A proposed IFC extension for timber construction buildings to enable acoustics simulation

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ABSTRACT: More and more architects and planners are choosing timber in construction because of its sustainability. However, timber elements have low mass, consist of multi-layered structures, and require complex junctions which makes the design process and construction challenging. The design of the junctions influences the sound insulation quality of a building and affects the quality of life for the inhabitants. To save time and cost, the detailed information on junctions should be included already in the early phases of the design process. In this paper, we present an improved building information modelling (BIM) workflow for timber construction. We develop new entities, relations, and property sets with detailed information on junctions that can be included in a BIM model using Industry Foundation Classes (IFC). These improvements will allow the designers to incorporate an acoustic data model that forms the basis for further prognoses of the airborne and impact sound insulation already in early design phases which in turn will reduce time and cost, and improve the quality of the design and the overall design process.

1 INTRODUCTION

The sustainability of timber encourages practitioners and domain experts to choose timber in construction (Andersen et al. 2022), (De Araujo 2021). Various reasons make wood attractive for construction. Wood is often available in abundance in Europe; it does not have to be transported over long distances; the construction process is faster than concrete construction; wood has excellent thermal properties; and finally, wood is aesthetically pleasing – it feels, looks, and smells good (Sakuragawa et al. 2005), (Lowe 2020). However, timber construction is challenging for architects and engineers. Lightweight construction requires multi-layered elements which in turn make designing junctions a very complex process. Particularly challenging is to achieve proper sound insulation between neighboring spaces, as it has a direct impact on the perceived quality of the resulting building.

According to our analysis (Timpte 2016), there are fifteen types of junctions based on the number and types of elements and their geometric properties. The type of junction affects the flanking transmission of sound and therefore the overall sound insulation. Sound insulation is very important for the quality of living and working in buildings. However, designing junctions in timber construction requires specialized modelling, analysis, and evaluation tools. The current building information modelling (BIM) authoring tools as well as the neutral data model Industry Foundation Classes (IFC) do not include detailed information about the properties of junctions. This leaves the planning of junctions for the end of the design process, which often requires expensive and time consuming changes to the design (Kaufmann et al. 2019). This paper identifies and defines the relevant properties of junctions and, using IFC, incorporates them in the BIM workflow. The improvement to the BIM design process will shorten the design time and the automation of the process reduces the possibilities of errors. The improvements will in turn help timber construction to move from a niche area to a ubiquitous mode of construction.

The design process can make use of the open or closed BIM workflow. The advantage of the open BIM workflow is that different authoring tools can export vendor-neutral data exchange IFC format which are then used for specific design processes like structural, thermal or fire safety analysis. A data model based on IFC that includes the relevant information for a prognosis of the airborne and impact sound insulation (acoustic analysis) would improve the open BIM workflow significantly and enable the use of junction information for sound insulation prognosis in early design phases. To accomplish this, IFC models require further analysis to infer and identify missing junction information.

Additional input values for acoustic analysis are typically obtained from acoustical databases that contain values like the sound reduction index or the sound insulation level according to established standards (ISO 12354-1 2017), (DIN4109 2016). Different problems occurs in the use of databases with IFC models: the connection between the IFC models and databases are only possible via external references which need to be set manually by users, the import of values from databases into property or quantity sets require manual work, and the results of sound analysis can not be stored in the IFC model as no predefined acoustic property set exists for frequency-dependent values.

To address the identified limitations, this study has three goals. We define the requirements for a high-quality IFC model suitable for acoustics analysis, identify the relevant junction information and include it in the IFC model, and provide a path to save the acoustic analysis results in the acoustics IFC model. First we define the four aspects for IFC model quality required at different Levels of Development (LOD). We analyze the IFC data model to identify which information on junctions is missing and to design the classes of junction and transmission paths into the model. A high-quality IFC model allows us then to input the detailed junction information into the model. We use junction analysis to identify the junction parameters with which to enrich the acoustics IFC model. The basic information in the enriched model is used for acoustic analysis. After a prognosis is performed, the results can now be saved back to the acoustics IFC model (see Figure 1).

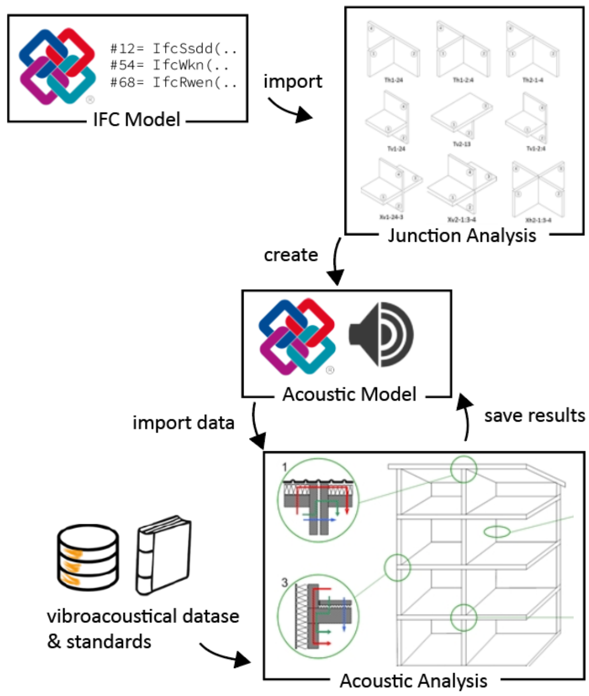

Figure 1: Optimized open BIM workflow for acoustic analysis in timber construction with junction analysis and a technical model

2 SOUND ANALYSIS IN TIMBER CONSTRUCTION

To understand the model requirements for acoustic analysis we need to look at the relevant parameters for the acoustic analysis. The first parameters describe the sound transmission. The sound 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 (e. g. walls and ceilings). 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 (only for slabs). In addition to the direct sound transmission, we need to consider the flanking sound transmission. In buildings, the separating element between the sending and the receiving room is linked to flanking elements, through which sound is also transmitted. This leads to different transmission paths as shown in figure 2. All parameters described are calculated according to the standard (ISO 12354-1 2017) and need to fulfill national requirements. The calculation and measurement should be done in frequency-dependent values ranging from 50 to 5000 Hz, in octave bands. Rated values are then derived for easier handling.

Flanking transmission plays a decisive role in lightweight constructions such as timber buildings. Flanking transmission is divided in flanking transmission paths which are characterized by the vibration reduction index K_{ij} and the normalized flanking level difference $D_{n,f}$. Equation 2 shows how the flanking sound reduction index R_{ij} is calculated, while Equation 3 indicates how the airborne sound insulation in situ R' is deduced, taking all flanking paths into account. A similar approach is used calculating the impact sound level of ceilings.

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

$$\begin{aligned} R_{ij} =& \frac{R_i + R_j}{2} + \Delta R_i + \Delta R_j \\ &+ K_{ij} + 10\lg \left(\frac{S_S \sqrt{a_i \cdot a_j}}{l_{ij} \sqrt{S_i \cdot S_j}} \right) \end{aligned} \tag{2}$$

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

For timber elements, the weight, the different shells, the insulation used, and the cladding and its fastening influence the sound insulation properties. This applies to all types of building components. In addition for slab elements, the dynamic stiffness of impact sound insulation and the properties of suspended ceilings are decisive (De Geetere and Ingelaere 2014), (Mecking et al. 2017).

Another factor, which influences the different transmission paths, is the junction design. The distinction between junction types is made to determine the correct vibration reduction index (Timpte 2016). Moreover, the fastenings in the junction, i.e. with screws, angles, or decoupled elements, affects the insulation performance (Morandi et al. 2018). In the standard (ISO 12354-1 2017) only a few junction situations are represented, but timber construction uses more types of junctions. Hence, the vibro-acoustical database from the Rosenheim Technical University of Applied Sciences (VaBDat) works with 15 different types of junction relevant for the transmission paths in timber construction (Timpte 2016). An excerpt of this types are shown in Figure 3. The junction types are needed for the sound insulation prognosis and therefore need to be specified in the data model used for planning purposes in the early design phase.

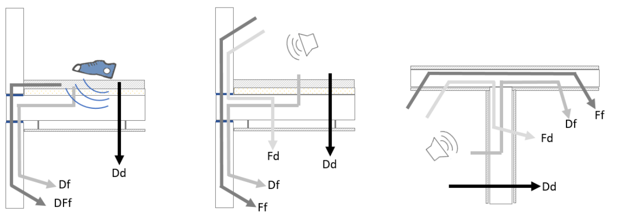

Figure 2: Sound transmission paths with the paths for flanking transmission Ff, Df, Fd, and DFf for the impact sound transmission of a ceiling (left), the sound insulation of a ceiling (middle) and the sound insulation of a wall (right)

3 REQUIREMENTS FOR IFC IN TIMBER CONSTRUCTION

The Industry Foundation Classes (IFC) (ISO 16739-1:2018 2018) is a vendor-neutral format to store element geometries and a large amount of semantic information. It is used for infrastructure and building construction planning. The use of IFC to forecast sound insulation would facilitate a seamless planning process between the different trades, modelling (architects and engineers), and simulation experts.

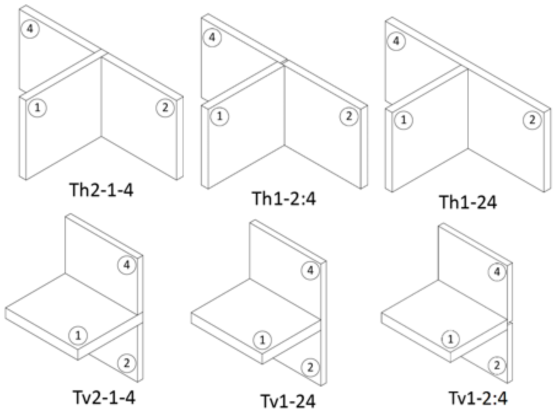

Figure 3: Excerpt of junction types for T-junctions between walls (above) and between walls and slabs (below)

3.1 *Model Quality*

In order to use an IFC model, it must contain the correct information in appropriate quality. There is no generally valid definition of quality for IFC models. In (Solihin et al. 2015), the model quality is defined according to fixed rules that apply to the use case. In (Preidel 2020) the quality of a model is defined by three levels: the raw data generated by the authoring tools, the content of the interpreted data (semantics and geometry), and the quality of the design regarding regulations, standards and guidelines as well as requirements from clients and best-practice from specialist domains. In (Wand and Wang 1996) the authors also state that the quality of the data depends on its use and name different criteria suitable to describe data quality: Complete, Unambiguous, and Meaningful.

We can apply the three criteria of model quality from (Wand and Wang 1996) to IFC models. A complete model provide all classes that are required to precisely describe the elements of a timber building. The IFC model for sound analysis requires entities for representation of the building elements and all entities required for spatial decomposition as well as shape representation. The second criteria for the data model is that it has to be unambiguous. Therefore, the most accurate entity possible should always be chosen. I.e. even if *IfcBuiltElement* is correct, *IfcWall* should be used for a wall. The last criteria for the quality of the data model is the meaningful model: The model should not have elements, that do not exist in the real building. Empty property set or attributes and relations that are not used specifically are not needed.

In this paper, we describe the quality and requirements of the IFC data model for the acoustic analysis. The IFC schema of buildingSMART is generic and flexible, so the rules mentioned here are meant to complement the schema. The criteria have been compiled by analysing different IFC data models that were created and used in during the research project.

3.2 *Specification for Timber Construction*

An accurate model is needed before any further analysis can be done. In timber construction the specialties that need to be addressed properly concerns multi-layered elements and framework constructions. Important points for the modelling process, respectively the IFC export, are:

- The spatial concept is complemented with *IfcReferencedInSpatialStructure* for elements going over more then one *IfcBuildingStorey*.

- All parts of an element like plates, studs, or insulation have to be aggregates of a main element using *IfcRelAgreggates*.
- Facing shells, floor structures, and suspended ceilings are modeles as *IfcCovering* and should be associated to their main element using *IfcRelAggregates*.
- Only main elements have relations to an *IfcBuildingStorey*, not their decomposition.
- Every main element needs a corresponding *IfcElementType* including the *IfcMaterialLayerSet* to define their structure semantically.
- All material layers are defined in the main element type with *IfcMaterialLayerSetUsage* relating to the *IfcMaterialLayerSet* of the element type.
- The material names in *IfcMaterial* should comply with the material database used for the analysis.
- The load-bearing layer should have the Category *LoadBearing* in their *IfcMaterialLayer*.

Some of the listed points are clarified in the next sections. First, a semantic differentiation between lightweight construction or timber frame elements and solid constructions is no longer feasible in IFC4 as the entities *IfcWallStandardCase* and *IfcWallElementedCase* are DEPRECATED. For elemented walls (or slabs), it is particularly important that a main element holds their individual parts together. Particularly in the case of more detailed planning, it can happen that individual element parts are modelled separately, e.g. separating the wall and facing shell or modelling plates and studs. However, these should always be combined into one main element. This also applies to roof elements, which should consist of an parent entity *IfcRoof* decomposed of *IfcSlab*s.

Another important point for a good model quality is to use the spatial structure correctly. Each element must belong to an *IfcBuildingStorey*. This holds even when elements span over multiple storeys. Every main element belongs to an *IfcBuildingStorey* and can be linked to other storeys with *IfcReferencedInSpatialStructure* if needed, e.g. for curtain walls. Additionally, every *IfcSpaces* has corresponding *IfcSpaceBoundaries* that are connected to space-enclosing surface like the *IfcCovering*. If needed, *IfcZone* complements the subdivision of the building by grouping *Ifcspace*s together.

The model quality also depends on the (geometric) details it is able to represent. The specification of suitable levels of development (LOD) is especially complex for timber framed elements and multi-layered elements. If one considers a wall with a free-standing facing shell, the use of element and material entities varies. At LOD 200 only one wall element with two material layers is needed. At LOD 300 we must have two elements, one for the wall (*IfcWall*) and one for the facing shell (*IfcCovering*) which are connected with *IfcRelAggregates* (as *IfcRelCoversBldgElements* is DEPRECATED since IFC4) and boths elements need information about material layer. Only with a LOD 350 a modelling of the stud frames is relevant and the material layer association remains the same as in LOD 300. In LOD 350 the *IfcWall* and *IfcCovering* additionally consists of individual element parts connected with *IfcRelAggregates*. The layer of the supporting structure with the studs and insulation is represent as *IfcElementAssembly* decomposed of various *IfcMember* with the predefined type *STUD* and *IfcBuildingElementPart* with the predefined type *INSULATION*. The layer with planking elements can be modelled as one *IfcPlate* with the correct material or with *IfcBuildingElement* with predefined type *PRECASTPANEL*. In LOD 400 all single plates need to be modelled separately.

The shape representation of the framing construction and the separate plates is only required in a higher level of development (LOD 350 and higher). In early design phases this information is not needed in so much detail. The information about the construction inside the layers is specified in the material entities *IfcMaterialLayer* and *IfcMaterial*. A layer with multiple materials can be described with *IfcMaterialConstituentSet*. However, the use of *IfcMaterialConstituentSet* is only available for description of windows or doors. It cannot be used in combination with *MaterialLayerSet* and is therefore not suitable for the representation of walls, slabs or similar elements.

In higher level of development, information about fasteners can be included. It should be mentioned that the representation of mechanical fastener is possible in IFC data models, but it should be used carefully as the information of cut-out parts and the modelling of fasteners highly inflates the amount of data. For the acoustical analysis this information is only needed for few applications and it is therefore enough to describe it semantically.

4 JUNCTIONS IN BIM MODEL

As described before, the identification and description of junction types is important for the sound analysis. In this section we define what a junction is and how it can be represented in data models. We will also describe how junctions and transmission paths belong together, and describe the properties belonging to both junction and transmission paths.

4.1 *Definition of Junction*

A junction is formed when at least two components meet. In the acoustic analysis, junctions are built with up to four different elements. Every junction has a common length l_{ij} of all elements where they form the junction. In (Timpte 2016), 15 different junction

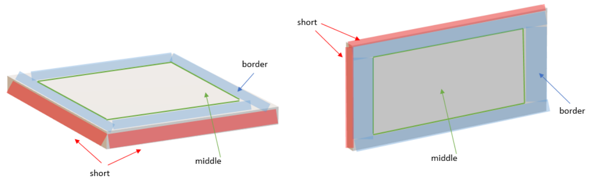

Figure 4: Connection zones for a wall and a slab: in red the zone *short*, in blue the zone *border*, in grey the zone *middle*

types where defined which are also used in the vibro-acoustical database VaBDat. These types are valid for timber construction in cross-laminated timber (CLT) as well as framework construction or others.

Considering the transmission of sound from one room (sending room) to another (receiving room), we see a separating element for the direct transmission. The junctions on each edge of this separating element are the connection of the separating element to the flanking elements.

Therefore, the junctions influence decisively the flanking sound transmission. The characterization of the junction is done with the vibration reduction index K_{ij}, which has different values depending on the type of the junction and the elements involved. For each junction it is important to know the separating element, the flanking elements and to identify the different transmission paths as shown in Figure 2. Another important information is the used fasteners like screws, angle brackets, elastic layers or similar.

4.2 *Analysis of Junction Types*

The difference of the junction types lays in the geometry of their core layer. This layer is the load-bearing layer. In massive timber construction like CLT, the layer with the massive timber is the core layer. In framed construction it is the layer with the supporting studs.

To find a junction in a BIM model, semantic information can be used to pre-filter the model. For example spatial composition like spaces, space boundaries or building storey give important information about the position of the separating element and it's possible flanking elements. Additionally, a geometric analysis measuring the distance between the elements helps find the correct flanking elements.

When the flanking elements are clearly defined, we subdivide all elements into three different zones and analyse in which zone they touch one another in the point of the junction. These zones are: a) the edge around a selected element called *short*, b) the border of the large surface called *border*, and c) the remaining part of the element called *middle* (see Figure 4). With this analysis, we have a matrix of reciprocal *touch* predicates, that defines the type of junction. A more detailed description of this method is provided in (Châteauvieux-Hellwig et al. 2021).

4.3 *Junction representation in IFC*

The IFC schema has limitations when providing input data for sound analysis. Especially junctions are only rudimentary supported in the schema with *IfcRelConnectsElements*. This definition is inaccurate when it comes to identifying the junction type, only because elements with a path definitions can be connected. This means that just wall-to-wall connections are possible. But slabs have no path description and its connection to other elements can not be represented.

Besides the limitation regarding the element types, *IfcRelConnectsElements* is limited in the number of possible connection. One entity always describes a connection between two elements. Therefore, to describe a junction with three elements we need three *IfcRelConnectsElements* relations and for a junction with four elements we need six relations. This is not an efficient way to describe junctions (especially in the case of timber construction). For example, a separating wall with four edges would need 12 direct *IfcRelConnectsElements* relations with their flanking elements and 12 additional relations between the flanking elements themselves, to describe a junction semantically. The latter are only known if every flanking element is queried for their connection relations too. This is a complex and error-prone query.

5 TECHNICAL MODEL FOR SOUND ANALYSIS

The technical model is the basis for acoustic analysis, calculations, and simulations. The authors define technical model as discipline-specific model that contains only model elements needed for a specific discipline or trades. The technical model for acoustic, or acoustic model, can store acoustical properties and save results of calculations and measurement. Even if the amount of information in a data model varies greatly according to the planning phase during which it was produced (Abualdenien et al. 2020), acoustic analysis requires minimum, in particular, the design of the junctions. The extent to which the IFC standard can contain this information is limited. Therefore, a separate junction analysis is required. How the junction is represented and the type of junction is generated is described in (Châteauvieux-Hellwig and Borrmann 2020) and (Châteauvieux-Hellwig et al. 2021).

5.1 *Junction Definition for the Technical Model*

As discussed before, the IFC schema is not able to represent acoustical junctions in a suitable manner. A first approach to defining junctions in IFC for the acoustic model was proposed in (Bodenschlägel et al. 2022) and (Lauschke 2021) with the help of existing entities. The junction was represented with an different *IfcVirtualElements* and with *IfcRelConnectsWithRealizingElements* to created the connection between the junction, the elements of the junction, and the Property Sets. This solution can be interpreted by some IFC viewers, but is only a temporary solution because it uses entities not according to their definition and a lot of entities are needed due to the restriction in their definitions. Thus, the authors of this paper propose that the schema is extended not only by Property Sets but also by additional entities for the junction and transmission paths and the relationship between both entities. Figure 5 explains how the entities *IfcJunction* and *IfcTransmissionPaths* should be used. A *IfcJunction* can aggregate multiple *IfcBuildingElement* and has the following attributes:

- *CommonLength* representing the common length of the element in the junction L_{ij} according to ISO 12354-1 as a single value.
- *JunctionType* describing the direction of the junction and the elements included in it according to (Timpte 2016) as label from a fixed enumeration.
- *RealizingType* illustrating the type of fastening devices used as label.

The relevant part of *IfcJunction* is the attribution of various *IfcTransmissionPaths* with a new relationship *IfcRelAccociatesPaths*. The transmission paths need to have an attribution of the elements i and j as defined by the ISO standard (ISO 12354-1 2017) and calculation presented in section 2. This association is shown in Figure 6 depicting a T-junction with three elements and all corresponding transmission paths.

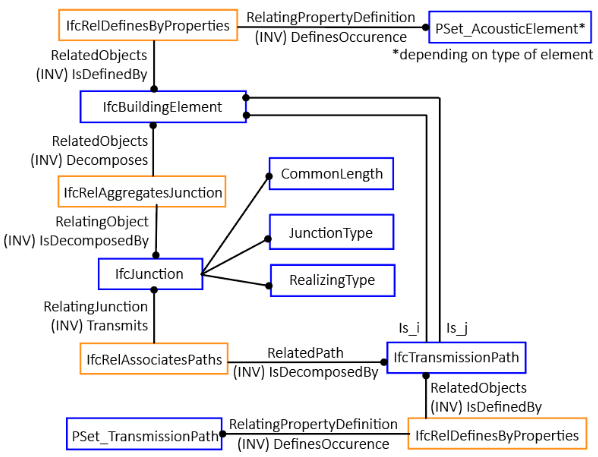

Figure 5: IFC schema extend by new entities to describe acoustic junctions

5.2 *Acoustic Properties*

Two different types of Property Sets to complement the IFC schema specification including acoustic characteristics are proposed. The first one is an acoustic Property Set for building elements like walls, slabs, and other *IfcBuiltElements*. The second set describes the properties of a transmission path. All properties

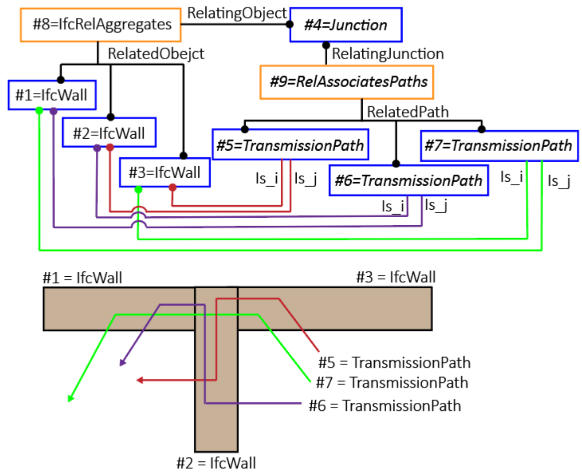

Figure 6: Example of a T-junction between 3 wall elements described with *IfcJunction* and all associated *IfcTransmissionPath*

represent information needed for the calculation of sound insulation results from those calculations and from measurements in the construction phase. Table 1 shows the different sets, describing for which element they are valid and which kind of values are saved. Additionally, the IFC schema (ISO 16739-1:2018 2018) allows different kind of values in property sets beneath *IfcPropertySingleValue* which is used to refer to a single value. *IfcPropertyBoundedValue* specifies an interval for a value, *IfcPropertyEnumeratedValue* refers to an enumeration of numeric or descriptive values, *IfcPropertyListValue* use an ordered list of values, and *IfcPropertyReferenceValue* use values of type of an resource level entity. The last way to describe value is with *IfcPropertyTableValue*. This property has a value range defined by two lists of (numeric or descriptive) values. It enables to use *DefiningValues* for the values of the third octave band in Hz and the *DefinedValues* for the sound insulation property in dB. With *IfcPropertyTableValue* we are able to store all 21 frequency-dependent values in third octave bands for all usual acoustic properties, or more if needed. Where those data come from is saved in the attribute *Origin* of the corresponding Property Sets.

5.3 *Acoustic Layers*

To properly assign the values of sound insulation R and of improvement of the sound insulation ΔR due to facing shells, floor screeds, coverings, or suspended ceiling, a clear division between the core layer and covering element is needed in the semantic of the model. An example with a slab is shown in Figure 7.

Another reason for the subdivision of the elements in different layers is the determination of the junction types. Here, the core layer is the one which defines the junction type and not the overall layers. An example of this is shown in Figure 8 with two kind of timber constructions. This emphasizes that the method developed in (Châteauvieux-Hellwig and Borrmann 2020) and (Châteauvieux-Hellwig et al. 2021) can be used

Table 1: Property Sets required for acoustic analysis

Pset	Elementtype	Symbol	Properties	Propertytype
AcousticElement	IfcWall, IfcSlab, IfcDoor, IfcWindow, IfcCovering, IfcRoof IfcCurtainWall	R_w	SoundReductionSingle	single value
		R_d	SoundReduction	table value
		m'	SurfaceRelatedMass	single value
		f_0	Eigenfrequency	single value
			Origin	label
AcousticImpact	IfcSlab, IfcFloor, IfcCovering, IfcRoof	$L_{n,w}$	ImpactSoundSingle	single value
		$L_{n,d}$	ImpactSound	table value
			Origin	label
AcousticImprovement	IfcCovering	ΔR_w	SoundReductionImprovementSingle	single value
		ΔR	SoundReductionImprovement	table value
		$\Delta L_{n,w}$	ImpactSoundImprovementSingle	single value
		ΔL_n	ImpactSoundImprovement	table value
			Origin	label
AcousticPath	TransmissionPath	K_{ij}	VibrationReductionIndex	table value
		$D_{v,ij}$	DirectionAvrVelocityLevel	table value
		R_{ij}	FlankingSoundReduction	table value
		$L_{n,ij}$	FlankingImpactSound	table value
			Origin	label

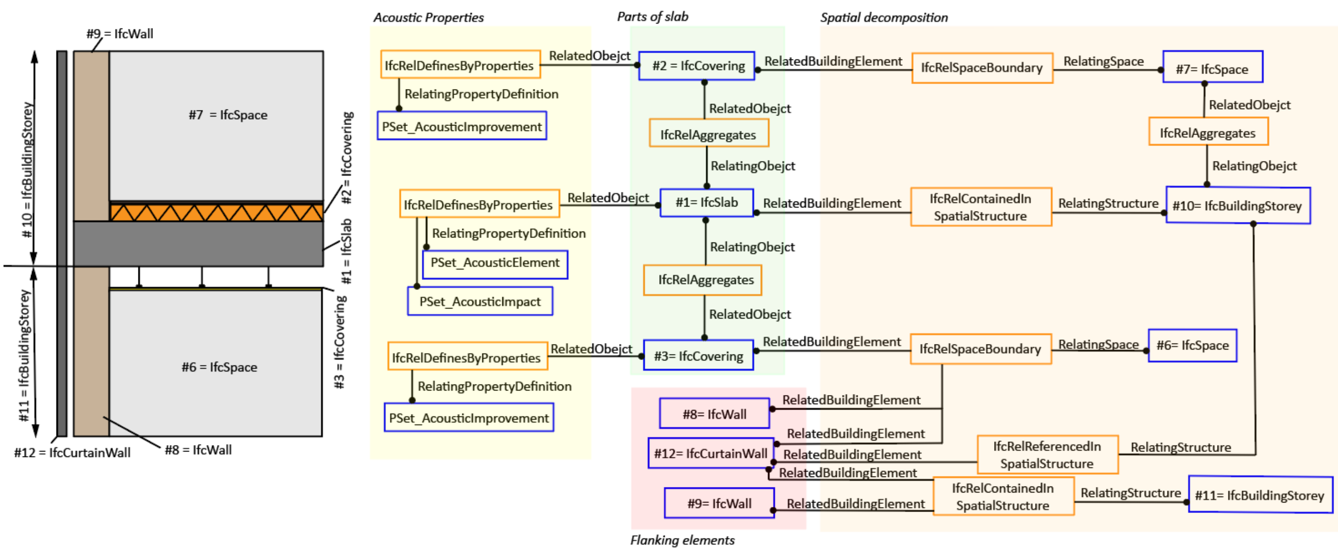

Figure 7: IFC Schema correctly describing a slab element with floor and suspended ceiling with their corresponding Property Sets for acoustical analysis, their flanking elements, and the spatial decomposition

for both timber frame and solid wood constructions.

6 CONCLUSION

Industry Foundation Classes (IFC) used in the building information modelling (BIM) workflow lack the detailed information required for the modeling of junctions which causes costly delays in the design process. This paper introduces new entities to improve the technical IFC model. The improved model includes the *IfcJunction*, *IfcTransmissionPath*, and the relation *IfcRelAssociatesPaths* which contain the detailed information on junctions: type?Intro?. The detailed information on junctions in IFC can be used for acoustic analysis and sound insulation prognosis from the early stages of the design process. The results of

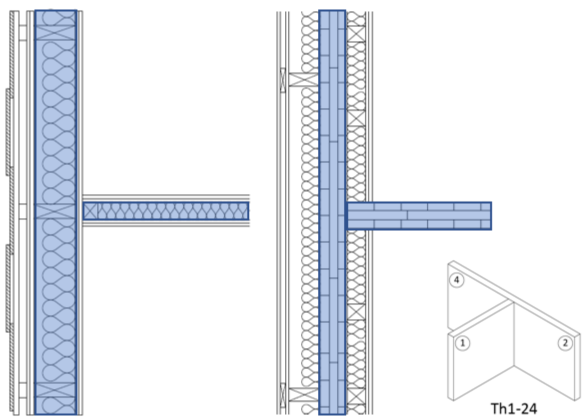

Figure 8: Example of junction types depending on the core layer for an T-junction between two walls with framing stud walls (left) and elements of cross-laminated timber (right)

the calculations can now be saved in the technical IFC model and used in further optimization processes. The digitized process accelerates the planing and the construction of a building, reduces errors, and is cost effective.

The improvements to IFC presented in this paper demonstrate the high potential of IFC for sound analysis. The improved IFC model can be incorporated into an open BIM workflow to facilitate the complex design process of timber construction. In the next step, the developed technical model can be used for vibro-acoustical simulations with SEA and FEM. This would just require additional relevant properties like the dynamic stiffness of elements. Similar improvements to the IFC model can also be designed and applied for other building physics analyses. In technical terms, the improvements are minimalist extensions that reuse existing elements to the greatest extent possible which makes the new IFC model very user friendly.

The improvements of the IFC technical model are not only complex, but they do not come without some practical limitations. The practical application of the improvements to the IFC schematic will require complex changes to the original IFC and undergo the complete normative process. While the similar approach can be applied to develop technical models for the different trades of building construction having an individual model for each area would result in an unnecessarily overblown and cluttered IFC files. A solution would be a single technical model for building physics that combines different aspects that can use synergies as some aspects have the same modelling requirements, e.g. the spaces defined for acoustic analysis can also be used for thermal analysis.

This paper presents the improvements to the IFC technical model that provides the bases for acoustic planing process in timber construction. This approach makes the design process more efficient, reduces cost and time, and makes the sustainable timber construction more approachable.

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