Towards semantic enrichment of early-design timber models for noise and vibration analysis

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ABSTRACT: Low carbon footprint and high sustainability characterize timber construction. Accordingly, architects and engineers are increasingly using it in their designs. However, a major challenge in timber construction is to provide a sufficient sound insulation. In contrast to masonry and concrete construction, timber construction lacks software tools to evaluate sound insulation and usability with regard to vibrations. Using Building Information Modelling (BIM), the design phases already incorporate model-based calculations for sound insulation prognosis. However, performing such evaluations requires specific information that describes the junctions between elements. For example, relevant factors are: the type of elements in the junction, the connecting elements like screws or angle brackets, and the decoupling materials used. Typically the building information model lacks this information; hence, we present a semantic enrichment approach overcoming these limitations.

1 INTRODUCTION

Managing the carbon emissions resulting from the architecture, engineering and construction (AEC) represents a major factor in mitigating these emissions globally (Wong 2013). The sustainability of timber construction encourages architects and engineers to choose this construction method for their projects. However, there is a lack of specialized evaluation tools for the seamless application of this construction method. The innovative approach of Building Information Modelling (BIM) opens up the possibility to integrate model-based evaluations and analysis for a complete noise control prognosis as well as for the compliance with the usability requirements directly into the design phases via BIM-compatible interfaces.

In this paper, we use the architectural discipline as a basis, which contains the necessary positions and dimensions of walls and ceilings. In this regard, the acoustic engineer analyses the architectural model during the design phases to perform the calculation. Such prognosis requires the selection of the separating elements between the different rooms and analyses all junctions between each separating element and its flanking element. For every junction, the acoustic engineer needs to find all transmission paths and assign them a vibration reduction index K_{ij} to calculate the sound transmission index R.

In the future, the goal is to automate this procedure. The determination of junctions out of an IFC data model is part of a thesis project at the University of Applied Sciences Rosenheim in cooperation with the Technical University of Munich.

2 IFC IN TIMBER BUILDING DESIGN

In solid wood constructions, the timber constructor is responsible for the detailed planning of the construction site. Therefore he creates manufacturing plans for the building components, according to the architect's design plans. The manufacturing model is created with programs that are capable of both CAD (computer automated design) and CAM (computer-aided manufacturing). After drawing CNC machines (Computerized Numerical Control) uses the plans directly for manufacturing. However, linking the manufacturing model to the architectural model is not yet a common practice (Huß 2017).

The vendor-neutral IFC data exchange format is available for construction projects to be independent of software manufacturers. In addition to the geometric representations, the IFC data model stores information describing the semantics of the different components. These semantics are defined as topological relationships as well as a set of Property-Sets which can hold multiple properties. Although these building models define the material information they are not provided by a fixed catalogue. Additionally, multiple properties need to be collected from manufacturers or assumed by experience. Currently, there are some properties available in the common Property-Sets. For example, the Property-Set `Pset_MaterialWood` defines the properties of

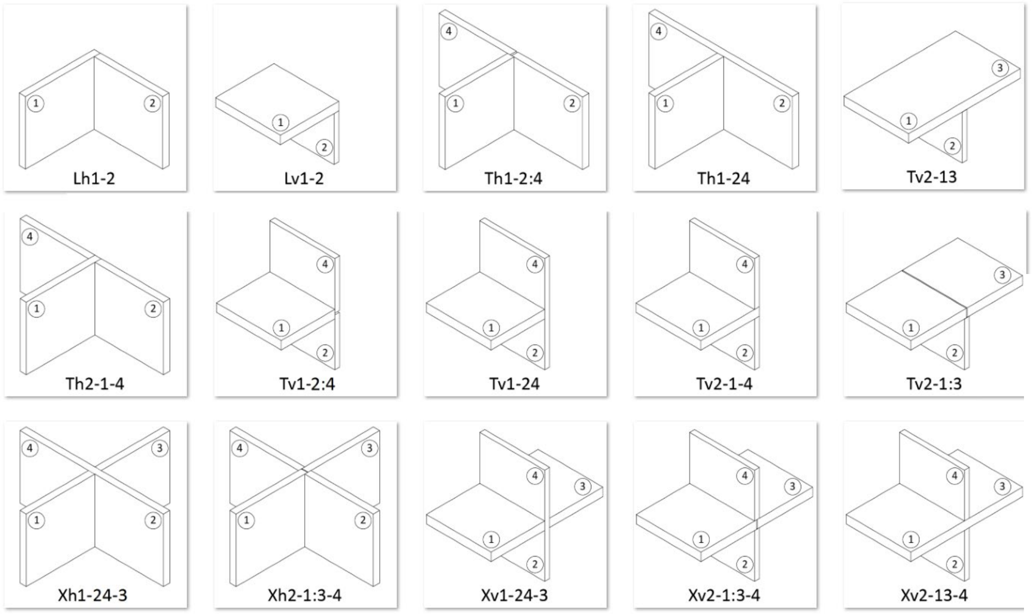


Figure 1. 15 types of junction without consideration of elastic layers for decoupling (Timpte, 2016)

timber elements. However, it relates to properties of structural analysis and is not suitable for sound insulation in timber construction. Further, the current version of the standard does not sufficiently represent acoustic properties.

3 SOUND TRANSMISSION IN WOODEN BUILDINGS

The prognosis of sound insulation includes the calculation of airborne sound insulation and impact sound insulation. The calculations are performed in building construction according to (ISO12354-1, 2017) and are frequency-dependent from 50 to 5000 Hz:

$$R_{ij} = \frac{R_i+R_j}{2} + \Delta R + \overline{D_{v,ij}} + 10lg\frac{S_S}{\sqrt{S_i \cdot S_j}} \qquad [\mathrm{dB}] \qquad (1)$$

With

$\overline{D_{v,ij}}$	velocity level difference [dB]
R_i, R_j	sound insulation of element i and j [dB]
S_S	surface of separating element
S_i, S_j	surface of element i / j [m²]

$\Delta R = \Delta R_i + \Delta R_j$ improvement of sound insulation due to wall linings, screeds or suspended ceiling [dB]

For timber construction, the calculation models are still in development (Rabold 2017 & Rabold 2018a). The existing models need to be optimized: The unique features of timber construction concern the building components, which have a much lower mass than solid components, and the connection situation of components to each other.

3.1 *Flanking transmission*

Not only the separating component directly transmits the sound but also the flanking elements.. Figure 1 shows the sound transmission paths depending on the direction and excitation.

3.1 *Vibration reduction index Kij*

The calculation takes into account the joints based on the vibration reduction index K_{ij}, which depends on the direction of the junction, the design of the connection details, and the component types used. All elements in the sending room have the index i and all elements in the receiving room have the name j.

$$K_{ij} = \overline{D_{v,ij}} + 10lg\frac{l_{ij}}{\sqrt{a_i \cdot a_j}} \qquad [\mathrm{dB}] \qquad (2)$$

With

$\overline{D_{v,ij}}$	velocity level difference [dB]
l_{ij}	junction length between element i and j [m]
a_i, a_j	equivalent absorption length of element i / j [m]

3.1 *Details for Kij*

The length of the junction l_{ij} between both elements is a geometrical length. The equivalent absorption length a_i for the element i depends on the area of the element and its structural reverberation time. The velocity level difference $\overline{D_{v,ij}}$ is measured in laboratory.

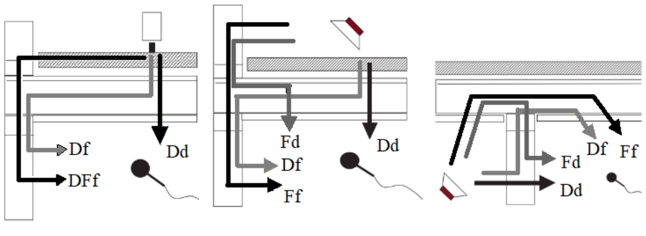


Figure 2. Schematic representation of the transmission paths Ff, Df, Fd and DFf in timber construction: impact sound insulation (left), airborne sound insulation through a slab (middle) or a wall (right)

The vibration reduction index is also investigated from existing measurements and simulations. Factors of influence for K_{ij} are the construction material of the elements, the dimensions of the elements, the mass ratio between the elements, the execution of the junction details, elastic layers and their stiffness, the excitation and the direction of the junction.

3.2 *Types of junction for CLT constructions*

In the beginning, we only consider constructions of CLT (cross laminated timber). Starting from one to three possible flanking elements in a junction, there are 15 possible combinations of junctions (see Figure 1). The distinction between the types of junction is essential. The flanking transmission depends on how and where the elements met. This is shown in Figure 3 for a T-junction. The 3 different combination of elements leads to very different vibration reduction indices K_{ij}. There exists more combinations if we consider putting elastic layer for decoupling in the junction or if the walls are fixed with angles instead of screws. Each of those details needs to be considered to find the correct value forK_{ij}.

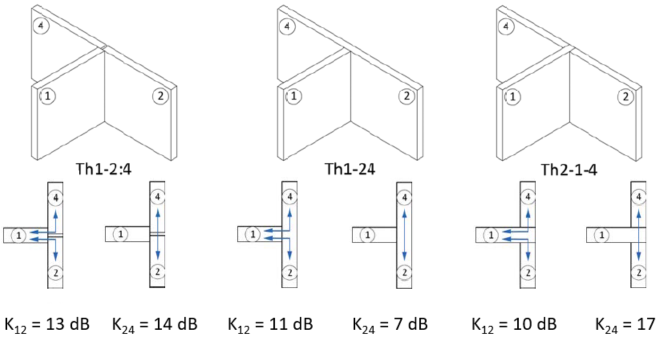


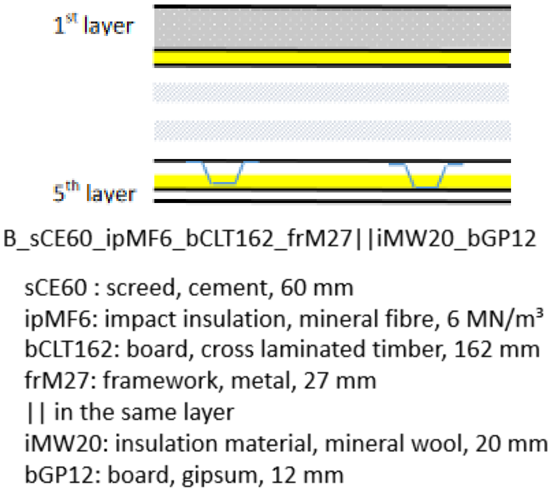
Figure 3. Types of T-junction of wall elements in CLT construction without consideration of elastic layers for decoupling (Timpte 2016)

4 PREVIOUS WORK

The University of Applied Sciences in Rosenheim has worked for many years on the acoustics in timber buildings. The aim of the project “vibroacoustic” (Rabold et al. 2018b) was to lay the scientific foundations for a calculation based on FEM and other model approaches of the vibroacoustic properties of a wooden building. One outcome of this project was an spreadsheet tool to simplify the calculation of the sound insulation of elements for a single value. Another result was the creation of the online database (vabdat 2018), which stores frequency-dependent measurement and calculation results from vibroacoustic properties of construction products and building parts.

In the database, every building element (“Bauteil”) is formed by different layers of construction products (“Bauprodukt/-stoff”). The single layers get abbreviations depending on their material. The name of the building elements is then put together from the name of the single layers of construction products. Thus, the name of the building element describes its construction (see Figure 4).

Furthermore, the database also stores the vibration reduction index from specific junctions. It also stores the junction type according to Figure 1, information about elastic layers and the fastener. The values for the vibration reduction index K_{ij} are stored frequency-depend and for every transmission path.



B_sCE60_ipMF6_bCLT162_frM27||iMW20_bGP12

sCE60 : screed, cement, 60 mm
ipMF6: impact insulation, mineral fibre, 6 MN/m³
bCLT162: board, cross laminated timber, 162 mm
frM27: framework, metal, 27 mm
|| in the same layer
iMW20: insulation material, mineral wool, 20 mm
bGP12: board, gipsum, 12 mm

Figure 4. Description of a building element using his layers with the abbreviation of layer in (vabdat 2018)

5 JUNCTIONS IN IFC

The information provided by the IFC model enormously depends on who built the model and how. If the model comes from an early planning phase, it has fewer details than a model created for manufacturing. Since the planning of the sound insulation should take place at an early stage of the planning, we assume the IFC data model to have only rudiment information about the elements and their junctions.

Additionally, junctions do not explicitly exist in the IFC standard. But there are many different possibilities to form relations between objects with the `IfcRelConnects` class. Relevant classes are `IfcRelConnectsElements` to connect elements together and `IfcRelContainedInSpatialStructure` to position elements in a space or building storey. `IfcRelConnectsElements` includes two classes: `IfcRelConnectsPathElements` where the connection of two elements is described by the attributes `AtStart`, `AtEnd` and `AtPath`. In `IfcRelConnectsWithRealizingElements` the elements are connected the same way, but it is possible to add elements that realize the connection. In both options, `IfcConnectionGeometry` stores the connection geometry. Depending on the quality of the model, this information may not be available.

The relation does not describe a junction because it can only be a relation between two elements: 3

relations describe a junction with 3 elements and 6 relations describe a junction with 4 elements.

Besides, there is no intended connection between walls and ceilings. Such a connection would require additional attributes to specify if the connection is `AtBottom` or `AtTop` of the wall. A connection can still be forced without specifying the connection type or with `AtPath` to characterize the connection on the slab.

6 FLANKING ELEMENTS

The identification of the flanking elements plays a central role in the calculation of sound insulation. Flanking elements are all elements, which have a common edge with the separating element. For a wall as a separating element, this is usually 2 walls and 2 slabs. For a slab as a separating element, this is then 4 walls. A flanking element is one continuous element or it consists of 2 different elements that both met at the junction. The approach used to identify the flanking elements depends on the information provided in the IFC-Model.

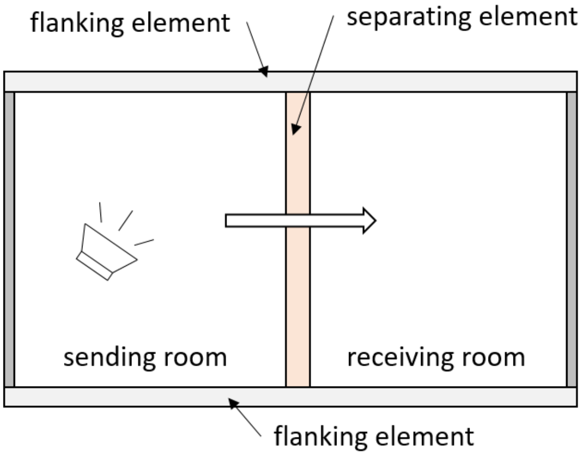


Figure 5. Schematic representation of the separating element and the flanking elements: a standard, rectangular wall has 4 flanking elements: 2 walls and 2 slabs (floor and ceiling)

Furthermore, a sending room and a receiving room need to be identified. The separating element is in between both rooms, for example, for a wall as a separating element, both rooms must be on the same floor. In this case, it does not matter which of the rooms is named sending or receiving room. If the separating element is a slab, then the room existing on the higher floor is automatically the sending room and the room under the slab is the receiving room. In this regard, the separating element and four flanking elements characterize both connected rooms. Additionally, the last elements are parallel to the separating element.

6.1 *With IfcRelConnectsPathElements*

If a relation between the separating element and another element exists as `IfcRelConnectsPathElements`, this is used to determine the flanking elements.

6.2 *With IfcRelSpaceBoundary*

It is possible to find all flanking elements if the adjacent room to the separating element is an `IfcSpace` and `IfcRelSpaceBoundary` describes the adjacent building elements. Then only the elements related to the space need to be analysed for distance to the separating element.

6.3 *Semantic Enrichment by Geometry Analysis*

If the IFC data model does not provide any of the above semantical information, a geometric analysis of the model defines the flanking elements.

At first, the model is filtered by building storeys to reduce the number of elements for the analysis. If the separated element is a wall, the filter considers walls and slabs on the same storey and slabs above. For a slab as separating element, walls of the same storey and of the storey below are filtered out.

Then elements that are close to the separating element are considered: The distance between the separating element and each of the other elements is calculated to find any adjacent elements. Afterward, the position of the element, depending on the separating element, is computed and stored for each adjacent element. Algorithm 2 shows the calculation of the distance and the determination of the position in X-Y-plane. Algorithm 1 defines if the element is above, below or in the same height as the separating element.

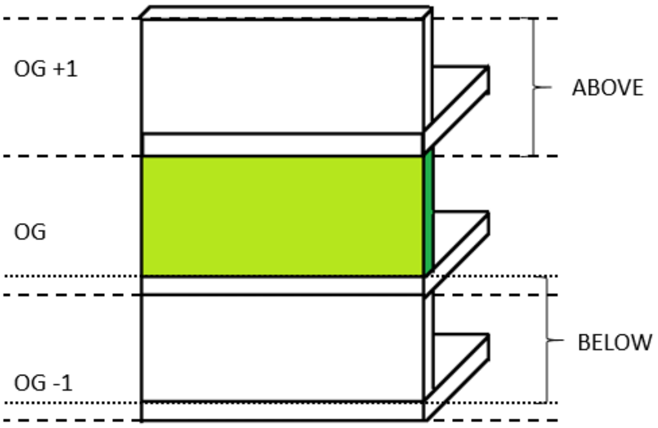


Figure 6. Elements filtered before distance checking: consider all walls and slabs one storey above the separating wall, the slabs and walls in the same storey and walls one storey below.

In combination, both algorithms determine the position of an element in comparison to the separating element as North (higher on the y-axis), South (lower on the y-axis), West (lower on the x-axis), East (higher on the x-axis), Above (higher on the z-axis), Below (lower on the z-axis) and the combinations. The reference coordinate system is the coordinate system of the separating element.

7 DEFINING JUNCTIONS

The currently developed prototype works for straight elements with a rectangular shape. Regardless of whether the separating element is a wall or a slab, it has 4 edges. For each separating element, four junctions are created. Each junction gets information about the flanking elements involved and about other separating elements like elastic layers and fastener elements.

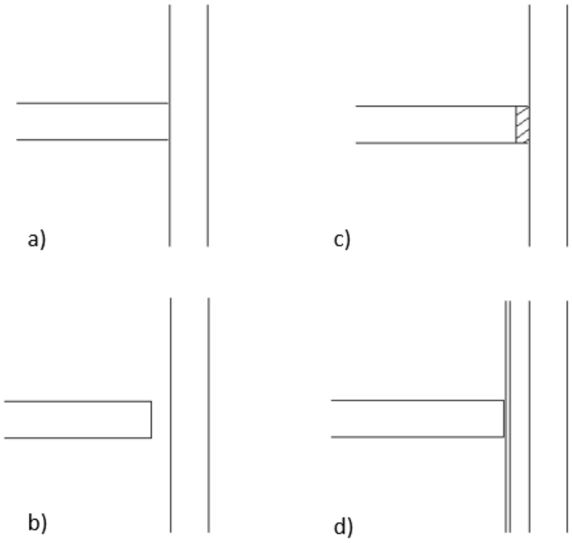


Figure 7. Consideration of junction for an element which is a) touching the separating element (d=0) or adjacent (0 m < d < 0,1 m) to the separated element with b) air in between, c) an elastic layer or d) a facing layer.

Not only elements, which touches the separating element, are considered as flanking elements, but also adjacent elements with a certain distance (see Figure 7). It can be the case if the modeling of the elements is not entirely correct and the elements do not touch each other, even if they should. Sometimes intermediate layers like elastic layers are in between or even a facing layer if it is modeled separately from the flanking element. If the algorithm finds such an element, other elements in the same direction with a distance $d < d_1 + d_2 + d_3$ with d_1 distance to the first element d_2 thickness of the flanking element d_3 distance to the next flanking element, $d_3 < 0{,}1m$ could be adjacent and relevant for the junction. Here the material helps to distinguish between a flanking element or an intermediate layer.

```
double string position p
foreach element (E)
if E.type = slab
    if E.storey = SE.storey
        $p = +Under$
    else if E.storey = SE.storey +1
        $p = +Below$
    end if
else if E.type = wall
    if E.storey = SE.storey
        $p = p$
    else if E.storey = SE.storey +1
        $p = +Above$
    else if E.storey = SE.storey -1
        $p = +Below$
    end if
end if
```

Algorithm 1. Assignment of position p in Y-Z-plane with help of storeys for the Element E in comparison to the separating element SE

A new object is defined to describe the 4 junctions of the separating element. The junction elements contain 4 slots each. Intermediate layers in the junction are also saved in the corresponding slot.

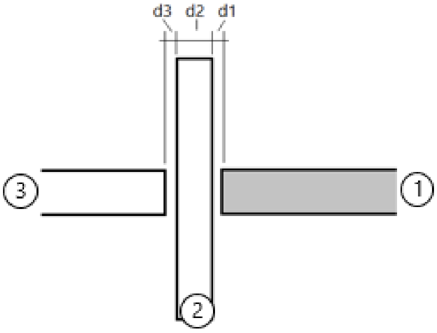


Figure 8. Distances considered to define a X-junctions with the separating element in grey (1) and the added flanking elements in white (2, 3)

A set of rules finds the adjacent element, their position and stores them in the correct slot of the junction object. Algorithm 3 shows an example of defining a T-junction with 3 elements.

```
double distance d, string position p
foreach element (E)
if angle to separating element (SE) = 0 OR = 90
if E.Max.Y <= SE.Min.Y
    if E.Max.X <= SE.Min.X
        $d = \sqrt{(E.Max.X - SE.Min.X)^2 + (E.Max.Y - SE.Min.Y)^2}$
        $p = SouthWest$
    else if E.Min.X >= SE:Max.X
        $d = \sqrt{(E.Min.X - SE.Max.X)^2 + (E.Max.Y - SE.Min.Y)^2}$
        $p = SouthEast$
    else
        $d = SE.Min.Y - E.Max.Y$
        $p = South$
    end if
else if E.Min.Y >= SE.Max.Y
    if E.Max.X <= SE.Min.X
        $d = \sqrt{(E.Max.X - SE.Min.X)^2 + (E.Min.Y - SE.Max.Y)^2}$
        $p = NorthWest$
    else if E.Min.X >= SE.Max.X
        $d = \sqrt{(E.Min.X - SE.Max.X)^2 + (E.Min.Y - SE.Max.Y)^2}$
        $p = NorthEast$
    else
        $d = E.Min.Y - SE.Max.Y$
        $p = North$
    end if
else
    if E.Max.X <= SE.Min.X
        $d = E.Max.X - SE.Min.X$
        $p = West$
    else if E.Min.X >= SE.Max.X
        $d = E.Min.X - SE.Max.X$
        $p = East$
    else
        $d = 0$
        $p = 0$
    end if
end if
```

Algorithm 2. Calculation of distance d and assignment of position p in X-Y-plane (not considering above and under) from the element E in comparison to the separating element SE

8 MATERIAL LAYER

Each element needs a sound transmission index R, which depends on his material and the structure of the different layers. In the IFC data model, `IfcRelAssociatesMaterial` assigns the material to an element. The `IfcMaterialLayerSet` assigns different materials to one element consisting of different layers.

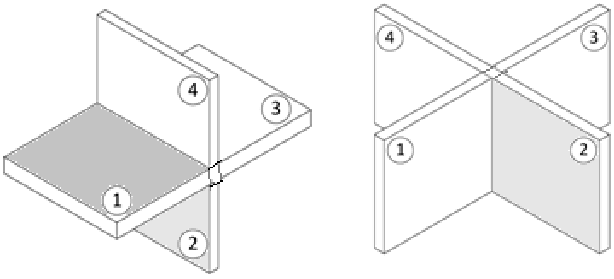


Figure 9. Definition of slots for junctions: a slab as separating element is in slot 1, a wall as separating element is in slot 2.

The sound transmission index R_i considers the main element, while ΔR_i takes into account the facing layers like a screed or a suspending ceiling. For double-layered walls, R_i considers both parts, but the vibration reduction index K_{ij} is only relevant for the shell on the inside. To find the correct values the online database (vabdat 2018) can be used.

```
junction j
if E1.type = wall
AND if E1.distance < 0,5
AND angle (SE,E1) = 90
AND if E1.position = South
AND if E1.X.Max = SE.X.Max
then
  {$j.type = Lh1 - 2$
   $j.slot1 = SE$
   $j.slot2 = E1$
   if E2.type = wall
   AND if E2.distance < 0,5
   AND angle (SE,E2) = 90
   AND if E2.position = North
   AND if E2.X.Max = SE.X.Max
   Then
      {$j.type = Th1 - 2 - 4$
       $j.slot3 = E2$}
  }
```

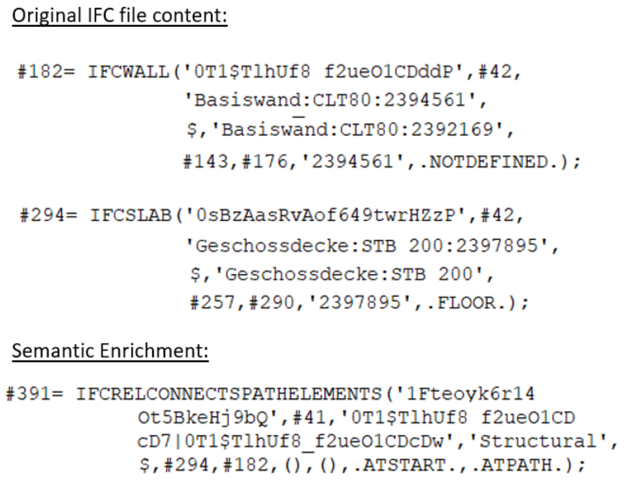
Algorithm 3. Definition of a T-junction for a separating element (SE) of type wall and a first flanking element E1 and the second flanking element E2

9 SEMANTIC ENRICHMENT

To supplement the IFC file with semantically useful content, Belsky uses the concept of semantic enrichment (Belsky 2015). In contrast to the MVD approach where the software companies develop an IFC export based on the MVD, the semantic enrichment uses a domain-specific rule-sets to infer semantics from geometry and material properties of the IFC data model. The task for semantic interpretation is then in the importing application and not at the exporting software.

For example, in (Belsky 2015), a rule-set is used to identify the joint of precast concrete walls that were initially declared as `IfcColumn` and rename them to `IfcFastener`.

Figure 10 shows an example using semantic enrichment for the junctions of elements. It illustrates how the connection between a wall as `IfcWall` and a slab as `IfcSlab` can easily be executed by using `IfcRelConnectPathElements` even if the Attribute `AtPath` is not a perfect description of the junction position.



Original IFC file content:

```
#182= IFCWALL('0T1$TlhUf8 f2ueO1CDddP',#42,
             'Basiswand:CLT80:2394561',
             $,'Basiswand:CLT80:2392169',
             #143,#176,'2394561',.NOTDEFINED.);

#294= IFCSLAB('0sBzAasRvAof649twrHZzP',#42,
             'Geschossdecke:STB 200:2397895',
             $,'Geschossdecke:STB 200',
             #257,#290,'2397895',.FLOOR.);
```

Semantic Enrichment:

```
#391= IFCRELCONNECTSPATHELEMENTS('1Fteoyk6r14
          Ot5BkeHj9bQ',#41,'0T1$TlhUf8 f2ueO1CD
          cD7|0T1$TlhUf8_f2ueO1CDcDw','Structural',
          $,#294,#182,(),(),.ATSTART.,.ATPATH.);
```

Figure 10. Semantic enrichment for the connection between a wall and a slab

10 NEXT STEPS

The next steps are to generate the complete rule-sets to identify all junction types and demonstrate the workflow with prototype software. Then the inferred information needs to be added to the IFC data model. The semantic enrichment can either use existing entities like `IfcRelConnectsPathsElements` or create new `PropertySets`.

Afterward, particular junctions that are not symmetrical, like in Figure 11, need to be considered to extend the use of the developed prototype for more applications. Also, exceptional cases with the separating element being bigger or smaller than the separating area between the sending room and the receiving room will be a major challenge to solve in the future.

11 ACKNOWLEDGMENT

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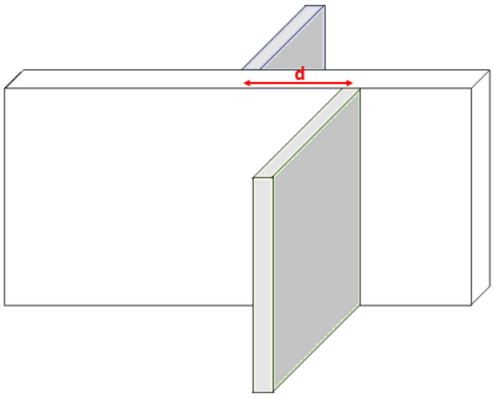

Figure 11. Example of a special junction: offset between the flanking elements (blue and green wall). For d < 0,5 m the green wall is considered being on the exact opposite of the blue wall and the junction is handle as an X-junction (ISO12354-1, 2017)

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