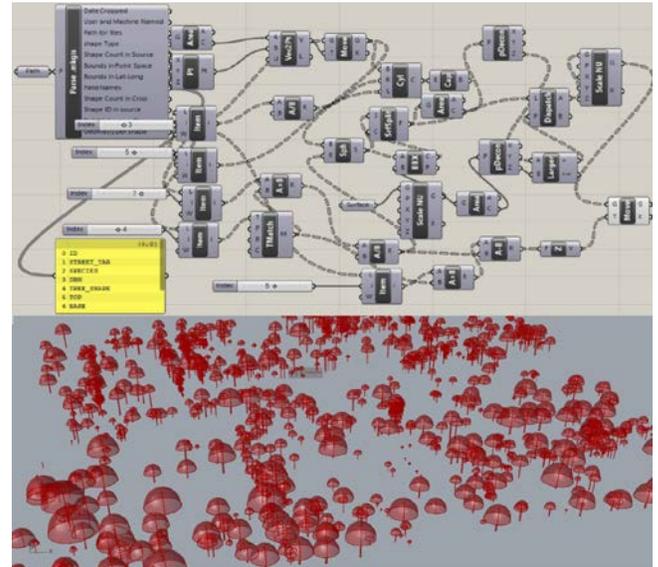
**Figure 5.** Components used for trees with paraboloid canopies.
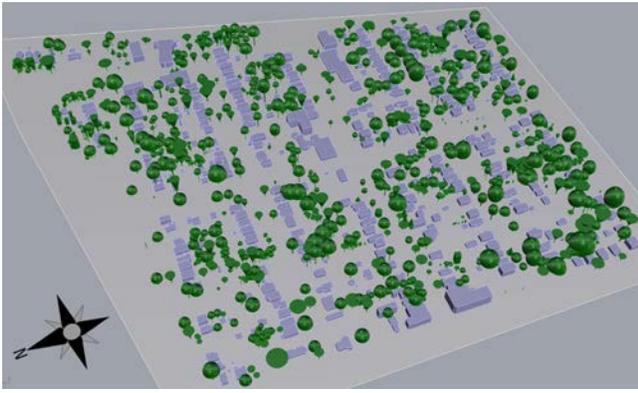
Figure 6. Final "Baked" visualization model in Rhinoceros.

Baking Grasshopper Model to Rhinoceros

The Grasshopper modules containing the buildings and trees were then exported to Rhinoceros 3-D using the "Bake" command to create a visualization (Figure 6).

6   RESULTS AND DISCUSSION

The model provided input into *umi* to simulate the energy performance of each building in the selected neighborhood area for two scenarios, with and without trees. Simulations were performed assuming typical meteorological year (TMY) conditions using the TMY 3 data set for Des Moines [14]. For the initial simulation, each building was assigned a template for construction type and condition of the building (generated using the GIS and assessor's data). Templates (37 of them) were created in *umi* for buildings by combining construction information to describe the material properties and performance of an entire structure. According to the assessor's data for the 340 buildings, 259 of them had active air conditioning systems and 81 were naturally ventilated. In the templates, air infiltration rate was set in a range between 0.34-0.75 ACH and insulating material resistance (R-value) differed between 1 and 4 m^{2}K/W. We created a visual simulation to illustrate annual cooling energy demands for buildings in the model with the presence of trees, based on construction template, location, and orientation (Figure 7).
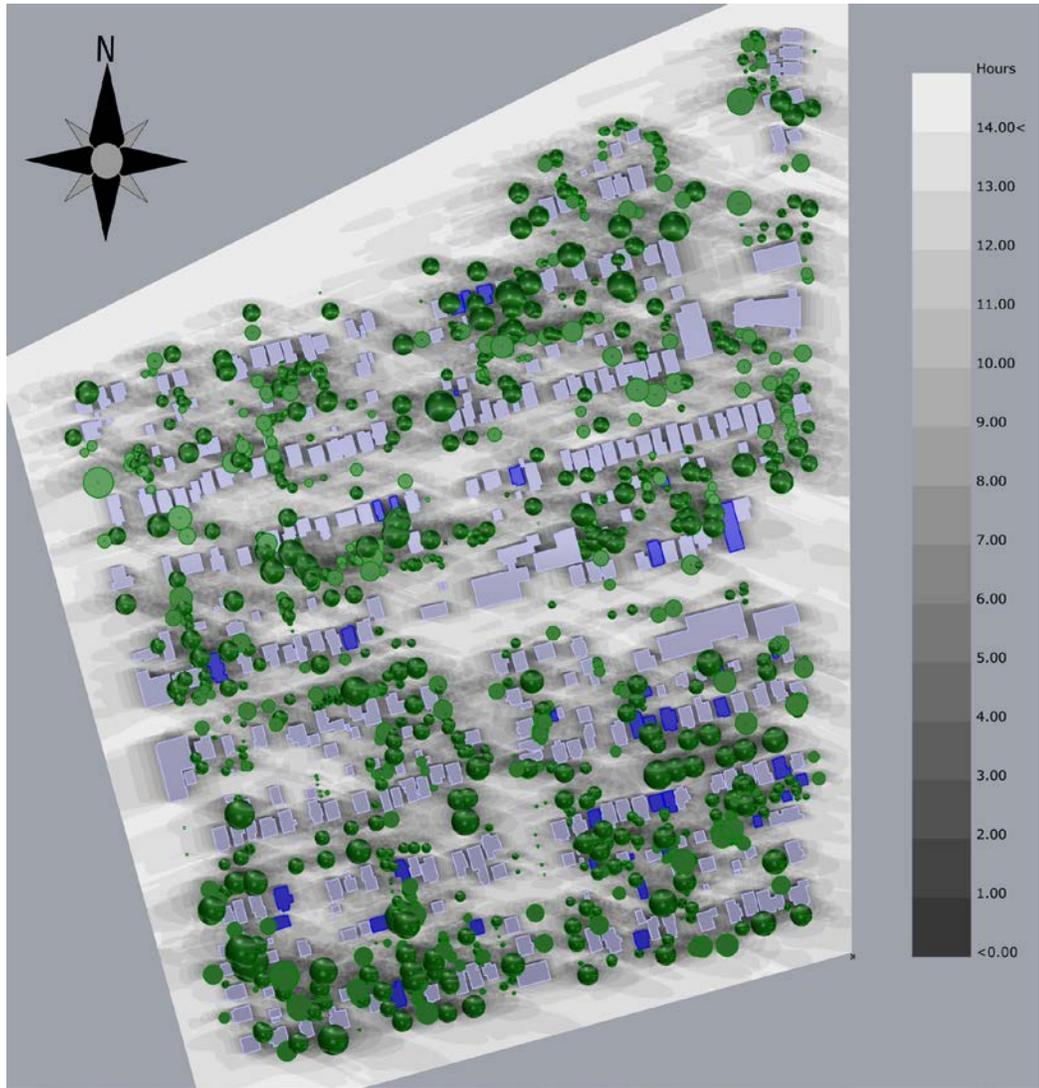
Figure 7. Shadow range analysis (May-September). Hours of direct sunlight received by buildings increases from dark to light colors; buildings indicated in blue are those with more than 5% reduction in cooling demand for the scenario with trees.
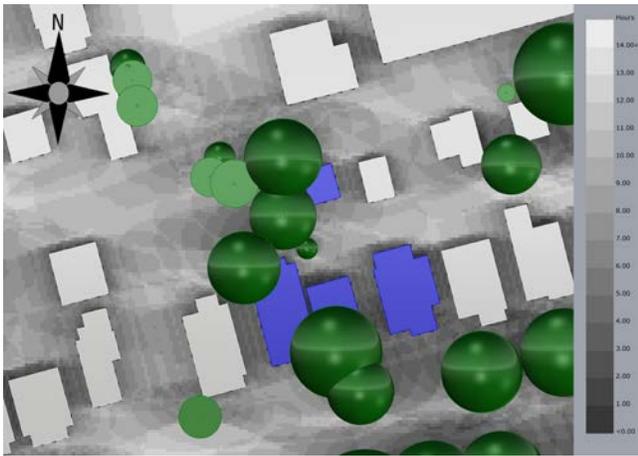
Figure 8. Close-up of a group of buildings with more than 5% reduction in cooling demand.

For this simulation, the trees were considered simple shading devices in order to monitor their effects on total operational energy and cooling demands based on their location and the size and shape of their canopies. The preliminary positive impact of trees as shading devices was confirmed in the *umi* model for annual cooling energy consumption. Trees resulted in 1% to 20% potential active cooling energy savings for spring and summer months (May to September). There were approximately 40 buildings with potential cooling energy savings more than 5% (shown in blue, Figures 7 and 8). Buildings with significant cooling energy savings (5-20%) typically had templates with envelope R-values greater than 3 (m^2K/W), which were high compared to other building templates in the simulation. Nearly all buildings showing substantial differences in cooling demand in the model with trees are well shaded by trees, especially those located south of buildings (Figure 8), which limit exposure to direct sunlight. It is important to note that *umi* also incorporates the effect of nearby buildings as shading devices in calculation of cooling demand by each building. Many buildings in this neighborhood do not have active cooling systems, so the primary impact of trees is reduction of air temperature and mitigation against overheating in these structures (rather than energy savings); further investigation of other relevant building characteristics is ongoing.

7   CONCLUSION AND FUTURE WORK

Our preliminary results indicate a relatively modest effect of trees on potential cooling savings, but the model and simulation does not yet include evapotranspiration, which is likely to increase the effect of trees on building energy dynamics, as suggested by other researchers [6, 15]. The method we used shows great promise for development of more comprehensive energy models for buildings and near-building environments, and will likely allow us to discern the relative impact of tree shading in relation to other building characteristics. The current model is now ready to be incorporated into *umi* for additional analyses we expect to conduct that will include evapotranspiration, specifically using computational fluid dynamics (CFD) techniques that incorporate other tree canopy characteristics (percent canopy filled, leaf area and density).

One potential drawback of this technique is the amount of effort required to collect comprehensive tree inventory data. Although many municipalities have such data for street trees, there are relatively few comprehensive urban forest inventories that include such data for trees on private property. It may be that development of specific empirically-based models will allow calibration of models using other available data (such as LiDAR imagery with detail for tree canopy shape and size) in the future. Another drawback is use of generic weather files, which in our case did not allow us to account for urban heat island and specific microclimate effects in the vicinity of the buildings, which would also be necessary to further refine the thermal environment. However, the method presented here does provide the opportunity to easily update shapefiles using the Meerkat plug-in, and incorporate additional information in the model to include these phenomena. We expect to update the tree shapefile to include trees in a larger portion of the study area, and to incorporate more refined weather and building parameter information. Continual updates will allow us to extend the model and generate more accurate results.

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