Automated multi-zone building energy model generation for schematic design and urban massing studies

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Abstract

In this paper we present an algorithm for automated multi-zone building energy model production for urban and schematic design. By reviewing current guidelines for thermal zone discretization of early design building energy models [BEM] we present an argument that current zoning guidelines effectively recommend the use of a straight-skeleton like subdivision. Based on this finding, our procedure accepts an arbitrary building massing and subdivides each floor into core and perimeter thermal zones. As a proof of concept the algorithm was implemented as a plug-in for the parametric design environment Grasshopper for Rhinoceros. A number of examples of various complexities are shown to demonstrate its robustness and suitability for automated multi-zone BEM generation.

Keywords: energy modeling, urban and schematic design, automatic zoning.

1. Introduction

The earth's urban population is expected to double by 2050, requiring the construction and densification of hundreds of cities and neighborhoods [UN, 2012]. With 30-40% of the world's energy consumption coming from buildings and more than 60% of the increase in building related CO2 emissions coming from developing countries [UNDP, 2010], creating livable and energy efficient buildings and urban environments can thus be seen as the defining planning challenge of our century. The use of tools for building energy use optimization is, however, underutilized when it comes to understanding and predicting the energetic implications of schematic and urban design decisions. Computer-based building performance simulation (BPS) tools have been developed since the early seventies to test drive different design concepts during schematic design in order to ensure that individual buildings provide "high comfort spaces" while having a "minimum environmental impact" [Hensen & Lamberts, 2011]. Yet, despite the improved usability of these tools, they tend to be mostly applied during design-development or for demonstrating code compliance. As a direct result of this delayed use of tools within the design process, a recent survey of energy modelers and architects by Samuelson et al. [2012] revealed that even in AEC (Architecture, Engineering, and Construction) firms which employ in-house energy models the results of simulations had in over 30% of cases only "rarely" or "occasionally" an impact on design decisions. This finding is problematic since architects would benefit most from simulation-based feedback during the exploration of rapidly changing design variants, as it is common practice in the early design stages. Similarly, urban designers, a group that traditionally does not employ energy modeling tools,

would also greatly benefit from using energy simulations to inform site layout, massing studies and program distribution [Besserud & Hussey, 2011].

One of the reasons for the aforementioned delayed use of BPS in design is that the generation of BEMs out of existing architectural or massing models currently involves multiple manual steps and is therefore time and resource intensive [De Wilde, 1999][Mahdavi et al., 2003][Ianni et al., 2013]. Applying current modeling practices to urban level projects that involve multiple buildings therefore remains the exception and (if at all) is done using a combination of spreadsheets with simulations of more generic building archetypes. Such a modeling approach is unsuitable for resolving details of urban microclimate and detailed neighborhood planning. An alternative approach to the spreadsheet method would be to use already available 3D models (that are produced anyhow e.g. for renderings or plan production) and automatically convert them into energy models. Over the years, different groups have worked on various aspects of this problem [van Treeck & Rank, 2007] [O'Donnell et al. 2013] [Pratt et al. 2012] [Jones et al. 2013].

A key distinction between previous methods is the level of detail of the architectural input model that is to be converted into a BEM. In 2007 van Treeck demonstrated how a full 3D Building Information Model (BIM) that includes interior walls and usage definitions can be auto-translated into an energy model. The method presented performs a "dimensional reduction of 3D building models using graph theory" [van Treeck & Rank, 2007]. The algorithm uses Boolean operations to decompose the input geometry and then performs surface overlap tests to establish a connectivity network for a multi-zone energy model. Similarly, O'Donnell et al. [2013] worked on a semi-automated BIM to BEM conversion process implementing automated space boundary identification. Pratt et al. [2012] presented a geometric modeling protocol and framework that included geometry correction and surface heuristics that would allow the conversion of more traditional 3D CAD models with interior space subdivisions into BEMs. Later that same group refined this approach, presenting additional methods for "cleaning up" real world architectural models by removing small holes, reducing the number of interior surfaces and using a view-factor based method to identify zones and their adjacencies [Jones et al. 2013].

All of these studies assumed that a detailed BIM or CAD model of a building with defined interior spaces is available for conversion into BEM. Typically such models are available later in the design process. The studies further tended to convert each room in the architectural model into a new thermal zone. In contrast to these previous efforts, this paper is mainly concerned with the conversion of more abstract massing models into BEM. Within the context of this paper a massing model is a geometric representation that approximates the shape of a building and that does per se not contain any information about the interior subdivision of a building such as floors and walls (Figure 1). This "empty hull" is then paired with

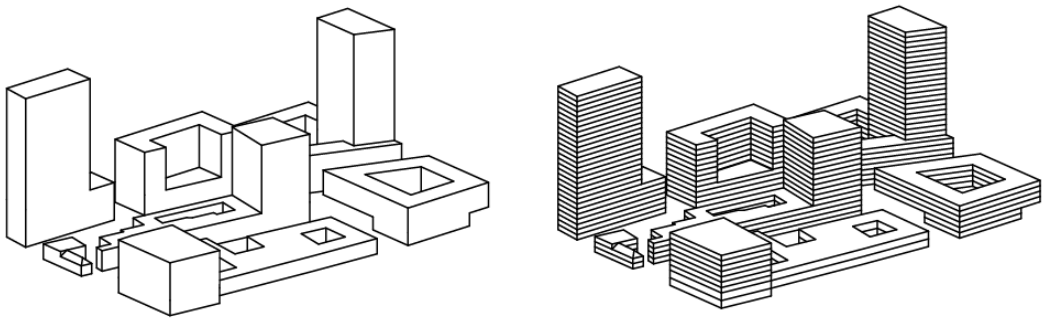

Figure 1: Massing model and its typical modeling styles in urban and schematic design. a) Building envelope b) Buildings as stacked floor volumes

a vague idea on how the interior can be used programmatically, how the building could be materialized and how the facade might look like, e.g. a mixed use building, office-residential, heavy construction with punched window facade. A thermal simulation, however, requires more specific inputs, windows have to be modeled explicitly and the building volumes need to be discretized more finely into thermal zones. Thus, two essential steps are required to convert massing models into BEMs automatically. During step one, the building volume, represented by poly-surfaces, has to be converted into multi-zone thermal model geometry, involving a discretization into multiple sub-volumes to represent floors and zones and geometrically articulated facades. In the second step, parameters have to be assigned to the individual zones including information such as materiality, space usage and space conditioning.

This manuscript is mainly concerned with the first step, i.e. the automated conversion of an architectural massing model as defined above into a meaningful multi-zone BEM geometry that can be used by a whole building energy modeling program such as EnergyPlus, TRNSYS and others [Crawley et al., 2000] [Klein, 1979] [ESRU, 2005]. The next paragraph reviews current guidelines for generating multi-zone thermal energy models of buildings and lays the foundation for the following methodology of our auto-zoning procedure.

2. Early design multi-zone energy models

For decades modelers have implemented multi-zone thermal models to simulate energy use of a building. It is therefore somewhat surprising that there exists relatively little scientifically backed advice as to how an “early design variant” should be broken up into discrete, thermal zones. According to the literature [Hirsch, 2010] [BEMBOOK, 2014] a thermal zone should roughly correlate with the spatial subdivision of a building into rooms and spaces. To simplify the simulation and also the HVAC system layout, multiple rooms may be joined together in one zone if they share similar load profiles. However, the floor plan that would provide a basis for such a room subdivision is usually unknown during the schematic design stage. ASHRAE 90.1 Appendix G hence provides a brief guideline for this case stating that the floor plan should be divided into a “core” and “perimeter" region. The perimeter is defined as the space along the facade with a depth of five meters. Further, the perimeter should be subdivided by orientation and spaces with glazed exterior surfaces with more than one orientation should be subdivided proportionally. The leftover region in the center of the floor plate forms the “core” [ANSI/ASHRAE/IESNA, 2007]. 90.1 Appendix G provides no binding guidance of how the boundary between different zones should be modeled.

The original motivation for breaking a building into thermal zones is that simulation programs treat all zones as a node within a thermal network that represent a perfectly mixed air volume. So, the theory goes that if one for example models a larger building as a single thermal zone than heat surplus that may occur during the winter near a south facing space may be absorbed by a space to the north that is underserved by solar gains. As a consequence the predicted energy demand decreases due to a balancing between loads, gains and absorption/dampening capacities of a space [Smith et al. 2011]. Figure 2 compares various multi-zone thermal models of the same floor to a single zone model assuming low and high internal loads. The figure shows that annual loads for heating and cooling may differ by up to 13% and 14% for low and high internal loads, respectively. As expected, the Appendix G method yields higher and thus more conservative annual loads than the single zone simulation.

As mentioned earlier, the 90.1 Appendix G guideline does not specify how to take inter-zone heat and mass transfer into account. Figure 3 reveals the magnitude of this effect by

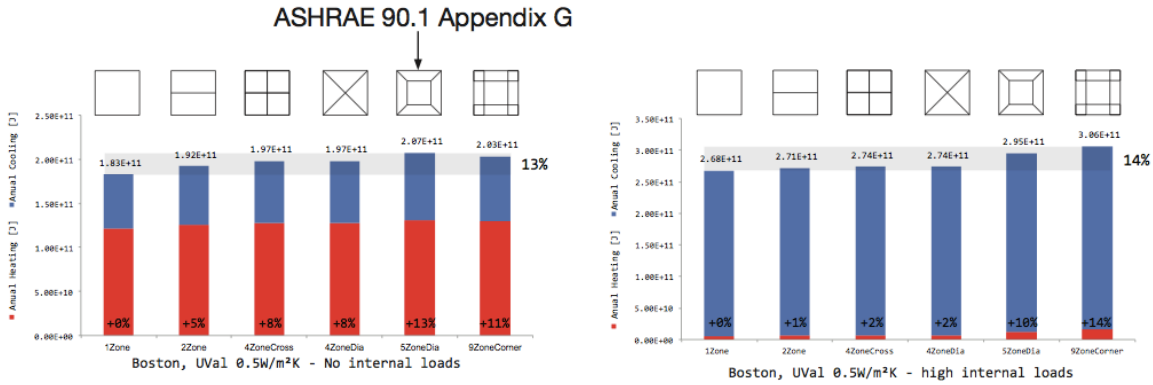

Figure 2: Comparison of subdivision schemata for two extreme internal load scenarios.

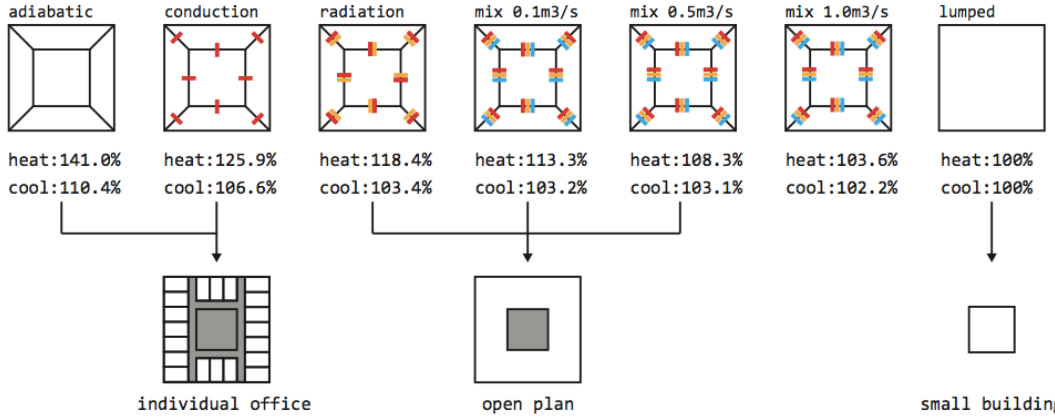

Figure 3: Comparison of a perimeter and core subdivision with different inter-zonal heat and mass transfer scenarios versus a single zone simulation and their correlation with architectural floor plan typologies.

comparing annual loads for the building from Figure 2 divided according to Appendix G but with interior zone boundaries being either adiabatic and step by step adding conduction, solar radiation and different levels of air mixing. As one would expect, adding these different inter-zone heat flows successively bring the Appendix G solution closer to the single zone solution. While ASHRAE 90.1 does not give recommendations on and leaves it up to the modeler to provide accurate assumptions, we conclude this mini experiment by grouping the heat and mass transfer into three useful architectural scenarios (floor-plan-typologies) that can be implemented as presets in the following energy modeling workflow. The “individual office scenario” only considers conduction heat transfer between the zones. The “open plan” scenario can consider radiation exchange and inter-zone air-mixing. The “small building” scenario allows to simulate lumped zones.

The previous paragraphs confirm the relevance of current practice to divide a building into multiple thermal zones and identify 90.1 Appendix G as the only existing guideline advising on discretizing a building volume into thermal zones. This paper proposes a method to carry out this step automatically. Several existing design tools also have auto-zoning methods implemented. Autodesk Vasari [Autodesk, 2013] is a commercially available schematic design tool for architects, can automatically split up a building massing into perimeter and core zones. Details of the zoning algorithm and its implementation have not been publicly released. Similarly, Reinhart et al. [2013] introduced software for multi-zone energy model production. The software is, however, limited to simple and strictly orthogonal shapes and adjacencies to neighboring buildings are not recognized. In the following section a general algorithm is described that overcomes these limitations.

3. Methodology

The presented research builds on three tools for simulation and geometric modeling: EnergyPlus, the McNeel Rhino Platform and Archsim Energy Modeling for Grasshopper. EnergyPlus is a whole building energy simulation program that can model building related energy flows in a sub hourly time resolution [EERE, 2013]. It is validated thoroughly and it is distributed free of charge. This makes it one of the most accessible professional energy simulation tools available and thus is the simulation environment of choice. McNeel Rhinoceros is a CAD modeling software that can create, edit, analyze, and translate curves, surfaces, and solids. McNeel offers extensive support for plug-in development with the RhinoCommon SDK. This research relies heavily on this basic geometric modeling ecosystem [McNeel, 2013]. Rhino was also chosen due to its popularity among architects and urban planners. Archsim Energy Modeling for Grasshopper is a user and programming interface for energy model production. It features a thermal model class library containing abstract definitions for zones, faces, materials, etc. and can translate those into a simulation engine specific syntax. Archsim supports EnergyPlus and the TRNSYS. Given a set of geometry and parameters it constructs multi-zone thermal models and writes out the simulation input file [Dogan, 2013]. For rapid energy model production two essential capabilities are added to the above toolset:

- **Automated geometry production:** The massing model input geometry has to be divided into sub-volumes representing the floors, perimeter and core zones of a building.
- **Efficient parameter assignment:** The produced geometry has to be paired with additional information such materiality, loads, schedules and HVAC settings to generate a complete thermal model.

In the following section the automated geometry production workflow is explained in detail. Methods for efficient parameter assignment are introduced afterwards. We then present three test cases that show the robustness of the algorithm and its feasibility for an ArchSim/ EnergyPlus modeling workflow.

Automated Geometry Production

Input: Based on the authors experience from practice and teaching, urban and schematic design processes mainly produce two types of input geometry. In the earliest stages, the buildings are modeled as a single volume. This form of representation helps the designer to understand basic morphologic features such as the massing and the proportions of a design. It usually originates from a 2D drawing that is extruded. Another very common representation involves “stacking” floor-volumes. This adds a notion of “scale” since it immediately allows one to read floor heights from the model. It is also popular since it is inline with the architectural design process, thinking of distributing program and densities. The following algorithm can work with both styles (Figure 1). If “Case A” is encountered one volume is interpreted as one building envelope. For “Case B”, the algorithm requires the user to group the volumes if they belong to the same building. For "Case A" the algorithm begins with a floor to floor subdivision of the envelope based on a floor height that is specified by the user. The floor to floor distance can be given as array to take into account varying floor heights. For "Case B" the floor subdivision procedure is skipped. Starting point for all following steps is a “Building” that consists of a list of sub volumes for each floor.

Subdivision: The next step is to subdivide the floor volumes into thermal zones. For a limited number of cases the perimeter and core zone subdivision, as described by the previ-

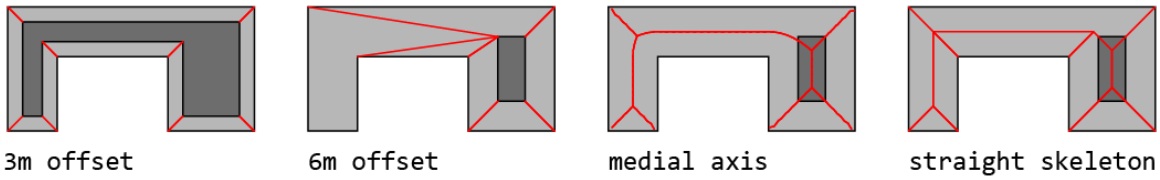

Figure 4:
a) Perimeter split b) Failure c) Medial axis d) Straight skeleton (with a concave cell)

ously mentioned ASHRAE 90.1 Appendix G guideline, is a trivial and fast operation. The core region can be found by offsetting the outer edge of the floor plan. Then a simple search for the closest point from the outer polygon vertices to the inner ones can already yield the desired subdivision. This is shown in Figure 4a. When the search function returns pointers to the inner vertices, the lists of points that make up a zone outline can be constructed, even if edges of the offset polygon collapse. For more complicated cases the above mentioned approach fails. Figure 4b shows a convex floor plan with a core region that retreated completely from the left part of the polygon due to a series of collapsing edges during the offset. It subdivides parts that have good “core visibility” as intended but leaves the entire left half undivided. Now, an ear-clipping method [Meisters, 1975], [ElGindy et al., 1993] could divide the rest into convex regions. However, with a certain thickness of the remaining polygon-tip it might be desirable to split the tip into single sided zones instead of a lumped region with access to multiple cardinal directions.

This would require a splitting axis somewhere along the medial axis [Preparata, 1977] of the polygon. A medial axis approximation is shown in Figure 4c. The medial axis however, does not consist of straight line segments and instead can involve parabolic curves. This is not desirable since the final output of the algorithm are 3D thermal zones that should ideally consist of as few as possible planar surfaces. Very similar to the medial axis but involving just straight lines is the "straight skeleton" that was first described by Aichholzer et al. [1996] and extensively discussed [Aichholzer & Aurenhammer, 1996], [Barequet et al., 2003]. The straight skeleton of a polygon as shown in Figure 4d divides the polygon into cells for each outer edge and is thus fulfilling the requirement of splitting perimeter zones by orientation. In order to obtain a core and a valid thermal zone subdivision a couple of simple steps have to be added. In a second step the algorithm produces the core region by performing an offset of the outer and hole polygons. Then the core overlap is removed from each skeleton cell by a 2D boolean difference operation. Due to limitations of the radiation distribution algorithm of EnergyPlus and TRNSYS the thermal zones have to be strictly convex spaces. Thus, the resulting perimeter and core zones have to be further subdivided if they are concave. Various polygon partitioning techniques exists for this task and have been described in detail [O’Rourke, 1998]. Since the resulting perimeter regions are guaranteed to be hole-free, a simple split at each concave vertex perpendicular to the longest exterior edge of the polygon delivers the desired result. The core regions however, can consist of polygons with holes. One simple example is a donut-shape floor plate with a circular core region. Here, a triangulation and a subsequent diagonal-removal procedure is used to obtain strictly convex zones [Hertel & Mehlhorn, 1983]. The result of the previous steps is a set of 2D regions for the perimeter and the core of each floor plate. Pseudo code that briefly summarizes the previously described steps is given below.

The implementation of a robust straight skeleton algorithm that can handle complex polygons is not a trivial task. The presented algorithm uses a ported and slightly improved

Algorithm **TWODIMENSIONALZONING**(*F*)
Input. A set *F* of poly-lines in a plane representing the outlines of a floor plan.
Output. A list of doubly connected edges describing the cellular core and perimeter subdivision $\mathcal{TDZ}(F)$.

1. Compute the straight skeleton S(F) and store the resulting skeleton cells in a list
2. Compute an inward offset O(F) of the input poly-lines *F*.
3. O(F) describes the core region(s)
4. **FOREACH**
5. **DO** obtain c
6. **IF** p
7. split c
8. **ELSE**
9. append c
10. Split $\mathcal{R}_{\text{CORE}}$
11. append $\mathcal{L}_{\text{CC}}$
12. **RETURN** $\mathcal{TDZ}(F)$

version of an implementation that has been provided by Petr Felkel and has been extensively described by Felkel & Obdrzalek [1998]. For both the offset and the Boolean operations the algorithm rely on the polygon clipping library “Clipper” by Johnson [2012].

Form 2D regions to 3D zones: The 2D core and perimeter cells have to be further processed to obtain the final 3D volumes that represent a thermal zone. The simplest approach is to extrude the cells by the floor height. This however, is only possible if the facades of the initial envelope are vertical. In order to avoid this limitation the algorithm uses the previously generated or provided floor volumes. Analogous to cutting styrofoam blocks with a hot wire the algorithm computes vertical clipping planes along the 2D perimeter and core regions while skipping outer edges and then cuts out the zones from each floor volume. Pseudo code is given on the next page.

Adjacency: In urban scenes it is quite common that buildings touch each other and not every face of the envelope is a facade with outward facing windows. In such a case the algorithm needs to identify such faces in order to assign the correct boundary conditions and materials later. Additionally, the zoning should also react to inter-building partition walls to avoid building a perimeter zone there. In order to detect adjacencies the algorithm uses Archsim EM's adjacency graph building functionality. Archsim relies on congruent faces with opposing face normal in order to find a connection. It provides a recursive face splitting algorithm to handle geometry that has touching surfaces with non-congruent surfaces. With the adjacencies identified, the zoning procedure can now build adjacency aware core and perimeter regions. Adjacencies are handled by joining the neighboring floor plans into a single plate before core and perimeter region offsets are computed. Considering the possibility that floor plans are not always at matching Z-coordinates, the closest floor plan in the neighboring building is used. The offset regions are then trimmed back to the buildings original size, resulting in a core region that now touches the adjacent wall element. However, his procedure is not always straight forward: In an extreme case where the core offset in the neighboring building completely collapses and "retreats" back into only one building, undesirable core geometry can be produced.

Algorithm **THREEDIMENSIONALZONEGEOMETRY**($\mathcal{TDZ}(F)$, V)
Input. A set of planar zoning cells $\mathcal{TDZ}(F)$ and the corresponding floor volume V.
Output. A list of closed volumes representing the thermal zone geometry for core and perimeter $\mathcal{ZG}(\mathcal{TDZ}(F), V)$.

1. **FOREACH**
2. **IF** c_p
3. Create an extrusion of c
4. Append E(c
5. **ELSE**
6. Duplicate V as V
7. **FOREACH**
8. **IF** e is an interior edge
9. Trim V
10. Append V
11. **RETURN** $\mathcal{ZG}(\mathcal{TDZ}(F), V)$

Automatic window/shading modeling: After the zone geometry is modeled, we have to further articulate the facades. The user can specify orientation dependent window to wall ratios that are then used to model the window surfaces on all outward facing zone surfaces. This can be done by duplicating and then scaling the windows parent surface. Alternatively, standard Grasshopper modeling capabilities can be used to implement more elaborate facade design patterns such as punched hole facades with multiple small openings or simple horizontal window stripes. Manual intervention is also possible.

Parameter assignment

In addition the algorithm producing the zone geometry the user needs to be presented with an efficient way to assign essential simulation parameters, such as materiality of the building elements, usage patterns and control strategies in form of schedules as well as the internal loads, to each zone. Regarding usage patterns and loads for various space types, early design simulations often rely on standards as they are defined in the "SIA Merkblatt 2024" [SIA, 2006]. Thus, parameter templates for the various zone types that exist in the model can easily be defined. These zone types however, are distributed throughout the entire model and thus a diverse type-mix might exist within one building. Consequently, a parameter definition via a building-template seems inadequate. Since selecting each and every zone individually to assign the appropriate template is also not an option, a more general method that can assign zone templates throughout the various buildings is required. In our workflow, analogous to the architectural zoning in a master plan, the user defines large 2D or 3D regions to assign parameters to the individual thermal zones. To define a 2D region a closed curve, surface or image map can be used. Alternatively, 3D regions that are modeled by large closed volumes allow better control over the vertical distribution of the zone templates. Each region carries settings for perimeter and core and a simple point containment test is performed on the geometric centroid of each zone to assign the parameters. This allows the user to create complicated mixed-use scenarios with a minimal amount of effort.

Testing the algorithm

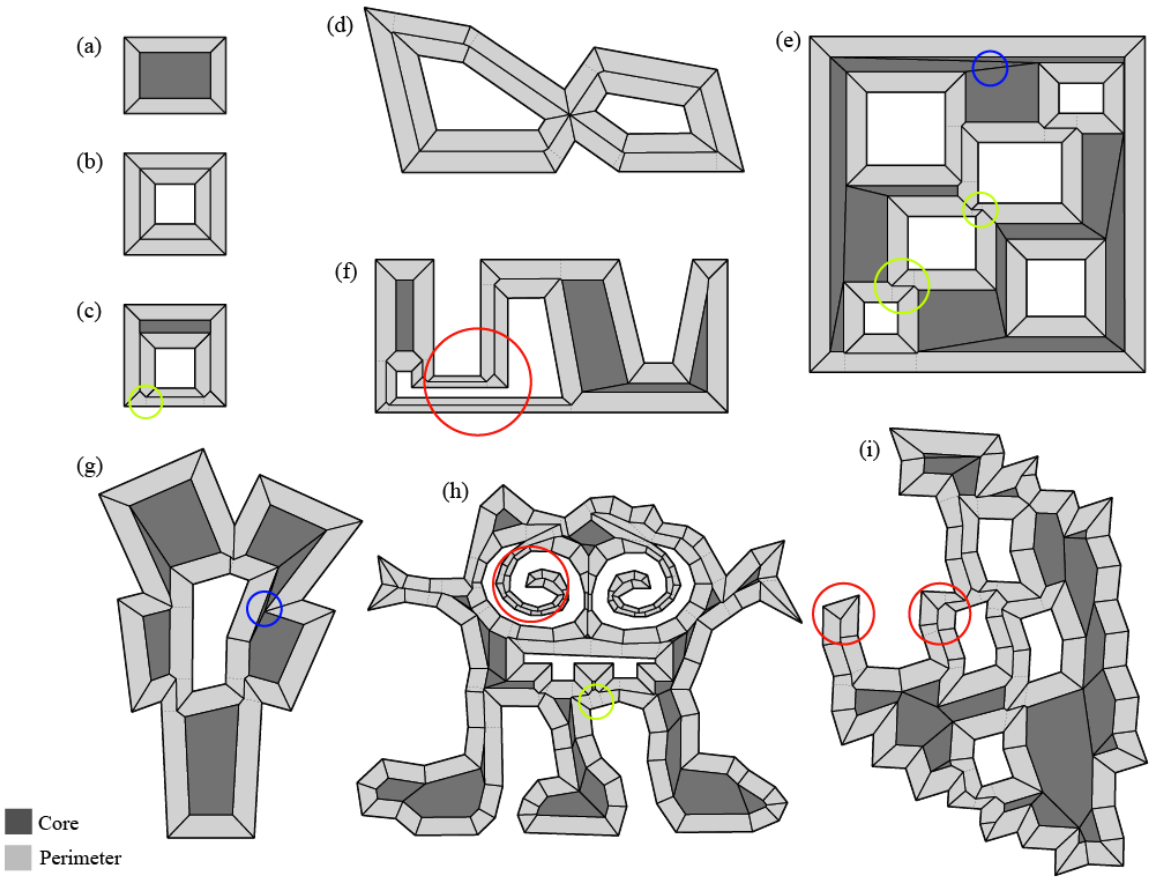

Figure 5: Various zoning test cases of varying complexity. Light grey represent the perimeter and dark grey the core.

In order to test the algorithms planar zoning functionality we tested various floor plan outlines with varying complexity (Figure 5). Starting with a simple rectangle we continue by adding convex and non-convex holes. We then use our algorithm for one building of the massing model from Figure 1 and run a multi-zone energy simulation in the Boston climate to test the feasibility of our automated zoning algorithm within an ArchSim and EnergyPlus workflow (Figure 6). Simulation results for one building are visualized by false coloring the zone geometry for heating, cooling and lighting energy demand (Figure 7). While test case in Figure 6 only requires a simple extrusion after we have obtained the 2D zoning due to its vertical facades, we show the discretization of a complex 3D massing model with sloped facades that requires the "wire cutting" approach in Figure 8.

4. Results

In Figure 5 the zoning result of our algorithm is shown for floor plan geometry of varying complexity. The offsetting procedure has defined the core and perimeter regions, both visualized in a dark and light gray. The core region completely disappeared from regions that are thinner than two times the offset distance as marked by red circles in the figure. The perimeter cells that further subdivide the perimeter region into single sided zones were defined by the straight skeleton procedure and are visualized by black outlines around each cell. The green circles mark additional cell splits into strictly convex zones as described earlier. The darker core regions are also subdivided into strictly convex zones. The blue circle highlights a region where some diagonals could not be removed and thus resulting in very narrow/ flat triangles.

In Figure 6, the ArchSim EM, EnergyPlus workflow integration is demonstrated. 11b shows the 3d geometry of perimeter (medium gray) and core (dark grey) zones as well as the window geometry (light gray). 11c shows only the inner surfaces of the model. The image validates that all interior heat transfer surfaces have been recognized as such by ArchSim EM and illustrates the complexity of the connectivity graph of the thermal model. The overall model complexity is outlined in Table 1. The shown building consists of 118 zones that in total consist of 877 faces such as roof- , partition-, facade- and window surfaces. Figure 7 shows exemplarily how the EnergyPlus simulation results can be visualized. The zone geometry is false-colored according to the cumulative annual energy use intensity for heating a),

Table 1: Model complexity (for partial model as shown in Figure 6)

Number of zones	Number of opaque surfaces	Number of glazed surface
118	772	105

Table 2: Runtimes [s] (for partial model as shown in Figure 6)

New algorithm		ArchSim EM			Energy Plus
Automatic zoning	Face splitting	Zone setup	Connectivity network	Generate IDF	Simulation
3	63	3	5	19	526

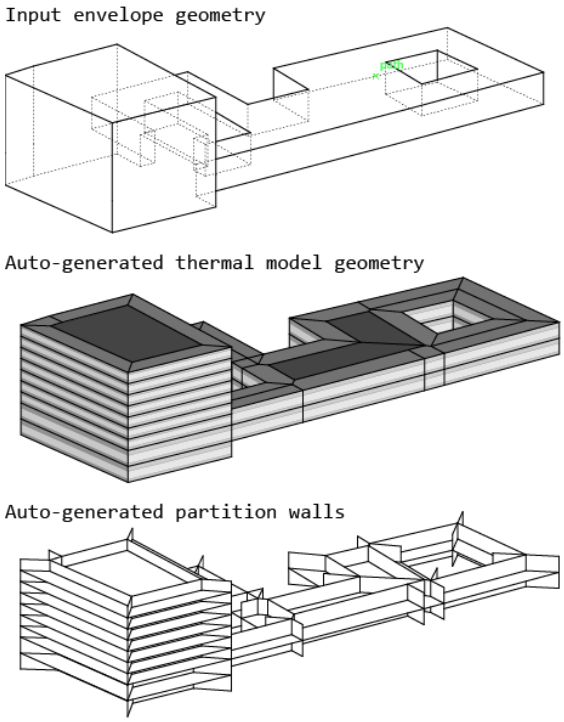

Figure 6: Detailed model visualization:
a) Input volume
b) Zone and window geometry
c) Surface connectivity

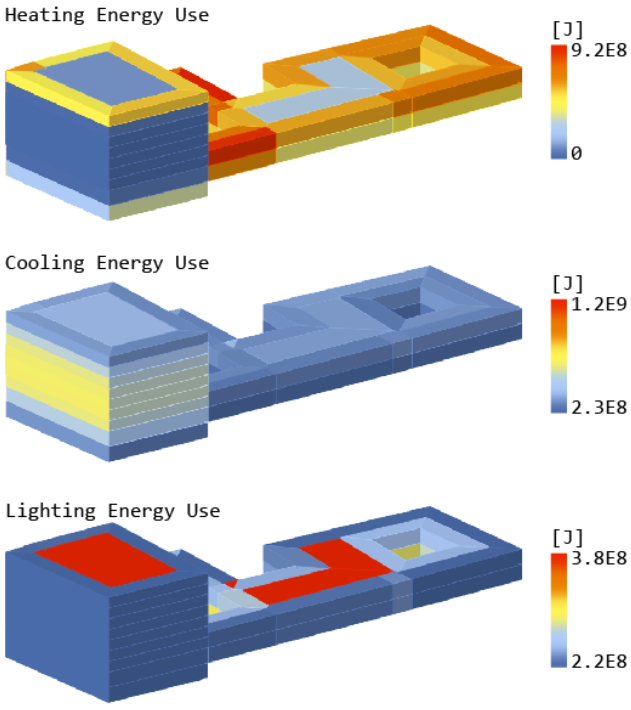

Figure 7: False colored zones to visualize EUI[J]:
a) heating
b) cooling
c) lighting

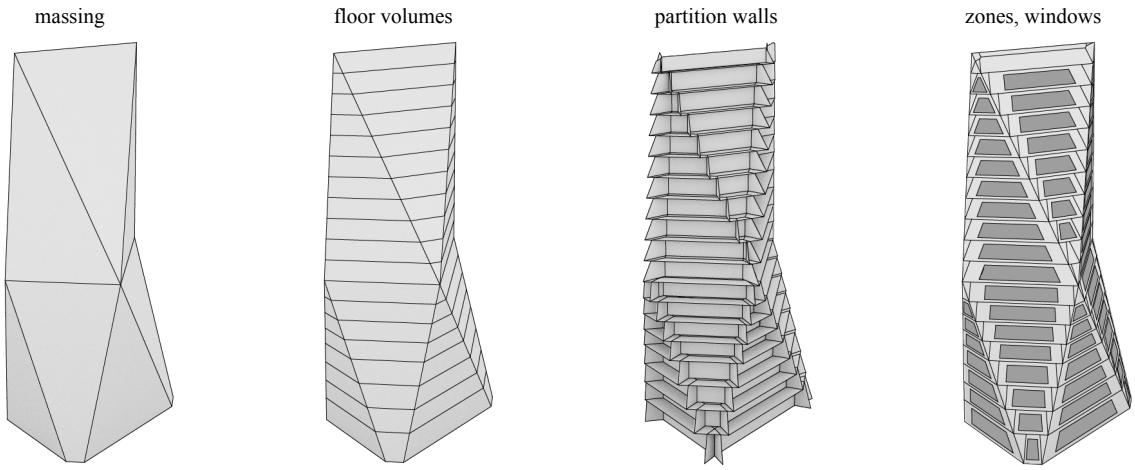

Figure 8: Complex massing: Input, floor subdivision, inner subdivision and facade.

cooling b) and lighting c). In Table 2 the computational cost of each step is listed for the example model of Figure 6.

In Figure 8 the 3D decomposition of a high-rise massing with sloped facade surfaces is shown. The input geometry is split into floor volumes before the inner subdivision is computed. The figure visualizes this by rendering the generated partition walls. Finally the perimeter zones and windows are shown. Note the triangular surfaces that appear along the edges of the massing where vertical zone partition wall meet the sloped facade surfaces.

5. Discussion

The current manuscript serves the purpose of describing a general and flexible multi-zone energy model production algorithm that can be used by others. It is our hope that the introduced procedure can simplify and accelerate BPS in early design significantly and that it can integrate smoothly into workflows already used by design and planning teams. In Figure 5 our procedure proved its robustness with complicated geometry. It strictly follows the current convention for zoning early design variants as defined in the previously mentioned ASHRAE 90.1 guideline. The straight skeleton of a polygon per se follows the rule to partition the affiliation of a space to a facade proportionally. This fact is particularly useful for the zone subdivision of more complicated floor plans since coming up with a “correct” subdivision manually can easily become a time consuming and non-trivial task. As shown in Figure 5c moving the courtyard of a simple rectangular shape off-center can already produce complex space affiliations that are not directly obvious.

The convex partitioning of the core can occasionally lead to very long and narrow zones due to the character of HertelMehlhorn based procedure which first triangulates and then removes unnecessary diagonals to obtain convexity. To avoid this, the implementation of a more elaborate splitting mechanism is planned for the future.

Another future goal is to compare simulation results generated with the multi-zone discretization algorithm against an altogether different urban modeling approach which is based on abstracting an arbitrary neighborhood massing that consists of hundreds of buildings into a meaningful group of “typical” two zone thermal models [Dogan & Reinhart 2013]. The approach has been implemented into a fully automated procedure that makes informed simplifications based on micro-climatic boundary conditions and internal loads. The methodology

offers easy multi-building energy model management and drastically reduced simulation complexity and runtimes and thus facilitates rapid early design evaluation and optimization.

6. Conclusion

A general algorithm for creating multi-zone building energy models for urban and schematic design massing models is introduced. The algorithm can handle complex building shapes and may facilitate and accelerate building energy modeling in early design.

7. Acknowledgements

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