SPACE BOUNDARY REQUIREMENTS FOR MODELING OF BUILDING GEOMETRY FOR ENERGY AND OTHER PERFORMANCE SIMULATION

Vladimir Bazjanac, Staff Scientist, v_bazjanac@lbl.gov
Lawrence Berkeley National Laboratory, University of California, Berkeley, California, USA

ABSTRACT

Data definitions that represent a given building conform to the internal data structure of the CAD software that is used to define the building. They include data which facilitate the representation of the building in CAD, but do not necessarily by themselves define any other pertinent information about the building. CAD representations of buildings are based on detailed definitions of building geometry; those definitions include significant amounts of information needed by CAD tools but not by other types of tools, which need only rudimentary definitions of building geometry to operate. Building energy performance simulation tools, as well as many other types of building simulation and analysis tools, have their own internal data models for building geometry. These internal data models are typically simpler than those in CAD and represent views of building geometry used by the disciplines which are served by these tools.

Most simulation and analysis tools define building geometry as systems of surfaces called "space boundaries" that delineate spatial zones (such as thermal or acoustical zones) and are the critical part of the building geometry definitions for non-CAD tools. This paper clarifies and systematizes information about building geometry that energy performance and similar simulation and analysis tools must contain, and explains the five types (here in referred to as "levels") of space boundaries. The paper briefly discusses space boundary testing and applicable testing tools, as well as the implications of space boundary definition on software development and use. While the discussion emphasizes the use of space boundaries in sophisticated building energy performance simulation tools like EnergyPlus, it is pertinent to other simulation and analysis tools that need building geometry data to run.

Keywords: space boundaries, building geometry, IFC, performance simulation, testing and verification

1. INTRODUCTION

Software tools that simulate building performance and are currently used in Architecture-Engineering-Construction-Owner-Operator (AECOO) industry have a common characteristic: They assume that all transmission and flow of energy through a building element or object is only perpendicular to the surface through which it penetrates the element or object. Two- and three-dimensional transmission and flow are always "out of scope" and are ignored. This is a fundamental consideration and constraint which explains how and why the true geometry of buildings is redefined to facilitate the simulation of building performance with such tools.

CAD models of buildings typically represent architects' views of buildings. Data definitions that represent a given building conform to the internal data structure of the CAD software that is used to define the building and typically include data which facilitate the representation of the building in CAD, but do not necessarily define by themselves any other pertinent information about the building. CAD representations of buildings are based on detailed definitions of building geometry; those definitions thus contain significant amounts of information needed by CAD tools but not used by most other types of tools. These other tools require only rudimentary definitions of building geometry to operate, such as simulation and analysis tools.

Building energy performance simulation tools, as well as many other types of simulation and analysis tools (like acoustics and fire propagation simulation tools) have their own internal data models of building geometry. Such internal data models represent views of building geometry typically used by the disciplines served by these simulation and analysis tools, and are usually much simpler than the geometry data models of CAD tools. Consequently, CAD building geometry representations must be transformed (i.e. simplified, reduced, translated or interpreted) before they can be directly used by other tools (Bazjanac and Kiviniemi 2007).

Most simulation and analysis tools define building geometry as systems of surfaces (i.e. surfaces that delineate walls, slabs, roofs, columns, beams, windows and doors) which are all part of the definition of spaces and/or zones identified in the model of the building. Such surfaces are called "space boundaries" and are the critical part of the building geometry definitions for spatially dependent non-CAD tools. Space boundaries come in "pairs:" One defines the inside, the other the outside of a given wall, slab, roof, column, beam, window or door. Exterior walls, slabs, roofs, windows and doors are an exception – because of how simulation and analysis tools typically deal with exterior surfaces (the exterior cannot be modeled as a space or a zone), they only have one space boundary that corresponds to their interior surface. Space boundaries are flat polygons with an outward or inward normal which defines the direction of transmission or flow through the given space boundary.

Zones defined in a building model usually contain several individual spaces or rooms that have the same behavioral characteristics that characterize the zone. Space boundaries that delineate a zone are those space boundaries of individual spaces which make up the boundaries of that zone. Space boundaries of individual spaces that belong to that zone but which do not coincide with the boundary surfaces of the zone are ignored (i.e. omitted) in the zonal definition of building geometry.

The original building geometry, from which space boundaries are derived, is typically created by model-based CAD tools. These are "intelligent" tools: object oriented tools which define building elements as object/attribute/relationship sets. All major CAD tools used in the U.S. and global AECOO industry are now model based.

The current practice of modeling building geometry for simulation usually amounts to manual re-creation of the original building geometry that describes the particular simulation view of the building (e.g. thermal, acoustical, fire propagation, security or some other view). This can results in the definition of wall, slab, roof, window, door and other building geometry input data for the simulation without the realization that these definitions actually represent space boundaries. The manual process does not follow any established rules of data transformation and is typically ad hoc, inconsistent and often inaccurate, and is one of the reasons why simulation results (such as the results of sophisticated building energy performance simulation) cannot be readily reproduced (Bazjanac 2008).

This paper clarifies and systematizes definitions a "simplified" or "reduced" building geometry for building energy performance and similar simulation and analysis tools must contain; this should help standardize the preparation of building geometry input data for simulation, set the basis for semi-automatic building geometry data transformation, and should help prevent further misunderstandings and misrepresentations often encountered in the AECOO industry today. It describes and explains the five "levels" of space boundaries, why and how they are defined, and how they are used by simulation and analysis tools. In addition, the paper provides the space boundary classification in the Industry Foundation Classes (IFC) data model. It discusses the implications of space boundary definition on software development and use. It also discusses the testing of space boundaries pertinent to semi-automated modeling of building geometry for energy performance simulation, defined and exported in IFC format by model-based CAD tools. Finally, it discusses available tools that check and test instances of IFC definitions of building geometry exported by CAD tools.

2. FIRST (1ST) LEVEL SPACE BOUNDARIES

Homogeneous walls are defined in model-based CAD as one (single) wall object in its full length per instance (Fig. 1). The interior wall shown in as red in Figure 1 is modeled as a single object that extends from one exterior wall to the other on the opposite side. This is how architects would model such a wall, even though the wall separates zones 1 and 2 from zones 3 and 4, and is intersected by lateral walls that separate zones 1 and 2, and zones 3 and 4.

Figure 1: Typical wall representation in model-based CAD software

If one stood in zone 1, one would see only a portion of the same wall between the exterior wall on the left and the lateral wall that separates zones 1 and 2 on the right, as shown in red in Figure 2. This long wall's surface that is visible without interruption in zone 1 constitutes a *first (1^{st}) level space boundary*. Correspondingly, continuously visible surfaces of the long wall (outlined in blue in zone 2, in orange in zone 3, and in green in zone 4 in Figure 2) also constitute 1^{st} level space boundaries.

Figure 2: First (1^{st}) level space boundaries

1^{st} level space boundaries are implemented in visualization tools to facilitate the showing of what the eye sees in a space or a zone. These tools do not consider transmission or (energy) flow through the modeled surfaces.

3. SECOND (2^{ND}) LEVEL SPACE BOUNDARIES

If transmission or flow through building elements (e.g. through walls, slabs, ceilings, or roofs) is modeled and simulated, space boundary definition becomes subject to an additional mandatory criterion: Such space boundaries must assure that the entire areas defined as their surface provide unique and consistent rate of transmission or flow. The difference in thermal or other pertinent conditions in zones separated by the building element determines the rate of transmission or flow through the building element. For example, only considering heat flow that is perpendicular to the surface of the wall through which it is flowing, the temperature difference (Δt) between zones 1 and 3 determines the amount of heat flowing through the segment of the wall that separates zones 1 and 3 (outlined in red in Figure 3). However, since the temperature in zone 4 may differ from that in zone 3, the rate of transmission or flow through the segment of the wall that separates zones 1 and 4 (outlined in blue in Figure 3) may be different from the rate of transmission or flow through the red segment of the wall. Thus, viewed from zone 1, the previous 1^{st} level space boundary is subdivided into two segments which facilitate two different rates of transmission or flow. Such space boundaries constitute *second (2^{nd}) level space boundaries*.

The definition of a 2^{nd} level space boundary that is interior always mandates the definition of its "pair:" a space boundary of exactly the same shape and size, offset from the original 1^{st} level space boundary by the thickness of the "parent" building element. It is worth noting that one 2^{nd} level space boundary in the pair may be identical to the same zone's 1^{st} level space boundary, as is true for space boundaries for zone 3 in Figures 2 and 3. Exterior 1^{st} and 2^{nd} level space boundaries are identical, as exterior building elements have only one surface.

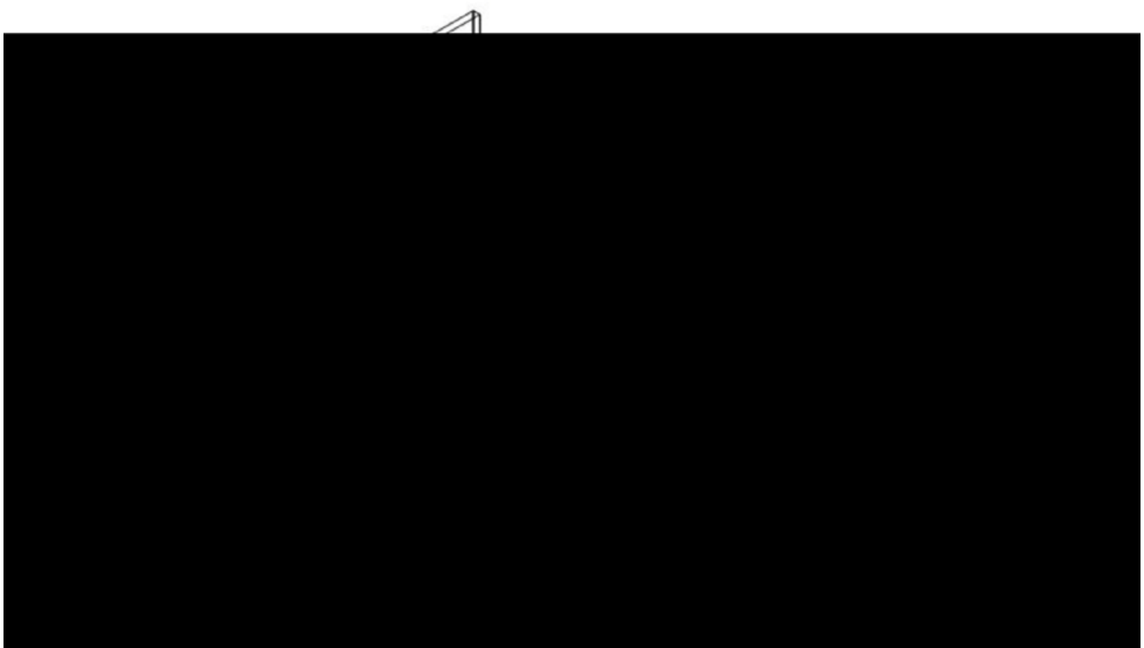

Figure 3: Second (2^{nd}) level space boundaries

The definition and use of 2^{nd} level space boundaries is mandatory in the use of tools that simulate the transmission or (energy) flow through the modeled interior surfaces. Windows, skylights and doors, as well as virtual surfaces (e.g. simulated "air walls") which constitute non-physical boundaries of zones, are also represented as 2^{nd} level space boundary pairs in such simulation.

4. THIRD (3^{RD}) LEVEL SPACE BOUNDARIES

Definition of 2^{nd} level space boundaries does not account for building element surface areas that do not play any role in the transmission or (energy) flow through the building element because there is no other zone to receive the perpendicular transmission or flow through these unaccounted surface areas. Figure 4 shows orthogonal projections of the top and bottom surfaces of wall 3-4 on top and bottom surfaces of the top and bottom slabs, respectively, that vertically enclose all four zones; these are some of the "remainder" narrow (sliver) surfaces which were not accounted for in Figure 3. It also shows a projection of the vertical end of wall 3-4 at intersection with the long wall on what is the 1st level space boundary in Figure 2; this is also one of the unaccounted "remainder" sliver surfaces in Figure 3. These previously unaccounted surface segments constitute *3rd level space boundaries*.

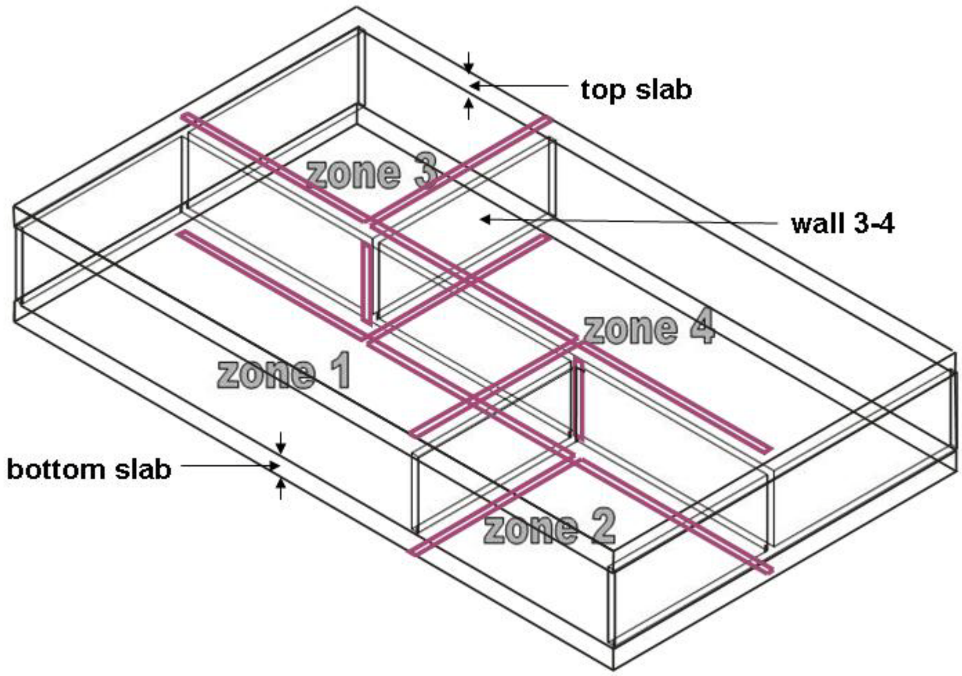

Figure 4: Third (3rd) level space boundaries

It is important to note that 3rd level space boundaries cannot have a "pair" space boundary. Figure 4 shows all 3rd level space boundaries in the image in purple color. Exterior building elements (roofs, exterior walls and exterior slabs) do not have 3rd level space boundaries; interior slabs can have them if the slab ends within the interior of the building.

The definition and use of 3rd level space boundaries is mandatory in cases when the simulation requires complete enclosure of zone volumes, such as in the case of "Full Interior and Exterior" simulation with EnergyPlus (DOE 2010). Otherwise, the definition of 3rd level space boundaries may be ignored.

5. FOURTH (4TH) LEVEL SPACE BOUNDARIES

Some model-based CAD tools give the end user the opportunity to choose the position of the wall reference line when defining the wall: along the bottom of one side or the other side of the wall, or along the wall's center line. If the reference line is on the opposite side from which an intersecting wall merges with the wall being defined, the intersecting wall "stops" at the surface where it merges with the wall being defined and does not reach the other side of that wall. This leaves a small rectangle area unaccounted for on surfaces above and below the intersection (shown as the small white rectangle in the first graphic column of the "3rd level SB" line in Figure 5). That unaccounted for area has all the characteristics of a 3rd level space boundary. In this case the unaccounted area is bound by the orthogonal projection of the reference line on one side, and the 3rd level space boundaries of the involved walls on the other three sides (as shown in the cutout in Figure 6). If the wall reference line is along the center line of the wall being defined, the unaccounted area is bound by 3rd level space boundaries of the involved walls and appears as an indentation within the 3rd level space boundary of the wall being defined (shown as the even smaller white rectangles in the third graphic column of the "3rd level SB" line in Figure 5). These unaccounted for areas constitute *4th level space boundaries*. If the reference line is on the same side at which the intersecting wall encounters the wall being defined, there is no area left unaccounted for by 3rd level space boundaries of the involved walls (as shown in the middle graphic column of the "3rd level SB" line in Figure 5) and in this case the intersection will have no 4th level space boundaries.

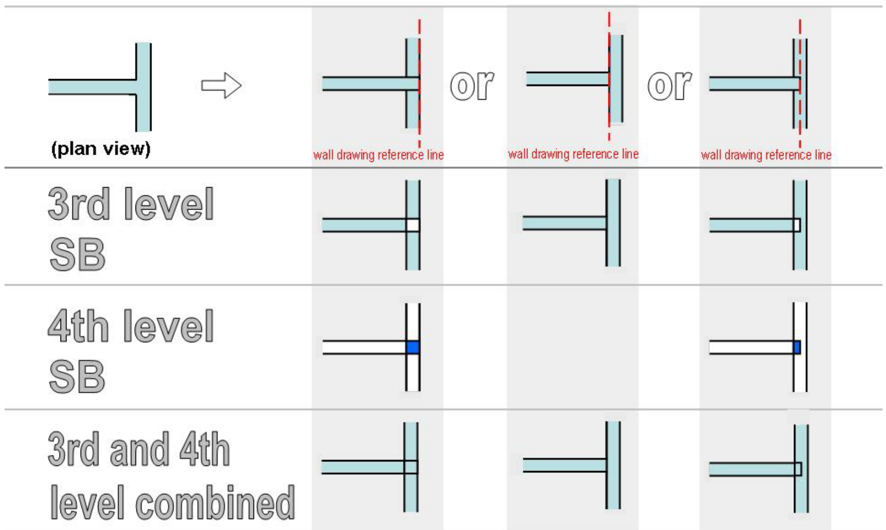

Figure 5: Third (3rd) and fourth (4th) level space boundaries at wall intersections

Figure 6 shows that horizontal 3rd and 4th level space boundaries are found on the floor of the story above and/or the ceiling of the storey below the story in which the intersecting walls actually are. As exterior walls, slabs and roofs can have only one surface in simulation tools' internal data models (on the interior side of the building element), exterior walls cannot include any 4th level space boundaries.

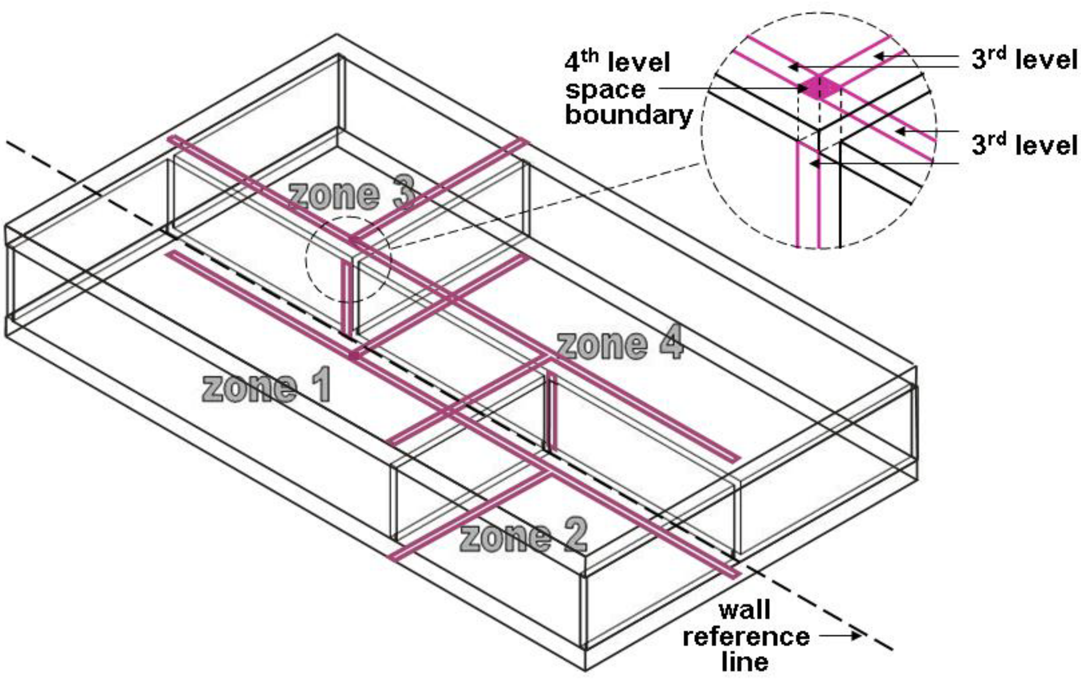

Figure 6: Fourth (4th) level space boundaries

Since the wall reference line in Figure 6 is drawn on the zone 1-2 side of the long wall, the Figure shows only two 4th level space boundary. Both appear at the intersection of wall 3-4 and the long wall – one is above the intersection, the other below it. The intersection of wall 1-2 and the long wall involves no 4th level space boundary, as the wall reference line is on the wall 1-2 side of the long wall.

As there is no functional difference between them in data export from software that calculates space boundaries, 4th level space boundaries are merged with 3rd level and are treated as 3rd level. However, the notion of 4th level space boundary is necessary for verifying that all space boundaries were calculated correctly and are accounted for in the calculation.

6. FIFTH (5TH) LEVEL SPACE BOUNDARIES

When walls intersect at an angle other than right angle (as is the case with wall 1-3 in Figure 7), a narrow sliver of the intersecting wall remains unaccounted for (shown as the yellow area in the cutout of Figure 7). This is because there can be no transmission or (energy) flow through that surface area that is perpendicular to that surface and also reaches another zone. Transmission or flow in direction A shown in the cutout, perpendicular to the surface of wall 1-3, cannot reach zone 3, and in direction B (perpendicular to the surface of the exterior wall) it is not perpendicular to the surface of wall 1-3. The unaccounted area in this case constitutes a *5th level space boundary*, which behaves the same way as 3rd level space boundaries do.

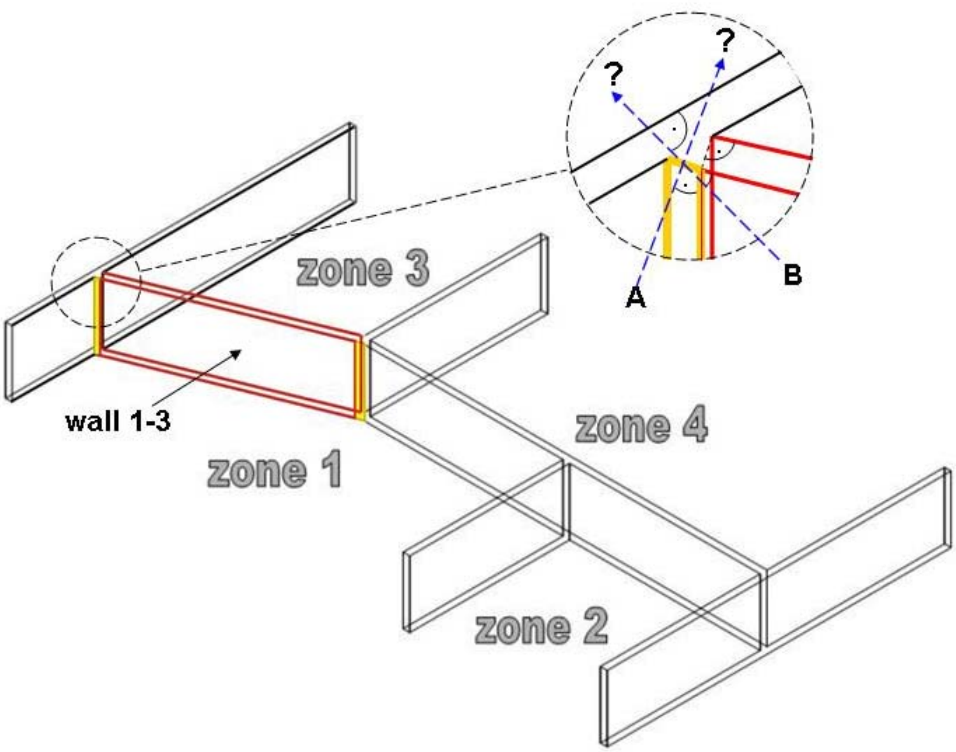

Figure 7: Fifth (5th) level space boundaries

As is also the case with 4th level space boundaries, exterior walls, slabs and roofs cannot include any 5th level space boundaries, since they have only one surface in the internal data models of simulation tools. The definition of 5th level space boundaries is mandatory when simulation with tools like EnergyPlus requires complete enclosure of zone volumes, as is the case with 3rd and 4th level space boundaries (DOE 2010).

7. CLASSIFICATION OF SPACE BOUNDARIES IN IFC

Space boundaries can be interior, exterior and virtual. If exterior, they can be only 1st or 2nd level, as exterior building elements have only one surface in simulation tools' internal data models. Thus it should be noted that exterior 2nd level space boundaries do not have a pair like other 2nd level space boundaries do.

The IFC data model of buildings is currently the only such data model that recognizes and classifies all levels of space boundaries as specific model entities (buildingSMART 2010a). Table 1 shows how space boundary levels defined in this paper are classified in the IFC data model. 1st level space boundaries are classified as space boundary type 1 in IFC; 2nd level are classified as type 2a. 3rd, 4th and 5th level space boundaries are all classified as IFC type 2b because they all exhibit the same behavior.

Table 1: IFC type classification for space boundary levels

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

The Open Green Building Schema gbXML recognizes the "2a" class of space boundaries as defined in IFC (gbXML 2008). Space boundaries in the gbXML schema are linked to construction type via the building element's surface attributes and trigger energy flow calculation. A future update of the schema will presumably account for IFC class "2b" space boundaries. As gbXML serves primarily thermal simulation and analysis applications, there will probably be no demand to include IFC class "1" space boundaries in it.

8. TESTING AND VERIFICATION OF SPACE BOUNDARIES

Definition of space boundaries in not a trivial matter, especially when dealing with complicated building geometries. To test and verify their correct definition generated by different software, the research team at the Lawrence Berkeley National Laboratory (LBNL) of the University of California developed 55 "issue" test cases – small models of simple one- and two-story buildings that feature a specific building element configuration which is known to have caused problems in space boundary generation in the past. Examples include issues with the positioning of windows in corners, slabs that include voids, columns that are partially or fully embedded in walls, subdivision of zones with virtual walls, and more. The tests consist of running full sets of these test cases in software that is subject to testing and then checking space boundaries generated by the software for each test case. The research team is continuously creating new test cases; some of the "issue" test cases are documented in a forthcoming report (Weise et al. 2010) for the Open Geospatial Consortium's (OGC) AECOO-1 Testbed (OGC 2009).

Space boundary level differentiation (2nd through 5th) is critical to space boundary testing and verification. It facilitates the counting of instances of different level space boundaries exported by generating software and helps find problems: instances of duplicate, missing or ill-formed space boundaries.

Two currently available model checking tools have proved to be particularly useful in testing and verification: Solibri Model Checker (SMC 2010) and FZKViewer (FZK 2010). Both tools, among other features they provide, analyze building models defined in IFC and check space boundaries. SMC is a general model checker that uses selectable constraint sets to check specific issues in the building model. FZKViewer offers analysis and checks of models defined in IFC and CityGML. Both provide effective model visualization for visual checks, offer space boundary counts, display active model object trees, and generate detailed performance and error/failure reports.

9. IMPLICATIONS FOR SOFTWARE DEVELOPEMNT

Model-based CAD tools may be the most natural software environment for the definition of space boundaries; several leading model-based CAD vendors have developed or are currently developing add-on utility software that calculates or will calculate all levels, types or classes of space boundaries. Alternatively, space boundaries could be defined in dedicated middle-ware; this would require the use of geometry libraries. Definition of space boundaries by simulation and analysis tools would not be appropriate, as such tools do not employ sophisticated CAD engines capable of proper treatment of imported raw CAD data.

Calculation of space boundaries and their export by software which employs proprietary data models of buildings is not public knowledge and cannot be discussed here. To export a full set (i.e. all levels) of space boundaries such software must currently use IFC interfaces capable of such export, unless it can share them with the target simulation tool or pass them point-to-point.

In the current open data exchange environment in the AECOO industry it is essential that all software tools that generate space boundaries, as well as those that import them, have robust IFC interfaces and/or IFC utilities. Otherwise, while the definition of space boundaries may be correct, their export or import may fail or may cause inaccuracies and other problems.

It is important that all IFC interfaces that export and/or import space boundary data implement a proper view of the IFC data model, one that includes the definition of space boundaries and that will assure the other software which implements the same view will be able to properly import and/or export space boundary data (buildingSMART 2010b). Model views assure that only the pertinent data are represented and that they are always exchanged in proper form, content and format.

Some of the space boundary data have to be transformed before they can be used by a given simulation or analysis application. Many of the necessary data transforming are of the "interpretation" variety, where available data are used to derive new data content (Bazjanac and Kiviniemi 2007). Space boundary data transformation can include the conversion of columns into walls with the equivalent geometry and construction type, or the subdivision of slabs into segments around a void they contain (both cases have to be resolved before use in DOE-2 and EnergyPlus simulation). All data transformation should be done per established rules and is best done in dedicated middleware. Bazjanac lists data transformation rules that were embedded in GST/IDF Generator, a tool developed to provide semi-automatic import of building geometry into EnergyPlus (Bazjanac 2009).

Finally, a comment is necessary about a tendency shown by some CAD software developers. They prefer to implement space boundaries that do not account for the thickness of the building element: Both space boundaries in a pair are defined in the same plane positioned along the center-line of the modeled building element. While that may simplify their development effort, it distorts the geometry of the building in subsequent simulations and causes possibly significant errors in the calculation of zone areas and volumes. In other words, the building defined this way is no longer the same building as the one in the original model definition. Incorrect area and volume can subsequently distort the results of simulation. The argument that this is a "close enough" or "good enough" approximation is not valid, as it is not known how close is "close enough" or how good is "good enough" – what may be an insignificant error for one building design may become quite significant for another. Such practice should be avoided.

10. CONCLUSIONS

The primary objective of this paper is to offer the description and understanding of space boundaries that are required for the use of building geometry representations by building energy performance and other types of simulation and analysis. This paper explains what constitutes each of the five identified space boundary levels and discusses the general definition requirements for each. This is required knowledge for all who develop software tools that involve the use of building geometry (CAD and "downstream" simulation and analysis tools alike), as well as for those who use such tools to define virtual models of buildings. Proper understanding of space boundaries should yield better compatibility among some of the "mission critical" software applications used in the AECOO industry. Other considerations, such as in-depth discussion of the IFC data model, gbXML, testing tools and methodology, etc., are topics that merit extensive analysis and are out of scope of this paper.

For those who are involved in the development or use of IFC compatible or compliant software, the classification of space boundaries in IFC – the only open data model of buildings in which space boundaries can be directly defined as such – provide an insight what space boundary levels are contained in which class. Users of gbXML and similar data models which import space boundaries predefined in IFC can understand what the imported definitions actually represent.

Testing and verification of space boundaries performed at LBNL can be performed by any developer of space boundaries. Model checking tools should be an integral part of any space boundary developer's toolkit, and should also be regularly used by those who define virtual models of buildings to verify the "cleanness" of the models they create.

The discussion of some of the implications of space boundaries on software development considers a "larger picture" of what is involved in software development that includes the definition and export/import of space boundaries. To be useful to the industry, delivered software product must be robust. Existing software applications must have functional IFC interfaces and/or utilities, which must be based on carefully defined and properly selected IFC model views.

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