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BIM - GEOMETRY MODELLING GUIDELINES FOR BUILDING ENERGY PERFORMANCE SIMULATION

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ABSTRACT

Building Information Models (BIM) are increasingly used as a central data repository from which designers transfer data from 3D CAD applications to building performance simulation (BPS) tools. For a widespread use of BIMs for this purpose, these models need to comply with a certain data quality standard. Based on a thermal viewpoint and underlying physical principles the authors develop data requirements for these models. These requirements are used to evaluate current data standards and to develop guidelines for the creation of these models. This paper will also describe several case studies and problems found in models that did not comply with those guidelines. Finally, the authors describe current limitations of tools and processes and propose future developments.

INTRODUCTION

In recent years, numerous tools and processes (Bazjanac 2009; Bazjanac et al. 2011; EQUA 2011; Hitchcock and Wong 2011; Karola et al. 2002; LBNL 2013a; b) have been developed that convert original spatial 3D CAD geometry into thermal geometry that is used for building energy performance simulation. While these object oriented and intelligent geometry models have the potential to provide all necessary data and relationships, often these modeling capabilities are not used to their full potential. Inconsistencies in geometry models, as defined by architects, are a major hurdle for all efforts that aim to transform spatial geometry into thermal geometry. The current necessity to fix, clean and complete geometry models hinders a smooth conversion process into thermal models.

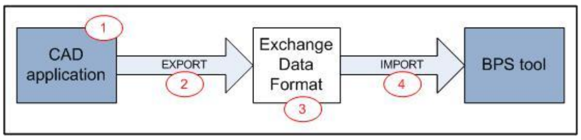

Figure 1: Generic geometry conversion process

For a successful data transformation, different aspects need to work together as illustrated in Figure 1. First, the model in the originating application needs a certain level of quality. Second, the originating application needs to successfully save the model into a data format. Third, the used data format needs to be able to store all required information. Fourth, the receiving application needs to successfully import the model from the data format.

Different physical processes are simulated in a BPS tool. These physical processes require specific data. Thus, we derive data requirements for geometry CAD model based on these underlying physical processes and eventually trace these data requirements back to the modeling process in the CAD application.

The export process from originating CAD applications can still cause problems, but has improved over recent years. One recent effort of the buildingSMART International to require a more stringent certification process (buildingSMART 2013a) should improve the quality of export in the future.

In context of the third aspect of the data format, the authors will focus on the Industry Foundation Classes (IFC) format (buildingSMART 2013b), since it is the only truly open ISO standard in the building data exchange context. For the IFC format, various mechanisms have been developed, such as the Model View Definition (MVD) and the Information Delivery Manual (IDM). The MVD focuses on the IFC properties and software, while the IDM focus on the definition of the industrial process. One example of such a process would be the geometry conversion from CAD to BPS. A number of IDM's are related to converting spatial geometry data into IFC and subsequently into the BPS tool (See and Welle 2008, 2009). Based on the participation in the development of these IDM's and involvement in the pilot projects, the authors gained expertise in this area. Based on the developed data requirements and our experience, we provide the context for the IFC format and describe the current status, advantages and shortcomings of the format.

The last aspect the import of BIM data into BPS tools is covered by numerous publications (Bazjanac 2009, 2010; Bazjanac et al. 2011; Hitchcock and Wong 2011) and greatly depends on the first three aspects to work well.

In this paper, we will develop the required data requirements of geometry models for use for energy simulation, put these requirements into context of the

IFC data model and provide a number of case studies that exemplify problems found in current models that were not created based on these guidelines. Finally, we develop future steps that will improve these two problematic issues.

DATA REQUIREMENTS ORIGINATING IN THE THERMAL VIEW

Today's designers that use Building Performance Simulation tools face a challenge when trying to use 3D Geometry from CAD models as their geometry representation of the simulation model. Typically, the 3D models are for other purposes, such as an architectural or visual representation, and do not fulfill the required quality of geometry models for comprehensive BPS.

In order to define these quality requirements, we will briefly discuss three fundamental physical principles that are used in BPS tools today. We focus on these principles, since they form requirements for the spatial model. Other principles do not carry additional requirements. In this paper we will focus on one BPS engine: EnergyPlus (LBNL 2013c). The most important principle is heat transfer between thermal zones through surfaces. However, BPS tools also include solar radiation calculations and daylighting calculations that rely on the spatial model representation. The resulting requirements are numbered throughout the paper for easier reference.

Heat transfer requirements

Heat transfer is one of the most important principles in a BPS in this context. In EnergyPlus, heat transfer is one-dimensional and thus there are three different cases of heat transfer (Figure 2).

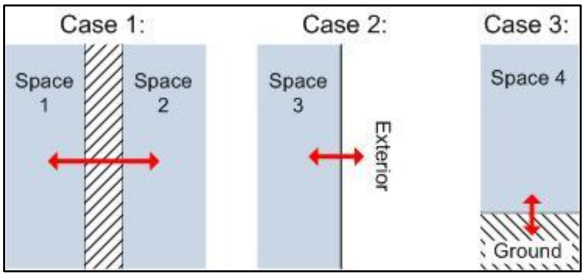

Figure 2: The three different heat transfer cases

The first case is internal (between two spaces), the second one is external (between a space and the exterior) and the last case is ground (between a space and the ground). Generically, heat transfer is calculated based on:

Req. 1: surface area
Req. 2: material properties

The one dimension at first seems easily accountable for with a 3D model. However, in context of heat gains and losses for each space the following relationships are required:

Req. 3: relationship between surfaces and spaces
Req. 4: relationship between materials (and their properties) and the surface
Req. 5: relationship between two opposite surfaces for internal heat transfer

These relationships and variables seem to call for few data requirements. Nevertheless, two aspects consideration. First, the direction of the heat transfer is important and determined by the normal vector of the surface (req. 18). In order to clearly identify the three different heat transfer cases (see Figure 2), surfaces need to be tagged with a related surface type (e.g. internal, external, etc) (req. 19).

Solar radiation requirements

Another important principle in BPS is solar radiation. The primary concern of solar radiation relates to windows and radiation that enters the space through them.

The properties that determine the solar radiation entering a space are:

Req. 6: window surface area
Req. 7: window frame area
Req. 8: 3D position of the surfaces
Req. 9: window glazing material properties

The window frame and surface area are important to determine the actual glazing surface. The glazing material properties influence the process of solar radiation incident on the window surface and actually entering the space. The 3D position of the window determines the actual solar radiation that falls on the window. Here external shading (including self-shading from the building) and the sun position and cloud cover further influence the solar radiation on the window surface. Focusing on the exterior, the BPS tool calculates the position of the sun based on coordinates and date and time, takes external shading (including self-shading) into account and determines the solar radiation incident on the external window surface. An enclosed space is required to ensure that these self-shading calculations are correct.

Obviously, in the same manner as a non-window surface type, an "internal" or "external" window surface type is required (req. 19). Based on the window material properties the BPD tool calculates the resulting solar radiation on the inside of the window.

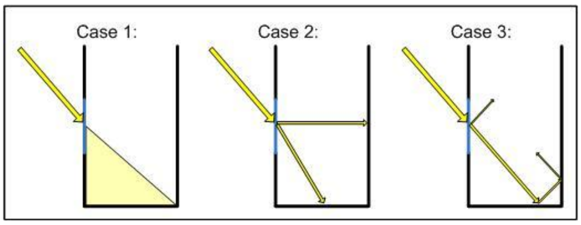

Figure 3: Cases of solar radiation through windows

There are three different ways to distribute the solar load within a space (Figure 3):

- Solar radiation is assumed to fall only on the floor surface

- Solar radiation distributes between internal surfaces based on predetermined view factors.
- Solar radiation distribution is calculated based on the ray path within a space.

Based on these principles, additional relationships are required:

Req. 10: relationship between window surface and spaces
Req. 11: relationship between materials (and their properties) and the window surface

Daylighting requirements

Another optionally used principle in BPS is daylighting. Daylighting is closely related to solar radiation, since it reduces the electrical power on lights if enough sun light from the outside enters a space. The major difference is that daylighting in EnergyPlus uses reference points that define the exact location where sun light is considered. The algorithm used in EnergyPlus also considers reflectance from internal surfaces besides the direct sunlight (Figure 4).

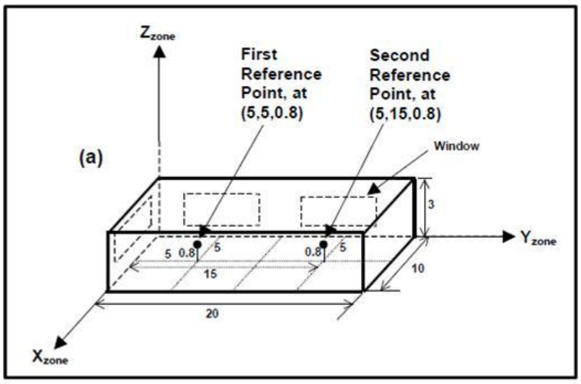

Figure 4: Daylighting reference points (LBNL 2012)

The additional properties needed for a calculation are as follows:

Req. 12: 3D position of the reference points
Req. 13: Reflectance properties of surrounding surfaces

Besides these geometry related properties, a number of relationships are necessary to perform these calculations.

Req. 14: relationship of reference point to space
Req. 15: relationship of surrounding surfaces to space
Req. 16: relationship of window to space

Due to the consideration of reflectance, it becomes obvious that the space must be completely enclosed by its surfaces (req. 20). In addition, the surfaces need to have the correct direction or normal in order for the reflectance calculation to work.

Basic requirements from EnergyPlus' geometry model

In addition to these derived data requirements, the EnergyPlus geometry data model poses another relational requirement:

Req. 17: Window/Door surface must be a child of a building element surface

The other convention used in EnergyPlus is that the order of the coordinates determines the normal vector (req. 21).

Summarizing the data requirements

These three major principles in BPS combined lead to the following data requirements. We acknowledge that some simplified simulations may not impose a number of these requirements. Aiming to support a wide range of simulations, we list all the requirements organized by categories:

A. Property data
   a. opaque material properties (Req. 2)
   b. Reflectance properties of surrounding surfaces (Req. 13)
   c. window glazing material properties (Req. 9)
   d. surface type (Req. 19)
B. Property data that can be derived
   a. surface area (Req. 1)
   b. window surface area (Req. 6)
   c. window frame area (Req. 7)
C. 3D coordinate data
   a. 3D position of surfaces (including windows) (Req. 8)
   b. 3D position of the reference points (Req. 12)
   c. normal of surface (Req. 18 and 21)
D. Relationships
   a. relationship between surfaces (including window surfaces) and spaces (Req. 3, 10, 15 and 16)
   b. relationship between materials (and their properties) and the surface (including window surface) (Req. 4 and 11)
   c. relationship between two opposite surfaces for internal heat transfer (Req. 5)
   d. relationship between parent and child surface (Req. 17)
   e. relationship of reference point to space (Req. 14)
E. Enclosed space through its surfaces (Req. 20)

DATA REQUIREMENTS IN CONEXT OF MODEL CREATION

These data requirements require an additional task of the CAD modeler. While most data requirements can be fulfilled with readily available objects and data within BIM-capable CAD tools, some modeling aspects are difficult to resolve. For example, the definition of material properties (such as density) could be integrated into the material libraries of the CAD tools to make them readily available for the users. (On the other hand, the BPS analyst may be better qualified to assign correct material properties.) Currently, BPS import tools either link a material database into the process or enable manual user input and selection.

DATA REQUIREMENTS IN CONTEXT OF IFC

The IFC model can store all data defined by the requirements above except the direct relationship between two internal surfaces.

This omission is due to the fact that surface objects (called "IfcRelSpaceBoundary") are relationships themselves between building elements and spaces, and, as of IFC2x3, there is no way to directly relate two relationships. Currently, this relationship is deducible because an internal space boundary pair must reference the same building element and must be opposite to each other spatially. However, this was resolved in the new IFC version IFC2x4 and will be available in the future (buildingSMART 2013c).

The required property data can easily attach to objects in IFC either though explicitly defined properties of objects or by easily extensible property sets. In the same manner, surface area properties can attach to surface objects if supported by the exporting applications. The building element references material layer sets, material layers and materials, and thus material properties. Similarly, 3D coordinate data can be stored in IFC in numerous different formats. The variety of different geometry representations is one of the strengths of IFC, but at the same time a weakness, since this great flexibility causes additional implementation requirements for software tools. In the context of space boundary geometry, this flexibility allows to define the surface as a 2D plane and the normal to that surface as part of the relative placement definition of the surface (buildingSMART 2013c).

Reference points for daylighting are not considered here and it could be argued that these reference points should be entered or auto calculated within the BPS tool.

In summary, the IFC data format supports all data requirements and solutions exist for the current noted limitations through additional processing of derived information.

EXPORTING SPATIAL DATA TO THE IFC DATA MODEL

The next aspect of successful data transformation between CAD applications and BPS tools is the export of data into the IFC format. The development of a specific space boundary generation tool (SBT) (Bazjanac et al. 2011) points to the problems with IFC export in particular related to space boundaries. Due to the difficulties of reliable data export, buildingSMART International developed and is currently implementing a new certification process: certification 2.0 (buildingSMART 2013a). Assuming that this certification will result in improved data export and correct definition of all IFC data, the remaining consideration is the quality of the 3D CAD model.

IMPORTING SPATIAL DATA TO THE BPS MODEL

A number of software tools have been developed that perform the conversion of spatial building data from CAD tools into BPS tools (Bazjanac 2009; Bazjanac et al. 2011; Hitchcock and Wong 2011). While the process and algorithms have improved over time, we believe the quality of spatial models has not. This is a significant problem for these conversion tools that already contain some logic to detect and fix geometry problems. For example, the inconsistent normal vectors of the parent wall surface and its child window surface can be detected and corrected. The next section will describe a number of such problems as found in numerous case studies.

CASE STUDIES ILLUSTRATING GEOMETRY PROBLEMS

To provide evidence of the lack of quality in geometry models, we present some typical problems found in case studies. The authors participated in geometry conversion in the following projects: NASA Ames Sustainability Base (O'Donnell et al. 2013), pilot projects in context of the AECOO test bed (OGC 2013), pilot projects in context of the CDB 2010 (See and Welle 2009), building models of existing buildings in context of a doctoral dissertation (Maile 2010) and numerous other buildings, projects and case studies.

Duplicate objects

Possibly the most common problem in IFC geometry files is the duplication of objects. For example, the same wall might be defined twice at the exact same location.

Incorrect space volumes

Spaces are often defined without the proper height, in particular in context with ceiling plenum. This recurring issue causes missing or incorrect space boundaries for the ceiling slabs.

Missing spaces

Another common problem is missing space objects. Either the models do not have any space objects at all, or several may be missing.

Missing space boundaries

If spaces and building elements do not align properly space boundaries are often missing or are not properly calculated. Another factor that causes missing space boundaries are geometric representations for which space boundaries are not supported (e.g. curved geometry).

Missing exterior walls

In the case of very large models, complete building elements (such as walls) can be missing and cause the omission of space boundaries and other problems (Figure 5).

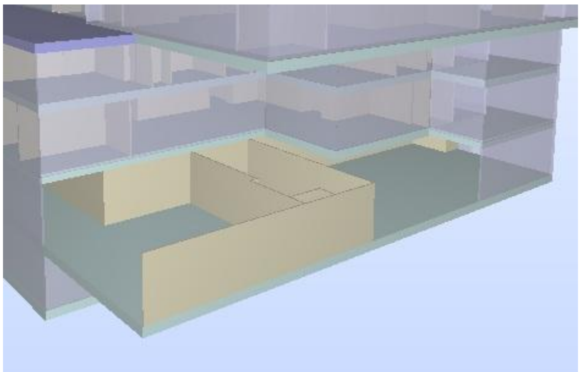

Figure 5: Missing external walls

Alignment of space and building element

Misalignment of space geometry and building element geometry can also cause missing and incorrect space boundaries (Figure 6).

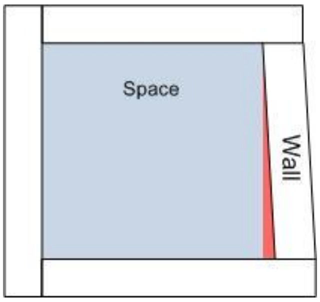

Figure 6: Misalignment (in red) of space and wall

Building elements are modeled with multiple instances to represent material layers

Models sometimes contain building elements that are defined next to each other in the attempt to represent different material layers of the same wall or slab construction. This causes a significant problem in space boundary generation and should be avoided.

Column dislocation

Figure 7 shows a great example of inconsistencies that will cause problems for other scenarios as well as for energy simulation. Here the column is placed in the middle of a door.

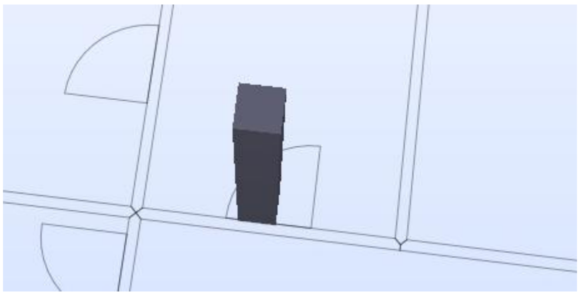

Figure 7: A column that blocks a door

Incorrect 2nd level space boundaries

Another example of a problem is the incorrect generation of 2nd level space boundaries (Figure 8). In this example the column space boundaries are only generated on one side, but ignored on the other side. While this is most often a software issue with the IFC export, it may also happen due to misalignments.

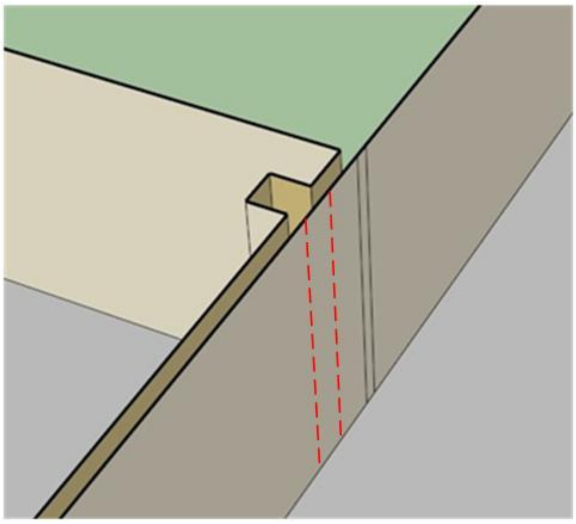

Figure 8: Incorrect 2nd level space boundary generation (the column should be reflected by the red dotted space boundary segments)

Incorrect normal vector direction

Since the normal vector direction of a surface is required and defined to point outward of the space (LBNL 2012), this normal vector can point in the opposite direction. In Figure 9, most of the external surfaces point inwards (lighter color) rather than outwards (darker color). This is also an implementation issue of the IFC export, but is also often found in very complex models.

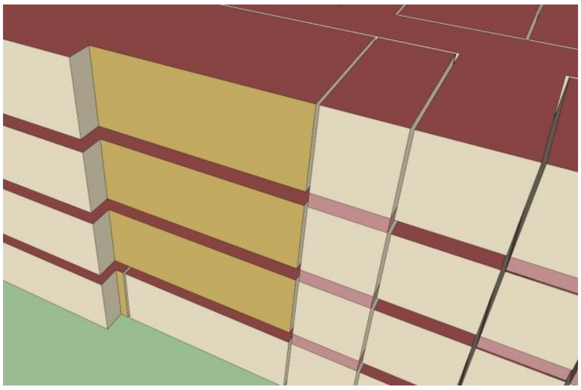

Figure 9: Incorrect normal vectors (lighter color) of external wall space boundaries

Geometric tolerance and "snapping"

Building elements and spaces sometimes, terminate at points that are very close to each other and not connecting at the common points in 3D space as they should. Such discrepancies can cause marked increase in processing time and even program instability in downstream conversion tools.

GUIDELINES FOR MODELLING

Based on the developed data requirements and our experience in converting numerous models as illustrated by the case study examples, we develop the following guidelines:

The space is the most important object for BPS

Given the dependency of most of the relationships on the given space object and the problems caused by incorrectly defined spaces, this object and its geometry demand correct definition and regular checking during the geometry generation process. No spatial duplication or overlapping with other building elements is acceptable.

Spaces must be completely enclosed

The space and its surrounding building elements must touch each other and form a spatial construct to ensure that building elements completely enclose the space volume. A useful feature in some CAD applications helps achieve this by automatically updating space footprints based on the actual location of modeled building elements. However, the space geometry is a 3-dimensional object and must be touching a building element in all directions.

Building elements need proper geometry

Building elements should be defined using the proper corresponding definition tools within a CAD application. Usually, more complex geometry types will cause problems down the road and are thus not recommended. Building elements must properly align with the space objects and must have the correct dimensions to enclose the spaces. Thus, building elements should not overlap, spatially duplicate or be too short to fit into its position in the building.

Building elements need proper material definitions

Building elements should at least have material layer sets assigned that name the material layers. It is problematic to define multiple building elements to model single material layers and place them next (in parallel) to each other. This is not the intended use of building elements and causes significant problems in the space boundary calculation, since the relationship between building element and two neighboring spaces in such case cannot be defined.

Checking geometry regularly for correctness

Most CAD applications do not provide functionality to check the correctness of their models' geometry. Thus, the modeler often needs to check visually the model by using sections and elevations. The user should also rely on external tools that can check the correctness of IFC files externally to the CAD application. These external tools can provide various manual and automated checks, but do not cover all aspects of the discussed requirements.

RECOMMENDATIONS

Based on the guidelines and shortcoming of the current process we recommend the following:

Material properties

While it is theoretically possible to transfer materials with their thermal properties, most CAD applications do not include such data. Our recommendation is that CAD applications start to incorporate these material properties within their standard libraries. First CAD tools are starting to enable this in their current versions (Stine 2013). Thus, the user can select a specific wall construction and already has typical material properties assigned. Ideally, these libraries will be based on industry data standards.

Improvement of IFC export

Based on our experience and problems encountered we encourage the improvement of IFC export functionality of software applications and hope that the new certification 2.0 process will yield a significant data exchange quality improvement.

Addition of model checking within CAD applications

In order to provide instant or relatively quick feedback to the CAD modeler we recommend the development of model checking functionality in CAD applications. For example, detecting duplicate wall instances should not be a hard to solve problem for a CAD tool.

Model checking process

We recommend that the modelers start to use various ways to check and validate their models to ensure an acceptable level of model quality. Existing tools provide enough checking and validation capabilities to increase the quality of models and drastically decrease the number of errors.

Quick adaption of the forthcoming IFC2x4

Due to the substantial improvements of IFC2x4 related to space boundaries, we recommend a quick adaption of the IFC2x4 standard.

CONCLUSIONS AND FUTURE WORK

In this paper, we describe the fundamental principles that drive spatial data requirements for BPS. Based on these principles we developed data requirements for CAD geometry models that are for the explicit purpose of BPS. We describe the current process of data transformation and put them into context of these data requirements. The most restricting requirement here is the enclosure of a space through space boundary surfaces that requires geometry models to be a 3D geometrical structure filled with spaces and building elements throughout the building and is ending at its external shell. Based on these data requirements, we developed modeling guidelines that help the modeler to improve the quality of their models. Finally, we provide recommendations to further improve this process and address the current problems for more reliable data transformation in the future.

In the future, the problem of low quality geometry models needs to be addressed. In particular, often-repeated problems could either be fixed automatically or detected much sooner perhaps by the user. Thus, integrating these guidelines and recommendations into the model generation process is the next logical step. This aspect of the application side and additional training to enable model creators to generate higher quality models will drastically boost the reliability of using BIM models for BPS.

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