

## **AUTOMATED TRANSLATION AND THERMAL ZONING OF DIGITAL BUILDING MODELS FOR ENERGY ANALYSIS**

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### **ABSTRACT**

Building energy simulation is valuable during the early stages of design, when decisions can have the greatest impact on energy performance. However, preparing digital design models for building energy simulation typically requires tedious manual alteration. This paper describes a series of five automated steps to translate geometric data from an unzoned CAD model into a multi-zone building energy model. First, CAD input is interpreted as geometric surfaces with materials. Second, surface pairs defining walls of various thicknesses are identified. Third, normal directions of unpaired surfaces are determined. Fourth, space boundaries are defined. Fifth, optionally, settings from previous simulations are applied, and spaces are aggregated into a smaller number of thermal zones. Building energy models created quickly using this method can offer guidance throughout the design process.

### **INTRODUCTION**

Throughout the design process, the architect's digital models serve as the latest and most up-to-date representations of a building. Designers, engineers, clients, and regulators frequently need simulation results based on those models in order to make and evaluate design decisions. Interdisciplinary exchange demands that each discipline receive a specialized view of the model (Wilkins and Kiviniemi, 2008), but this requires the design to be substantially complete. Building energy simulation (BES) tools require "clean" models that are complete, self-consistent, and populated with domain-specific parameters. However, architectural working models made with computer-aided design (CAD) tools are inherently "messy" as a result of the rapid exploration, revision, and elimination of design ideas that occurs early in the design process. While surface-based CAD models are understood intuitively to represent the appearance of a building, they often contain geometric inconsistencies and lack non-visual data vital to energy simulation. Hence, most design-process CAD models are not suitable for BES analysis with current tools.

While the necessity of making early design stage CAD models available for BES and other disciplines is widely recognized (Hitchcock and Wong, 2011),

the problem of interpreting "messy" models has received little attention. If BES is to realize its potential to guide designers during early stages of design, when they make decisions that will limit their later flexibility, it must be able to operate on design-process CAD models.

The primary challenge in preparing CAD geometry for BES analysis is the determination of *space boundaries*. Space boundaries are collections of surfaces that fully enclose *spaces* (e.g. rooms). These spaces in turn serve as the building blocks of *thermal zones*, well-mixed volumes of air with uniform temperature and controls. Surfaces that make up space boundaries serve as paths for one-dimensional heat transfer into and out of zones. They are classified as either *heat-transfer surfaces* (walls, floors, ceilings, and roofs) or *heat-transfer sub-surfaces* (windows and doors) and are distinct from shading surfaces, which reflect but do not transmit energy. Each *heat-transfer object* in the building has two heat-transfer surfaces, one belonging to the space on either side, and each surface in turn has a *front* and *back* face defined by its normal direction. In a "clean" model, all heat-transfer surfaces form boundaries between at most two zones and have normal directions facing either the outside or a corresponding surface of an adjacent space.

This paper describes a series of automated steps allowing the translation of geometric data from an unzoned CAD model into a multi-zone thermal building model. This method offers three advantages relevant to architectural models. First, it is surface-based, rather than object-based. As such, it is applicable to many architectural CAD tools, which tend to model surfaces, as well as to building information models (BIMs), whose geometric objects are easily decomposed into surfaces. Second, it has no expectation that the surface normal directions are correctly oriented in the input geometry, allowing a greater variety of model-making styles. Third, it detects space boundaries around enclosed volumes so that the user is not required to identify or label rooms. It tolerates space boundaries that are not watertight and can create missing surfaces in some cases. While the method presented here does not handle arbitrarily "messy" models, it can translate significantly "messier" CAD models than other automated translation algorithms.

## PREVIOUS WORK

The creation of a building energy model (BEM) for BES analysis requires interpretation of a CAD model and other data sources. The modeller must decide both how to represent CAD geometry with elements understood by BES software and how to augment the model with non-geometric data related to materials, building occupancy, and mechanical systems (Bazjanac and Kiviniemi, 2007). Typically, an energy modeller creates the BEM manually after the architectural design is substantially complete. Manual translation involves as much art as science; over time, practitioners develop unique methods and rules-of-thumb that cement into individual modelling styles (Hitchcock and Wong, 2011). As a result, separate modellers may produce very different BEMs of the same building, making reproduction of BES results difficult (Bazjanac, 2008).

In order to reduce variation and error in BEMs, it is desirable to automate as much of the translation process as possible (Bazjanac, 2008). BEMs can be created through automated or semi-automated processes in one of three ways. Most commonly, energy analysis tools are embedded into multi-featured BIM programs (Smith *et al.*, 2011; Hitchcock and Wong, 2011). The translation process and rules are hidden from the user, who is often constrained to a subset of the program's modelling tools. Second, BES front-ends can accept CAD data and translate it to a BEM internally (Pratt *et al.*, 2012). This approach has the advantage of working with most CAD software, but it requires the architect to adhere to certain modelling protocols. Finally, in recent years the building performance simulation community has promoted the Industry Foundation Classes (IFC) (buildingSMART, 2013), an open BIM database format, as a standard for data transfer between authoring CAD programs and various simulation packages (van Treeck and Rank, 2004; Bazjanac and Kivimieni, 2007; Bazjanac *et al.*, 2011; Hitchcock and Wong, 2011).

Regardless of the method chosen for translation, the human modeller or automated system producing the BEM must choose a convention for delineating space boundaries. A common solution is to define imaginary boundary surfaces at the centrelines of walls and floor slabs. Though this method is simple for modellers who trace existing floor plans, it does not accurately represent volumes of spaces or areas of surfaces available for interzonal heat transfer. BEM-oriented modelling interfaces such as those in Ecotect (Autodesk, 2011), Simergy (LBNL, 2012), and OpenStudio (NREL, 2013) offer extrusion tools to create spaces with associated boundaries, encouraging centreline modelling and discouraging creation of geometrically complex or non-prismatic spaces. This approach is at odds with most architectural modelling styles, in which designers tend to manipulate surfaces rather than spaces.

When BIM tools are used to create only simple geometric objects, space boundaries can be determined by graph theoretic relationships (van Treeck, 2004). BIM objects have watertight boundary representations (B-reps) with correctly oriented surface normal directions. Using solid Boolean operations, a set of connected solids with connecting surfaces can be identified within the BIM. Reversing the normal directions of the unconnected B-rep surfaces forms a new set of B-reps representing space boundaries and the building envelope's hull. Individual spaces are identified as the minimum closed B-reps found within a connected edge graph.

However, additional interpretation is necessary when the BIM contains excessive geometric detail. LBNL produced a rule-based Geometry Simplification Tool (GST) to transform geometrically "rich" IFC data to comply with the expectations of EnergyPlus (LBNL, 2013; Bazjanac, 2008). Since current BES engines simulate only one-dimensional heat transfer, it is also necessary to divide whole surface faces (space boundary type 1 in IFC) into heat transferring portions (type 2a) and adiabatic terminations and joints (type 2b) (Figure 1) (Bazjanac, 2010). A pre-processor for GST, the Space Boundary Tool (SBT), creates type 2a and 2b IFC space boundary objects for spaces previously identified in the BIM (Bazjanac *et al.*, 2011).

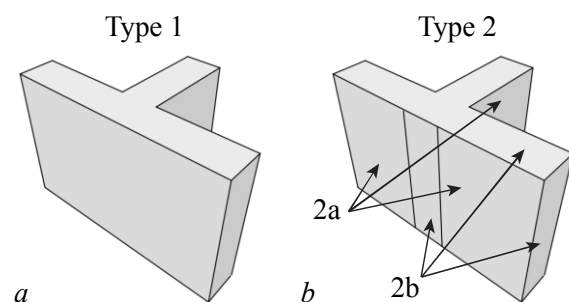


Figure 1 Space boundary type 1 surfaces (a) and type 2a and 2b surfaces (b)

In cases where BIM objects are unavailable due to the CAD tools used, or BIM data is incomplete, as is often the case in early design models, heuristics must be applied (Pratt *et al.*, 2012). The heuristic approach relies on a minimal amount of surface information available from virtually any CAD software: geometric polygon vertices, material, and layer. First, degenerate polygons are removed from the model, and nearby vertices are "welded" together. Next, surface-level heuristics assign materials, zones, and types to surfaces based on normal directions and naming conventions. Finally, neighbourhood-level heuristics identify boundary surface pairs for adjacent spaces and parent-child relationships between heat-transfer surfaces and sub-surfaces. This allows automated translation of non-BIM CAD models, provided the architect follows certain modelling protocols to ensure "clean" input.

## METHOD OVERVIEW

The method presented in this paper converts a surface-based CAD model to a simulation-ready BEM in five steps (Figure 2). In step 1, data from a file or input stream are interpreted as geometric surfaces with associated materials. In step 2, pairs of type 2a surfaces defining heat-transfer objects of various thicknesses are identified. In step 3, unpaired surfaces are categorized as either heat-transfer surfaces in contact with the outside or ground, thin intrazone or interzone heat-transfer objects, or type 2b space boundaries. In step 4, space boundary definitions are developed by searching a view factor graph for connected components. Optionally, in step 5, user-specified input parameters from previous simulations are applied to spaces in the new model, and adjacent spaces may be aggregated into a smaller number of thermal zones.

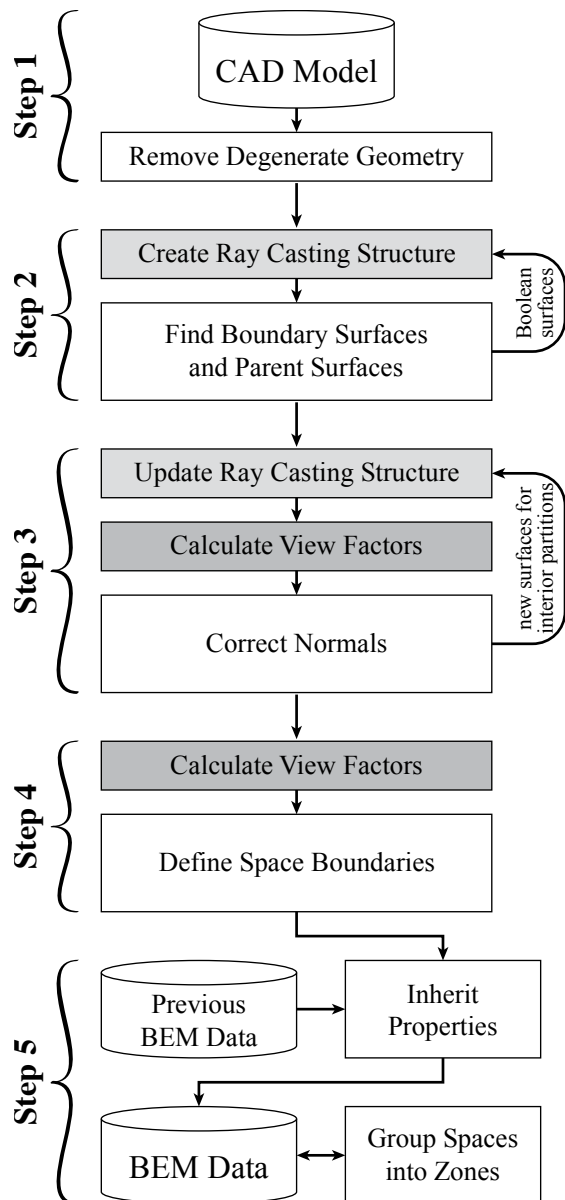


Figure 2 Flow chart of translation steps, with pre-processing steps for ray casting shown in grey

## Modelling Styles

Steps 2 through 4 make use of neighbourhood-level heuristics that tolerate a number of modelling styles and several common modelling errors. Heat-transfer objects such as walls and slabs may be modelled *thick*, with an offset between inside and outside surfaces, or *thin*, with single or coplanar surfaces. Where solids or B-reps exist within the model, they may represent either physical objects or spaces. These distinctions produce four modelling styles (Figure 3a). Because neighbourhood-level heuristics operate on surfaces, models may also contain composites of multiple styles (Figure 3b).

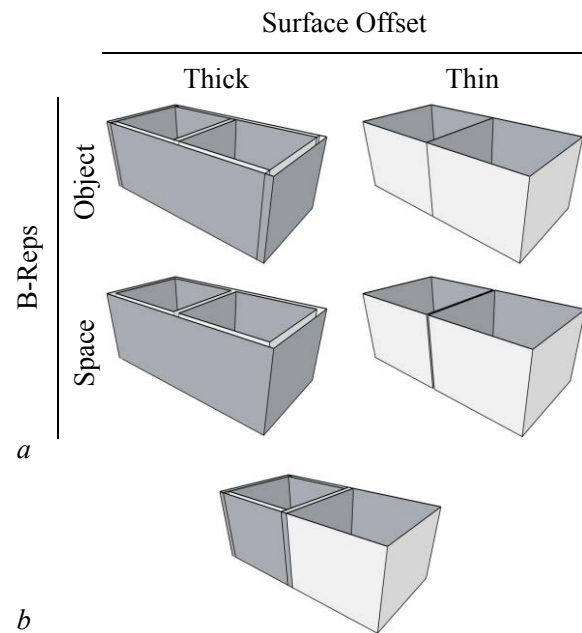


Figure 3 Surfaced-based building models are classified into four styles (a) and composites (b)

While it is desirable to allow as much variation in modelling styles as possible, any CAD program capable of producing models that do not represent buildings can also produce building models for which automated interpretation fails. Hence, the architect must adhere to certain modelling protocols when using automated translation. The method presented here imposes the following constraints:

- For heat-transfer objects modelled with two faces, the faces must be parallel and separated by no more than a user-specified maximum thickness  $t_{max}$ .
- Surfaces must be planar or decomposed into planar faces.
- Heat-transfer sub-surfaces must overlap their parent heat-transfer surfaces.
- Spaces must be enclosed by heat-transfer surfaces with minimal gaps.
- Detached shading surfaces must be labelled as such, for instance, by being placed on a separate CAD layer.

This method focusses on the automated translation of geometric data for BES. While it detects the space boundaries needed by thermal zones, it does not address schedules, HVAC systems, or other algorithm settings required for BES. Instead, it is assumed that default settings can be applied to each thermal zone created by the automated process, and afterwards the user can edit these settings. The fifth step in the process allows custom settings from previous translations of a CAD model to be reused.

### View Factors

The fraction of radiant energy exiting one surface that directly reaches another surface is referred to as the *view factor* from the first surface to the second (Pellegrini, 1997). View factors are required for radiant heat exchange calculations within thermal zones, but more broadly, they describe a spatial relationship between surfaces. The presence of a view factor between the backs of two surfaces intuitively indicates that these surfaces belong to the same space. Because the same visual relationship allows human modellers to associate groups of surfaces with a space, view factors are more useful for interpreting “messy” CAD models than are edge graphs or semantic object hierarchies that depend on the consistency and completeness of CAD data.

Analytical calculation of view factors is possible, but this is computationally expensive for all but simple geometries and requires modification to account for occlusion (Schröder and Hanrahan, 1993). While EnergyPlus allows manual entry of view factors, the program itself is only able to calculate an area-weighted approximation of view factors for convex zones (EnergyPlus Development Team, 2013).

Alternatively, view factors may be calculated through geometric analogy. The view factor  $f_{dA \rightarrow R}$  from a differential element  $dA$  of a sending surface  $S$  to a receiving surface  $R$  is found by projecting  $R$  onto a unit hemisphere around  $dA$ , and then projecting the hemisphere onto the plane of  $dA$  (Figure 4a). Then  $f_{dA \rightarrow R}$  is the portion of the resulting circle occupied by the projection of  $R$  (Nusselt, 1928). Integrating over  $S$  produces an overall view factor  $f_{S \rightarrow R}$  in the range from zero (invisible) to one (filling the field of view).

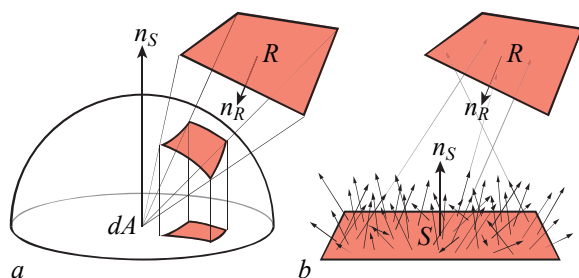


Figure 4 Nusselt analogue view factor calculation (a) and approximation by the Monte Carlo method (b)

A good approximation is produced by selecting points on  $S$  and casting a ray from each point (Figure

4b). Then  $f_{S \rightarrow R}$  is the fraction of rays whose first intersection is with  $R$  (Howell, 1998). Points and ray directions are chosen using a four-dimensional quasi-random sequence to guarantee independence, uniform distribution, and low noise (Pellegrini, 1997; Sobol, 1976). Increasing the number of rays increases the accuracy of the view factor calculation. In tests, casting 512 rays provided accuracy to three decimal places, which is sufficient for the algorithms described here. Because ray casting can occur in parallel, view factors can be calculated very quickly on multi-core processors.

### STEP 1: PRE-PROCESSING

When the automated translation process is initiated, the first step is to read a file or stream from the CAD program to obtain surfaces. The data transferred for each polygon in the CAD model must at minimum include Cartesian coordinates of geometric vertices, a material assignment, and a CAD layer name. The layer name identifies external shading and terrain geometry, which are ignored in the remaining steps. Material assignment will later provide BES with thermal properties of surfaces but is immediately useful to differentiate heat-transfer sub-surfaces, which have glazing or door materials, from other heat-transfer surfaces.

At this point, it is useful to collapse, or *weld*, vertices within a small distance of each other. This helps to eliminate rounding error caused by geometric transformations of floating point coordinates.

### STEP 2: BOUNDARY SURFACE PAIRS

The next step is to identify relationships between surfaces. Each surface may enter into two types of relationships with other surfaces in a BEM. First, each surface may have a single *boundary surface*, which represents the opposite side of its heat-transfer object. The boundary surface may be coplanar, as in centreline wall models, or it may be parallel with an offset representing the thickness of the heat-transfer object. It may also be missing from the model entirely if an object is modelled as a single surface. Outside faces of building envelope components are generally omitted from the BEM; EnergyPlus version 8.0 has no exterior surface object, for instance. If surfaces for both sides of an object are present, they may not be congruent or of equal area, which is necessary for one-dimension heat transfer. Second, each sub-surface overlaps a *parent surface*. A parent surface may have multiple children or none, but a sub-surface has only one parent, and its boundary surface is a child of its parent’s boundary surface.

Boundary and parent surfaces are found through ray casting. Random points are chosen on the surface of interest, and a ray normal to the surface is passed through each point, starting a distance  $t_{max}$  to one side of the surface and extending  $t_{max}$  to the other side. A list of parallel surfaces intersected by the rays is generated, and the closest surface of the same type

(surface or sub-surface) is chosen (Figure 5). To test that the two surfaces are compatible for one-dimensional heat transfer, one surface is projected onto the other along their normal direction, and they are checked for complete overlap. If the overlap is incomplete, a polygon Boolean operation is performed (Vatti, 1992), and the resulting polygons are projected back to their original planes (Figure 6). Otherwise, the two surfaces become each other's boundary surfaces, and their normal directions are oriented to face each other.

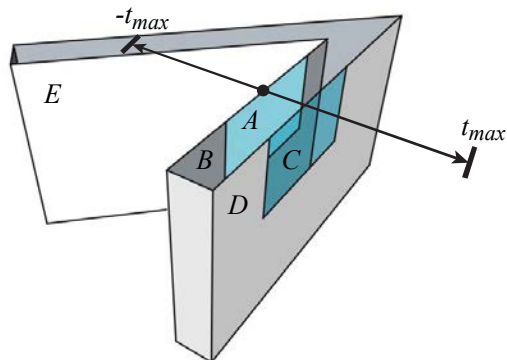


Figure 5 A ray originating from child surface A encounters parent surface B, boundary surface C, and parent's boundary surface D; non-parallel surface E is ignored

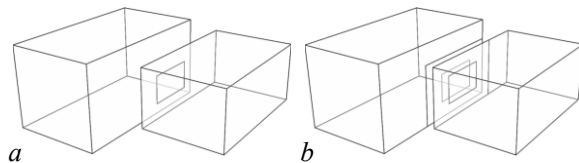


Figure 6 Projection and Boolean operations on surfaces of a messy model (a) produce clean geometry (b)

For a heat-transfer sub-surface, the closest heat-transfer surface is also chosen as the candidate parent surface. If both the sub-surface and its boundary sub-surface are closer to one parent surface than to its boundary surface, each sub-surface is assigned a different parent surface so as to minimize the sum of distances between sub-surfaces and their parents. If two potential parent surfaces are present but no boundary sub-surface is found, a new boundary sub-surface is created on the plane of the more distant parent surface. Sub-surface normal directions are oriented to match those of their parents.

At the end of this step, all boundary surface pairs that existed in the original model have been identified and corrected for normal orientation. However, in cases where a heat-transfer object was modelled as a single surface, including heat-transfer surfaces that form the building envelope, no boundary has been found, and the normal direction remains undetermined. Also, any coincident pairs of end-wall surfaces are incorrectly identified as boundary surface pairs. These issues are resolved in the next step.

### STEP 3: NORMALS

The next step is to correct surface normal directions. BES tools such as EnergyPlus require that all heat transfer surfaces and sub-surfaces have normal directions pointing out of the space they bound. For surfaces that are not in boundary pairs, the normal direction must be determined according to spatial relationships with other surfaces in the model. This is accomplished through view factor analysis.

For the purpose of this step, the view factor calculation is modified in two respects. First, rays that hit the back of a surface with a known normal direction do not contribute to the view factor calculations. Second, rays that have no intersection with any surface contribute to the view factor to a hypothetical null surface. A minimum view factor  $f_{min}$  filters false positives, where small numbers of rays pass through gaps between polygons and incorrectly indicate non-zero view factors. Gaps between polygons arise either from numerical error in floating point intersection calculations or from the user's failure to create watertight space enclosures in the CAD model. A second minimum value  $f_{int}$ , chosen such that  $f_{min} \leq f_{int} < 1$ , filters surfaces that touch in wall-wall and wall-slab intersections. In tests, setting  $f_{min} = 0.01$  and  $f_{int} = 0.2$  produced good results, but these parameters may need to be tuned for different CAD programs or modelling styles.

For each surface  $S$  that has a boundary surface, the normal direction is known, and view factors are calculated only for the back face. If there exist two parallel, non-coplanar surfaces  $A$  and  $B$  such that  $A$  and  $B$  are a boundary surface pair and  $f_{S \rightarrow A} > f_{min}$  and  $f_{S \rightarrow B} > f_{min}$ , then  $S$  is not part of any space boundary, and its boundary surface is unassigned (Figure 7a).

For each surface  $S$  that lacks a boundary surface, view factors are calculated for both the front and back faces, and four conditions are tested in order:

1. If there exists a pair of parallel, non-coplanar surfaces  $A$  and  $B$  such that  $A$  is the boundary surface of  $B$  and  $f_{S \rightarrow A} > f_{min}$  and  $f_{S \rightarrow B} > f_{min}$ , then  $S$  is a type 2b space boundary (Figure 7b). The normal direction of  $S$  is oriented toward  $A$  and  $B$ .
2. If there exists a surface  $A$  such that  $f_{S \rightarrow A} > f_{int}$  and  $A$  has a non-coplanar boundary surface, then  $S$  is a type 2b space boundary (Figure 7c). The normal direction of  $S$  is oriented toward  $A$ .
3. If  $f_{S \rightarrow null} > f_{min}$ , then  $S$  is part of the building envelope. In most BES programs, there is no need to create a boundary surface for  $S$ . The normal direction of  $S$  is oriented toward the exterior.
4. If there exists a surface  $A$  such that  $f_{S \rightarrow A} > 0$  and  $f_{A \rightarrow S} > 0$  and  $f_{A \rightarrow null} > f_{min}$ , then  $S$  is part of the building envelope, even though it does not have a direct view to the exterior. The normal direction of  $S$  is oriented toward  $A$ .

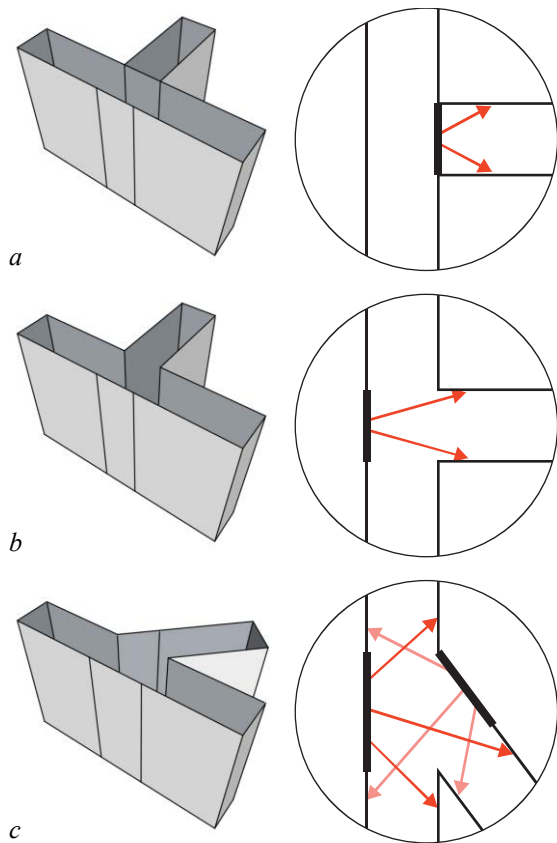


Figure 7 Important view factors indicated by arrows for detecting non-boundary surfaces (a) and type 2b boundary surfaces (b, c)

If none of these conditions is met, then  $S$  is an interior partition that is missing a boundary surface. A new surface with the same vertices and opposite normal direction must be added to the model.

At the conclusion of this step, all surfaces that require boundary surfaces for heat-transfer calculations have boundary surfaces. All heat transfer surfaces furthermore have normal directions pointing out of the space that they bound. It remains for the spaces themselves to be identified, which is now possible because the back face of each heat-transfer surface has a view into a potential space.

#### STEP 4: SPACE BOUNDARIES

This step groups surfaces together into spaces. Surfaces belong to the same space if a path exists between them that does not intersect another surface. In graph theoretic terms, each space is a *connected component* of the view graph of the building, where nodes in the view graph correspond to surfaces, and edges indicate view factors between surfaces.

Because the previous step may have added new surfaces to the model, it is necessary to re-evaluate view factors before proceeding. As with the view factors required for radiant heat exchange calculations, rays that hit the front of a surface do not contribute to calculated view factors. In cases where two coplanar surfaces with opposing normal

directions are encountered by a ray, the surface hit from the back is recorded. Again, rays that do not intersect any heat-transfer surface contribute to a view factor to a hypothetical null surface.

A view factor graph is constructed with nodes for each surface, including the hypothetical null surface. Edges exist between nodes where the view factor in either direction is greater than  $f_{min}$ . If an edge connects to the hypothetical null surface node,  $f_{min}$  is replaced by another minimum view factor  $f_{null}$ , which indicates the smallest significant view factor to the outside and has a value  $f_{min} \leq f_{null} < 1$ . In tests, a value of  $f_{null} = 0.3$  was sufficient to prevent errors involving large numbers of gaps. Each connected component of the view factor graph corresponds to a single space bounded by the surfaces with nodes in that component (Figure 8) and can be found in linear time (Hopcroft and Tarjan, 1973). Surfaces found to be connected to the hypothetical null surface are part of the building envelope's hull and not used for BES.

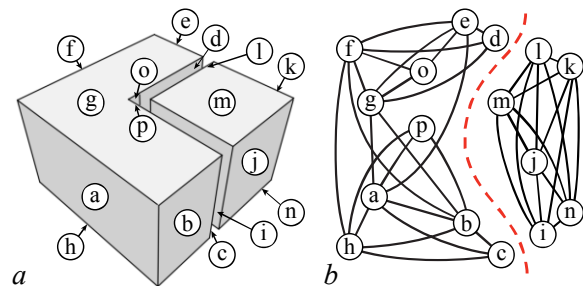


Figure 8 View factors from labelled surfaces (a) create a graph whose connected components correspond to spaces (b)

#### STEP 5: POST-PROCESSING

Once space boundaries are determined, each space can be assigned to a separate thermal zone with default settings and schedules, and the BEM is ready for simulation. However, in an iterative design framework, the ability to edit thermal zone assignments of spaces and carry over settings and schedules from previous design versions is desirable. This step outlines optional automated procedures that may be included in the translation process.

Frequently in design processes, it is necessary to repeat BES after changes are made to a CAD model. Thermal zone settings and schedules from the previous model often need to be reused for spaces in the new model. However, there is no guarantee that spaces' identifying information from previously saved design variants are preserved in the latest CAD model. Instead, automated matching of current spaces to those found in a previous model must rely on one of several heuristic approaches. The most rudimentary is to recognize spaces by position, so that if a space in the current model occupies part of the volume of a space in a previous model, its thermal zone receives the same parameters. More robust heuristic methods, including graph theoretic or

feature recognition approaches that identify similarity between model components, may allow thermal zone properties to be inherited through spatial translation or rotation of the model.

A second task that may be automated is reduction of the number of thermal zones in a model by grouping spaces. In a sufficiently developed design, spaces may be grouped manually according to the mechanical zoning of the building. Earlier in the design process, the building may be divided recursively along boundaries of least thermal coupling until the desired number of thermal zones is achieved (Dobbs and Hency, 2012). If a full simulation has been run, the building may also be zoned by analysing dynamic temperature modes (Georgescu *et al.*, 2012).

### VALIDATION

This method has been tested on models produced with several modelling styles in SketchUp (Trimble, 2013). SketchUp was chosen as a CAD program because of its extreme ease of use and simple generic data structure accessible through an application programming interface (API). While SketchUp lacks many features of more robust CAD and BIM tools, the geometric data available from SketchUp through its API can also be obtained from virtually all other CAD programs, so these tests have no dependence on proprietary tools or data structures.

In The New York Times Building example (Figure 9), the original SketchUp model contains 1844 unzoned faces, in addition to 1,193,569 faces labelled as shading surfaces. Automated translation correctly identifies 273 enclosed spaces in the model, and creates 500 additional surfaces as a result of polygon Boolean operations and missing boundary surfaces.

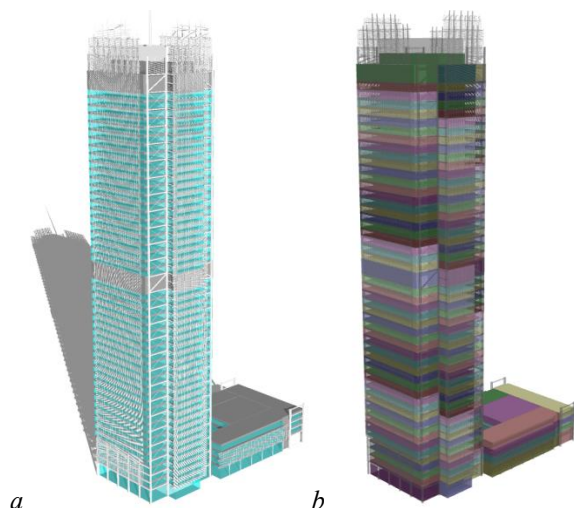


Figure 9 The New York Times Building unzoned CAD model (a) and zoned BEM (b)

### CONCLUSION

In order for BES to become a core component of the architectural design process, simulation-ready BEMs

must be quickly producible at any time. This paper has detailed a fully automated approach to generating a BEM from a CAD model, even when the CAD model contains certain topological errors and stylistic inconsistencies. The method uses view factors between surfaces to identify spaces and is able to correct surface normal directions and create missing boundary surfaces.

While this method for automated translation of CAD models allows immediate simulation of numerous models that previously would have required tedious manual alteration, many modelling styles and common modelling errors remain to be addressed. Further work could make translation tools more broadly applicable and, consequently, make modelling for BES more intuitive. Some specific areas for future work in automation include: differentiation between heat transfer surfaces and shading surfaces, differentiation of above- and below-grade surfaces based on topographic data, division of surfaces at out-of-plane intersections, capping of holes in incompletely enclosed spaces, including doorways that are modelled as openings, interpretation of windows and curtain walls modelled with detailed frame and mullion geometry, and assignment of material constructions in cases where materials are absent or inconsistent in the CAD model.

It is hoped that the algorithms presented here will lead to further effort to translate increasingly “messy” CAD models. Additional work could allow non-expert users to quickly produce accurate BES results early and often as a design aid. This is in keeping with the greater goal to encourage accurate thermal analysis of buildings early in the design process when there are more opportunities to positively affect building performance.

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