Analysis of the early-design timber models for sound insulation analysis

Camille Châteauvieux-Hellwig, Jimmy Abualdenien, André Borrmann
TH Rosenheim, TU Munich
Camille.Chateauvieux-Hellwig@th-rosenheim.de

Abstract. Timber construction is characterized with its high circularity and sustainability. However, such construction requires a careful evaluation of sound insulation between the different building zones. Currently, acoustic analysis is performed after the design is already detailed, which requires a substantial amount of time and effort to improve the design. Additionally, thus far, performing sound insulation analysis involves manual extraction and processing of building information, which is an error prone task. Hence, this paper proposes a framework for establishing a seamless workflow between building models and acoustic analysis tools across the design phases. In more detail, the junctions between the different elements are extracted and analysed to identify the corresponding acoustic junction types, with the help of topological reasoning and logical rules. The proposed approach was evaluated via a prototypical implementation, where the different possible junction types were extracted successfully.

1. Introduction

The building industry is a major consumer of the world's raw materials and highly contributes to carbon emissions globally (Wong et al. 2013). The circular economy framework aims to separate the economic growth from environmental destruction. In comparison to concrete building structures, timber structures are characterized with high recoverability when disassembled (Finch et al. 2021). Such sustainability of timber construction encourages architects and engineers to choose it for their projects. Using Building Information Modeling (BIM), a model is developed through multiple design phases to satisfy various design and engineering requirements. The decisions made throughout the design stages, especially the early ones, steer a project's success and results (Abualdenien et al. 2019). The impact of the decisions made in the early design stages (conceptual and preliminary stages) is significant, as they form the basis of the following stages.

The planning of sound insulation is very complex, especially in timber construction. The earlier this is included in the planning process, the more likely it is to find a satisfactory solution for the owner. Later modifications due to inadequate planning result in high costs and extensive construction work (Howell 2016). If sound insulation is included in an early planning phase, engineers from different disciplines can find an optimal solution for the individual building use cases (Châteauvieux-Hellwig et al. 2020). However, thus far, there is a lack of seamless integration between BIM-modelers and sounds insulation prognosis. Therefore, this paper proposes a framework for extracting the necessary information from BIM models, then reason about this information to identify the corresponding junction types. This information forms the bases for calculating the sound reduction index and impact sound level. Such calculations use information from databases of component catalogues, collected from standards and domain knowledge to provide a forecast. The result can then be compared with applicable standards and requirements to be optimized if necessary.

The proposed framework in this paper is based on the vendor neutral format industry foundation classes (IFC). IFC is capable of capturing the geometric and semantic building information, including the topological relationships as well as property sets that can include multiple properties. Using IFC makes it possible to establish a seamless workflow between the BIM-modelers and simulation tools. However, as the IFC schema does not have an explicit definition of the junction properties, the proposed framework presents further processing and reasoning to perform the sound insulation analysis.

The aim of this research is to us an IFC data model to find the junctions and define the junction types needed to calculate the prognosis of sound insulation. The process 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. The calculation takes into account the joints based on the vibration reduction index, which depends on the direction of the junction, the design of the connection details, and the component types used.

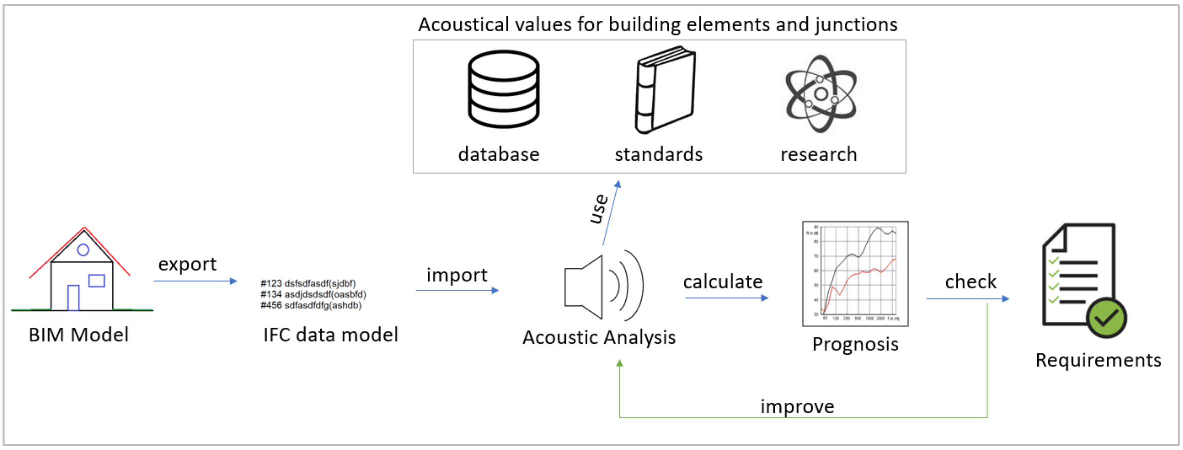


Figure 1: Workflow of an acoustic analysis

2. Sound Transmission in Timber Buildings

The prognosis of sound insulation consists of airborne sound insulation for walls and slabs. Ceilings have an additional impact sound level. The calculations are carried out according to ISO12354-1 (2017). For full information about the element's acoustic properties, the sound insulation needs with frequency depend on values from 50 to 5000 Hz.

$$R_{ij} = \frac{R_i + R_j}{2} + \Delta R + K_{ij} - 10lg\frac{l_{ij}}{\sqrt{a_i \cdot a_j}} + 10lg\frac{S_S}{\sqrt{S_i \cdot S_j}} \quad [\mathrm{dB}] \tag{1}$$

With

$\overline{D_{v,\imath\jmath}}$	velocity level difference in dB
R_i, R_j	sound insulation of element *i* and *j* in dB
S_S	surface of separating element in m²
S_i, S_j	surface of element *i* / *j* in m²
ΔR	improvement or deterioration of sound insulation due to wall linings, screeds or suspended ceiling in dB
l_{ij}	junction length between element *i* and *j* in m
a_i, a_j	equivalent absorption length of element *i* / *j* in m
K_{ii}	vibration reduction index in dB

In comparison to the other materials construction methods, such as concrete and steel, timber construction has a low mass. However, existing acoustic prognosis models were designed for concrete constructions. Hence for timber construction, the calculation models are still in development (Rabold et al. 2017, Rabold et al. 2018), and existing models need to be optimized: Due to the lower mass, the flanking transmission's importance is much more important than in usual buildings.

Flanking Transmission

Beneath the direct transmission through an element, it is essential to consider the sound transmission through all flanking elements. When the mass of all elements is low, the flanking paths are more important for the overall result of the sound insulation. Figure 2 shows the sound transmission paths according to the direction and excitation.

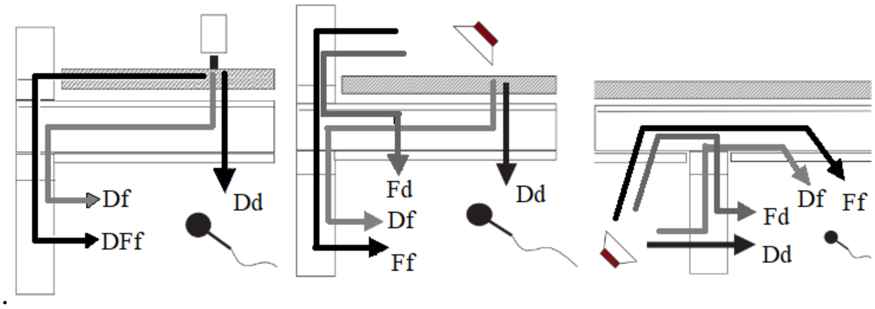


Figure 2: Schematic representation of the transmission paths Ff, Df, Fd and DFf in timber construction: impact sound insulation (left), airborne sound insulation through a slab (middle) or a wall (right)

The vibration reduction index K_{ij} rates the different transmission paths depending on the junction's direction and the design of the connection details, including, the use of elastic layers, the stiffness of the connection devices, separation cuts in flanking elements. The mass ratio between the elements also plays an important role. The excitation and orientation of the junction are necessary to determine the relevant transmission paths. Those are named with *d* for direct element and *f* for flanking element. On the sending room's side, all letters are in capital (*D*, *F*), and on the receiving room's side in small (*d*, *f*). For the general description, all elements on the sending room's side have index *i*, and on the side of the receiving room the index *j*.

Junction Type

The distinction between the junction types is essential to find the correct vibration reduction index. There are 15 different junction types when we consider a junction with one, two or three possible flanking elements. Figure 3 shows all different types and their names depending on their direction.

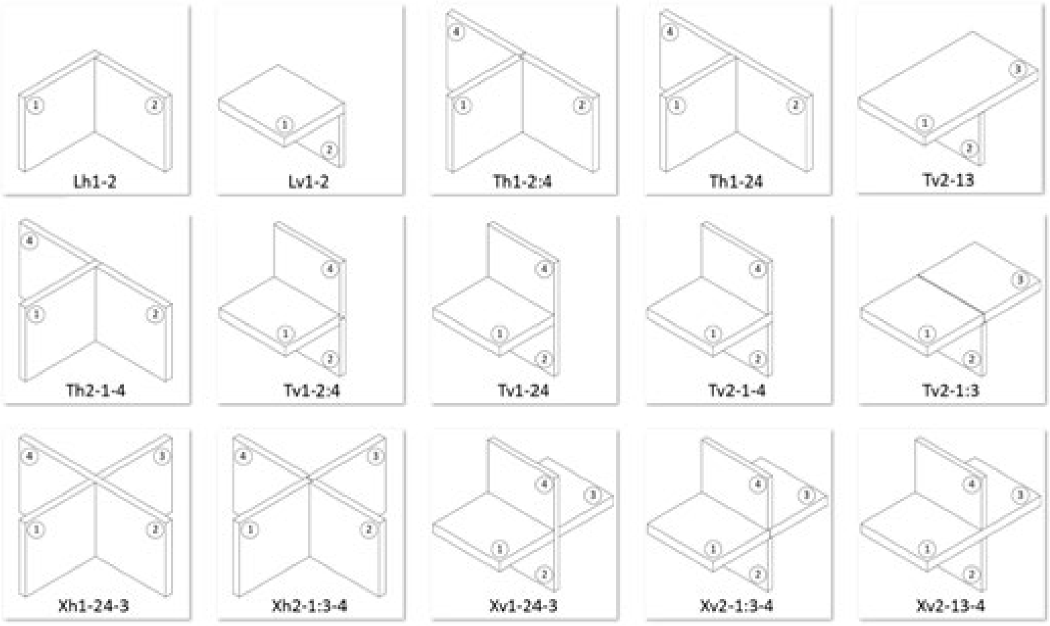


Figure 3: 15 types of junction without consideration of elastic layers for decoupling (Timpte, 2016)

Influence of the vibration reduction index K_{ij}

The joint's influence on the vibration reduction index K_{ij} is very high depending on the construction situation. These values vary from 3 dB to 26 dB depending on the selected joint and transmission path (Timpte 2016). Figure 4 shows the analysis results of a partition wall and four flanking elements. The results show the significant influence of the joint insulation In this example, the same vibration reduction index is used for all three transmission paths (*Df*, *Fd*, *Ff*) of all flanking elements as a simplification. The analysis results vary between 41 and 60 dB. The effect of an additional 10 dBs on the sound level is perceived as approximately doubling the volume (loudness).

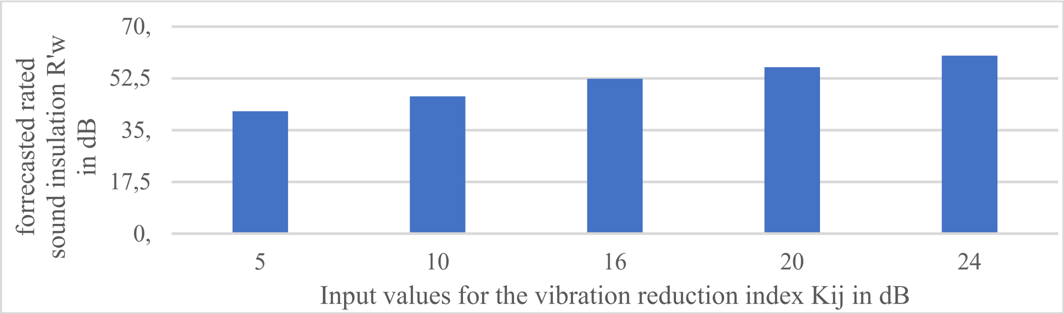


Figure 4: simplified prognosis for the rated sound insulation in which all flanking paths have the same vibration reduction index K_{ij}

3. Junctions in IFC

IFC data models differ in their information value if they are from an early planning phase or for manufacturing. In the early design phase, the models have only rudiment details about the element and connection. Nevertheless, enough information about the used building elements and the overall junction situation should also be provided in this stage.

The IFC standard does not provide an adequate entity to define the junctions for the acoustical analysis. It only allows setting connection relations between elements with *IfcRelConnects*. This class is subdivided into *IfcRelConnectsElements* to connect elements together and *IfcRelContainedInSpatialStructure* to position elements in a space or building storey.

The entity *IfcRelConnectsElements* includes two classes that each attribute to describe where the elements are connected: *AtStart*, *AtEnd* and *AtPath*. The connection geometry is stored in *IfcConnectionGeometry*. Depending on the quality of the model, this information may not be available. That information is not enough to adequately describe the junction from an acoustical perspective, it only allows connection between 2 elements. In this regard, a junction with 4 elements needs 6 relations. Moreover, IFC is not capable of describing a connection between a wall and a slab. Here, attributes like *AtBottom* and *AtTop* would help to define the connection.

4. Methodology

The proposed methodology in this paper is adapted to usual timber buildings. The first approach considers rectangular or almost rectangular building elements. Also all elements are either parallel or in 90 degree angle to each other. This simplification nevertheless makes it possible to represent a large part of the buildings. We assume an IFC data model with a level of detail of 300 to 350 coming from an architect. For this reason we consider the semantic relationships *IfcRelConnects* and *IfcRelSpaceBoundary* in the filter process. But we also do a geometric search for elements in a close range by using *IfcBuildingStorey* because not every BIM software is able to put the correct relationships between elements in the IFC data model. Also not every acoustical relevant space and room is defined by the architect at an early-design phase. So the methodology proposed consists of two main parts: filtering of the relevant components from the IFC data model, and reasoning about the topological relationships between them. In the first part, the separating elements for which the sound insulation has to be calculated are selected. Then we filter the IFC data model to identify possible flanking elements, that has joints with the selected separating elements. Therefore, three aspects are evaluated: Is there an element connection of type *IfcRelConnects*? Is there an *IfcSpace* and other elements adjacent using *IfcRelSpaceBoundary*? Are there other elements on the same or adjacent storey? All those elements have a potential of being flanking elements. Figure 5 shows an example of two adjacent rooms with a wall as separating element and its corresponding flanking elements. The slabs above and under the separating element are also considered as flanking elements.

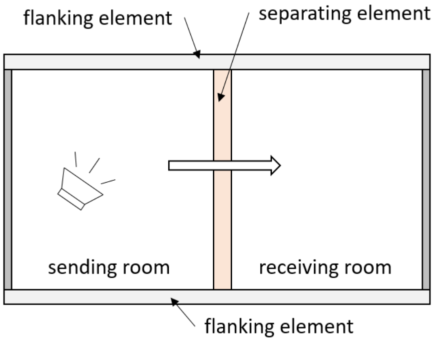


Figure 5: Schematic representation of the separating element and the flanking elements: a standard, rectangular wall has 4 flanking elements: 2 walls and 2 slabs (floor and ceiling)

4.1.Finding Flanking Elements

The first step for finding flanking elements is to filter the IFC data model. This filtering requires the combination of multiple semantic information. When an *IfcRelConnectsElements* exists between the separating element and another element, then, this other element is a flanking element. Additionally those elements may have the same *IfcRelSpaceBoundary*. The last filter option is checking the elements in the building storey around the selecting element. If the separated element is a wall, the filter considers walls and slabs on the same storey and slabs above (as illustrated in Figure 6). For a slab as separating element, walls and slabs of the same storey and walls of the storey below are filtered out. Elements like facades that are described in IFC as *IfcCurtainWall* have the relation *IfcRelReferencedInSpatialStructure* to show in which building storey they are relevant.

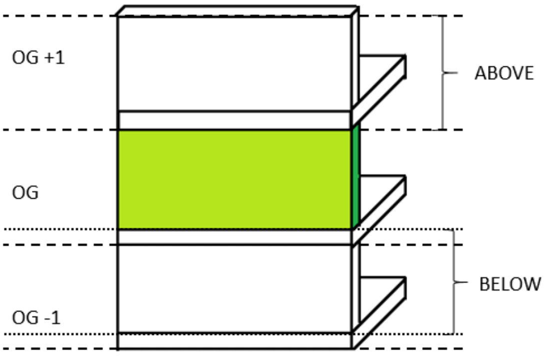


Figure 6: Elements filtered before distance checking: consider all walls and slabs one storey above the separating wall (green), the slabs and walls in the same storey and walls one storey below

In some cases, IFC data models are not rich with enough semantic information (due to issues when exporting to IFC or a modeling error). To overcome such limitation, geometrical operations are used to calculate the distance between the different elements. When the elements are forming a joint, then the distance between (gap) them is evaluated in more detail. Only elements that lay in a range below 0,3 m are still flanking elements. The distance does not need to be zero (as illustrated in Figure 7). Additionally, for flanking elements in a x-junction, another flanking element can lay in between the separating element and the chosen flanking element. For this reason usual collision detection is not suitable to find all flanking elements, because some flanking elements will not touch the separating element. We consider the smallest distance existing between the elements.

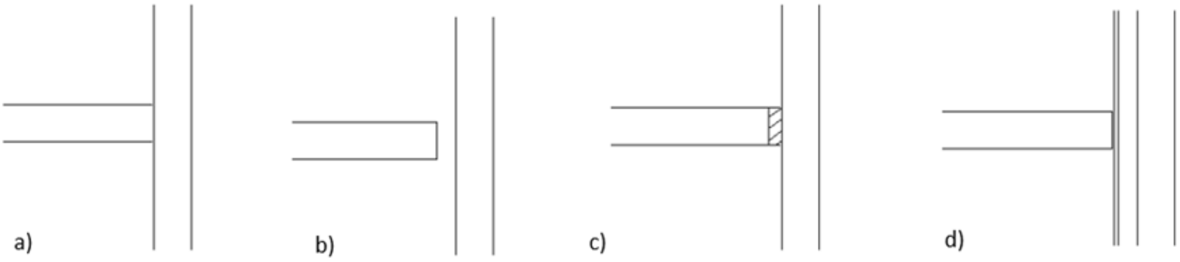


Figure 7: Consideration of junction for an element which is a) touching the separating element (d=0) or adjacent (0 m < d < 0,3 m) to the separated element with b) air in between, c) an elastic layer or d) a facing layer

4.2.Junction-Boxes

To identify the junction type we need different information about its comprising elements. Therefore, we first put every element that will be in the same junction in a separate container. Those containers are called junction boxes. Their position and size are defined by the geometry of the separating element. The vector *n* characterizes the direction of the separating element and the minimum and maximum point of its size and position. With those points, the bounding boxes are created. The following equations show exemplary definition of junction box 1 and junction box 2 for a wall element with n=(1/0/0).

Junction Box 1 for n = (1/0/0)	Junction Box 2 for n = (1/0/0)
JB-Min: X.Min-0,3/Y.Min-0,5/Z.Min	JB-Min: X.Min-0,3/ Y.Min+0,5/ Z.Min
JB-Max: X.Max+0,3/Y.Min+0,5/Z.Max	JB-Max: X.Max+0,3/ Y.Max-0,5/Z.Ma

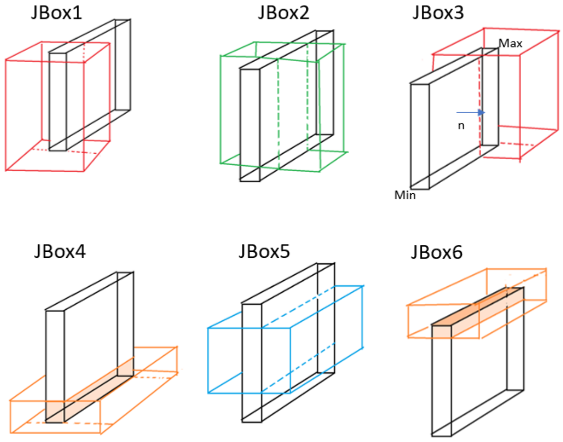


Figure 8: Junction Boxes of a wall element

Every junction box can handle four building elements, one separating element and three flanking elements. The building elements are stored with their entity label from the IFC data model, their element type, their minimum and maximum point, their direction *n*, their distance to the separating element, and the direction in which the distance is calculated.

The dimension of each junction box in the y-direction is due to the definition of the junction type. It determines if a junction is an L-junction, or a T-junction, or if opposite elements form a X-junction, or 2 separate T-junctions (see Figure 9).

4.3.Definition of Junction Type

The identification of the junction type takes into consideration all elements in the same junction box. In this regard, each connection needs to be described and represented to identify the exact junction type. For this, this paper proposes three connection zones with respect to its element: short, middle and border. The zone “short” forms the narrow border of an element. The “border” zone is the edge area on the largest element surface, parallel to the element edges. The zone “middle” indicates the remaining area in the middle of the largest area of the element. In addition, the direction of the elements in relation to each other is decisive. For this purpose, the direction “n” is defined starting from a wall element. All wall elements at a 90-degree angle to it are assigned direction “m”, while ceiling elements have direction “o”. With the element direction and the connection zones, all 15 junction types are identifiable. An excerpt is shown in Figure 11.

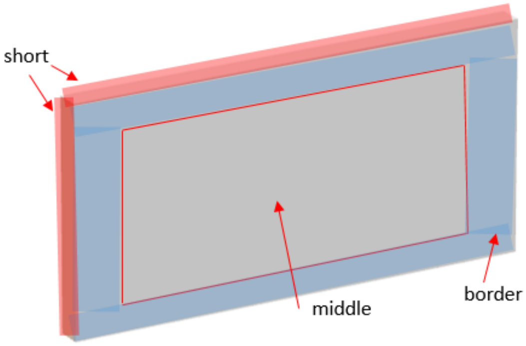
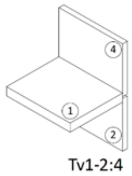


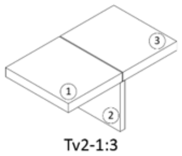
Figure 10: Connection Zones for a wall: short, middle and border

To identify the junction type, the different checks are combined and evaluated in order with if-then-clauses. The following pseudo code shows how this is done for a junction box with 2 elements:

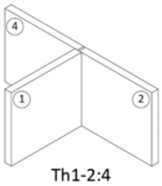
```
For SE.type = wall:
If 2 elements in JunctionBox1 then
        if FE1.n = m AND FE1.dd = n then
                if FE1.cz(SE) = short then "Lh1-2"
        if FE1.n = m AND FE1.dd = m then
                if SE.cz(FE1) = border then "Lh1-2"
                if SE.cz(FE1) = middle then "Th1-24"
End if
```



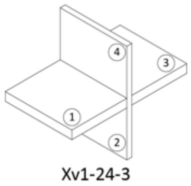
El.Di.	Co.Zo.	
o	short	short
n	border	short
n	border	short



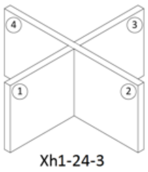
El.Di.	Co.Zo.	
o	border	short
o	border	short
n	short	short



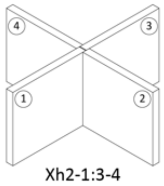
El.Di.	Co.Zo.	
n	short	short
m	border	short
m	border	short



El.Di.	Co.Zo.	
n	middle	middle
o	short	0
o	short	0



El.Di.	Co.Zo.	
n	short	0
m	middle	middle
n	short	0



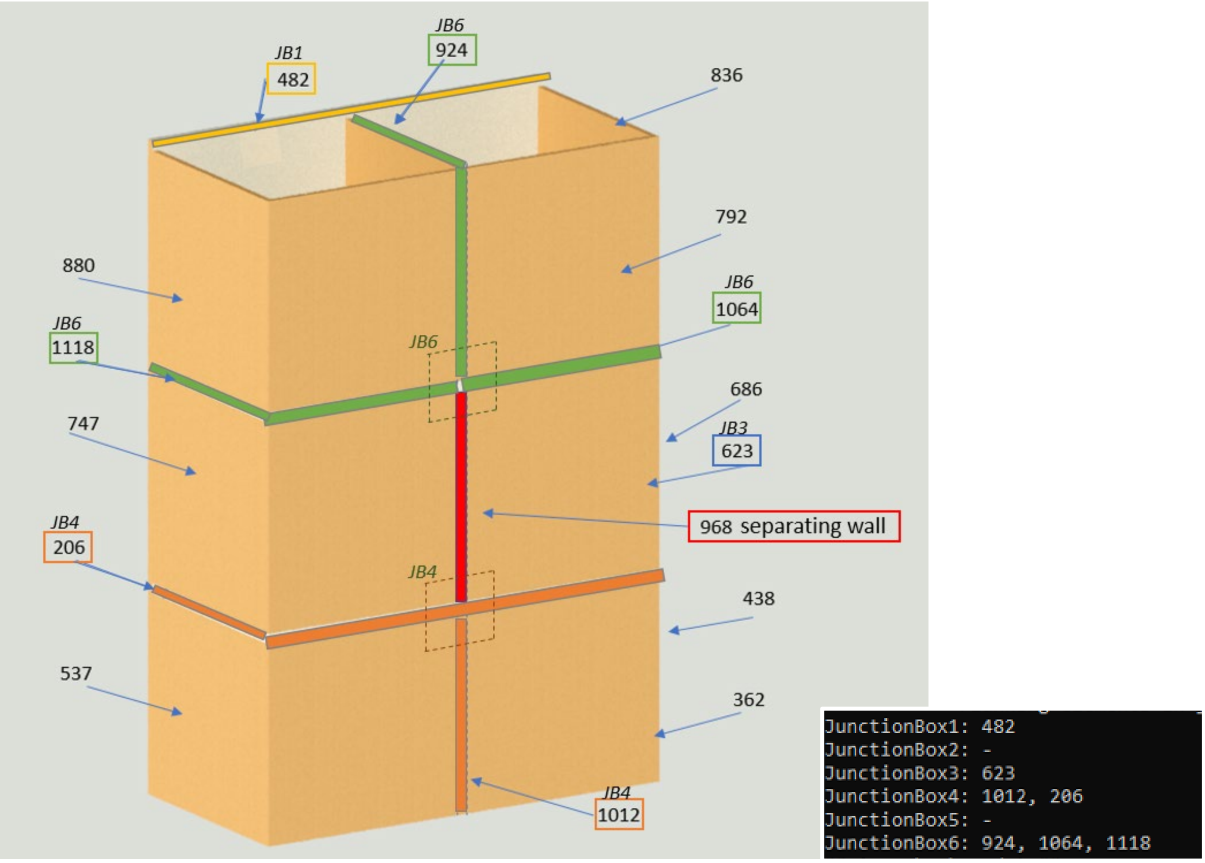
El.Di.	Co.Zo.		
n	short	short	0
m	border	border	short
m	border	border	short
n	short	short	0

Figure 11: Definition of Junction Type with Element Direction and Connection Zones (excerpt)

5. Use Case

To evaluate the proposed framework, a prototype was implemented as a .Net application, where the xbim Toolkit[1] was used to analyse the IFC data model. Afterwards, a fictions use-case of a model of three storeys was modelled in Autodesk Revit[2], which is then exported into IFC4. The modelling process took into account incorporating the different types of junctions.

Figure 12 shows the result of assigning flanking elements into junction boxes, where the element with number 968 is a separating wall element. As shown in the console, all the flanking elements were correctly detected. The elements were first filtered, then the junction boxes were calculated around the separating element. As a result, the flanking elements were placed into their corresponding junction boxes. The junction boxes 1 and 3 are on the side of the wall element and contain the flanking walls 482 and 623. The element 482 is a façade going from ground floor to the last floor. Junction box 4, for the elements below, includes the slab 206 and the wall 1012, which is located one floor below. The elements above the separating wall are in junction box 6: both slabs 1118 and 1064 and the wall 924. The position of boxes 4 and 6 are also indicated in the illustration. Accordingly, the extracted junction boxes provide the necessary information for identifying the different junction types.



```
JunctionBox1: 482
JunctionBox2: -
JunctionBox3: 623
JunctionBox4: 1012, 206
JunctionBox5: -
JunctionBox6: 924, 1064, 1118
```

Figure 12: Use Case with *IfcWall* as separating element (red box, number 968) and the result of the assignments of flanking elements into junction boxes. The numbers with a colored frame a flanking elements in the junctions box 1: yellow, box 3: blue, box 4 orange, box 6 green.

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[1] https://docs.xbim.net/

[2] https://www.autodesk.eu/

6. Conclusion and Future Work

The planning of sound insulation is a significant challenge while designing timber buildings. The performance forecast is based on calculation models from concrete construction. Moreover, choosing the right input data requires a high level of expertise and a lot of experience in timber construction. Thus far, no software tools can detect and predict the correct junction types from BIM models and interpret them for acoustic analysis. The proposed framework uses geometric analysis to classify zones of elements and distribute them into junction boxes. Based on this information, it is possible to identify the different junction types.

The proposed framework was implemented in a .NET application that automatically extracts the corresponding flanking elements. It is also capable of identifying the geometric placement of flanking elements into junction boxes and deduce the junction type according to that information. The outcome of this research provides a seamless integration with sound insulation prognosis tools, which supports the decision-making process during the design phases.

The current state is that the application does not take into account elements that a not located in the correct building floor. All elements should exist in their corresponding building storey. However, in some cases, some elements geometrically extend to other storeys. Handling this case requires extending the proposed framework to perform special checks. Furthermore, an extensive evaluation for processing complex junctions is necessary, for example, junctions could include double walls.

A next step will be to handle building elements with different material layers. This needs detailed filtering of the core layer of the elements, which builds the junction, and the facing layers, which can also get different acoustic characteristics if necessary. To improve the quality of the BIM model, information about the junction type can be included.

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