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Shoeboxer: An algorithm for abstracted rapid multi-zone urban building energy model generation and simulation

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ABSTRACT

In this paper the authors present an algorithm that abstracts an arbitrarily shaped set of building volumes into a group of simplified 'shoebox' building energy models. It is shown that for generic perimeter and core floorplans the algorithm provides a faster but comparably accurate simulation results of annual load profiles vis-à-vis multi-zone thermal models generated according to ASHRAE90.1 Appendix G guidelines. Envisioned applications range from rapid thermal model generation for urban building energy modelling to schematic architectural design. Following a description of the algorithm, its ability to produce load profiles for a mixed-use neighborhood of 121 fully conditioned buildings for a variety of climates is demonstrated. The comparison yields relative mean square errors in simulated annual building energy use intensity of five to 10 percent compared to ASHRAE 90.1 compliant building energy models while reducing simulation times by a factor of 296.

1. Introduction

The earth's urban population will nearly double by 2050, requiring the construction and densification of hundreds of new cities and neighborhoods [1]. With building related CO2 emissions tripling and quintupling in rapidly growing developing countries [2], urbanization is widely recognized as both a liability and opportunity to fight climate change. Building new livable and energy efficient urban areas can thus be seen as the defining planning challenge of our century. Until recently, the use of building energy modelling (BEM) tools to support the design of neighborhoods seemed unrealistic due to the immense effort required to even model the energy performance of a single building. However, the concept is becoming an increasingly active field of research and multiple key advances make urban building energy modelling (UBEM) tools a valid option for urban designers, planning boards and others.

In the literature, urban modelling approaches mainly follow three steps: Segmentation, characterization and simulation [3]; Cerezo et al. [30].

Segmentation and characterization are often done by selecting sample buildings to represent a larger group of buildings within the model [4–9]. Both steps require detailed building stock data sets as inputs that are available for several countries [10]. The simulation result of each sample building is then extrapolated. Thus, geometric detail is lost as diverse urban morphology cannot be taken into account.

More modern tools use the concept of building templates that contain all non-geometric energy model inputs of archetypical buildings and then apply these templates to each building geometry within the model. The individual buildings are modelled as single [11–13] or multi-zone buildings [31,14,36].

Single zone approach tends to rely on the simpler and therefore faster energy load estimation methods [15] vis-a-vis more detailed dynamic simulations. While simple heat balance methods are widely accepted for heating load estimation, cooling load predictions are found to be less reliable [16,17]. Simple methods usually also fail to capture detailed shading effects which makes them less relevant for urban design explorations.

Single-zone models also cannot model different space uses within a building and may therefore introduce unintended load cancellation effects. To address this issue, researchers implemented an automated zoning algorithm called "Autozoner" that generates multi-zone building energy models from arbitrary building volumes [18]. For urban modelling purposes, this algorithm can be applied to large sets of building volumes. The resulting thermal models yield hourly energy load predictions for every zone in every building throughout a city or neighborhoods. The reader may

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rightfully wonder whether such a detailed and calculation intensive modelling approach is justifiable and useful for an urban level analysis. One the positive side, multi-zone models can resolve what happens if building orientation and programmatic uses within a building are being redistributed. However, such detailed interior building explorations do not tend to happen during early urban massing design exercises, when floor plan layouts are still unresolved. As that point it is rather common to assume more generic and uniform space uses across a building. The separation of a building into multiple adjacent zones with equal or similar programmatic use will typically lead to small internal heat flows between those zones whose calculation requires a significant but often unjustifiable computational overhead.

In such cases, it is common practice to utilize zone or floor multipliers to simplify and therefore accelerate the simulation. For example, a free-standing tower with uniform program could be reduced to three floors; one that models the ground contact, another for the roof and finally the in-between condition. The remaining floors would be modeled by simply scaling up the in-between floor loads accordingly. However, this approach can only be used when contextual shading is not existing or simple enough so that it can be adequately represented in the simplified model. For urban applications, which are the focus application of this manuscript this is generally not the case.

These observations triggered the authors to explore automated procedures to substantially simplify multi-zone UBEM simulations that can capture complex urban shading situations by abstracting groups of buildings as simplified perimeter and core shoebox models. The resulting urban simulation algorithm, called the "Shoeboxer", is described in the following section and simulation results from models generated using the Shoeboxer are compared to conventional multi-zone UBEM simulations for a mixed-use neighborhood of 121 fully conditioned buildings. Comparison criteria are similarity between the simulations, calculation speed as well as the capability to perform parametric design explorations on urban massing models.

2. Methodology

The methodology section is divided into two main parts: First, a detailed description of the Shoeboxer algorithm is given. Then a systematic comparison to multi-zone thermal models is described.

2.1. Shoeboxer algorithm

As shown in Fig. 1, the Shoeboxer algorithm consists of five steps: 1) input generation and organization, 2) discretization and clustering, 3) shoebox simulation and result compilation 4) and representation.

2.1.1. Input generation and organization

Algorithm inputs are closed poly-surfaces, so called boundary representations (BREP), of all buildings or building-subsections within a given neighborhood. Each BREP should only contain spaces of equivalent programmatic use, i.e. a building with retail spaces at the bottom and offices on top should consist of at least two BREPS. For each programmatic use there should be a zone template that contains all non-geometric building assumptions such as construction assemblies, internal gains, occupancy schedules as well as HVAC settings and controls. As described by Cerezo et al. [29] the advantage of this separation is that an engineer or consultant with specialized knowledge can assemble the building template data for a given project whereas urban designers and planners can work with these templates by simply assigning them to individual building BREPs.

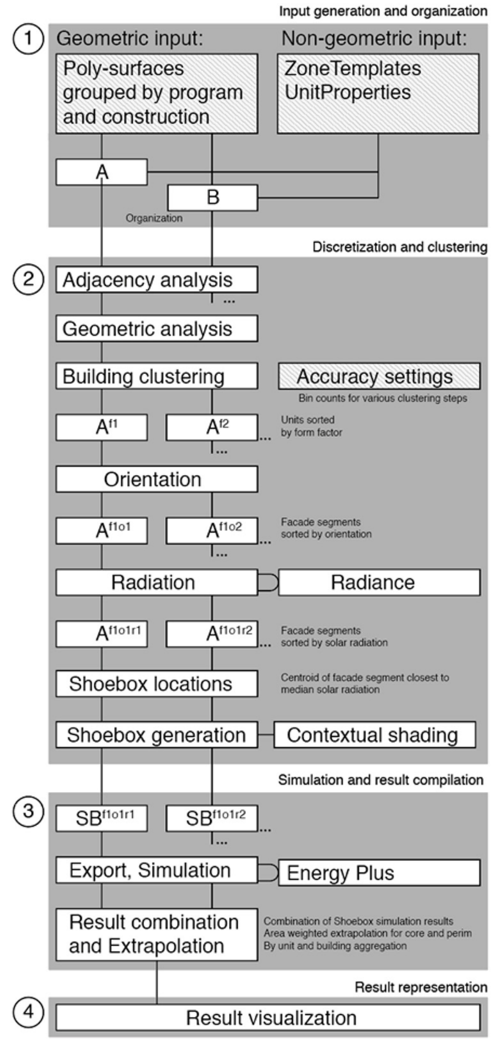

Fig. 1. Shoeboxer algorithm flow chart.

2.1.2. Geometric input

The street grid is the most dominant organizational pattern that defines all kinds of flows (traffic, energy, waste) within a city. The layout and resolution of the grid also define block size and anticipate, to a certain degree, the built densities and functional distribution within the design. Fig. 2 shows a typical, early design

Fig. 2. Block Layout.