Testing Space Boundaries That Transcribe Complex CAD Building Geometry Into Surface Geometry Usable By EnergyPlus And Similar Building Energy Performance Simulation Engines

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This documents describes the 33 “unit tests” that were developed by the Interoperability Team in the Energy Efficient Technologies Division at the Lawrence Berkeley National Laboratory of the University of California to test and verify the generation of *space boundaries* by the Space Boundary Tool (SBT). The 33 unit test files described here are a selection from a larger set of unit test files that includes files testing transcription of 2D-curved surfaces into space boundaries, not included here because these feed curved surface geometry to special versions of SBT and EnergyPlus which were never announced or released by the U.S. Department of Energy (DOE). Selected files test individual basic issues encountered in typical transformation of original building geometry and were submitted for use in the EnEff-BIM project (German Ministry of Economy 2015).

Space Boundaries and the tool that generates them: SBT

Building geometry, as defined in CAD models, typically represents the architect’s view of the building, not its thermal view. Most of the sophisticated building energy performance (BEP) simulation engines that support whole-building life-cycle simulation, such as EnergyPlus, have internal data models of building geometry that are much simpler than the corresponding models found in CAD software. Before CAD geometry can be used in BEP simulation, it has to be transformed as necessary to represent the thermal view of the building geometry, reflecting the one-dimensional thermal flow through objects in EnergyPlus simulation (DOE 2017). Since EnergyPlus geometry model is a surface geometry model (DOE 2017), this means that the “rich” CAD geometry (containing a lot of data irrelevant to thermal simulation) must be transcribed into a relatively simple surface geometry, in which surfaces enclosing spaces are called “space boundaries.” SBT performs this task semi-automatically.

SBT imports original building geometry and associated composite construction definitions, defined in CAD in IFC format (ISO 2016) by an architectural model-based CAD tool (i.e. CAD tool with object-oriented internal architecture), transforms imported data as needed by applying data transformation rules embedded in software code, calculates all relevant space boundaries and adds those to the imported IFC file. If desired, SBT semi-automatically links original definitions of composite constructions to libraries of thermal properties of building materials, and also generates and exports building geometry definitions in input format and syntax required by EnergyPlus. The generated complete building geometry definition includes the definition of construction materials (including glazing) as defined by the original building design.

Per the original classification of space boundaries (Bazjanac 2010), SBT recognizes five levels (types) of space boundaries:

1. First Level space boundaries represent *continuous* object surfaces that are fully visible from one end to the other, while the opposite side of the object is not uninterrupted and is not continuous. They can be used in computer rendering of buildings, but misrepresent

the object surface areas that participate in thermal transmission. Thus First Level space boundaries are not useful for BEP simulation and are ignored.

2. Second Level space boundaries represent object surfaces for which the entire defined surface areas provide unique and consistent rate of thermal transmission or flow, without interruption on the opposite side surface. In other words, they define surfaces with a rate of one-dimensional thermal flow that is constant across their area.
3. Third Level space boundaries represent surfaces of objects with no one-dimensional thermal flow through them because they have no other thermal zone on the opposite side, or the other thermal zone is too far (i.e. the objects are too long) to enable successful one-dimensional thermal transmission or flow through the given object. These space boundaries typically represent end surfaces of objects terminating in a thermal zone and cover the thickness of the given object. Third Level space boundaries are often needed to complete the enclosure of spaces that is needed for successful simulation.
4. Fourth Level space boundaries are a *special case of Third Level* which occurs when one of the merging objects in its original definition does not reach the opposite side of the other object, leaving a small unaccounted for surface area surrounded by Third Level space boundaries (Bazjanac 2010). Thus, after calculation, Fourth Level are merged with the surrounding Third Level space boundaries.
5. Fifth Level space boundaries represent small surfaces that have no one-dimensional thermal flow through them and are not accounted for when objects intersect at an angle that is smaller or larger than 90 degrees (Bazjanac 2010). As such surfaces have the same characteristics as Third Level space boundaries, Fifth Level space boundaries are treated as Third Level.

When buildingSMART International (bSI) later developed the Coordination View (bSI 2011) of the IFC2*x*3 data model (IFC 2007), it classified space boundaries according to their ability to transmit energy through the object(s) they define. The IFC data model of buildings now recognizes Type 2A and Type 2B space boundaries: The former defines space boundaries through which energy is transmitted in the given solid object perpendicularly to the object-bounding space boundary surface (in this case, the only angle of incidence acceptable to EnergyPlus simulation), the latter space boundaries through which no energy passes in the simulation but which facilitate the complete enclosure of the space they belong to. The two space boundary classification systems are mutually interchangeable (Table 1). It should be noted that EnergyPlus defines exterior walls and slabs as single surface objects with the single surface positioned on the inside of the object.

Table 1 – Correspondence of space boundaries between the Level and Type classification systems

SPACE BOUNDARY LEVEL \ IFC TYPE	INTERIOR	EXTERIOR	VIRTUAL
First (1st) level	1	1	1
Second (2nd) level	2a	2a	2a
Third (3rd) level	2b	N/A	2b
Fourth (4th) level	incorporated in 2b	N/A	incorporated in 2b
Fifth (5th) level	incorporated in 2b	N/A	incorporated in 2b

SBT calculates space boundaries for all five Levels, but writes the data back to the original IFC input file as one of the two possible Types, in accordance to the definitions of the IFC data model.

SBT code is in C++, written in Microsoft's .NET programming environment (Rose and Bazjanac 2013). It deploys a geometry library from Geometry Factory (a French software company) under

a GNU license. The logic and approach of SBT is based on graph theory and is limited to solid-to-solid heat exchange; solid-to-fluid and fluid-to-fluid heat exchange is not considered.

Data transformation rules embedded in SBT

SBT transforms data imported by SBT from the IFC file per data transformation rules embedded in the tool's code. Each embedded rule is represented by one or more algorithms which actually perform the transformation. The following the list with descriptions and objectives of data transformation rules, not all of which are tested by unit test case files listed in the next section:

- Skipping of internal wall objects when walls, slabs, columns or beams which are entirely contained within the same thermal zone (unless the simulation involves daylighting) – when there is no difference in temperature at opposite sides of the given object(s) that is necessary for thermal transmission to take place, which makes each such object irrelevant to the simulation.
- Reversal of the order of construction material layers for "other side" second-level space boundaries for walls and slabs which have asymmetric construction – EnergyPlus assumes that the sequence of defined material layers in a construction is always from "outside–in."
- Redefinition of columns defined in CAD into walls that have the same geometry and thermal properties as the columns they represent – EnergyPlus does not contain column nor beam objects (DOE 2012).
- Redefinition of columns completely embedded in walls as separate wall objects with the cross-section that includes the column and the remaining parts of the wall, as well as the resulting sequence of material layers in the redefined construction definition.
- Definition of the remaining wall construction parts when columns are only partially embedded in walls – definition of part(s) of wall remaining between the outward-facing embedded column surface and the exterior surface of the wall.
- Recognition of exterior building shade types – SBT recognizes types of exterior building shading systems and automatically generates the proper EnergyPlus syntax for them when it finds such systems in the IFC input file.
- Positioning of exterior building shades right outside the space boundaries of exterior walls – any exterior wall has only one space boundary (positioned at the inner surface of the wall), so any external shading surface protruding from the wall must be moved to "touch" the space boundary in order to eliminate the gap otherwise caused by the thickness of the wall and the wall's outside surface that is not included in EnergyPlus simulation.
- Detection and redefinition of virtual walls and slabs – openings in walls and slabs are treated as virtual objects in EnergyPlus simulation.
- Assignment of "virtual constructions" to virtual walls and slabs – openings in walls and slabs are filled with a virtual material that has thermal properties of air.
- Identification of floor and ceiling surfaces of a slab that have concave shape, and braking of concave-shaped objects into sets of convex-shaped objects of same kind – EnergyPlus cannot simulate objects that have concave shape (DOE 2017) and such shapes must be redefined as a set of convex shapes.
- Subdivision of slabs with voids fully enclosed in a single slab into "void-free" slab segments – EnergyPlus cannot simulate voids in single concave slabs unless they represent windows, skylights or doors, so concave slabs are redefined to leave the voids fully enclosed with sets of convex slabs.
- Redefinition of "exterior ceilings" as EnergyPlus roof objects.

- Connection of slab-on-grade objects to the ground object.
- Creation of the parent wall's space boundaries for windows (when missing).
- Adjustment of window area to effective glass area.
- Linking of glazing definitions to Window 6.X tool (i.e. the latest version of the Window 6 software).
- Linking of material and construction objects to the EnergyPlus library of materials' thermal properties – SBT interactively maps construction material names and specifications (if any) of materials it finds in the input file, to corresponding names and thermal performance specifications defined in a library of construction materials specified by the user.

Unit test cases

SBT was rigorously tested before release. The following list describes files and the respective tested geometry issue used in testing SBT that apply to EnEff-BIM project work, Notation "_SB" at the end of file names indicates that the files include the definition of space boundaries, which can be properly visualized in Solibri Model Checker (SMC) software (Solibri 2017).

- AWS-1_SB.ifc: Tests 2nd and 3rd (2A and 2B in IFC classification) level space boundaries in single- with multiple-story configuration.
- AWS-2_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries when internal walls in lower and upper spaces are not aligned, in a single- with multiple-story configuration.
- AWS-3_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries when spaces on the upper level are surrounded by concave multi-story space(s) on the same level.
- AWS-4_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries when multi-story internal walls have voids on lower and upper levels that open to a multi-story space, are not vertically aligned.
- AWS-5_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries when multi-story internal walls have voids on lower and upper levels that open to a multi-story space and are vertically aligned.
- CSC-1_SB.ifc: Tests 2nd, 3rd and 4th (2A and 2B) level space boundaries defining IFC columns, in a multi-story configuration.
- CSC-2_SB.ifc: Tests 2nd, 3rd and 4th (2A and 2B) level space boundaries defining columns that split internal walls, in a multi-story configuration.
- CSC-3_SB.ifc: Tests 2nd and 4th (2A and 2B) level space boundaries resulting from columns partially embedded in external walls, in a multi-story configuration.
- CSC-4_SB.ifc: Tests 2nd and 4th (2A and 2B) level space boundaries resulting from columns partially embedded in internal walls, in a multi-story configuration.
- CSC-5_SB.ifc: Tests 2nd (2A) level space boundaries resulting from original concave slab configurations transformed into sets of convex slab configurations because of columns protruding through the slab(s).
- CSC-7_SB.ifc: Tests 2nd, and 4th (2A and 2B) level space boundaries defining free-standing columns, in a multi-story configuration.
- CSO-1_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries resulting from slab configurations that are vertically separating multiple spaces and include a simple rectangular opening in their middle.
- CSO-2_SB.ifc: Tests 2nd and Virtual (2A and 2B) level space boundaries resulting from slab configurations that are vertically separating multiple spaces and include a simple rectangular opening that borders on exterior wall(s).

- CSO-3_SB.ifc: Tests 2nd and Virtual (2A and 2B) level space boundaries resulting from slab configurations that are vertically separating multiple spaces and include multiple joined rectangular openings in their middle.
- CSW-1_SB.ifc: Tests 3rd (2B) level space boundaries resulting from multiple interior walls, in single- with multiple-story configurations.
- CSW-3_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries depicting a smaller space entirely enclosed in a larger space, in a multi-story configuration.
- CSW-4_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries of opposite diagonally-mirrored corner spaces, in a multi-story configuration.
- CSW-8_SB.ifc: Tests 2nd, 3rd and 5th (2A and 2B) level space boundaries resulting from multiple interior wall intersections at degrees other than 90, in a multi-story configuration.
- SOAW-3_SB.ifc: Tests 2nd, 3rd and Virtual (2A and 2B) level space boundaries when a void in an interior wall matches a side of a rectangular opening in a slab, in a multi-story configuration.
- SOWW-1_SB.ifc: Tests 2nd, 3rd and Virtual (2A and 2B) level space boundaries when a void in the center of a slab is part of multiple spaces, in a multi-story configuration.
- SOWW-2_SB.ifc: Tests 2nd, 3rd and Virtual (2A and 2B) level space boundaries when a side in a void in a slab is bordering on an interior wall, in a multi-story configuration.
- SOWW-3_SB.ifc: 2nd, 3rd and Virtual (2A and 2B) level space boundaries when a void in a wall is part of two spaces that border on an opening in a slab, in a multi-story configuration.
- SWW-3_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries when smaller spaces entirely enclosed in a larger spaces on multiple levels do not align vertically, in a multi-story configuration.
- SWW-4_SB.ifc: Tests 2nd, 3rd and 5th (2A and 2B) level space boundaries resulting from multiple interior wall intersections at degrees other than 90 on one level(s), with interior wall intersections at 90 degrees on other level(s).
- SWW-5_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries resulting from a typical five-zone floor configuration (that includes one interior zone) on one, in a multi-story configuration.
- Wi-1_SB.ifc: Tests 2nd (2A) level space boundaries resulting from a window that has a parapet and a header, centered in a wall.
- Wi-3_SB.ifc: Tests 2nd (2A) level space boundaries resulting from a floor-to-ceiling window centered in a wall, in a multi-story configuration.
- Wi-4_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries when a window spans more than one space.
- Wi-5_SB.ifc: Tests 2nd (2A) level space boundaries resulting from a window that has a parapet and a header and borders a corner of a space, in a multi-story configuration.
- Wi-6_SB.ifc: Tests 2nd (2A) level space boundaries resulting from a double window that has a parapet and a header, centered in a wall.
- Wi-7_SB.ifc: Tests 2nd (2A) level space boundaries resulting from a floor-to-ceiling window that borders a corner of a space, in a multi-story configuration.
- Wi-9_SB.ifc: Tests 2nd (2A) level space boundaries resulting from a window that has a parapet but no header and borders a corner of a space, in a multi-story configuration.
- WW-3_SB.ifc: Tests 2nd and 3rd (2A and 2B) level space boundaries of interior walls which are intentionally short of the length/width/height of the space they are in, in a multi-story configuration.

References:

Bazjanac, V. 2010. Space boundary requirements for the modeling of building geometry for energy and other performance simulation. *CIB W78, Proc. 27th conf., Applications of IT in the AEC Industry*, Cairo. November 2010.

Bazjanac, V. 2009. Implementation of semi-automated energy performance simulation: building geometry. In Dikbas, A., E. Ergen and H.Giritli (eds.), *CIB W78, Proc. 26th conf., Managing IT in Construction*. Istanbul, TK 595-602. CRC Press. ISBN 978-0-415-56744-2.

bSI 2011. Coordination View Version 2.0, buildingSMART International. http://www.buildingsmart-tech.org/downloads/view-definitions/coordination-view.

DOE 2017. EnergyPlus Documentation – Engineering Reference. https://energyplus.net/sites/default/files/pdfs_v8.3.0/EngineeringReference.pdf

DOE 2012. EnergyPlus IDD Conventions. http://bigladdersoftware.com/epx/docs/8-0/input-output-reference/page-004.html#idd-conventions.

German Ministry of Economy (BMWi) 2015. EnEff-BIM project (Förderkennzeichen 03ET1177A).

IFC 2007. IFC2*x* Edition **3 -** Technical Corrigendum 1, buildingSMART International. http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/index.htm.

ISO 2016. ISO 10303-21:2016. Industrial automation systems and integration -- Product data representation and exchange -- Part 21. https://www.iso.org/standard/63141.html.

Rose, C.M. and V. Bazjanac. 2013. An algorithm to generate space boundaries for building energy simulation. *Engineering with Computers*, An International Journal for Simulation-Based Engineering, DOI 10.1007/s00366-013-0347-5, ISSN 0177-0667.

Solibri 2017. Solibri Model Checker. http://www.solibri.com/products/solibri-model-checker/.