Analysis of early-design timber models for sound insulation

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Abstract

Timber construction is associated with a low carbon footprint and offers a high degree of sustainability. However, it poses challenges considering sound insulation. Acoustic analyses, which could require major expensive and time consuming changes in the building design, are typically performed once the design is already in the detailed stage. By using building information modelling (BIM), it is possible to shift the planning of the building physics, including acoustic analysis, to earlier phases. To make this possible, building models must include all the information necessary to perform acoustic analyses. One important part of acoustic analysis is identifying junctions between elements and map them to the junction types in standards. Until now, this investigation involves tedious manual processing for extracting multiple topological dependencies between different elements. Hence, this paper presents a framework for a seamless workflow between building models and acoustic analysis tools, based on an analysis of data models. The framework extracts and analyzes the element types, their geometry, and the connections of the individual elements in relation to each other. Through topological reasoning, along with a set of logical rules, the proposed framework identifies fifteen types of junctions, which can be distinguished acoustically for timber construction. The approach was evaluated in a prototypical implementation using a real-world model based on Industry Foundation Classes (IFC) as an example, in which the potential connection types were successfully extracted. This paper shows that junction analysis can be done with a geometric anal-

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ysis to fill in missing semantic information about junctions of elements from the original data model.

Keywords: Timber construction, Sound insulation, BIM, Interoperability, Early stages

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1. Introduction

Responsible consumption of energy and resources is of great importance in the face of the current climate change. As a major consumer of the world's raw material resources, construction industry contributes significantly to global carbon emissions [1]. Therefore, it is increasingly important to design sustainable buildings, with due regard for the circularity of materials. Timber construction plays an essential role in increasing sustainability. Compared to buildings based on concrete and masonry, it is more resource-efficient as it uses renewable raw materials, while the deconstruction process is more ecological [2]. The use of timber in multi-storey buildings is suitable for a wide variety of facilities, such as residential houses and offices.

Building Information Modeling (BIM) opens up possibilities for interdisciplinary cooperation in the early-design phase in building construction. It enables digital collaboration between architects, civil engineers and specialist planners. Open BIM also makes it possible to exchange data and edit models independently of platforms and software. These advantages are particularly useful in the early planning phase, when decisions strongly influence each other and have a crucial impact on the construction project's success [3]. For example, the design of a load-bearing wall depends not only on its design, but also on its structural requirements, fire safety specifications, and minimum acoustic values. The building model is created using BIM with ongoing enhancement throughout the planning phase, which provide architects and engineers with reliable information. It is therefore crucial to choose the right options early in the planning phase, as changes performed later on due to inadequate planning are expensive and lead to construction delays [4]. It usually makes sense for experts in sound insulation, fire protection, thermal insulation, and structural engineering to work together to enable the best solution to be developed early on.

The review of the literature showed that a high level of detail is needed in early planning phases when constructing buildings with prefabricated timber [5]. Consequently, simulations and forecasting would be feasible at this stage.

Early-design phases mentioned in this paper are phases in conceptual and schematic design, when the architects know the general design and layout of the building and the materials of its main components. At this stage, the first ideas for different building physics problems are discussed and evaluated including regulations, possibilities, and limitations.

In timber construction, building acoustic is a crucial aspect that needs to be addressed carefully. Especially in higher quality buildings, residents and users are sensitive to acoustical issues. Thus, an essential challenge is the sound insulation, since the material's physical properties, together with the design of junctions, have a high impact on the sound transmission behaviour [6, 7, 8]. This is a more complex matter in timber buildings than in concrete and masonry constructions. As timber is not an homogeneous material and has a low mass per unit area, it enables a variety of design options for structural elements and details. Acoustic designers need to consider not only the direct transmission, but also the flanking transmission. This is the sound that goes from one room to another indirectly, over, and around the separating element between both rooms. Even with a good separating element, sound can be transmitted between rooms when the junctions and flanking elements do not fit the acoustic requirements.

The design of junctions affects the quality of sound insulation in lightweight buildings, particularly in timber constructions. In this case, the low mass of the elements promotes the transmission of sound through flanking elements. If the junctions are poorly planned or executed, they can negatively influence the complete acoustic quality of a building. How the junctions are designed also plays an important role for the structural engineers and for the planning of manufacturing. This is especially important because most of timber buildings are built of prefabricated elements.

However, the review of the literature also reveals that little research has been carried out into the implementation of sound insulation in BIM processes. In addition, although the use of models for computer-aided design and computer-aided manufacturing (CAD/CAM) applications is common in timber construction, there are only limited possibilities of creating BIM models and exchanging them with manufacturer-neutral formats in the early-planning stages. Additionally, to the best of the authors' knowledge, there is to date no research that considers the integration of the analysis of building acoustics into the planning process of an open BIM workflow [9, 10]. In building data models the positions of the element in relation to one another or the junction between elements are not described. Especially, the description of junction between elements is missing in building models.

The aim of this paper is to develop a methodology for integrating sound insulation prognoses in timber construction into a BIM-supported planning process. The authors aim to evaluate the building acoustics in the early-design phase in timber construction. This paper formalizes a method for the geometric analysis of junction details, providing a basis for calculation, pursuant to ISO 12354-1 [11]. Based on the knowledge gained through literature review and the identified gaps, the contributions of this paper are as follows:

- Show how acoustic analysis can be integrated into an Open BIM workflow.
- Demonstrate that junction between elements can be described from data models.
- Formalize the description of acoustical junction types.
- Define requirements for BIM models to perform sound analysis.

The paper shows how tangible results can be provided with geometric analysis. Therefore, we analyse data models and extract input data for sound analysis. The data is then evaluated to identify building components, including the types of junction involved. The components constitute an input for the calculation of sound insulation and impact sound level. Such calculations require additional information from external databases to create a forecast. The database also includes component catalogues, which are typically extracted from standards and domain knowledge. It is also important to continuously integrate any new input data provided by research in the prediction models [12]. The results are compared with applicable standards or requirements and optimized as necessary. Figure 1 presents a schematic workflow for integrating the acoustic analysis in the planning phase, early on.

The paper is organized as follows: Section 2 discusses background knowledge and related work about early-design phases and sound insulation in timber construction. The methodology used in this research is described in Section 3. Section 4 demonstrate a prototypical implementation on a showcase building and discusses issues with the chosen data model. This helps to formulate basic requirements for the data model. Section 6 summarize the progress and presents an outlook for future work.

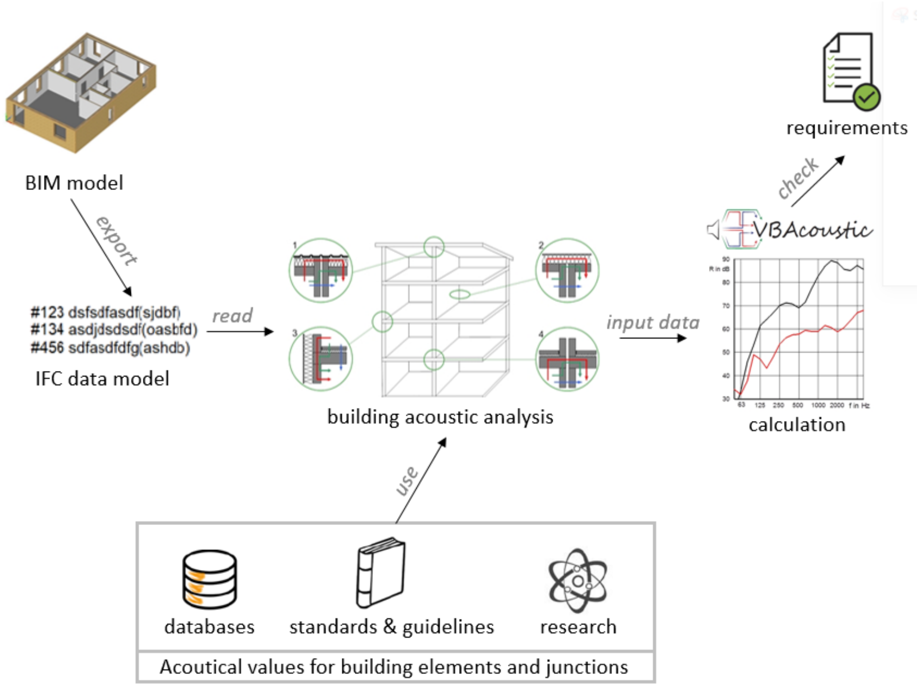


Figure 1: Workflow for predicting sound insulation using an IFC data model to perform the acoustic analysis and obtain qualified input data

2. Background & Related Work

It is a complex and error-prone task to plan lightweight timber buildings with efficient sound insulation . Additionally, existing forecasting methods used in concrete and masonry constructions are not fully transferable to timber construction. Specifying design details require expertise in acoustic and timber construction in order to provide the input data needed for calculation. Planners have to ensure that the designs take into account different trades, such as structural engineering and fire protection. In current practices, acoustic optimization remains an independent process, even if it has a strong impact on the design and vice versa, as the example of room acoustics shows [13, 14].

2.1. Performance assessment in the early planning phases

The focus in the early-planning phase is on providing a number of initial workable concepts for the building project. Decisions taken in this stage have a strong impact on the building's performance and cost, as well as on subsequent stages [15, 16]. Also, it is easier and, importantly, cheaper to make changes in the early stages [17].

Typically, the conceptual design process is complex due to the existing demands, constraints, and boundary conditions, as well as the wide range of possible solutions, combinations, and variants. While the effect of some may be to enhance the performance of the building in certain aspects, they may, at the same time, have a negative effect on other aspects. At this point, interdisciplinary work must be pursued to find an ideal solution. Many different methods, algorithms, and research work are available to handle multidisciplinary optimization problems [18]. Therefore, the evaluation of the model in the early design stages is important while maintaining the consistency of information refinement. The industry has well understood the need for early-stage decision-making to improve a building's performance [19]. Multiple consultants provide their expert knowledge to clients and designers as a basis for their decision making.

The definition of early-design varies minimally from country to country. In the UK, these are phase 2 (concept design) and 3 (spatial coordination, formerly known as the 'developed design' stage) in the RIBA plan of work from 2020 [20]. In this phases, the detail is described by the level of development (LOD) 200 for phase 2 and LOD 300 for phase 3. The phases 2, 3 and 4 are used in an iterative circle to enhance the design assuring all required planning permissions and building regulations. For prefabricated timber elements information from the technical design are integrated earlier to ensure that the prefabrication runs ideally. This necessitate a LOD 300 for some elements, i.e. walls and slabs, and their junctions. The level of development includes not only the geometry of the element, but also the information associated with it. The planners have to think about the requirements and constrains of the elements. This process is done in building physics design, so the application of level of development concept makes sense.

The BIM methodology lends itself well to simulations and forecasts in the early planning phase [3], because objects in BIM data models have geometrical information, semantic information, and object-specific properties. The options produced at each design stage are typically evaluated for compliance with regulations and design requirements [22]. Early-design methods serve a variety of planning processes in the building industries [9], such as the prediction of pedestrian behavior [23], the exploration of structural designs [24, 25] and the evaluation of energy consumption and costs [26, 27].

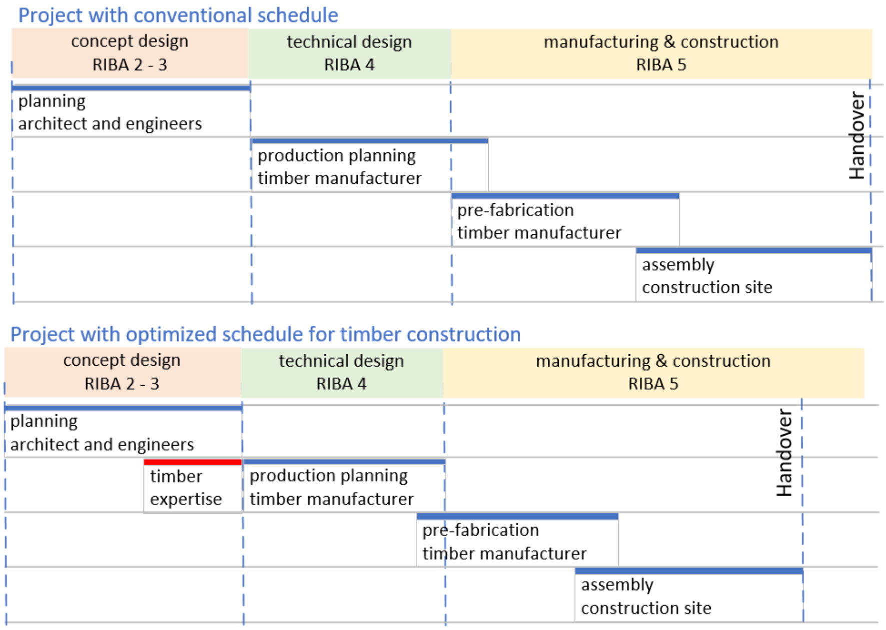


Figure 2: Comparison of project schedules for conventional and optimized construction processes [21, 20]

The development of the preliminary design of a building should also focus on aspects such as fire protection, the supporting structure, thermal, and sound insulation. This leads to a design phase in which timber professionals are integrated in the process of developing the timber construction system, the layer structures, and the junctions between elements. Ultimately, this leads to shorter project duration as shown in Figure 2 [21]. As it relies on prefabrication, timber construction requires accurate production planning with a substantial proportion devoted to the execution phase. This forms a good basis on which to incorporate the timber planning process into a BIM workflow [28, 29]. To facilitate the complex planning process, parametric modelling adapted to timber construction is currently being studied [30], and individual solutions (add-ins) and object libraries are being developed [29].

However, the use of automated early-design methods in acoustics is not typical in today's practice, as acoustic engineers only become involved in the planning process at a later stage. Even specified software tools for complex room acoustics problems are used in later planning phases, although room acoustic optimization has a strong impact on the design [13]. There are very few publications that make reference to sound insulation planning with BIM solutions [9, 10]. Some publications deal with the matching or mapping of measurement data and the verification of requirements with a BIM model [31, 32, 33]. Some authors indicate that data models, like IFC, contains insufficient information for sound insulation calculations [34, 35, 36]. This is the reason why BIM solutions mainly use Closed BIM methods, even in research [37, 38]. The authors are not aware of any attempts in the literature to automatically determine junctions for the complex calculation according to EN12354-1 from BIM data models, which would enable an Open BIM workflow.

2.2. Topological predicates in BIM models

Buildings consist of various geometric objects, but data models only allow a few spatial relationships. Further, many modelling tools are unable to create data models with appropriate spatial relationships [39]. Topological predicates are commonly used to describe the positions of two elements in relation to one another. Various approaches have been discussed in publications over the years. Guesgen defines 64 relations between two-dimensional objects using only four different predicates: left of, attached to, overlapping, inside, and their negation [40]. In [41], multiple additional relations are specified using minimum bounding box for two-dimensional objects. In Frank and Goyal the topological predicates are called North, South, East, West, plus the directions in between [42, 43]. Unlike Frank's method, which only handles two-dimensional objects, Goyal additionally manipulates three-dimensional objects using a 3x3-matrix to define 218 different element positions. In [44], the authors present an algorithm that calculates the distance between three-dimensional objects depending on their positions in relation to one another. This algorithm is used to solve problems concerning collision detection and the computation of distances in robotics.

The approaches mentioned above describe the positions of elements in BIM models in various applications. The lack of spatial query capabilities of BIM data management systems causes multiple limitations. As spatial objects, buildings would benefit enormously from the analysis and verification of spatial relationships [45]. In [46] and [47], the positions of objects in a BIM model are described by eastOf, westOf, northOf, southOf, above, and below. Daum and Borrmann also performed research on this topic after highlighting the insufficient handling of geometric information [45]. They developed a Query Language for Building Information Models (QL4BIM), which provides metric, directional, and topological operators. The queries use distance between elements to describe their relative position to each other. Additionally, the publication by Zhou et al. considers on the state-of-the-art 3D Spatial Data Analytics for BIM models and make reference to the urgent need for efficient 3D spatial analysis of IFC models [39]. They conclude that the performance of spatial queries and databases is not sufficient to handle the large quantities of data typical of BIM models. They also stress that a combined analysis of geometric and semantic information is the most effective for an IFC model.

The research gap concerns a description of several elements in relation to one another, that can be used to define junction types. None of the approaches are capable of describing the element junctions in a formal manner that is fulfilling the needs of acoustic calculations. For this purpose, it is necessary to describe the positions of up to four elements in relation to one another and describe the point at which they are embedded in the junction.

2.3. Sound transmission in timber buildings

Key parameters indicating the level of protection against noise are airborne sound insulation (for walls and ceilings) and impact sound level (for slabs). In the early-design phase, both airborne and impact sound insulation are calculated according to ISO 12354-1 [11] to meet national requirements of the different European countries [48, 49, 50, 51, 52]. This paper uses the German standards [53, 54], but the procedure is similar for other countries. To gain full information about an element's acoustic properties, the sound insulation is analysed with frequency-dependent values ranging from 50 to 5000 Hz, in octave bands. The rated values are easier to handle, but lose their frequency information.

Sound is transmitted in the form of either airborne or structure-borne sound waves, i.e., through a building's structural elements. Transmission from one room (sending room) to another (receiving room) through a separating element is referred to as direct sound transmission and is described by the sound reduction index R_w for all building elements. The impact sound level $L_{n,w}$ describes how much noise passes through a ceiling when it is structurally excited by footsteps or falling objects. In buildings, the separating element between the sending and the receiving room is linked to flanking elements, which also transmit sound. Therefore, different transmission paths need to be specified. For symmetric room positions, it exists 3 type of transmission paths. Figure 3 illustrates the different paths. The names of flanking paths for elements at the side of the sending room are given in upper case (D and F), while those on the receiving side are lower case (d, f). Mixed transmission paths are called Df and Fd, and pure flanking transmission called Ff. Considering impact sound transmission, there is the path Df and the additional path DFf, which describes the influence of the floating screed on the upper flanking wall, particularly in timber construction.

2.3.1. Special nature of timber construction

The sound insulation properties of timber elements are influenced by many factors. In general, timber constructions are lighter than solid concrete and masonry constructions. The lower mass per unit area also means, however, that the sound insulation of a single panel is lower. For this reason, timber constructions are usually fabricated as multi-shell elements. The shells must be either as free-standing facing shells or, in the case of suspended ceilings, have elastic hangers or spring rails.

The thickness and mass of a solid timber element (or the width of the timber space in stud constructions) influence the sound insulation properties, as do the type and thickness of the insulation used, the cladding and its fastening, and the design of the installation levels. Regarding ceiling con-

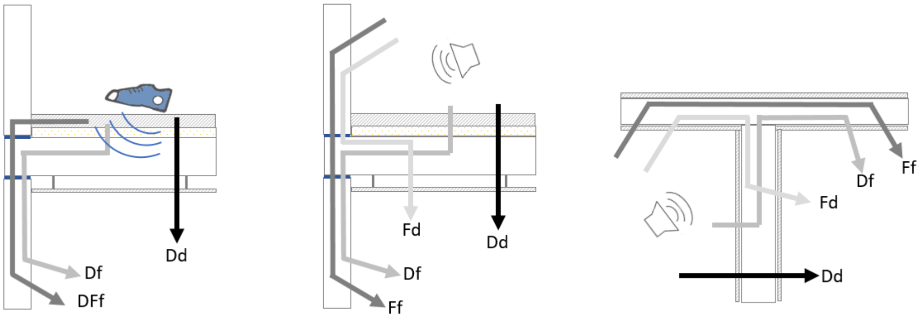


Figure 3: Sound transmission paths with the paths Ff, Df, Fd and DFf for the impact sound transmission of a ceiling (left), sound insulation of a ceiling (middle), and sound insulation of a wall (right)

structions, special attention must be paid to the weighting of the raw ceiling, to the screed construction (i.e. the type of impact sound insulation, the weight of the screed, and the design of the edge insulation strip) and the construction of the suspended ceiling (either direct planking or a suspended construction with cavity insulation) [55, 56].

A decisive factor of junction design is the shape of the junction geometry. Flanking elements can be continuous, separated by a gap, or completely interrupted by the separating element. It is essential to distinguish between junction types in order to determine the correct vibration reduction index [8]. Intermediate elastic layers in the junction improve the flanking insulation, especially in junctions between ceilings and walls [57]. The type of fastening in the junction, i.e. with screws, angles or decoupled elements, also affects the insulation performance [6].

2.3.2. Flanking transmission

In addition to direct sound transmission, flanking transmission plays an decisive role in lightweight constructions such as timber buildings. Flanking transmission is characterized by the vibration reduction index K_{ij} and the normalized flanking level difference $D_{n,f}$. It can be used with frequency-dependent values as well as for each separate transmission path. Considering one separating element with four flanking elements, it is necessary to examine at least 16 transmission paths. In case of timber ceilings, there are four more paths that may be relevant if DFf has an effect on the construction. The sound reduction index K_{ij} for the flanking path is calculated as shown in

Equation 1. Equation 2 shows how the flanking sound reduction index $\mathrm{R_{ij}}$ is calculated, while Equation 3 indicates how the airborne sound insulation in situ R' is deduced, taking all flanking paths into account.

$$K_{ij} = \overline{D_{v,ij}} + 10 \lg \frac{l_{ij}}{\sqrt{a_i \cdot a_j}} \tag{1}$$

$$R_{ij} = \frac{R_i + R_j}{2} + \Delta R_i + \Delta R_j + K_{ij} + 10 \lg \left(\frac{S_{\mathrm{S}} \sqrt{a_i \cdot a_j}}{l_{ij} \sqrt{S_i \cdot S_j}} \right) \tag{2}$$

where

R_i, R_j	represent the sound insulation of element i and j in dB,
S_{S}	is the area of the separating element in m^2,
S_i, S_j	is the area of flanking element i and j in m^2,
ΔR_i, ΔR_j	are the sound reduction improvement indexes for element i or j, respectively, for a resilient wall skin, suspended ceiling, or floating floor in dB,
l_{ij}	is the common length of element i and j in m,
a_i, a_j	are the equivalent absorption lengths of elements i and j in m,
K_{ij}	is the vibration reduction index for the transmission path i-j in dB.

$$R' = -10 \lg \left(10^{(-0.1 \cdot R_{Dd})} + \sum_{j=1}^{n} 10^{(-0.1 \cdot R_{ij})} \right) \tag{3}$$

A similar approach is used calculating the impact sound level of ceilings. All acoustic parameters can be calculated either in octave-bands for frequency-depended calculation or as rated values in the frequency range of 200 to 2500 Hz.

2.3.3. Influence of the vibration reduction index K_{ij}

The junctions type influences the vibration reduction index K_{ij}, which in turn has a strong effect on the rated sound reduction index R'_w. The values of K_{ij} diverge between 3 dB and 26 dB, depending on the selected junction type and resulting transmission path [12, 11, 56, 8, 6, 58]. To demonstrate how important the correct choice is, a brief analysis of a separating wall element with four flanking elements was conducted. Values were chosen for all transmission paths (Df, Fd and, Ff) that represent situations ranging between unfavourable and very good (5 dB, 10 dB, 16 dB, 20 dB, 24 dB). The results shown in Figure 4 illustrate the significant influence of the the vibration reduction index. The results of the analysis range between 41 dB and 60 dB. The effect of an additional 10 dB in the sound level is perceived as an approximate doubling in volume (loudness). A more detailed example is given in the use case in Section 4.

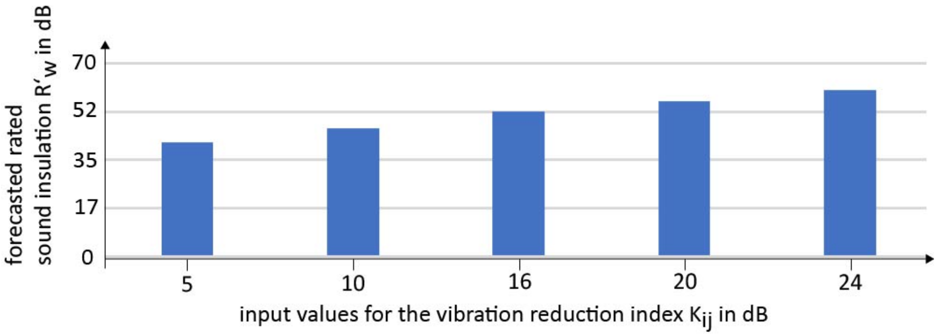


Figure 4: Simplified prognosis of the rated sound insulation R'_w, in which all flanking paths have a vibration reduction index K_{ij} between 5 dB and 24 dB

The hearing threshold of the human ear is approximately 0 dB. If the sound level increases by 3 dB, this is usually clearly perceptible. An increase of 10 dB is roughly equivalent to a doubling in volume. A nocturnal noise exposure with a sound level of 30 dB(A) is already enough to impair sleep quality [59], while stress and loss of concentration occur at lower sound levels [60]. This shows how important it is to carefully design not only the separating elements, but also the junction details.

3. Methodology

The method presented in this paper focuses on standard timber buildings and excludes irregular architectural designs. Moreover, such designs constitute exceptions in terms of sound insulation, as they cannot be directly represented by regulations and standards. Since ISO 12354 [11] and DIN 4109-2 [54] only refer to rectangular rooms for the purposes of calculating sound insulation, a rectangular situation is also assumed for this method.

In this section, we define the term of junction and show how junction boxes select the junction position and the elements for a junction. Then we define connection zones to be able to formalize various junction types. Figure 5 shows the four main steps with reference to the section numbers.

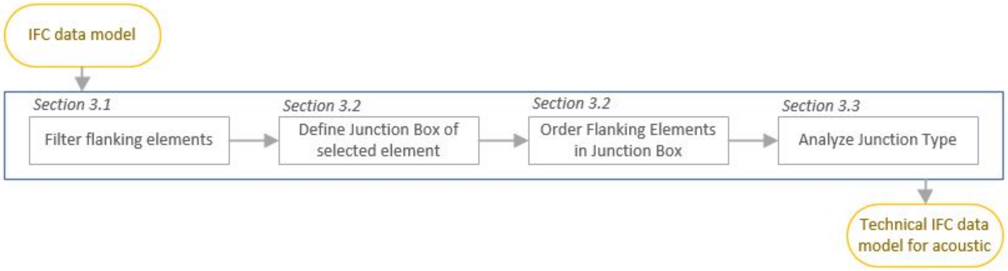


Figure 5: Flowchart with the main steps of the junction analysis

In early-design phases architects and practitioners explore possible design variants, trying different element compositions to evaluate the performance of each combination. At this phase, elements like walls and slabs have approximate shape, location, and orientation. Therefore, we presume at least LOD 200 for the walls and slabs (according to the BIMforum specification [61]), as at this level the correct geometry of the junctions can already be deduced.

Further, building elements with LOD 300 provide more precise results due to the layered structures. But it is not necessary for all elements in the model to have the same LOD. Only those building elements that are relevant to the junction analysis are important, i.e. the interior walls, slabs including suspended ceilings, floor structures, exterior walls and facade elements. The layer structure of the materials in the elements should be approximately correct, and the positions and geometries of the elements must be given. The layer structure is required already in the early planning stages to enable planning of a building in timber construction with a high degree of prefabrication.

3.1. *Definition of flanking elements*

The evaluation of the sound insulation starts with a sending room and a receiving room separated by a building element called *separating element.* In rectangular, symmetric room situations, this element has four junctions with different flanking elements. A flanking element is an element that is parallel or in 90° angle to the separating element. In such case, the flanking element must be adjacent to the separating element. However, they do not have to be in contact (i.e. distance $d = 0$) for instance, as a result of inaccurate modelling and design features. A distance of $d < 0.5m$ is considered suitable for this method. This figure needs to be relatively high, because with elements that are parallel to the separating element and oriented in the same in direction as an edge, it is possible that another flanking element might lie in-between (see Figure 6). For this reason, the term "close to" is defined as follows: for two elements A and B with parallel planes

$$\vec{n} \cdot \vec{x} = e \text{ and } \vec{n} \cdot \vec{x} = f$$

with a distance

$$\frac{|e-d|}{|\vec{n}|} \text{ of } d(A,B) = d(e,f) < 0.5m.$$

Element A is considered "close to" element B and vice versa. The direction in which the distance between element A and B is measured is described by $d(A.B).\vec{n}$.

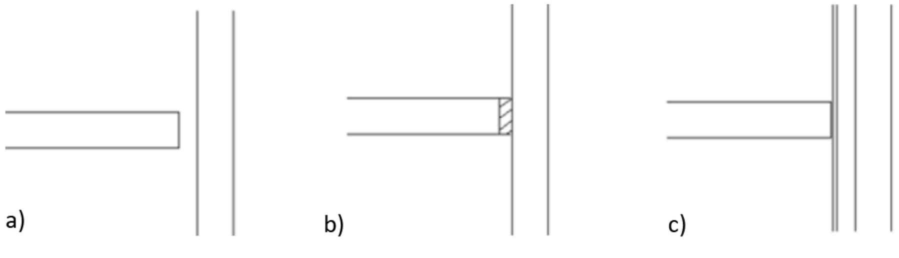


Figure 6: Flanking elements with distance $0m < d < 0.5m$ o the selected element resulting from a) improper modelling, b) a junction with elastic layers c) elements with facing layers

3.2. Definition of junction box

Now that we know the flanking elements, we need to position them relative to the separating element. Each separating element has four possible connections with other elements at its edges. This is where the junction boxes are located. For this purpose, six types of junction box are created around the separating element. Four of them describe the edges and are the same size for each component, and two describe the central element area and adapt to the size of the element. The following equations show example definitions of junction boxes 1, 2 and 3 for a wall element with the direction of the biggest surface is $n = (1/0/0)$. The vector n characterizes the direction of the separating element and the minimum and maximum points of its size and position.

$$\begin{aligned}
&\text{Junction box 1, where } n = (1/0/0)\\
&\text{JB-Min: } X.Min - 0,3/Y.Min - 0,5/Z.Min\\
&\text{JB-Max: } X.Max + 0,3/Y.Min + 0,5/Z.Max\\
&\text{Junction box 2, where } n = (1/0/0)\\
&\text{JB-Min: } X.Min - 0,3/Y.Min + 0,5/Z.Min\\
&\text{JB-Max: } X.Max + 0,3/Y.Max - 0,5/Z.Max\\
&\text{Junction box 3, where } n = (1/0/0)\\
&\text{JB-Min: } X.Min - 0,3/Y.Min - 0,5/Z.Min\\
&\text{JB-Max: } X.Max + 0,3/Y.Max + 0,5/Z.Max
\end{aligned}$$

The dimension of each junction box in the y-direction is based on the definition of the junction type in the standards [11]. The distance between opposing elements that defines whether those elements form a junction or not is limited to 0.5 m. This limit also determines whether it is an L-junction or a T-junction, or whether opposing elements form an X-junction or two separate T-junctions (see Figure 9).

After building the junction boxes around the separating element, the flanking elements are distributed to them, depending on their direction compared to the flanking elements (Figure 8). How the position of the flanking elements is determined (X+, X-, Y+, Y-, Z+, Z-) and each flanking element placed in the corresponding junction box depends on the direction of the selected element (n=1/0/0, n=0/1/0 or n=0/0/1). Each junction box contains up to three flanking elements in addition to the separating element, which

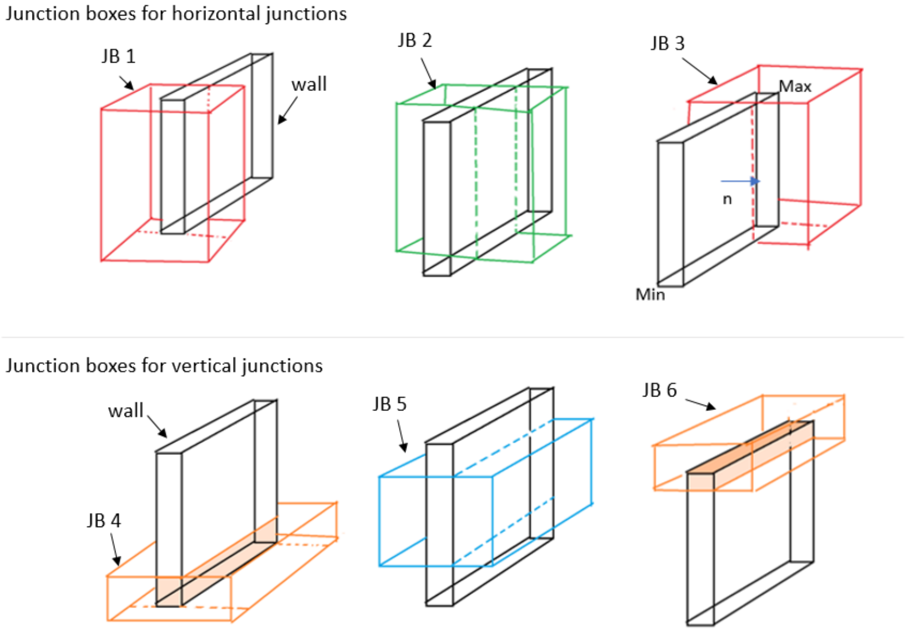


Figure 7: Junction boxes in a wall element

is always included. The elements are stored with their distance from the separating element, their direction and their geometry.

Every junction has four possible slots that can be filled with elements. Slot one contains the separating element, while slot two, three and four are filled with flanking elements.

3.3. Definition of junction type

Many studies of relative element positions use positional predicates such as *north*, *east*, *south*, *west* [41, 43]. These can also be applied to three-dimensional space by adding *above* and *below* [46]. Describing junctions in this way is only possible to a certain degree, as it can lead to multiple descriptions of the same junction type, in different rotated variants. In addition, this application always requires models to distinguish very precisely between touch, disjoint and overlap [45]. However, as shown in section 3.1, this is not always the case for the execution of the junctions, since the load-bearing structure is relevant here, which would not fulfil the touch condition due to insulation strips, facing shell or inaccuracy in the junction. Therefore, the following method deviates from the classical collision detection.

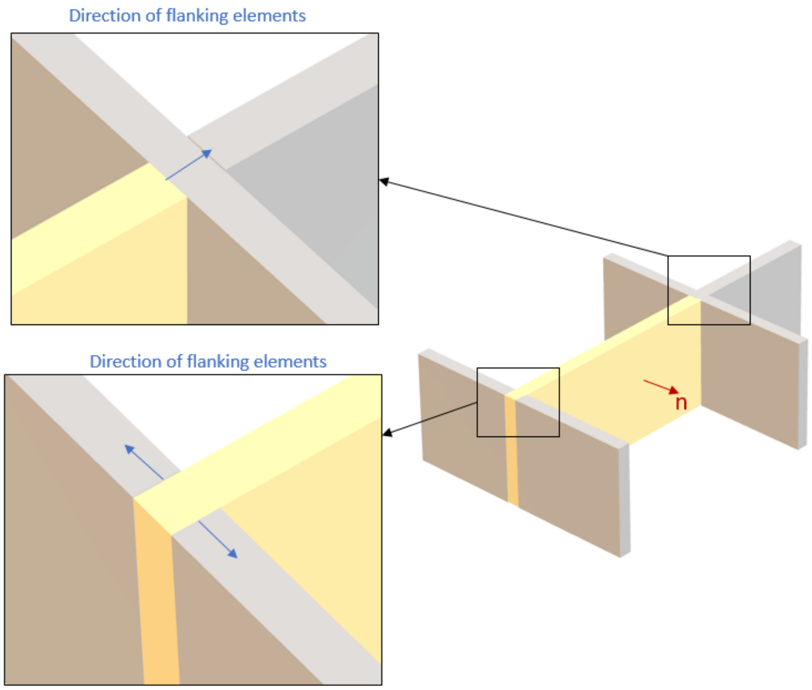


Figure 8: Sketch showing the direction of flanking elements (grey) relative to the selected element (yellow) in different junction situations: above, flanking elements are at 90° to the selected wall direction n, while below, the flanking elements are in the same direction (i.e. n or $-n$)

A junction describes the meeting of several elements at one point. How they meet, which element is cut and which not, is described by the junction type. A decisive factor of junction design is the shape of the junction geometry. Flanking elements can be continuous, separated by a gap, or completely interrupted by the separating element. It is essential to distinguish between junction types in order to determine the correct sound transmission paths. Junctions are defined with two, three or four elements meeting at one point. Six different basic types exist as shown in Figure 10.

The difference between these basic types is at which point the elements are close to each other. We can describe these areas as touching at the short side of the element, at the border of the bigger surface or in the middle of the bigger surface. Thus, all elements can be divided into *connection zones*, as shown in Figure 11. The edge around a selected element forms the connection zone *short*. Around the large area runs a border area called *border* and the

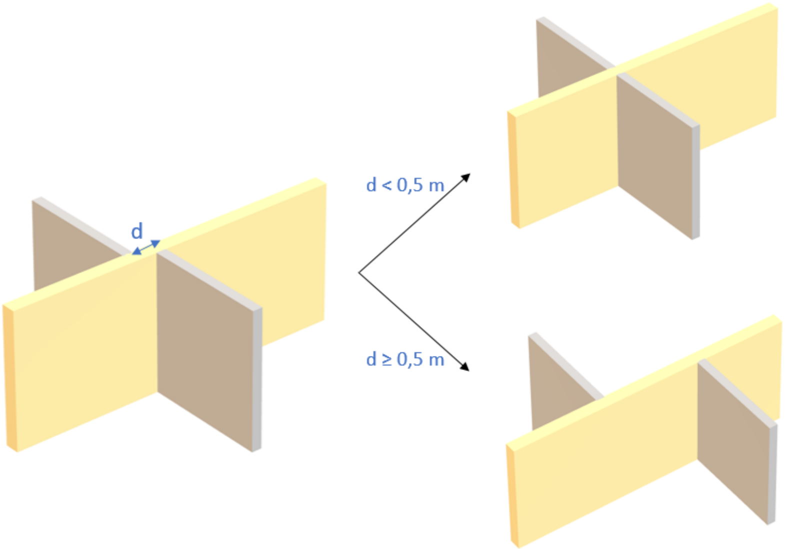


Figure 9: The definition of junction type with offset the elements on the length of the offset d (as described in [11])

remaining part of the element form the connection zone *middle*. Figure 10 shows the connection zone matrix belonging to the junction type. The 4x4 matrix describes with which connection zone one element is close to the other. It needs to be read one line at a time. The first junction is a L-junction with two elements whose matrix is read as follows: element 1 is close to element 2 with the connection zone short. element 2 is close to element 1 with a connection zone border.

If only the connection zones are considered, then the junction type is not clear. Figure 12 shows with an example of a junction with two elements, how the element direction adds different possibilities of junction type. The direction of the separating element is the reference for the direction of the other elements. The direction of the separating element is always n, that of adjacent walls at 90° is always m, and ceiling elements are always the direction o. If the separating element in the junction is a ceiling, the first wall that is considered as a flanking wall is given the direction n. From the six basic types up to 15 kind of junction exists, when considering the different direction and kind of elements involved. Figure 13 shows all 15 junction types in timber constructions that need to be distinguished from one another [8].

Algorithm 1 Setting a flanking element (FE) into the slot of a junction box from the selected element (SE) with direction $SE.\vec{n}$

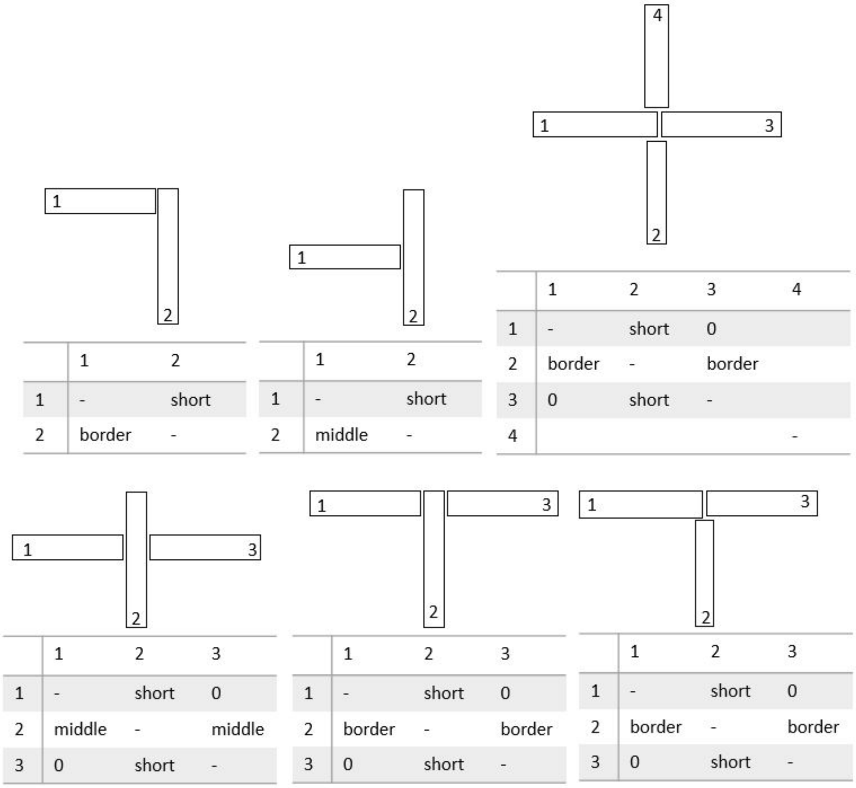
```
if $SE.n \parallel FE.n$ then
    if $d(SE, FE).\vec{n} \neq SE.\vec{n}$ then
        Fill in JB1, JB3, JB4 or JB5: Slot 3
    else if $d(SE, FE).\vec{n} = SE.\vec{n}$ then
        Fill in Slot 1
    end if
end if
if $SE.\vec{n} \nparallel FE.\vec{n}$ then
    if $d(SE, FE).\vec{n} \neq SE.\vec{n}$ then
        Fill in JB1, JB3, JB4 or JB5: Slot 2 or Slot 4
    else if $d(SE, FE).\vec{n} = SE.\vec{n}$ then
        Fill in JB2: Slot 2 or Slot 4 AND SE in Slot 3
    end if
end if
```

3.4. Use of bounding boxes

The data model must have a geometric representation of the relevant elements from which bounding box can be generated. The method presented in this paper uses bounding boxes for the geometric analysis of all elements. This includes the distances and positions of elements relative to each other. This enables the investigation of models with a low LOD (LOD 200). Accordingly, only the correct external shape dimensions, location, and orientation. Level of Detail is essentially how much detail is included in the model element. Level of Development is the degree to which the element's geometry and attached information has been thought through – the degree to which project team members may rely on the information when using the model [61].

If the LOD is higher and a definition of the wall layers already exists, consideration must be shifted to the load-bearing layer. Since this layer is responsible for sound transmission, it also determines the type of junction.

For this paper, only straight, axis-aligned elements are considered. This method should be transferable to other elements as well, because the relevant parts of the junction can be approximated as straight elements with a 90° angle between each one.



	1	2
1	-	short
2	border	-

	1	2
1	-	short
2	middle	-

	1	2	3	4
1	-	short	0	
2	border	-	border	
3	0	short	-	
4				-

	1	2	3
1	-	short	0
2	middle	-	middle
3	0	short	-

	1	2	3
1	-	short	0
2	border	-	border
3	0	short	-

	1	2	3
1	-	short	0
2	border	-	border
3	0	short	-

Figure 10: Six basic types of junctions

4. Case Study

In this section the proposed methodology is demonstrated through a showcase of a real-world building. The proposed approach was implemented in a prototype as a .NET application, using the xbim Toolkit [1] to analyse the IFC data model. The results of the junction analysis are discussed in section 4.3. Section 4.4 gives an overview of the identified challenges when using the data model. Additionally, it states quality requirements that are necessary for conducting the acoustic analysis.

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

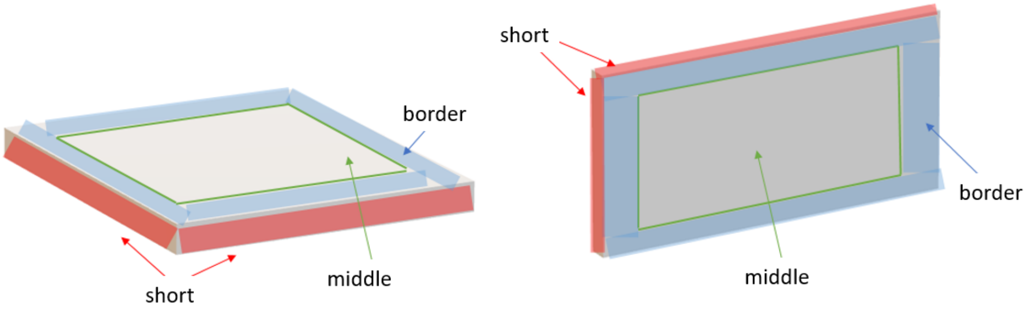
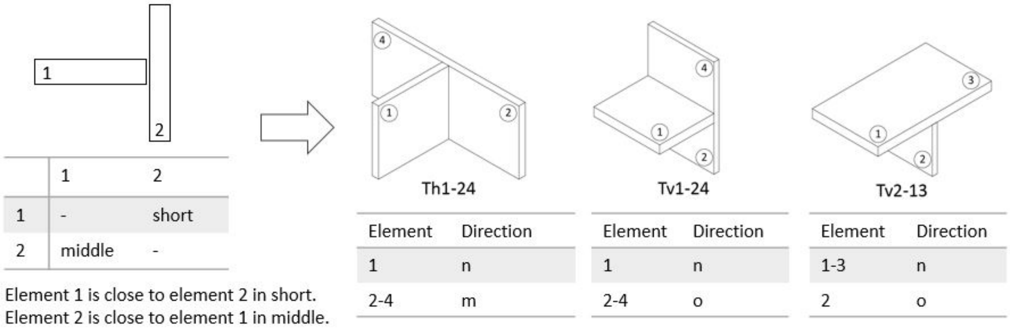


Figure 11: Connection zones in a slab (left) and a wall (right): short, middle and border



	1	2
1	-	short
2	middle	-

Element 1 is close to element 2 in short.
Element 2 is close to element 1 in middle.

Th1-24

Element	Direction
1	n
2-4	m

Tv1-24

Element	Direction
1	n
2-4	o

Tv2-13

Element	Direction
1-3	n
2	o

Figure 12: Different junction type with the same definition of junction zones

4.1. Showcase building

A showcase project for climate-friendly living has been under construction since 2010 on a former US military base in Bad Aibling near Rosenheim in Germany. The area comprises several residential complexes, offices, kindergartens, schools and restaurants. Highly energy-efficient new timber buildings were constructed, and existing buildings were renovated to enhance their energy efficiency. One of the first showcase buildings to be completed was a four-storey high-rise in timber construction with containing residential units. It was planned and built by Schankula Architekten [62]. Throughout the planning and construction phase, they were supported by researchers from the Technical University of Munich, the University of Applied Sciences Rosenheim and the ift Rosenheim for the purpose of demonstrating that wood can also be used for tall buildings [63]. The building was made almost exclusively from local timber, and the entire supporting structure is made of

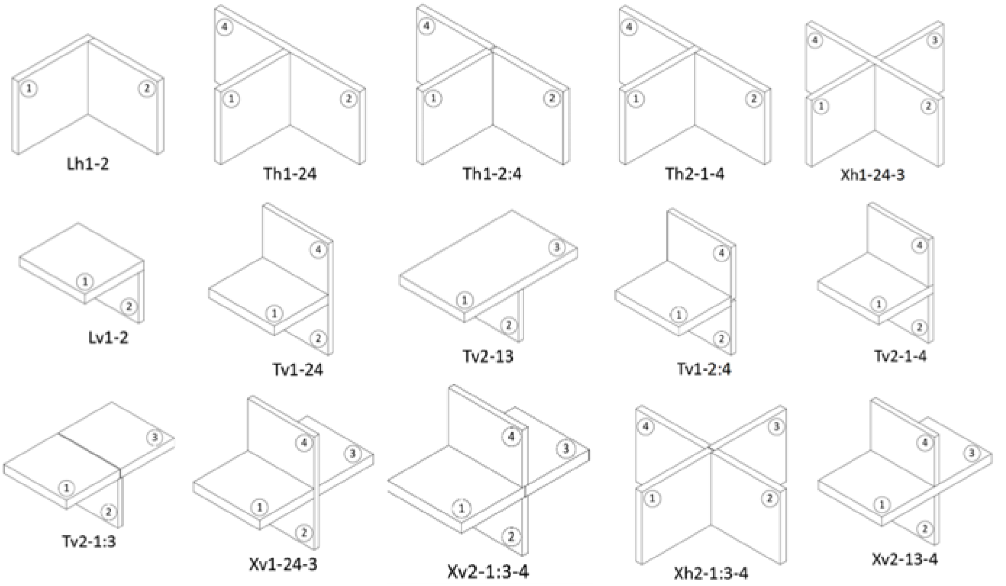


Figure 13: The 15 junction types, not considering the elastic layers for decoupling as specified in [8]

wood.

To analyse the effect of the the vibration reduction index K_{ij} on the weighted sound reduction index R'_w and the weighted sound impact level $L'_{n,w}$ calculations were made with different parameters. A separating ceiling of cross-laminated timber was chosen with a loose weighting (fill) on the top, impact sound insulation and a cement screed. Typical input values were chosen for the flanking elements of the internal and external walls. The sound reduction index values of all the elements were based on the Swiss lignum database [64], so as to be realistic. For each value of the sound reduction index K_{ij}, the range of possible junction types and their values were analysed. In situation 1, all junction paths are worst case values but the values improve from one situation to the next. Situation 4 shows perfect flanking transmission with high damping values.

Figure 15 shows the results of the analysis. The weighted sound reduction index fulfils the increased sound insulation requirements of VDI 4100 only in situation 3 and 4, while situation 2 is borderline and permits neither any prognosis nor construction uncertainties. Regarding the weighted impact

Figure 14: four-storey residential building developed in a research project together with the Technical University of Munich, the Rosenheim University of Applied Sciences and the ift in Bad Aibling. The building's entire supporting structure is made of wood and is self-stiffening without any concrete parts. Ceilings and walls, lift shaft and loggias are also made of wood. [62]

sound level, the values in situations 2, 3 and 4 give good results. Here results need to handled carefully, because the prognosis was not done based on frequency-dependent values. Especially in the lower frequencies, i.e. below 250 Hz, timber constructions tend to have poorer values. Only a frequency-dependent analysis and measurements can give more accurate results. Nevertheless, in this short use case, the analysis underlines the importance of the vibration reduction index. This is relevant for obtaining high-quality sound insulation in timber buildings, where the elements themselves have good input values but the overall sound insulation could be rendered ineffective by poor junction values.

So far the influence of the vibration reduction index K_{ij} was discussed on

Table 1: Input data for sound reduction indices R_w and impact sound level $L_{n,w}$ in dB for the separating ceiling and his four flanking walls

situation	Rw	Ln,w
separating ceiling	70	38
flanking element 1	53	-
flanking element 2	53	-
flanking element 3	72	-
flanking element 4	43	-

Table 2: Input data for sound vibration reduction indices K_{ij} in dB for situation 1, 2, 3, 4

	Situation 1		Situation 2		Situation 3		Situation 4	
junction	KFf	KDf/KFd	KFf	KDf/ KFd	KFf	KDf/KFd	KFf	KDf/KFd
fl. el. 1	3	10,1	10,5	13,6	18	17	25,5	20,5
fl. el. 2	3	10,1	10,5	13,6	18	17	25,5	20,5
fl. el. 3	3	10,1	12,5	16,2	22	22,4	31,5	28,5
fl. el. 4	3	13,6	12,5	18,6	22	23,5	31,5	28,5

the overall results. Next, the proposed approach will be used to evaluate the junction types and the values of K_{ij}.

4.2. IFC data model

To demonstrate the method proposed, the framework uses the vendor-neutral format of Industry Foundation Classes (IFC) [66]. IFC is capable of storing elements' geometries and a large amount of semantic information, i.e. element properties and topological relationships. The use of IFC to forecast sound insulation would enable a seamless planning process between the different trades, modelling (architects and engineers) and simulation experts.

The building was modelled with Autodesk Revit [2] and junction types were modelled as carefully as possible. The model was then exported into IFC using the Coordination View 2.0. Afterwards, the quality of the exported model was enhanced manually in a process we call *Model Healing*. Model healing evaluates the elements' entity types, structure (such as material layers), and relative positions. During this experiment, another modelling software (cad-

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[2] `https://www.autodesk.com/products/revit/overview`

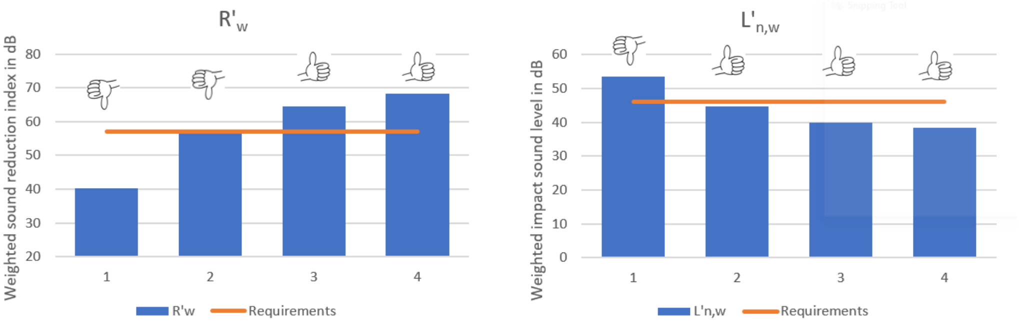

Figure 15: Result of the prediction for the sound reduction index R_w and impact sound level with 4 different values for the vibration reduction index K_{ij} (situation 1 to 4) in each case with requirements for increased sound insulation

work [3]) that is specialised in designing timber construction was also used. But the IFC export of cadwork does not use preset MVDs, hence, it was excluded from the scope of this paper.

The description of a junction is only rudimentary supported by the IFC schema. A semantic relation can exist between elements. It is created with *IfcRelConnectsElements*, which distinguishes between *IfcRelConnectsPathElements*, in which a path definition describes the connection point, and *IfcRelConnectsWithRealizingElements* specifies the connection elements. In both cases, however, only elements with a path definition can be connected. Consequently, ceilings cannot be connected to other ceilings or other elements. Furthermore, the IFC schema enables two elements to be connected, but it is not possible to form a junction of three or more elements. Thus, describing a junction of several elements requires several connection relations, for instance, a junction with four elements needs up to six relations. In *IfcRelConnectsElements*, the *connection point* attribute indicates where the elements meet with the values *AtPath*, *AtStart* or *AtEnd*. However, this specification is inaccurate when it comes to identifying the junction type, as shown in Figure 16. Additionally, a connection between elements of a junction cannot be created, because these elements are not in direct contact, unlike in the case of junctions with three elements (see Figure 17).

Even if the amount of information in a data model varies greatly according to the planning phase during which it was produced [67], acoustic analysis

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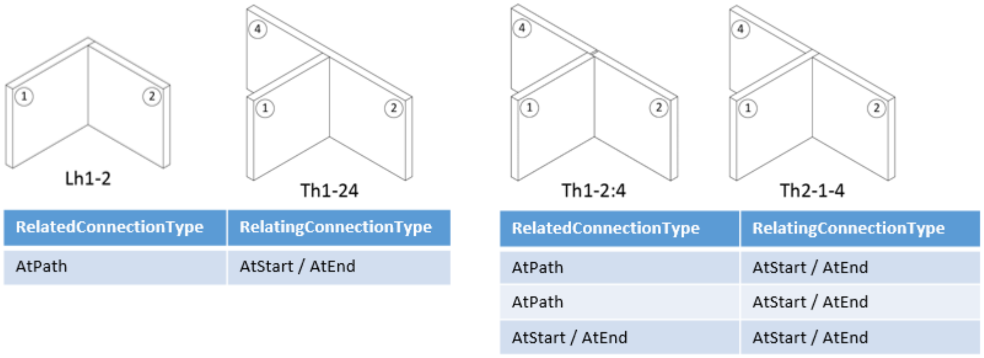
[3] `https://www.cadwork.de/cwde/Module/3D-Konstruktion_Holzbau`

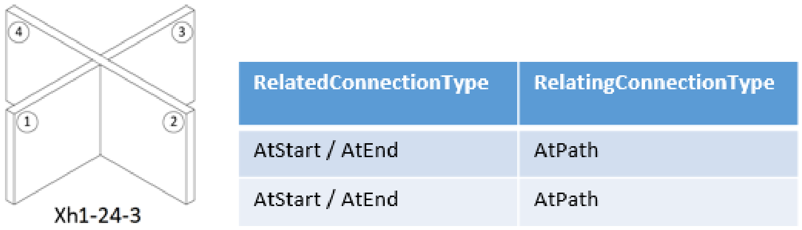
requires minimum, in particular, the design of the junctions. The extent to which the IFC standard can contain this information is restrained. Therefore, junction analysis is required.



RelatedConnectionType	RelatingConnectionType
AtPath	AtStart / AtEnd

RelatedConnectionType	RelatingConnectionType
AtPath	AtStart / AtEnd
AtPath	AtStart / AtEnd
AtStart / AtEnd	AtStart / AtEnd

Figure 16: Inaccuracies in the definition of connections between elements with IFC schema for different T-and L-junctions



RelatedConnectionType	RelatingConnectionType
AtStart / AtEnd	AtPath
AtStart / AtEnd	AtPath

Figure 17: Absence of a connection between elements 1 and 3 needed to describe the full junction

4.3. Results of junction analysis

The analysis began by defining the separated ceiling with the aid of the GUID. Then, the framework selects all flanking elements and orders them into the junction boxes before evaluating the junction type. The results are displayed in the console. Figures 18 and 19 show the results for a separated ceiling, while Figures 20 and 21 show the results for a separated wall. In both analysis, the flanking elements were correctly assigned to the junction boxes, and the respective junction types were correctly identified.

The Figures shows the results from the console: the 4x4 matrix with all connection zones are displayed as well as the direction of the elements below. The results are ordered by junction boxes. The combination of connection zones and element direction determine the junction type, which is displayed below. There are no results for junction box 2 and 4, because no relevant junction is located there.

In a simpler test, various junction types were modelled more accurately, in consideration of the material layers. Figure 22 shows an example of these junctions, the results of the console with the chosen junction box, and the element direction. Here, the supporting layer represents the core of the junction. This leads to correct definition of the junction type, so that the framework also works in these cases.

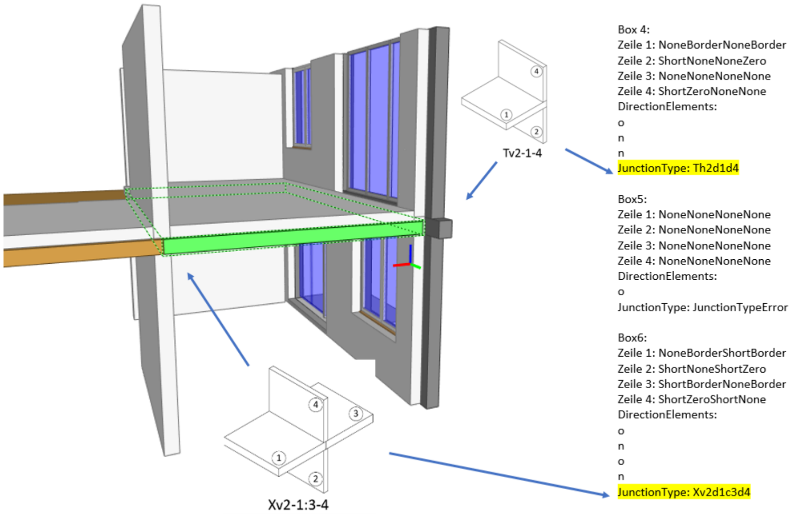
Based on an IFC data model, the framework identified the flanking elements affiliated to the separating elements. It affiliated the flanking elements correctly into junction boxes, which were built around the separating element. All elements were divided into connection zones. The combination of connection zones and element direction was sufficient informational content to identify the junction types in a degree of detail required for the acoustic analysis. The analysis of junction details with multi-layered elements was also successful.

4.4. Requirements to a data model and problems with IFC

Overall the model quality plays a major role for all model analysis. We need an object-oriented data model describing geometry and semantics of a building model. It need to identify building objects correctly as walls or slabs and thus, requires correct affiliation of the entity types to the elements. In addition, a correct geometry of the elements must be available, which can be represented in different ways. It is essential that a bounding box can be created as this will be used for further analysis.

Through conducting the presented use case the minimum requirements needed in the IFC data model were identified for the proposed approach to work. A faster computation of the junction types is possible if, additionally, the model is divided into building storeys and spaces. Then the model can be filtered for possible flanking elements first and don't need to check the distance with all other elements.

The main issue lays in correctly modeling different junction types in the first place, and to create a high quality IFC data model, particularly with

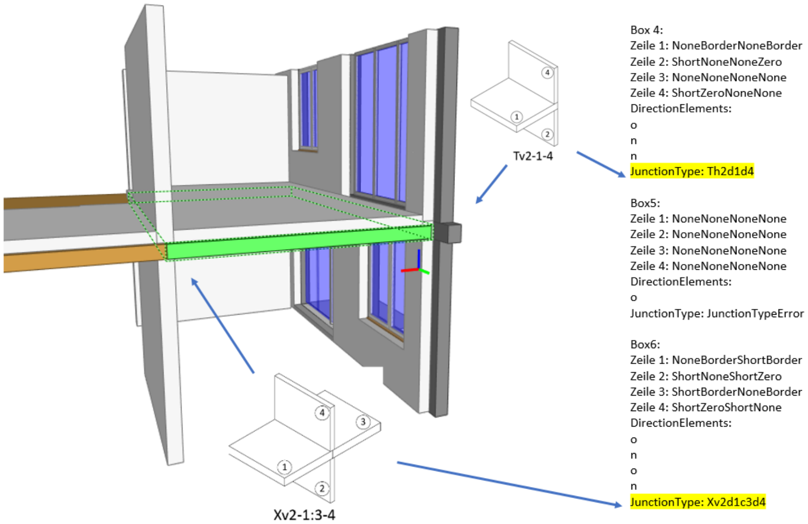


```
Box 4:
Zeile 1: NoneBorderNoneBorder
Zeile 2: ShortNoneNoneZero
Zeile 3: NoneNoneNoneNone
Zeile 4: ShortZeroNoneNone
DirectionElements:
o
n
n
JunctionType: Th2d1d4

Box5:
Zeile 1: NoneNoneNoneNone
Zeile 2: NoneNoneNoneNone
Zeile 3: NoneNoneNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
o
JunctionType: JunctionTypeError

Box6:
Zeile 1: NoneBorderShortBorder
Zeile 2: ShortNoneShortZero
Zeile 3: ShortBorderNoneBorder
Zeile 4: ShortZeroShortNone
DirectionElements:
o
n
o
n
JunctionType: Xv2d1c3d4
```

Figure 18: results of prototype for detecting junctions and defining junction types for the junctions on he left and right side of a separating ceiling (selected in green)

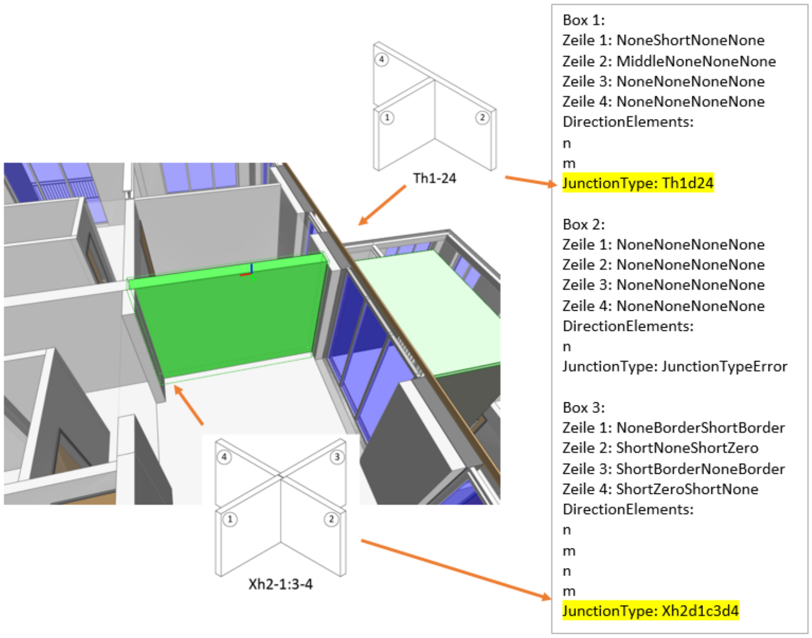


```
Box 4:
Zeile 1: NoneBorderNoneBorder
Zeile 2: ShortNoneNoneZero
Zeile 3: NoneNoneNoneNone
Zeile 4: ShortZeroNoneNone
DirectionElements:
o
n
n
JunctionType: Th2d1d4

Box5:
Zeile 1: NoneNoneNoneNone
Zeile 2: NoneNoneNoneNone
Zeile 3: NoneNoneNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
o
JunctionType: JunctionTypeError

Box6:
Zeile 1: NoneBorderShortBorder
Zeile 2: ShortNoneShortZero
Zeile 3: ShortBorderNoneBorder
Zeile 4: ShortZeroShortNone
DirectionElements:
o
n
o
n
JunctionType: Xv2d1c3d4
```

Figure 19: results of prototype for detecting junctions and defining junction types for the junctions on he left and right side of a separating ceiling (selected in green)

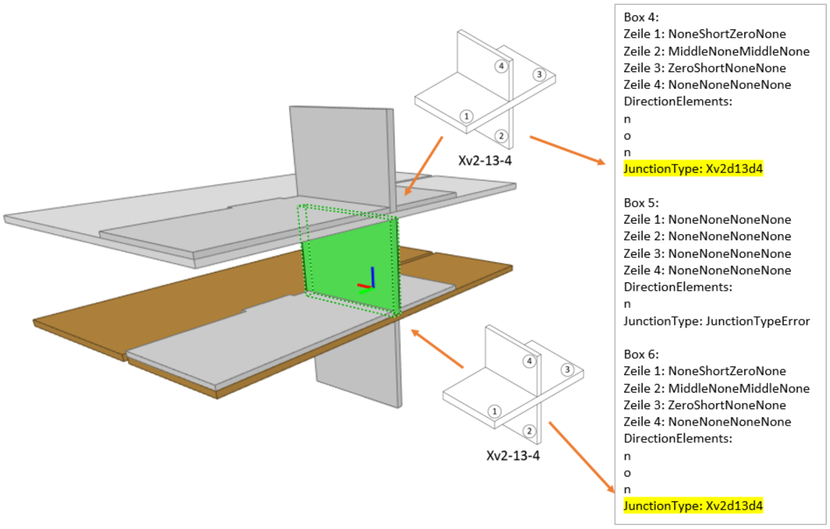


```
Box 1:
Zeile 1: NoneShortNoneNone
Zeile 2: MiddleNoneNoneNone
Zeile 3: NoneNoneNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
n
m
JunctionType: Th1d24

Box 2:
Zeile 1: NoneNoneNoneNone
Zeile 2: NoneNoneNoneNone
Zeile 3: NoneNoneNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
n
JunctionType: JunctionTypeError

Box 3:
Zeile 1: NoneBorderShortBorder
Zeile 2: ShortNoneShortZero
Zeile 3: ShortBorderNoneBorder
Zeile 4: ShortZeroShortNone
DirectionElements:
n
m
n
m
JunctionType: Xh2d1c3d4
```

Figure 20: results of prototype for detecting junctions and defining junction types for the junctions on he left and right side of a separating wall (selected in green)

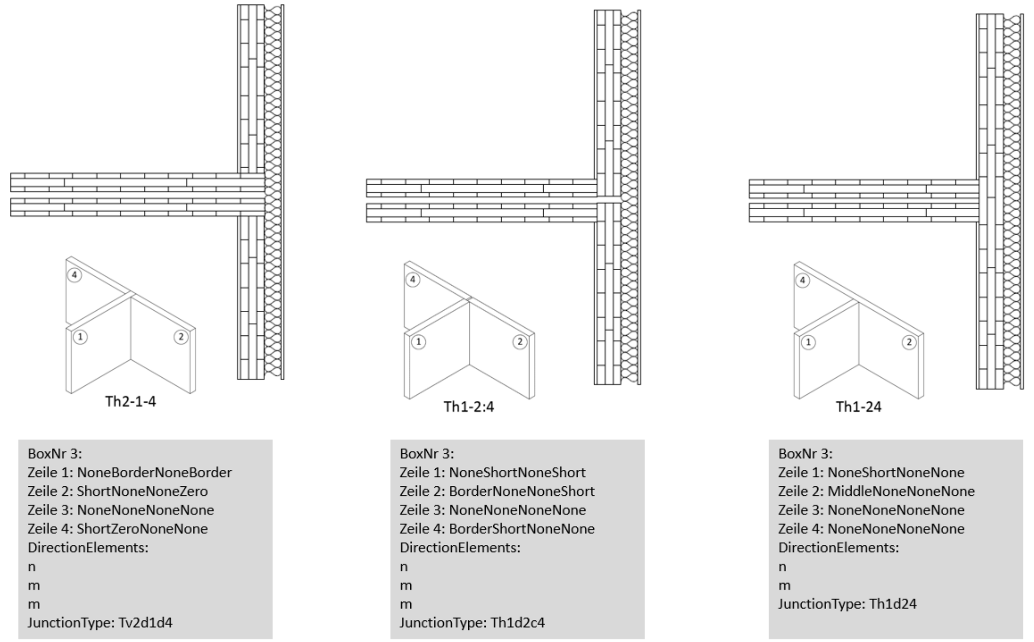


```
Box 4:
Zeile 1: NoneShortZeroNone
Zeile 2: MiddleNoneMiddleNone
Zeile 3: ZeroShortNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
n
o
n
JunctionType: Xv2d13d4

Box 5:
Zeile 1: NoneNoneNoneNone
Zeile 2: NoneNoneNoneNone
Zeile 3: NoneNoneNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
n
JunctionType: JunctionTypeError

Box 6:
Zeile 1: NoneShortZeroNone
Zeile 2: MiddleNoneMiddleNone
Zeile 3: ZeroShortNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
n
o
n
JunctionType: Xv2d13d4
```

Figure 21: results of prototype for detecting junctions and defining junction types for the junctions above and below a separating wall (selected in green), detail section from the entire model



```
BoxNr 3:
Zeile 1: NoneBorderNoneBorder
Zeile 2: ShortNoneNoneZero
Zeile 3: NoneNoneNoneNone
Zeile 4: ShortZeroNoneNone
DirectionElements:
n
m
m
JunctionType: Tv2d1d4
```

```
BoxNr 3:
Zeile 1: NoneShortNoneShort
Zeile 2: BorderNoneNoneShort
Zeile 3: NoneNoneNoneNone
Zeile 4: BorderShortNoneNone
DirectionElements:
n
m
m
JunctionType: Th1d2c4
```

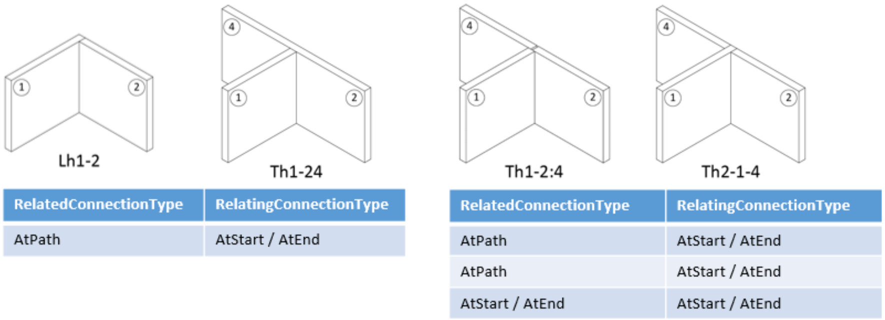
```
BoxNr 3:
Zeile 1: NoneShortNoneNone
Zeile 2: MiddleNoneNoneNone
Zeile 3: NoneNoneNoneNone
Zeile 4: NoneNoneNoneNone
DirectionElements:
n
m
JunctionType: Th1d24
```

Figure 22: results of prototype for detecting junctions and defining junction types for elements with material layers

wooden stud walls [68, 69]. First ideas of how to semantically introduce the junction types into an IFC data model were considered in [70].

In the IFC schema, semantic relations exist between elements, but junctions are only rudimentary integrated. The semantic relationship between elements is created with *IfcRelConnectsElements*, which distinguishes between *IfcRelConnectsPathElements*, in which a path definition can describe the connection point, and *IfcRelConnectsWithRealizingElements*, in which connection elements can be specified. However, in both cases only elements with a path definition can be connected. This means that, according to the schema, ceilings cannot be connected to any other elements. Furthermore, the IFC schema enables two elements to be connected, but it is not possible to form a junction of three or more elements. Thus, describing a junction of several elements requires several connection relations, i.e. a junction with four elements needs up to six relations.

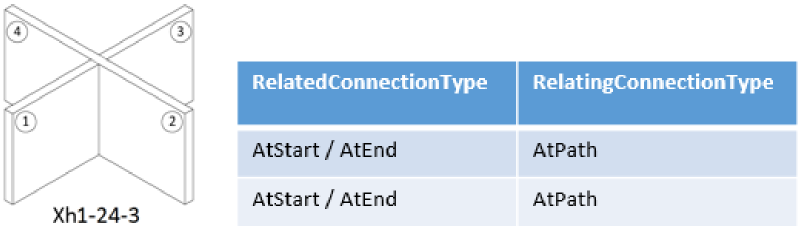
In *IfcRelConnectsElements*, the *connection point* attribute indicates where the elements meet with the values *AtPath*, *AtStart* or *AtEnd*. However, this specification is inaccurate when it comes to identifying the junction type, as shown in Figure 23. Additionally, a connection between elements of a junction cannot be created, because these elements lay not in direct contact, unlike in the case of junctions with three elements (see Figure 24).



RelatedConnectionType	RelatingConnectionType
AtPath	AtStart / AtEnd

RelatedConnectionType	RelatingConnectionType
AtPath	AtStart / AtEnd
AtPath	AtStart / AtEnd
AtStart / AtEnd	AtStart / AtEnd

Figure 23: Inaccuracies in the definition of connections between elements with IFC schema for different T-and L-junctions



RelatedConnectionType	RelatingConnectionType
AtStart / AtEnd	AtPath
AtStart / AtEnd	AtPath

Figure 24: Absence of a connection between elements 1 and 3 needed to describe the full junction

Also each element must be of the correct type. Suspended ceilings and facing shells should be declared as *IfcCovering* and connected to the element with *IfcRelCoversBldgElements*. Information about transmitting and receiving spaces make it easier to interpret the model. Connections between elements and room (*IfcRelSpaceBoundary*) are useful to pre-filter the model, but properly defined spaces are not always exported from modeling software. Here model healing to set correct spaces and boundary relations can be helpful. Solutions to this are being sought in the area of thermal insulation ([71, 72, 73]), so this paper will not go into it in detail.

Including additional information can simplify the data analysis process, to avoid checking each single element in the data model for their distance from a separating element. Therefore the data model should be divided into storeys and the elements assigned correctly to their respective storeys. Elements that extend over several storeys should be assigned to these storeys with *IfcRelReferencedInSpatialStructure*.

Whether or not information on a connection relations, space boundaries or belonging to building storeys are available in the IFC data model depends, among other things, on the model view definition (MVD) selected. Additionally, the modeling software must be able to create the connection between the elements before the export. However, since these semantic information are not always present or of sufficient quality, a geometric analysis of the elements should always be performed. For this purpose, the elements must have a geometric representation from which a shape and a bounding box can be generated.

4.5. Summary of results

By defining the small distance between elements "close to", it was possible to identify flanking elements that do not meet the classic requirements of "touch" conditions from other research projects. Thus, inaccurately modelled junctions were successfully analysed, but also flanking elements that are planned with a slight distance to the separating element were taken into account. Then, the use of junction boxes enables the assignment of these flanking elements to a specific junction. The junction types were clearly defined using predefined areas on the surfaces of the components (connection zones). The application of additional information regarding the element direction completes the exact assignment to the types. By using a 4x4 matrix, the information could be stored and evaluated during the analysis.

This method shows that junction analysis can be done with a geometric analysis to fill in missing semantic information about junctions and connections of elements from the original data model. The building elements need to have a proper geometric representation from which bounding boxes can be derived. The goal was reached to recognise flanking elements and assign junction types using the element's positions in relation to one another. It also shows how important the consideration of junctions is for the acoustic analysis. Additionally, the implementation with multi-layer elements successfully determines the correct junction types. However, this analysis poses the challenge of recognising the load-bearing layer, if this is not explicitly written into the data model.

This work also demonstrates that the accuracy of the results provided by the framework are strongly dependent on the quality of the model. Elements in the data model must have the correct entity type to avoid processing every single element included in the model. Semantic relations of spaces and building storeys help to scan the model before the final analysis. The spatial conditions needed are building elements assigned to the correct floors, complete spaces, and continuous space boundaries. Space boundaries present an advantage, as the previously used definition from thermal insulation meets all requirements needed also for sound insulation analysis. This enables us to reuse these algorithms.

5. Discussion

The core of BIM information is described through the essential geometry, semantics, and basic topological relationships. Model healing provides means for enhancing the content of BIM models through the incorporation of domain-specific engineering knowledge [74], [75], [76]. Various approaches exists to enrich models [77] like using implied but not stored information, joining external data sources, including semantic web technologies [78], and many more [79]. Performing domain-specific analysis and calculations always demand numerous custom information. Hence, formally representing domain knowledge and inferring additional information through reasoning assists in confining the content of the exchanged models on the essential information.

The specification of design requirements is crucial, especially in the architecture, engineering, and construction (AEC) industry, as multiple disciplines are typically involved and each requires a special set of BIM content requirements. This is the main motivation behind multiple concepts, such as Levels of Development (LOD) and Levels of Information Need (LOIN). In the early stages, the degree of freedom decreases with the progression of the design process and the LOD gets higher. The proposed methodology in this paper incorporates the LODs for specifying the minimum BIM information required before performing the model healing for assisting acoustic analysis. As the LOD 300 is specifying the dimensions as well as the combination of material layers, using our methodology to explore the performance of the different combinations before finalizing this LOD would support making informed decisions. Once a decision is made, our methodology could be further used to evaluate the performance of the different junctions in more detail. This is particularly important in the case of timber construction as the different elements are typically prefabricated by machinery in a project-customized manner.

In this paper, acoustics analysis knowledge was formally represented by a set of junction types, which are then inferred through multiple topological reasoning rules. However, in multiple other domains and use-cases, model healing and such topological reasoning might not be sufficient to enhance the quality of the exchanged models and provide the necessary information. A recent example is the project proposal by buildingSMART for fire-safety [80] engineering, where practitioners demand including various additional information through the extension of IFC to support performing different kinds of design evaluations. Hence, the applicability of using model healing methodologies vary, depending on the use-case and requirements. Identifying these requirements needs both engineering knowledge as well as experience in the existing BIM data structures.

6. Conclusion and Future Work

Buildings made of sustainable materials such as timber construction can make a significant contribution to the conservation of resources, which is of great importance in view of the climate crisis. Since timber construction also means choosing a lighter construction method, new challenges arise, especially in building acoustics. Building acoustics, especially sound insulation, have a major impact on the usability of the final building.

Using an open BIM workflow to consider the sound insulation prediction in an early-planning phase, would reduce time, costs, and vulnerability to errors. Different solutions could be considered in consultation with fire protection, structural analysis, and other trades.

Furthermore, the detection of junctions from data models can be used for factory planning, which is relevant for structural analysis as well. The method presented for junction analysis will improve acoustic analysis tools that aim to import data models.

The contribution of this paper to the field of Engineering Informatics and Acoustic Engineering is to provide a BIM-based methodology for the automated recognition of complex element junction and for mapping them automatically to the standardized junction types. Doing so allows engineers a seamless workflow between design and acoustic analysis and allows them to evaluate more options in less time, resulting in an overall improved performance of the resulting building. The demonstrated use case has shown that embedding acoustic analysis in an early planning phase is possible using an Open BIM Workflow. In an optimal planning process in timber construction, many details are already known at this early stage due to the factory planning. Using the presented method, it was possible to identify and analyse junctions in a BIM model and to differentiate various junction types.

This work also demonstrates the challenges that arise from the analysis of data models. In this regard, the accuracy of the results provided by the framework are strongly dependent on the quality of the model. Elements in the data model must have the correct entity type to avoid processing every single element included in the model. In addition to the knowledge of the modeller, the possibilities of the modelling software to export IFC models play a decisive role here.

On a more general level, we want to emphasize the challenges that come along with the different information needs to be fulfilled by a BIM model resulting from the variety of analyzing tasks, including structural analysis, energy performance analysis and acoustic analysis among others. In this regard, we want to highlight that computing missing information from the model's geometry is a much better approach than forcing the modelers to manually input large sets of properties. This not only reduces laborious effort, but also allows to reduce redundancy in the model and thus contributes to its consistency.

In the next steps of our research the method will consider less common junction situations, such as asymmetric junctions between differently sized sending and receiving rooms. It must also be made possible to convert slightly offset flanking elements in accordance with ISO 12354-1 [11]. Finally, using all information created during the analysis, a technical model for acoustic analysis will be developed comprising the results. This technical model can be used if recalculation is needed or for documentation of measurement results later on.

The use of BIM in the planning process offers many opportunities to work in a time- and cost-efficient way. Whether or not these possibilities can be used depends largely on the technical options available to the planners and the degree of automation providing a higher degree of efficiency. Therefore, methods for the subject-specific analysis of data models must be developed as fast as BIM implementation is growing.

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