

High-order second-level space boundary topology calculation for building energy performance simulation modelling

ABSTRACT: A second-level space boundary surface is the surface through which thermal energy flows between internal building spaces and the building environment. To set up whole building energy simulation models, knowledge of these boundaries is required. The geometric challenges associated with identifying these second-level space boundaries are compounded when considering overlapping multi-layer building constructions — a particular case but one often encountered in practice. In the present work, we introduce the concept of a high-order (greater than two) space boundary surface and a geometric algorithm to identify such surfaces from Building Information Models. The proposed algorithm extends our earlier work on first-order second-level space boundary calculation. We use as input building information models from real buildings, to demonstrate the efficacy of the proposed algorithm. In particular, we consider a facade retrofitting application scenario where external or internal multi-layer insulation elements are added. The application of the algorithm automatically identified correctly second and third order second-level space boundaries related to these additional elements.

1 INTRODUCTION

Research on the automated generation of energy models from BIM data has focused on approaches to automatically extract data from openBIM models (such as IFC files) and transform these to serve the input requirements of Building Energy Performance Simulation (BEPS) tools (Elagiry et al., 2020; Karlapudi & Menzel, 2020; G. N. Lilis et al., 2014). This transformation imposes several challenges to capturing relevant information domains: this covers the geometric aspects but can include building services and automation systems (Hitchcock & Wong, 2011). Implicit to this transformation is the assumption that the data are of “good quality” (G. Lilis et al., 2018) which in practice requires the existence of modelling guidelines and model checking tools. Considering the geometric aspect of this transformation (Bazjanac, 2009), the second-level space boundary information is required (Bazjanac, 2010). These surfaces are thermal exchange surfaces among the building’s internal space volumes and the building environment; we use the notation 2LSB as a short form for the term second-level space boundary. This information is not often contained in the input openBIM models, and manually including this information requires overhead and duplication of modelling efforts.

The latest IFC4 openBIM specification contains the necessary classes and data structures to capture geometric information of the building’s second-level space boundary surfaces. In models exchanged in practice, this information is often missing or is incorrectly specified (buildingSmart, 2018); oftentimes these geometric data structures are incorrectly populated in the respective IFC files. To bridge this gap, a number of geometric trans-

formation algorithms have been developed to generate these surfaces and populate the respective IFC classes (Ying & Lee, 2021; Rose & Bazjanac, 2015; G. N. Lilis et al., 2017; Ladenhauf et al., 2016). These algorithms assume that a single multi-layer building construction element lies among every internal second-level space boundary surface pair or between an external second-level space boundary surface and the environment (air, ground). Such assumption imposes an additional burden on the designer side to define every building element taking part in the thermal exchange among the internal building spaces as a single multi-layer construction. The situation becomes even worse when additional multi-layer insulation elements are added internally or externally to the external walls of the building facade. In such cases, redesign and regeneration of the BIM model are necessary to conform to the previous requirement. Furthermore, in cases the building model contains multiple walls or slabs modeled as distinct BIM elements stacked one on top of the other referring to different construction phases, redesign is also required, to replace the multi-element constructions with single multi-layered ones.

To avoid these unnecessary remodeling efforts, in all of the above cases, the concept of a high- (greater-than-one) order second-level space boundary surface is required. This new definition allows multiple multi-layer constructions to exist among the second-level space boundary surfaces. Given this definition, an extension of the existing second-level space boundary calculation algorithm (G. N. Lilis et al., 2017), is presented to obtain these new surfaces.

Based on the previous description, the paper is organized as follows. Initially, a review of the traditional approach to obtaining the second-level space

boundary surface topology is described. To prepare the description of the paper's main algorithm, a number of preliminaries are presented first which include: the definition of the order of a space boundary surface, a number of geometric assumptions and the paper's nomenclature. The description of the main calculation algorithm that extracts the higher-order second-level space boundary surfaces, follows next. Extensions of this algorithm to the calculation of external higher-order second-level space boundary surfaces and external shading surfaces formed by extruded multi-element building constructions are also presented. The paper concludes with an application example of the introduced algorithm referring to a real building.

2 TRADITIONAL APPROACH

The primary aim of calculation algorithm is to calculate a set of surfaces at the boundaries of the building space volumes, which intervene between the thermal exchanges among these spaces and the building environment as displayed with arrows in Figure 1.

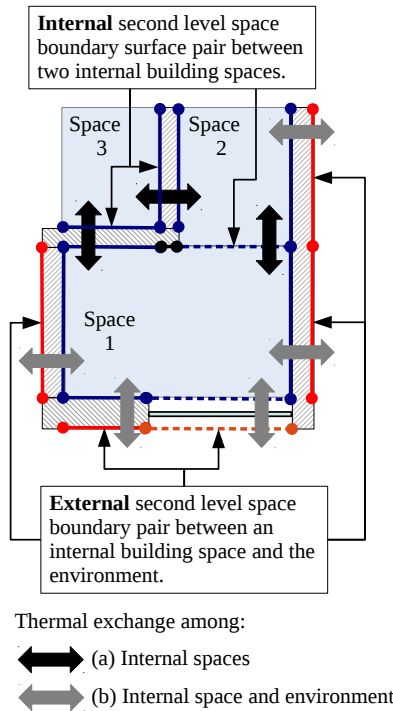


Figure 1: Illustration of thermal flow through external and internal second-level space boundary surface pairs in a building

These surfaces are organized in pairs and characterized as *internal* and *external*. If the second-level space boundary surfaces of the pair are internal, they are attached to two internal building space volumes. Internal second-level space boundary surface pairs are indicated with blue colour in Figure 1 and the respective thermal flow with a black arrow. If the second-level space boundary surfaces of the pair are external, then one surface is attached to the building space, and the other exposed to the

environment. The surface exposed to the environment is often omitted. External second-level space boundary surface pairs are indicated with blue and red colors in Figure 1 (blue for the surface attached to the building space and red for the surface exposed to the building environment) and the respective thermal flow with grey arrow.

For all calculation algorithms, it is assumed that between the 2LSB surface pairs a single (multi-layer) building construction exists such as a building wall or a slab. This is not always the case as more than one building construction might exist in different construction phases, as illustrated for a double construction among two building spaces in Figure 2. As shown in the example of Figure 2, for the double construction pictured in part A (constructions 1 and 2), three second-level space boundary surface pairs should be obtained, displayed in part C (one for construction 1, one for construction 2 and the middle one which includes both constructions).

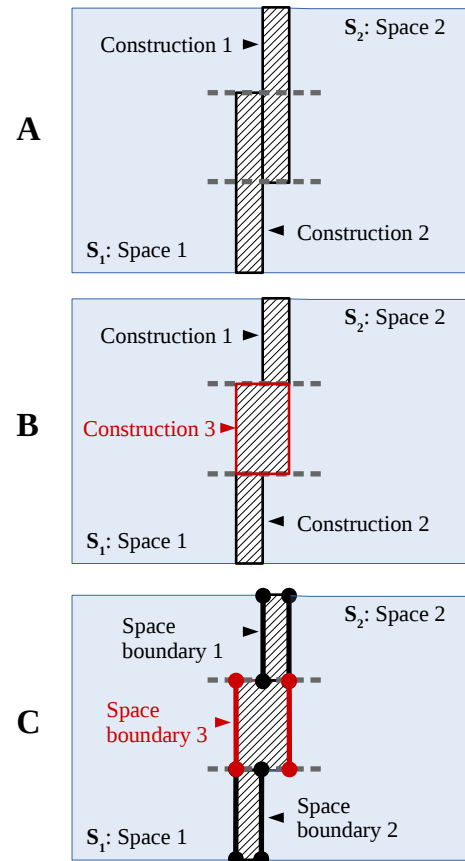


Figure 2: A. Modelling of double construction elements impeding thermal flow between spaces 1 and 2, B. Re-modelling of the double multi-layer construction, as three single multi-layer constructions, C. Second-level space boundary surface pairs of the double multi-layer construction

The traditional algorithmic process for second-level space boundary calculation requires updating the model and adding a third construction 3 between the two constructions (1 and 2). The new construction should include the layers of construction 1 and 2 sequentially (first the layers of construction 1, then the layers of construction 2). To avoid

the remodelling displayed in part B the definition of the second-level space boundary surface pair should be relaxed, allowing more than one multi-layer construction element to exist between the surfaces of the pair. This relaxation in the definition is possible by introducing the concept of order of a second-level space boundary surface, described next.

3 PRELIMINARIES

3.1 Order definition

The order of a 2LSB surface is defined as the number of multi-layer building elements related to this surface. For internal 2LSBs instead of a single surface, we refer to the corresponding surface pair. The traditional 2LSBs, which are currently supported in the IFC4 schema, have a single related building element and therefore are considered first order. As defined in the latest IFC4x3 schema, the attribute *RelatedBuildingElement* of the *IfcRelSpaceBoundary* class points to a single element. Although not defined in the IFC schema, second- and third-order second-level space boundary surfaces are often encountered in retrofitted building models. For example the application of internal or external multi-layer insulation elements, as retrofitting measures, results to the appearance of: second order 2LSB surfaces if one these measures is applied, and third order 2LSB surfaces if both measures are applied.

3.2 Boundary representation assumptions

The following three assumptions related to the boundary representations of the BIM elements are considered:

1. The surfaces of the boundary representations are plane polygons with their normal vectors pointing outwards according to the right-hand rule.
2. All boundary representations are assumed to be water-tight: the line segments at the boundaries of their surfaces belong to exactly two surfaces.
3. No clashes or intersections occur among all boundary representations.

3.3 Nomenclature

Before the presentation of the proposed algorithm and within the rest of the paper, the mathematical notation of the following table will be adopted.

Table 1: Nomenclature

Description	Symbol
Surface polygon	a
Boundary representation	A
Surface set	$\mathcal{A}$
Polygon intersection	$\cap_p$
Polygon difference	$\setminus_p$

4 EXISTING ALGORITHM

Although there are many 2LSB calculation algorithms the present work focuses on the extension of the algorithm CBIP (G. N. Lilis et al., 2017), to include second- and third-order 2LSB surfaces which are usually encountered in building retrofitting projects. This algorithm rely on 3D polygon intersection and projection operations on common boundaries among space volumes and neighbors to these volumes building constructions. These algorithmic operations are mathematically expressed by the following CBIP₁ function:

$$(sb_1, sb_2) = \text{CBIP}_1(S_1, C, S_2) \quad (1)$$

$$(cb_1, cb_2) = \text{CB}(S_1, C, S_2) \quad (1a)$$

$$(sb_1, sb_2) = \text{IP}(cb_1, cb_2) \quad (1b)$$

where (sb_1, sb_2) are the returned 2LSB surface pairs, (S_1, S_2) are the boundary representations of the opposite building space volume and C is the boundary representation of the construction between these space volumes.

The CBIP operation is completed in three stages (illustrated in Figure 3):

1. Initially in the common boundary extraction stage (stage 1), two common boundary surfaces between the space volumes and the building constructions are extracted (green surfaces in part 1 in Figure3). This common boundary surface extraction is expressed by the CB function in (1a) where (cb_1, cb_2) is the common boundary surface pair returned by this function. This function is also defined mathematically in subsection 4.4 by equation (5).
2. The two common boundaries (cb_1, cb_2) are projected one on the plane of the other resulting to two projected surfaces in the projection stage (stage 2), (blue surfaces in part 2 in Figure3).
3. Finally, the projected surfaces from stage 2 are intersected with the initial common boundary surfaces from stage 1, resulting to two intersection surfaces in the intersection stage (stage 3), (red surfaces in part 3 in Figure3).

These intersection and projection operations of stage 2 and 3, are expressed mathematically by the function IP (1b) which receives as input the common boundary surface pair (cb_1, cb_2) and returns the 2LSB surface pair (sb_1, sb_2) . The two surfaces (sb_1, sb_2) returned by the IP function form the 2LSB surface pair, returned by the overall CBIP₁ algorithm in equation (1).

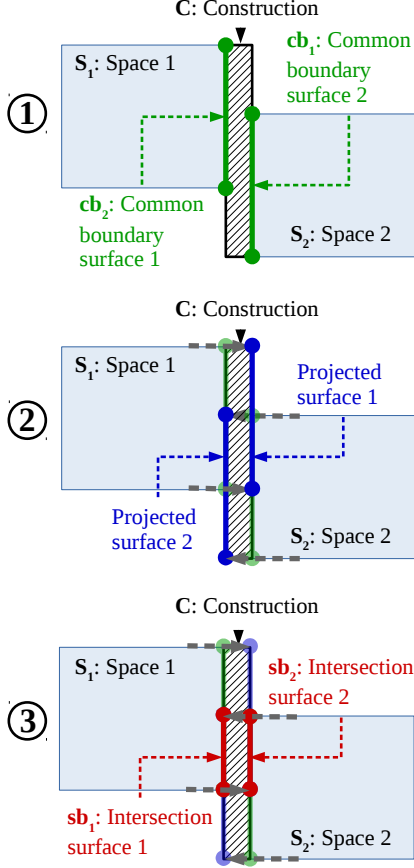


Figure 3: Illustration of the three stages of CBIP algorithm: (1) Common boundary extraction, (2) Projection of common boundaries, (3) Intersection of projections with common boundaries

4.1 Second-order extension

CBIP algorithm can be extended to include double multi-layer building constructions and calculate second-order 2LSB surface pairs, as illustrated for boundary representations of two spaces S_1, S_2 and two construction elements C_1, C_2 in the example of Figure4. This extended operations can be formulated in math terms by the following CBIP₂ function:

$$(sb_3, sb_4) = \text{CBIP}_2(S_1, C_1, C_2, S_2) \quad (2)$$

$$(sb_1, cc_1) = \text{CBIP}_1(S_1, C_1, C_2) \quad (2a)$$

$$(cc_2, sb_2) = \text{CBIP}_1(C_1, C_2, S_2) \quad (2b)$$

$$(sb_3, sb_4) = \text{IP}(sb_1, sb_2) \quad (2c)$$

According to equation (2), CBIP₂ function uses CBIP₁ and IP functions defined in equations (1),

acts on an input quadruple (S_1, C_1, C_2, S_2) and returns the second-order 2LSB surface pair (sb_3, sb_4) , in the following 2 stages:

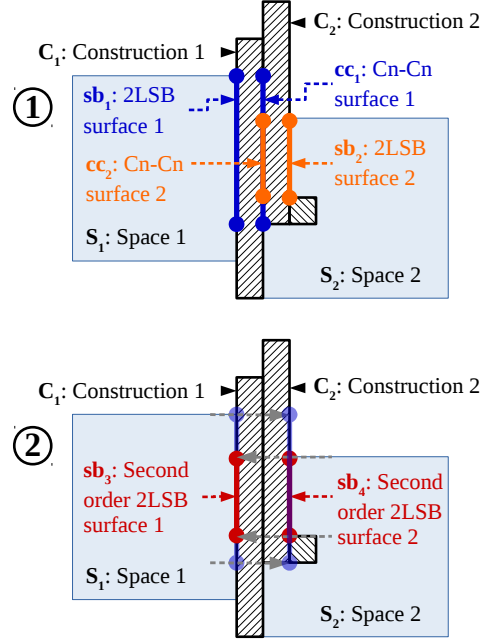


Figure 4: Illustration of second order 2LSB surface extraction: (1) CBIP process on space and 2 construction B-reps, (2) IP process on obtained 2LSB surfaces

- Initially, in the first stage, CBIP₁ function is applied on the triple (S_1, C_1, C_2) and returns the space boundary surface sb_1 and the intermediate construction-construction (cn-cn) surface cc_1 (equation (2a)). CBIP₁ function is applied again on the triple (C_1, C_2, S_2) and returns the intermediate construction-construction (cn-cn) surface cc_2 and the space boundary surface sb_2 (equation (2b)).
- Finally, in stage 2, the IP function defined in equation (1b) is applied on the two space boundary surfaces extracted from stage 1 (sb_1, sb_2) and returns the final second-order 2LSB pair (sb_3, sb_4) .

4.2 Third-order extension

As in the case of second-order 2LSB surfaces, the CBIP algorithm can be extended to include triple multi-layer building constructions and calculate third-order 2LSB surface pairs as illustrated for the boundary representations of: two spaces S_1, S_2 and three construction elements C_1, C_2, C_3 in the example of Figure5. This extended operations can be formulated in math terms by the following CBIP₃ function:

$$(sb_3, sb_4) = \text{CBIP}_3(S_1, C_1, C_2, C_3, S_2) \quad (3)$$

$$(sb_1, cc_1) = \text{CBIP}_1(S_1, C_1, C_2) \quad (3a)$$

$$(cc_2, sb_2) = \text{CBIP}_1(C_2, C_3, S_2) \quad (3b)$$

$$(sb_3, sb_4) = \text{IP}(sb_1, sb_2) \quad (3c)$$

Comparing equations (2) and (3), the only difference is the addition in equation (3) of the additional boundary representation of a building construction C_3 . Additionally, equations (2a) and (2b) share two common construction boundary representations C_1, C_2 , while equations (3a) and (3b) share only one common construction boundary representation C_2 . Apart from previous differences, the algorithmic extensions of CBIP for second and third order 2LSB surface pairs follow the same two-stage processes.

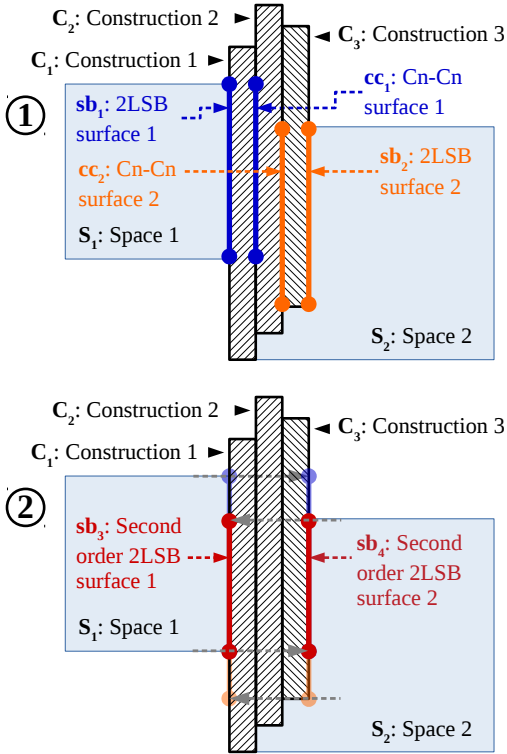


Figure 5: Illustration of third order 2LSB surface extraction: (1) CBIP process on space and 2 construction B-reps, (2) IP process on obtained 2LSB surfaces

4.3 Higher than third order extensions

Fourth and higher order 2LSB pairs, are obtained in a similar manner to second and third order pairs. Fourth order 2LSB surfaces are obtained again in two steps: (a) collecting two quadruplets of boundary representations (S_1, C_1, C_2, C_3) and (C_2, C_3, C_4, S_2) which share 2 common construction boundary representations (C_2 and C_3) and applying inductively the CBIP_2 function on them (defined in equation (2a)) and (b) application of the IP function on the returned pair of surfaces by the CBIP_2 function (as illustrated for the second order

in equation (2c)). Fifth order 2LSB surfaces are obtained in the same manner as fourth order using quadruples which only one middle common construction Boundary representation (C_3): (S_1, C_1, C_2, C_3) and (C_3, C_4, C_5, S_2) .

In the same manner and by induction n^{th} and $n^{\text{th}} + 1$ order of 2LSB surface pairs, with $n = 2K$ and $k \geq 3$, can be obtained in two steps: (a) by applying CBIP_k function on n-tuplets $(S_1, C_1, C_2, \dots, C_{n-1})$ and $(C_2, \dots, C_n, S_2)$ (n^{th} order) and $(S_1, C_1, C_2, \dots, C_{n-2})$ and $(C_3, \dots, C_n, C_{n+1}, S_2)$ ($n^{\text{th}} + 1$ order) and (b) by applying the IP function on the returned pair of surfaces by the CBIP_2 function.

4.4 External high-order 2LSB calculation

The examples presented so far are related to building space pairs and the related obtained internal high-order 2LSB surface pairs. External high-order 2LSB surface pairs are calculated in the same manner as the internal the high-order 2LSB surface pairs, with the only difference being the replacement of one of the building space boundary representations (S_1 or S_2) by the boundary representation of the environment surfaces contained in the surface set $\mathcal{E}$. These surfaces are external building areas exposed to the either the outside air or the building ground.

The surfaces of set $\mathcal{E}$ can be obtained by removing from the surfaces of the boundary representations of all building constructions (set $\mathcal{C} = \cup_i C_i$), the surfaces or surface parts that are common among these representations and the space surfaces in set $\mathcal{S} = \cup_i S_i$ (common boundaries). If no clashes occur and the boundary representations are water-tight the common boundaries are always shared among two boundary representations. Based on the previous definitions the calculation of the surface set $\mathcal{E}$, can be expressed in math terms as:

$$\mathcal{E} = \mathcal{C} \ominus \{\text{CB}(\mathcal{C} \cup \mathcal{S})\} \quad (4)$$

The introduced operation " $\ominus$ " and the CB function used in (4) use the polygon intersection ($\cap_p$) and subtraction ($\setminus_p$) which act on two coplanar polygons a, b using (Vatti, 1992) and return the common part and their difference, respectively. If polygons a and b are not coplanar then $a \setminus_p b = \emptyset$ and $a \cap_p b = \emptyset$. More specifically, CB in equation (4), is defined as a common boundary function, which when applied on a polygon surface set, returns polygons or polygon parts common in two or more input polygons:

$$\text{CB}(\mathcal{A}) = \left\{ \bigcup_{\forall a_i, a_j \in \mathcal{A}} (a_i \cap_p a_j) \right\} \quad (5)$$

The subtraction operation " $\ominus$ " applied on two surface sets $\mathcal{A}$ and $\mathcal{B}$: $\mathcal{A} - \mathcal{B}$, returns a surface set

in which contains polygonal surfaces obtained by coplanar pair-wise polygon subtraction operations, $a_i \setminus_p b_j$, $\forall a_i \in \mathcal{A}$ and $\forall b_j \in \mathcal{B}$:

$$\mathcal{A} \ominus \mathcal{B} = \left\{ \bigcup_{\forall (a_i, b_j) \in \mathcal{A} \times \mathcal{B}} (a_i \setminus_p b_j) \right\} \quad (6)$$

4.5 External shading surfaces

Using the rationale of the introduced algorithmic extension, the external shading surfaces of buildings formed by stacked multi-element, multi-layered constructions can be calculated. This can be accomplished by replacing the two boundary representations of the inner space shells with the building outer shell attached to the outside air. The building's surfaces of the outer shell attached to the air can be obtained by removing from the surfaces of the outer building shell contained in surface set $\mathcal{E}$, the surfaces or surface parts attached to the ground.

5 APPLICATION EXAMPLE

The proposed algorithmic extension is validated on a real BIM model related to a residential building in the island of Crete in Greece in the Akrotiri region at Korakies village built by ERGOPRISM (2022). The demonstration building has two floors one at basement level and one at ground level, as pictured in Figure. The BIM model of this building was detail enough to contained multiple wall and slab elements stacked one on top of the other reflecting the different phases of the building construction. The BIM model was developed in Autodesk Revit and exported in IFC4 format.6.

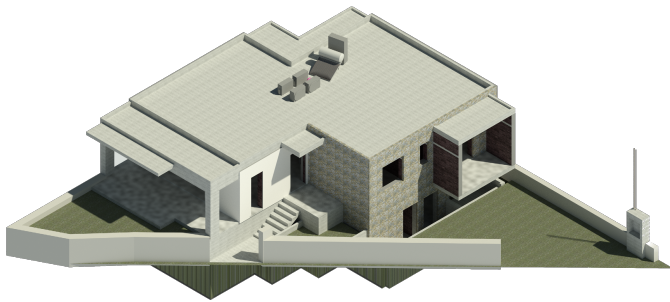


Figure 6: Demonstration building

Three building areas were examined highlighted in the section Figure 7 in the magnified parts A, B and C respectively. In these areas different high order 2LSB surface pairs were obtained by the introduced algorithmic extension, as described next.

The first examined area, displayed in the magnified part A of the section in Figure7, focuses on the ceiling of the ground floor and external walls of the building. The ceiling contains two building elements stacked one on top of the other which are,

from bottom to top: (a) 22cm thick compound ceiling exported as IfcCovering which has three layers: (a1) a 3cm plasterboard, (a2) 5cm rigid insulation and (a3) 14cm air gap and (b) a 18cm thick ceiling slab which has a single layer made of reinforced concrete which is exported as IfcSlab. As it is also indicated in the magnified part A of the section Figure 7, the external walls of the building contain two building elements stacked one after the other which are exported as IfcWalls. These elements are from inside out: (a) a 23cm thick double brick wall which has three layers: (a1) 9cm bricks, (a2) 5cm air gap and (a3) 9cm bricks and (b) an external facade wall which has a single layer of limestone of 13cm thickness.

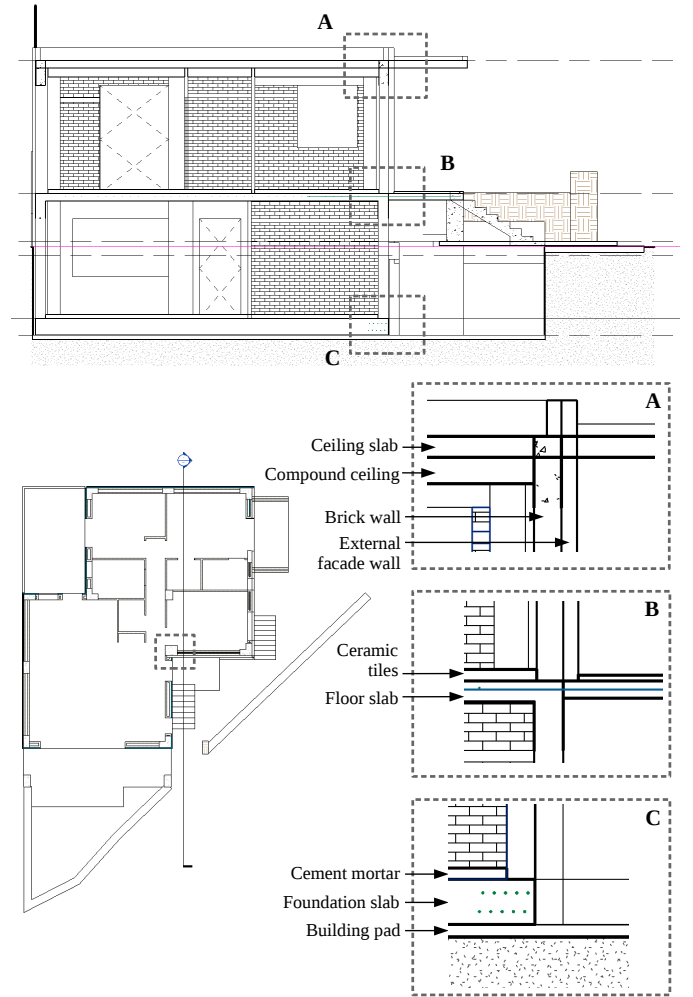


Figure 7: Building section highlighting the building's multi-element constructions

The algorithmic extension generates the second order 2LSB surfaces in the ceiling surfaces of the ground floor of the building as displayed in part 1 of Figure8. These 2LSB surfaces have as related elements: one element exported in the BIM file as IfcCovering element (Compound ceiling) and on element exported in the BIM file as IfcSlab element (Ceiling slab). Additionally the external second order 2LSB surfaces related to two IfcWall elements of the BIM file (Brick wall, External facade wall), are also identified as displayed in part 3 of Figure 8.

The second examined area, displayed in the magnified part B in the section Figure 7, refers to the slab construction among the basement and the ground floor space volumes. This construction consists of two single layer elements exported in the BIM file as IfcSlabs, which from bottom to top, are: (a) a 18cm thick floor slab made of reinforced concrete and (b) 10cm thick ceramic tiles of the ground floor. The respective internal second-order 2LSB surface pairs are identified correctly by the introduced algorithmic extension, as displayed in the part 4 of Figure 8.

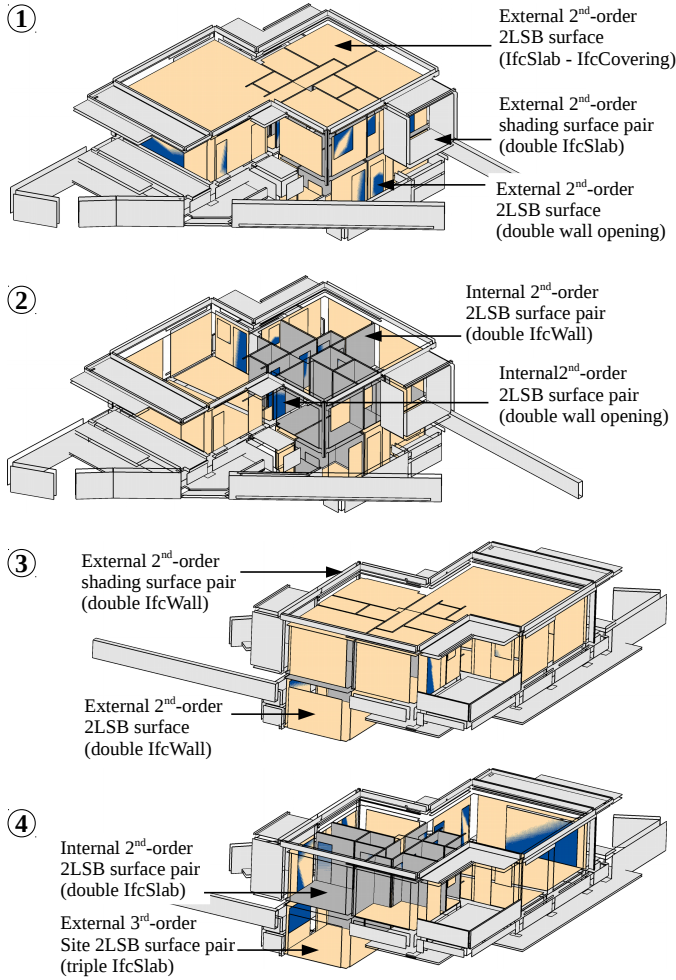


Figure 8: Identified high-order 2LSB surface pairs: (1) Front view, (2) Front view with surface culling, (3) Back view, (4) Back view with surface culling.

The third studied area displayed in the magnified part C in the section Figure 7, is related to the construction at the basement slab of the building. This construction is a multi-element construction consisting of three slabs, exported in the BIM file as IfcSlab elements, which are from ground level up: (a) a 10cm thick building pad made of concrete, (b) a 40cm thick foundation slab made of reinforced concrete and (c) 10cm thick cement mortar. The respective external third order 2LSB surfaces are identified correctly by the introduced algorithmic extension as displayed in the part 4 of Figure 8.

Second-order 2LSB surfaces related to double

wall openings are identified by the introduced algorithmic extension as displayed in part 1 of Figure 8(external) and in part 2 of Figure 8(internal). The double wall openings in these cases are formed by two single opening volumes attached to each other at their largest surface area. Finally, external shading surfaces related to double slab and double wall elements are identified as pictured in parts 1 and 3 of Figure 8, respectively.

6 CONCLUSIONS

The automatic generation of building energy performance simulation models from open BIMs (IFC) involves a considerable challenge, related to building geometry, which is the correct generation of the building's second-level space boundary (2LSB) surface topology. The generation of this topology becomes even more cumbersome, when multi-element building constructions are present in the BIM. Such cases are encountered when modelling building retrofitting projects (facade insulation) or building construction projects built in multiple phases (different elements in different phases). In these cases extending the concept of the 2LSB to higher orders is required to be able to identify the elements of the 2LSB surfaces correctly.

When single-element building constructions are present in the BIM model, traditional algorithms such as the Common Boundary Intersection-Projection (CBIP) algorithm, can be used to evaluate the respective first-order 2LSB surfaces. For the calculation of higher-order (≥ 2) 2LSB surfaces an extension of the CBIP algorithm is introduced, analyzed and tested on a BIM model of an existing residential building. This algorithmic extension identifies correctly the high(2,3)-order 2LSB surfaces of external and internal, double- and triple- element constructions as well as respective opening 2LSB and shading surfaces related to these constructions. The results displayed the correctly identified second and third order 2LSB surfaces on the demonstration building are also presented.

Although generalisation to the calculation of n^{th} -order 2LSB surfaces is possible by induction of this algorithmic extension, cases of order (≥ 4) are rarely encountered. The algorithmic extension is going to be included as updates of the online calculation services of an existing cloud platform (Katsigarakis et al., 2022).

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