A meta-model approach for formal specification and consistent management of multi-LOD building models

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Abstract

The design of a building is a collaborative process among experts from multiple disciplines. Using Building Information Modeling (BIM), a model is developed through multiple refinement stages to satisfy various design and engineering requirements. Such refinements of geometric and semantic information are described as levels of development (LOD). Thus far, there is no method to explicitly define an LOD's requirements nor to precisely specify the uncertainties involved. Furthermore, despite the insufficient information in the early design stages, a BIM model appears precise and certain, which can lead to false assumptions and model evaluations, for example, in the case of energy efficiency calculations or structural analyses. Hence, this paper presents a multi-LOD meta-model to explicitly describe an LOD's requirements, incorporating the potential fuzziness of both, geometric and semantic information of individual elements. The explicitly defined fuzziness can be taken into account when applying simulations or analyses for assessing the performance of different building design variants. To support the continuous elaboration of a building from the conceptual to the detailed design stages, the multi-LOD model makes it possible to ensure the consistency of the geometric and semantic information as well as the topological coherence across the different LODs. The feasibility of the approach is demonstrated by its prototypical implementation as a web-server and user-interface, providing a means for managing and checking the exchange requirements both at the meta-level and for concrete building model instances. The paper is concluded with a case study of a real-world construction project that demonstrates the use of the meta-model to support model analysis and the decision-making process.

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1. Introduction

The Architecture, Engineering, and Construction (AEC) industry is a collaborative environment that requires an iterative and cooperative exchange of information models [1]. For example, developing a structural design requires architectural design information as input. At the same time, the design of the HVAC system has to be coordinated with the structural system to take into account the required voids in slabs and structural members. In this collaboration, the information quality, such as compliance with regulations and analysis requirements, is essential for exchanging, coordinating and integrating the partial designs at various stages. A building design evolves through multiple stages, each of which is characterized by a set of consecutive and calibrated actions to satisfy the different design and engineering requirements.

Building Information Modeling (BIM) is a well-established methodology for cross-disciplinary building design based on the creation, management, and exchange of semantically rich 3D-models [2]. Recently, BIM has been increasingly adopted by the AEC industry [3] because it improves the process' efficiency and quality by promoting the early exchange of 3D building models. Through the stages of a construction project, the building model is gradually refined from a rough conceptual design to highly detailed individual components. The Level of Development (LOD) describes the sequential refinement of the geometric and semantic information by providing definitions and illustrations of BIM elements at the different stages of their development [4, 5].

The decisions made throughout the design stages, especially the early ones, steer a project's success and results [6]. The impact of the decisions made in the early design stages (conceptual and preliminary stages) is significant, as they form the basis of the following stages [7, 8]. In these stages, the uncertainty on how the design may evolve is high, as many decisions have not yet been made [9]. Hence, several researchers have emphasized the advantages of integrating performance simulations early by incorporating the information uncertainty [10, 11].

However, a well-reported gap exists between the predicted and actual building performance [12, 13]. One reason for this gap is the lack of information, where the practitioners quantify uncertainties in the model's inputs, such as geometric and material attributes, using information from literature, experience, or default values [14, 13]. Therefore, at every stage, the required information along with its uncertainties must be defined and communicated to the project participants to alleviate the uncertainties' impact on the simulation results and improve the quality of the decision-making [15].

The focus in the early stages is on the building's overall structural system, outer form, and interior organization [16, 7, 10]. Presently, a wide range of model-based planning techniques is available. However, these tools require extensive input data and produce too detailed designs, even in the early stages [17]. A BIM model appears precise and certain, which can lead to false assumptions and model evaluations, as in the case of energy efficiency calculations or structural analysis, which affects the design decisions made throughout all design stages [18, 19, 20]. Hence, these tools are not adequate to support the early stages or to preserve the building model's consistency from the conceptual design to the detailed design [21, 22, 8]. Additionally, the current LOD definitions are informal, textual definitions and graphical illustrations that do not incorporate potential uncertainties.

Within the scope of the research unit MultiSIM (FOR2363)[1], which is funded by the "Deutsche Forschungsgemeinschaft" (DFG), we aim to develop methods for evaluating building design variants in the early design stages. The variants may have different LODs as well as incomplete and uncertain information. The main approach focuses on providing:

- Consistent management of multiple LODs during the design stages
- Description of the information uncertainty
- Consistent management of design variants
- Support for model analysis at the early design stages
- Evaluation of design variants based on simulation results
- Improved communication between the domain experts

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[1] https://for2363.blogs.ruhr-uni-bochum.de

To provide a foundation for managing multiple LODs for BIM models, we propose developing a multi-LOD meta-model that explicitly describes the LOD requirements of each building component type, taking into consideration the potential uncertainties.

The multi-LOD meta-model introduces two levels, the *data-model level* and *instance level*, which offers high flexibility in defining per-project LOD requirements and facilitates the formal checking of their validity, such as defining and checking the required information to support the Life Cycle Assessment (LCA) at different design stages.

This paper discusses the advantages of representing the uncertainties during early design stages and highlights the benefits of systematically managing and checking exchange requirements between disciplines. In order to ensure the model's flexibility in handling different component types and applicability in supporting real-world data produced by different BIM authoring tools, its realization is based on the widely adopted data model Industry Foundation Classes (IFC). The IFC model specification is an ISO standard that is integrated into a variety of software products [23].

The paper is organized as follows: Section 2 describes the methodology used in this research and Section 3 discusses the background and related work. Section 4 provides an overview of the multi-LOD requirements and describes the design concepts, and Section 5 presents the meta-model design. A methodology for checking the refinement consistency across LODs is proposed in Section 6. In order to evaluate the multi-LOD model and the methodology proposed here, a prototypical implementation is discussed in Section 7 in terms of usability and potential integration in the design process. Finally, Section 8 presents a case study for applying the proposed approach on a real-world construction project, and Section 9 summarizes our progress hitherto and presents an outlook for future research.

2. Research method

This is an exploratory research study that seeks to find a solution to the current lack of methods for formally describing the design information fuzziness allowed (or provided) at a given LOD. The outcome is a novel building information representation concept based on the meta-model paradigm. This concept facilitates the formal checking of the refinement consistency of the building components across multiple LODs, overcoming the error-prone manual processes prevalent in the design practice today.

The research was based on a comprehensive literature review of the information management in the early design stages and the decision-making processes. The review covered different aspects, including common practices in the design process, the available information at the early stages, and the current support provided by existing standards and tools.

Based on the knowledge gained from this literature review and the identified gaps, the contribution of this paper is as follow:

- A multi-LOD meta-model for defining the component types' LOD requirements, incorporating the potential uncertainties, in a formal manner. The multi-LOD meta-model provides the means for defining project-specific requirements and facilitates the modeling of information uncertainty
- An Extension of the BIMForum's LOD specification to support the nature of the early design stages by facilitating the estimation of information at an earlier stage
- A new concept, *Building Development Level (BDL)*, is introduced to describe the maturity of the overall building model. A BDL can be conceived as a milestone where specific decisions need to be made. At the same time, each BDL can be used by engineers to specify the required building elements and their maturity to carry out a model analysis
- A methodology is proposed to check the refinement consistency of the geometric, semantic, and topological information across the BDLs

The aim of the proposed approach is to improve the communication and collaboration between the different disciplines as well as to ensure compliance with the design decisions made at previous stages. The approach's feasibility was evaluated by means of a real-world construction project. The information analysis and the evaluation results of the building model throughout the early stages are presented as a case study in Section 8.

3. Background & related work

3.1. Information uncertainty

Information uncertainty is complex, multidimensional, and has many interpretations. The terms uncertainty, fuzziness, and vagueness are used in various domains and application contexts [24]; most commonly, uncertainty is an umbrella-term that describes a lack of knowledge or information, causing the occurrence of an uncertain future state [25]. On the other hand, fuzziness, as a synonym for vagueness, is related to a specific state of a specific object, and it refers to having imprecise or inaccurate information [25, 26]. In the context of Computer-aided design (CAD) modeling, Steinmann [7] described fuzziness as the distance from the complete and exact description.

In this paper, uncertainty represents the unknown variables affecting design variants and their fulfillment of the project's requirements and objectives. Accordingly, defining these variables can lead to fundamental changes to the proposed design, like changing the overall building's shape, increasing its height to add a new storey, or changing the internal spatial structure. Fuzziness is related to the reliability of the building elements' attributes and their refinement through the LODs, for example, the load-bearing components' exact position and the external walls' openings percentage.

3.2. Level of Development (LOD)

The LOD concept is employed to describe the development of a digital building model through the different stages of the building life-cycle. It formalizes the progressive nature of the design process, which enhances the quality of the decisions made [5].

In most approaches, the individual levels of development are described by means of (informal) textual definitions and graphic illustrations for various building elements. Together these definitions represent the required information quality, i.e. reliability, preciseness, and completeness. A good example are the definitions provided by the American BIMForum [4], which are updated in a yearly cycle to provide a common understanding of the expected information at every LOD. In the course of a construction project, the LOD scale increases iteratively from a coarse level of development to a finer one, where additional object attributes are provided or specified more accurately.

Different information is required by the project participants at every stage to design and perform their analysis [27]. The LOD concept facilitates defining BIM-based exchange requirements throughout the design process. The American Institute of Architects (AIA) introduced a definition of the term LOD that comprises five levels, starting from LOD 100 and reaching LOD 500. The BIMForum working group developed LOD 350 and published the *Level of Development Specification* based on the AIA definitions [4].

The first level, LOD 100 (conceptual model), is limited to a generic representation of the building, meaning, no shape information or geometric representation. The second level, LOD 200 (approximate geometry), consists of generic elements as placeholders with approximate geometric and semantic information. At LOD 300 (precise geometry), all the elements are modelled with their quantity, size, shape location and orientation. Next, to enable the detailed coordination between the different disciplines, such as clash detection and avoidance, LOD 350 (construction documentation) is introduced, where it includes the interfaces between all the building systems. Reaching LOD 400, the model incorporates additional information about detailing, fabrication, assembly, and installation. Lastly, at LOD 500 (as built), the model elements are a field verified representation in terms of size, shape, location, quantity, and orientation.

The authors of the BIMForum specification have confined their LOD definitions to describe the maturity of the elements inside the building model. This means that it is not applicable to describing the overall building maturity, which is what the BDL concept proposed here addresses; in their words:

> "There is no such thing as an 'LOD ### model.' As previously noted, project models at any stage of delivery will invariably contain elements and assemblies at various levels of development" [4]

Besides the BIMForum's definitions, several guidelines have been proposed in an attempt to define the available graphical and non-graphical information at each LOD. The US Department of Veterans Affairs (VA) has published a comprehensive spreadsheet, the *Object Element Matrix*, that provides a list of the expected LOD attributes for the building components throughout the building life-cycle [28], which encourages the concept applicability in the industry. This spreadsheet was adopted by the Australian's NATSPEC National BIM Guide [29].

In the UK, the *Level of Definition* [30] has been introduced. It consists of seven levels and introduces two components: Levels of model detail, representing the graphical content of the models, and Levels of model information, representing the semantic information. The Danish definition includes seven *Information Levels* that correspond roughly to the traditional construction stages [31].

In practice, knowing when a building model is at a specific LOD is crucial since it is depicted as a milestone for performing new tasks using newly defined information. However, the current LOD definitions are informal and imprecise, bring only textual and graphical, which leads to multiple interpretations and opinions regarding the expected information at each level. Furthermore, even at early design stages, BIM authoring tools produce too detailed designs. Hence, precisely defining the LOD requirements incorporating their uncertainty improves the quality of the collaborative process among the disciplines.

Recent approaches propagate the terms Level of Information (LOI) and Level of Geometry (LOG) to clearly distinguish semantic from geometric detailing grades [32]. In this paper, the abbreviation LOD stands for the Level of Development comprising both the Level of Geometry (graphic-oriented) and Level of Information (semantics, non-graphic-oriented).

3.3. Refinement of LODs

Multiple efforts have been conducted for describing the LODs' refinement throughout the project's life-cycle. The main idea is the attempt to represent and formalize the model maturity, either by explicitly defining relationships or by controlling the amount of added details within an LOD, which makes it possible to check the model's consistency.

Biljecki et al. [33] argue that five LODs are not enough to capture the building model's development, as the information ambiguity is high. Thus, they restrict the LODs refinement by allowing less specification and modeling freedom using a set of 16 stages. Similarly, Van Berlo and Bomhof [31] looked into producing a more suitably refined set of LODs for the Dutch's AEC industry, they developed seven LODs after performing multiple geometric tests and analyzing the industrial practices.

From another perspective, Borrmann et al. [34, 35] presented a methodology for creating and storing multi-scale geometric models for shield tunnels by explicitly defining the dependencies between the individual levels of detail. For this purpose, a multi-scale product model is developed, including a geometric-semantic description of five levels; the levels 1-3 describe the outer shell in terms of the boundary representation of the tunnel volume, boundary surface as well as openings, and the fourth level includes the modeling of the tunnel's interior structure. It is shown how the LOD concept can be integrated into the IFC data model. In order to model the relationship between the different levels and maintain their aggregation, a new relationship class *IsRefinedBy*, a subclass of Aggregates, is introduced. The proposed multi-scale model makes use of the parametric modeling techniques to preserve the consistency among the different levels of detail by interpreting and processing the procedural geometry representations. Consequently, the change of a geometric object is propagated by updating all the dependent representations.

3.4. Interoperability

The design and construction of a building is a collaborative process that incorporates multiple disciplines. Each expert, such as the architect and structural engineer, uses different authoring tools and requires specific information to be present in the model to support a particular type of simulations and analysis. With the increasing specialization of the stakeholders, the building industry requires a high level of interoperability, which is deficient. The US national institute of standards and technology [36] as well as many researchers and case-studies [37, 38, 39] have confirmed the difficulties and high annual costs resulting from the lack of interoperability between the AEC industry software systems.

The Industry Foundation Classes (IFC) schema [40] is an open data exchange format promoted by buildingSMART for interoperability within the AEC industry. It aims to define a common interface for lossless geometric as well as semantic data exchange. IFC is a free vendor-neutral standard and includes a large set of building information representations, including a variety of different geometry representations and a large set of semantic objects modeled in a strictly object-oriented manner. To allow for dynamic (schema-invariant) extensions and adaptation to local or national requirements, the IFC data model provides the PropertySet (PSet) mechanism, which relies on dynamically definable name-value pairs.

Besides exchanging data using IFC, dealing with different kinds of building information, e.g. property sets and definitions, requires a standardized terminology. Thus, the buildingSmart Data Dictionary (bsDD) [41] was developed as a central repository that stores multilingual definitions of the IFC entities and common schema extensions, for instance, an *IfcWall* entity description and *Pset_WallCommon*. Additionally, bsDD integrates multiple classification systems, including *OmniClass* [42] and *UniClass* [43], which are widely adopted for structuring the building information. Each object in the dictionary is identified by a Globally Unique ID (GUID) which makes it computer-readable and independent from the object name and language [44].

As the IFC data model is too large for software vendors to be fully implemented [45], buildingSMART developed the Model View Definition (MVD) mechanism as a standard approach for IFC implementation. An MVD represents a subset of the IFC schema that specifies the requirements and specifications of the exchanged data between the involved software tools [46]. In order to ensure the exchanged data completeness, the required information for each discipline scenario needs to be documented and defined as computer-executable rules [47]. Hence, MVD and the associated open standard mvdXML [48] can be used to structure the exchange requirements with specific IFC types, entities, and attributes [49].

In order to facilitate the collaboration between multiple disciplines, multiple vendor-specific [50, 51] and IFC-based [52] BIM server technologies as centralized platforms have been introduced. As for IFC-based servers, the open-source BIMserver, developed by TNO and the University of Eindhoven [52], is becoming a popular solution among researchers, as it is open-source, free of cost and provides a high degree of flexibility [53]. It simplifies the storage, sharing, and management of IFC models through a set of extendable features, including versioning, visualization, and filtering. BIMserver parses IFC data and stores it in a relational database for later manipulation of model information, such as merging and querying. Furthermore, it is capable of generating up-to-date IFC files.

So far, the IFC data model supports neither the notion of LOD nor a description of its uncertainty. However, as it is a very widespread and well-established format, we will show how an external meta-model can be used to enrich IFC data by these aspects.

4. Multi-LOD meta-model

The early design stages involve the selection among variant designs and the determination of costs, forming the basis of the following stages [7, 8]. In these stages, the efforts and costs required to make changes in a building model are lower than in the subsequent stages [54]. However, the lack of adequate information impedes informed decision-making. Hence, it is crucial to maintaining the individual component's LOD requirements. Especially in the process of designing a building, the components are associated with diverse levels of development within the same stage. For example, load-bearing components can be described with a higher LOD than the interior fittings in the early design stages.

Currently, there is no approach for formally defining and maintaining multiple levels of development of a building information model as well as incorporating its information uncertainty. The developed building models throughout the design stages are decoupled and appear detailed as well as certain, even in the early stages. This can lead to false assumptions and model evaluations that affect the design decisions made throughout all design stages. To fill this gap, the authors developed a multi-LOD meta-model that allows for and supports the following activities:

- Define the building model's requirements at multiple design stages
- Define component types' LOD requirements
- Model the information fuzziness
- Represent a building model of multiple stages
- Describe the relationships between LODs
- Check the consistency across the design stages

To manage the requirements of the individual building component types for a specific LOD, a component type is associated with multiple LOD definitions. An LOD definition consists of two separate groups: one for defining the geometric representation and alphanumerical attributes, and another for specifying the semantic alphanumerical attributes. This separation helps to achieve and maintain the semantic-geometric coherence of the overall model [55, 56]. Finally, the building model is presented by multiple instances of the defined component types.

4.1. Design process in the early design stages

At the beginning of a building project, designers capture the main intent by producing spatial models as variants, providing an overview of different solutions (a.k.a early design exploration [57]). The early design stages are characterized by a large number of abstract design concepts. Each of the developed concepts consists of three main aspects: the structural system (construction-oriented), the outer form and the building's facade (shape-oriented), and the organization inside the building (functionality-oriented), including the required rooms, their dimensions, and relationships [16, 7]. Accordingly, these aspects within the developed variants are evaluated in terms of fulfilling the owners' requirements, building performance, and cost. Once a variant is selected, its geometry and semantics are gradually detailed. To check the consistency of the assumptions and decisions made in the conceptual design, the building information, as well as the potential fuzziness, must be captured.

The meta-model approach itself provides maximum flexibility and supports any kind of country- or project-specific LOD definition. In this paper, we use the BIMForum's definitions (LOD 100 – 500) as a basis, while diverging by introducing intermediate LODs, LOD 150 and 250, to better support the early stages of design. This way, the model's refinement is captured in minimal steps, which assists in developing consistent models.

Additionally, as the focus in the early stages is on the organization of the building as a whole, considering various functional and interrelated entities, it is essential to follow clear guidelines in describing the expected elements to be present in the building model as well as their maturity, i.e. LOD, at a particular stage. As the BIMForum's specification is not applicable for this purpose, we introduce a new concept, *Building Development Level (BDL)*, to describe the overall building refinement in five levels (BDL 1 – 5), as illustrated in Figure 1 and described below:

- *BDL 1*: The building is represented as a 2D site plan bounded by outlines of the external walls, without any geometric representation. In this level, information about the building usage, in addition to an estimated orientation and position is available. Additionally, the boundary conditions, such as side-way limitations, are considered.
- *BDL 2*: The building's height can be estimated, therefore, we can model the building's 3D volume. Here, information about the building foundation and external components' midsurfaces becomes available. Accordingly, the building's overall space is estimated.
- *BDL 3*: Information about the structural system, construction type, and the material is available. The building mass is divided into individual storeys, providing information about the number of storeys as well as the height and usage of each storey. As a result, the space of each storey is identified. Here, load-bearing components can be defined, usually represented by axis and grids.
- *BDL 4*: A more precise definition of the interior structure is modeled,

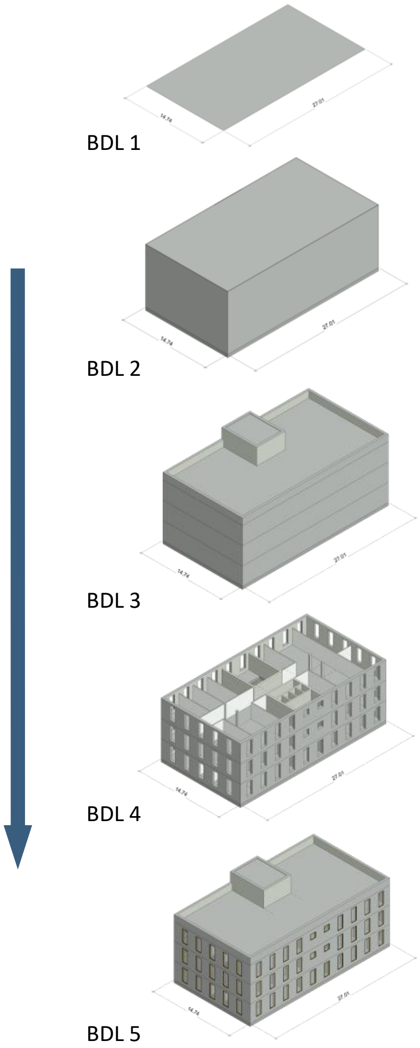


Figure 1: Refinement of building model at early design stages using the proposed Building Development Level (BDL) scale

which leads to a definition of the internal spaces. In this level, the percentage of the openings and an estimated load can be specified.

- *BDL 5*: A more precise material, construction type, load, and layer structure of building components is provided. The components can be represented by solids that provide a detailed geometry description.

The BDL concept describes the information quantity and quality with regard to the design process of an entire building model. A building model at a certain BDL comprises components with diverse LODs; for example, BDL 4 requires external walls in LOD 250, interior walls in LOD 150, and structural columns in LOD 300. This approach directly reflects the current BIM-based design practice [58].

In the context of the presented research, the primary goal of specifying the development of building design is to explicitly describe the maturity (or inversely, the uncertainty) of the information (both geometric and semantic) provided. This allows for the use of analysis and simulation tools to already assess a building's performance in the early design stages while preventing the false impression of high accuracy through the consideration of the fuzziness.

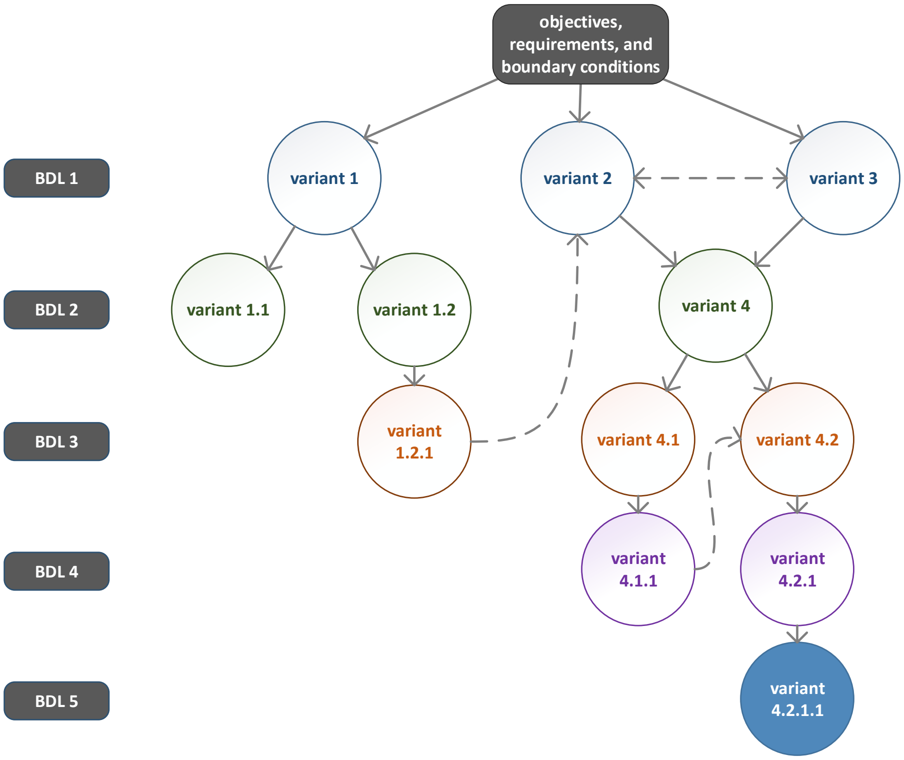


Figure 2: Development and selection of design variants during the early design stages (the BDL levels represent the detailing of the selected building model). This process is derived from the experience our research group has gained from the case study presented in Section 8

To illustrate the design process during the early stages, Figure 2 depicts the process of finding good building design solutions. The architect introduces different concepts based on the information available at every building development level by producing multiple variants. Subsequently, the project participants evaluate the proposed variants in terms of fulfilling the project's requirements. As a result, a design is selected or a new variant is proposed as a foundation for the next stage. The developed variants are evaluated iteratively until a consensus about the best solution is reached. In case not all requirements are satisfied after detailing a design, the process is repeated for a different variant. In Figure 2, *variant 1* was developed until BDL 3, but as it did not satisfy all the requirements, the project participants evaluated the other variants and proposed *variant 4* for the next stage. The process continued until they agreed that *variant 4.2.1.1* is a suitable solution for this project.

4.2. Geometric - semantic properties and fuzziness

The multi-LOD meta-model aims to maintain a clear separation between the building components' semantic and geometric requirements. In terms of the geometric representation of a building component, it is refined along with increasing the level of development. For example, as demonstrated in Figure 3, in LOD 100 an external wall's position can be estimated, therefore, it is presented as a *centerline*. Since in the next LODs additional information is available, such as a thickness and material, it is possible to render the wall's *solid* model in its 3D shape and dimensions. This kind of hierarchical development of a *centerline* towards a *solid* model defines the dependencies between the geometric representations at the different levels of development. Accordingly, the relationships between the semantic requirements are determined, which supports the checking of the consistency between the LODs.

By incrementing the LOD, additional information becomes available; for example, the construction type and material can be determined from LOD 200. In some cases, it is uncertain whether a specific property is available or can be estimated at a specific LOD. Thus, the multi-LOD meta-model provides the ability to specify whether a property is mandatory or optional and offers a level of accuracy in specifying the property's assigned value in case of uncertainty. The level of accuracy in assigning the attribute's value is related to its type; it might be achieved by specifying an abstract value, such as a classification category, or a fuzziness range. With that said, it is

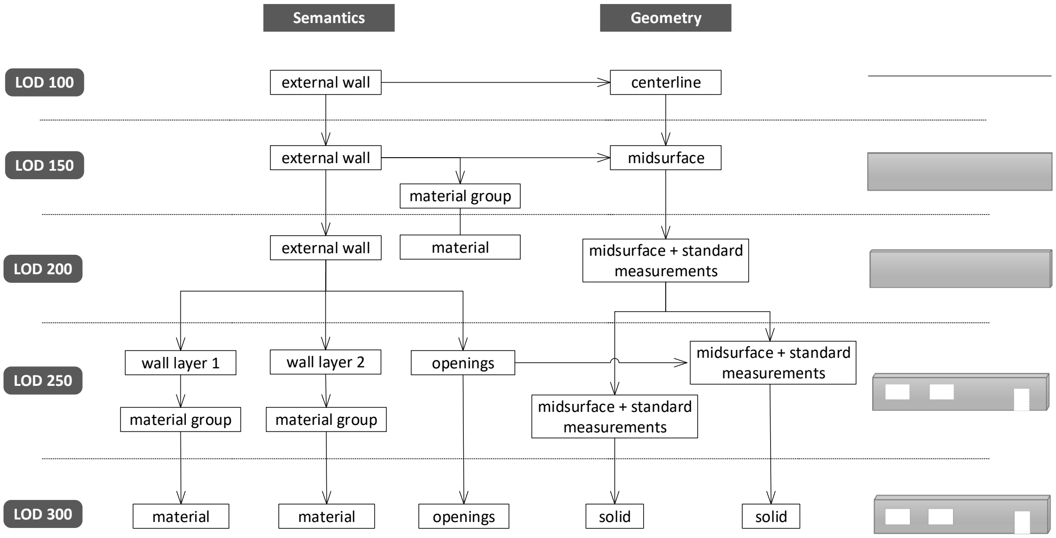


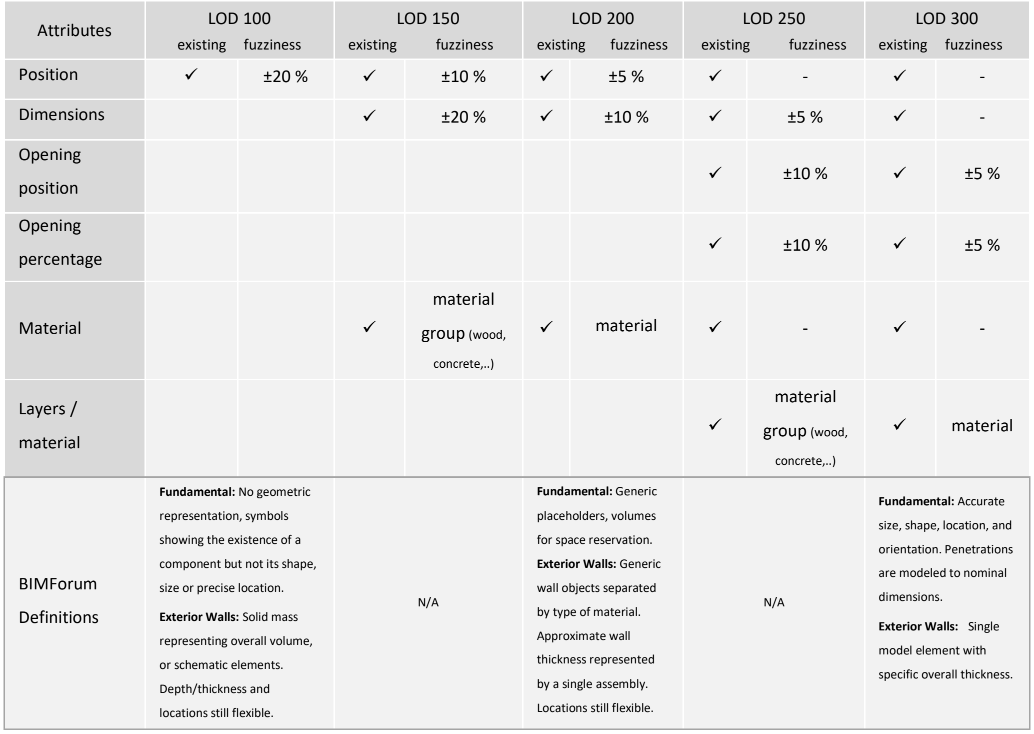
Figure 3: Separation of geometry and semantics at different LODs of an external wall, emphasizing the component types' refinement across the LODs

possible to model and analyze the known uncertainties of the building model at the early design stages where uncertainty is at its highest.

Figure 4 provides an example of the available attributes for an *External Wall* from LOD 100 to 300. The available BIMForum's definitions for each LOD are listed, which explains our interpretation with respect to the early stages. The BIMForum LOD specification provides a fundamental definition of each LOD that applies to all component types, and then it lists more specific definitions for each component type.

As Figure 4 exhibits, at LOD 100, the BIMForum's fundamental definition states that the components have no geometric representation and their existence can be represented as symbols with no shape or precise location. Whereas, the exterior walls' detailed definition assumes that a wall and its dimensions can be represented by a solid mass with flexible thickness and location.

Considering the early design stages, when modeling an external wall in LOD 100, the building model is at BDL 1, i.e. the main focus is on defining the building's boundaries, orientation, and side-way limitations. Hence, it is beneficial to estimate the wall's position, as it is important to provide a solution at this level. However, modeling additional information, such as the wall's overall volume and dimensions, would wrongly suggest that the design



Attributes	LOD 100		LOD 150		LOD 200		LOD 250		LOD 300	
	existing	fuzziness	existing	fuzziness	existing	fuzziness	existing	fuzziness	existing	fuzziness
Position	✓	±20 %	✓	±10 %	✓	±5 %	✓	-	✓	-
Dimensions			✓	±20 %	✓	±10 %	✓	±5 %	✓	-
Opening position							✓	±10 %	✓	±5 %
Opening percentage							✓	±10 %	✓	±5 %
Material			✓	material group (wood, concrete,..)	✓	material	✓	-	✓	-
Layers / material							✓	material group (wood, concrete,..)	✓	material
BIMForum Definitions	**Fundamental:** No geometric representation, symbols showing the existence of a component but not its shape, size or precise location. **Exterior Walls:** Solid mass representing overall volume, or schematic elements. Depth/thickness and locations still flexible.		N/A		**Fundamental:** Generic placeholders, volumes for space reservation. **Exterior Walls:** Generic wall objects separated by type of material. Approximate wall thickness represented by a single assembly. Locations still flexible.		N/A		**Fundamental:** Accurate size, shape, location, and orientation. Penetrations are modeled to nominal dimensions. **Exterior Walls:** Single model element with specific overall thickness.	

Figure 4: Example of assigning geometric-semantic attributes and fuzziness to an external wall for LODs 100 – 300. The information is estimated earlier using intermediate LODs with a fuzziness percentage or classification (the fuzziness percentages are estimated based on an interpretation of the BIMForum's definitions and domain knowledge)

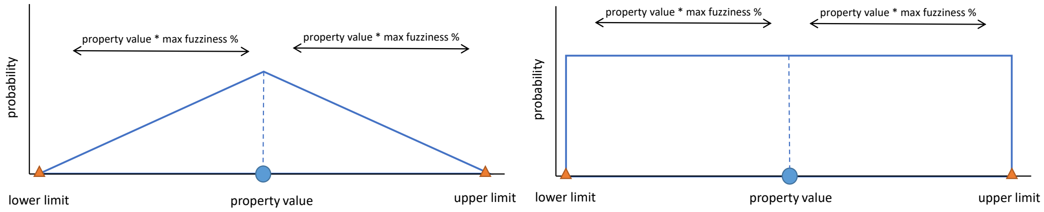
information is more elaborate than it actually is. At this level, we have no information about the wall's main material or layers, thus, including them would produce very detailed and inaccurate compositions as design variants.

The other BIMForum's definitions, LOD 200 and 300, fit the design process at the early stages. To increase the LOD concept's support for the early stages, we propose intermediate LODs to estimate the information one step earlier with some fuzziness.

In the example presented by Figure 4, the position can be estimated from LOD 100 with ±20% and it becomes more certain by incrementing the LOD. From LOD 150, the dimensions can be estimated with ±20% and become certain at LOD 300. Per the BIMForum's definitions, the doors and windows' openings (penetrations) are modeled starting from LOD 300 with nominal dimensions. Therefore, the openings position and percentage are estimated at LOD 250. Considering a different type of fuzziness, the information about material can be available at LOD 150, where in this level; it is defined by specifying the material group, such as *Ceramic*, whereas afterwards the exact material value, like *Brick*, should be assigned. Cross-validating the assigned values through the LODs ensures information consistency, as the model becomes more certain and mature.

4.3. Representing fuzziness through distribution functions

Modeling the fuzziness through a range of values means that all of them have a constant probability. This kind of probability, a.k.a *Uniform Distribution*, makes it easy to estimate the uncertainty, especially when the information is incomplete. In case the designer has a central tendency for some values than the others, the *Triangular, Quadratic,* and *Cosine Distributions'* characteristics fit into representing the values' probability [59]. To apply these types of probability functions, it is enough to know the upper and lower limits and the expected value, which the designer assigns to the attribute from their knowledge, as shown in Figure 5a and 5b.



(a) *Triangular* distribution (b) *Uniform* distribution

Figure 5: Modeling fuzziness range with distribution functions

Additionally, as the *Normal Distribution* is the most frequently seen in representing the physical universe [60], it is possible to apply it to the fuzziness range. However, the *Normal Distribution* represents the uncertainty of observations, which means besides relying on the *mean*, i.e. the expected value, the Standard Deviation (STDV) needs to be provided. This, however, is rather counter-intuitive and thus uncommon in architectural design practice.

A popular method that applies to normally distributed data is the *Empirical Rule* [61]. This rule states that 99.7% of the possible values lie within three STDVs of the mean. Moreover, extensive studies using hundreds of probability models have verified that at least 97.5% of the possible values

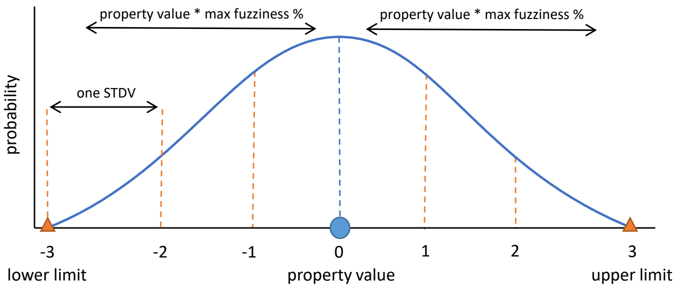


Figure 6: Modeling fuzziness range with *Normal* distribution

lie within three STDVs [62]. With that said, the ± fuzziness range provided from the designers' experience covers the possible values, and the STDV is concluded by dividing the fuzziness range into six regions, three deviations to the left and another three to the right of the mean as illustrated in Figure 6.

5. Meta-model design

The multi-LOD meta-model design provides a means for defining project-specific requirements. It defines the required components, including their LOD, at a specific building development level and incorporates formal LOD definitions for individual component types.

The multi-LOD meta-model introduces two levels: (1) the *data-model level* defines the component types as well as their geometric and semantic requirements for each LOD. Subsequently, the components' LODs are assigned to a BDL. (2) the *instance level* represents the actual building elements and their relationships at multiple LODs.

The meta-model design complies with the object-oriented modeling principles, which offers high flexibility and extensibility. It allows for a dynamic definition of any component type as well as its properties for the different LODs. This provides the flexibility required when dealing with different construction types, different domains, and different analysis tools. At the same time, the meta-model provides a consistent way to query information about LOD definitions at both the data-model level and instance level.

As illustrated in Figure 7, the data-model level consists of multiple Building Development Levels (BDLs) and component types. A component type definition is represented as a separate class, where it is linked to an IFC

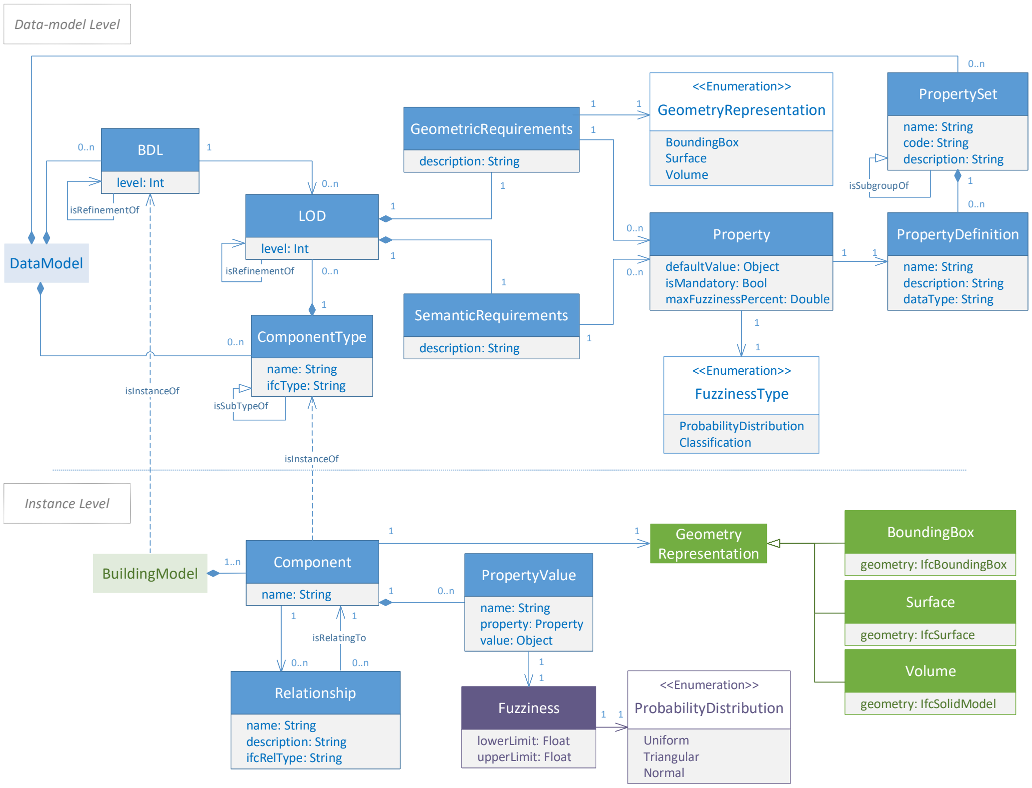


Figure 7: Multi-LOD meta-model (UML diagram)

entity, *IfcWall* as an example, and associated with a list of LOD definitions. The component types are mapped to instances of the IFC data model. This allows on the one hand, to make use of the rich geometry representations provided by IFC and on the other hand, to experiment with real-world data produced by IFC-capable BIM authoring tools.

A component type LOD definition is produced out of two objects, geometric and semantic requirements. Both requirements are explicitly described in the form of properties, and at the same time, the geometric requirements allow for the specification of the required geometry representation.

The properties are managed separately by means of grouping, the *PropertySet* class. A *PropertySet* includes multiple *PropertyDefinition* instances that define property details but exclude its fuzziness. The fuzziness type and maximum percentage as well as whether the property is mandatory are specified when assigning a *PropertyDefinition* to an LOD property. This has

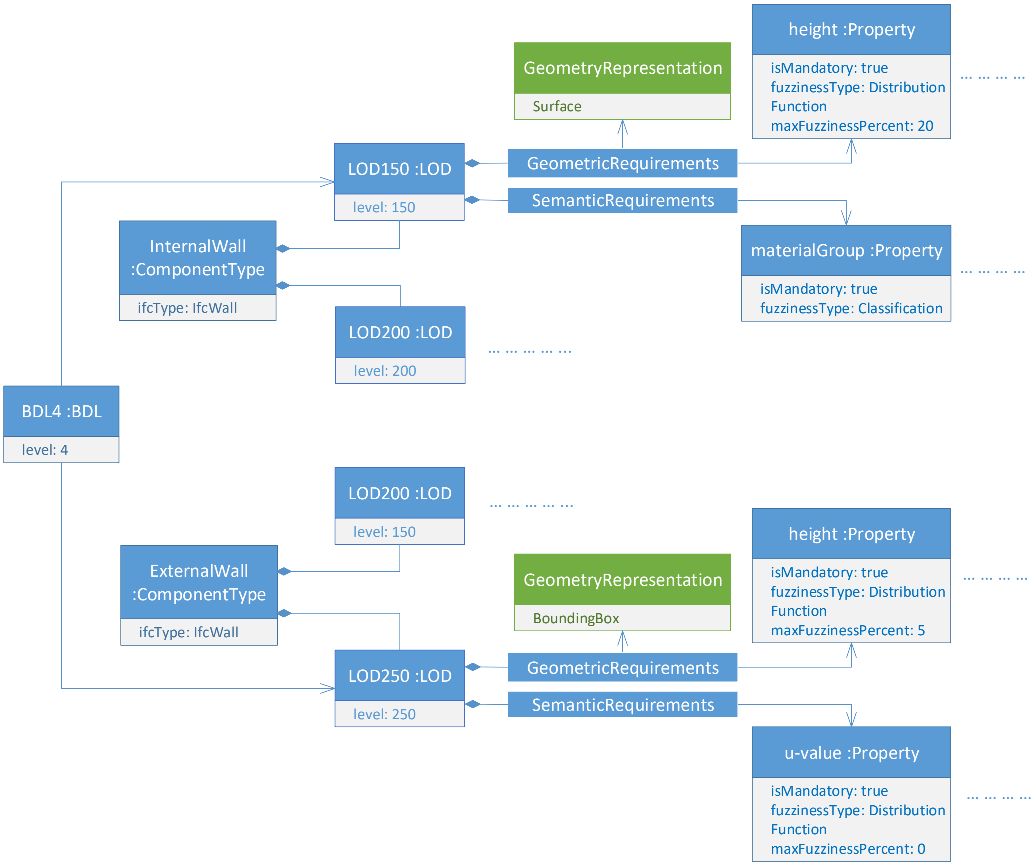


Figure 8: Instance of the multi-LOD meta-model for defining multiple component types' LODs and assigning the building model's requirements at BDL 4

multiple advantages, including the decoupling of the property definition from the LOD requirements, and flexibility in using the same property definition in multiple LODs along with different fuzziness.

In some cases, multiple components fall under the same category, such as *Heating, Ventilation, and Air Conditioning* (HVAC) systems, and share several properties. Hence, the *ComponentType* class supports the definition of the sub-types of a specific component type through inheritance. This means a sub-type inherits the parent component type's requirements in addition to specifying new requirements.

Thereafter, a BDL is comprised of a set of component types' LOD definitions to form the requirements of the overall building model. Figure 8 demonstrates the assignment of component types' LOD requirements for BDL 4. Each of the components is associated with two LODs, including geometric and semantic properties. BDL 4 here requires internal walls at LOD 150 and external walls at LOD 250.

After defining the component types' requirements, the building model is represented by multiple instances of the available types. Based on the defined requirements, each instance is assigned to a geometry representation, which complies with IFC, such as *IfcSurface*, and its properties are assigned to values. In terms of fuzziness, a probability distribution function is specified and its range is automatically generated from the maximum fuzziness percentage defined at the component type level. For example, 4% and an attribute value of 250 cm are translated into a range of ±10 cm. Moreover, at the instance level, it is possible to change the distribution function or increase the limitation of the range values, such as to between -5 cm and +7 cm.

Finally, the connections between the individual components within the same BDL, including aggregation and association, are presented through the *Relationship* class. The meta-model allows checking if the instance of a given component type at a particular LOD complies with the requirements defined in terms of semantics and geometric representation.

6. Consistency of BDLs

The design of the building model is developed through multiple BDLs. As a subsequent BDL brings additional information, new challenges arise. In some cases, overcoming these challenges requires the modification of previously made design decisions, like changing the structure of a load-bearing wall or moving a component into a different position, which is crucial for the model's structural integrity. Taking into consideration the collaborative nature of building projects, such modifications at an advanced BDL should be controlled properly in order to avoid any unexpected side-effects impacting the whole building model. Therefore, this paper proposes a methodology for checking the refinement consistency of the building components across the BDLs.

The building component's position, orientation, and dimensions define its existence in the overall model. This information is essential for many types of analyses, such as clash detection, where detecting whether a specific region touches or is included within another region is important.

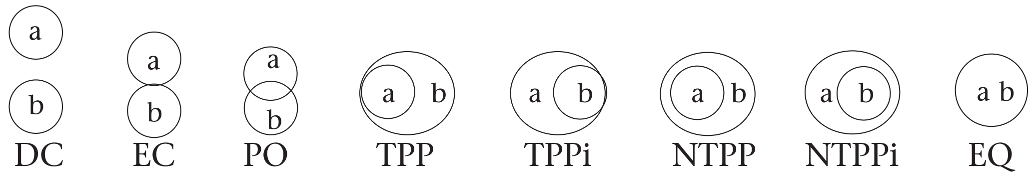


Figure 9: The Region-Connection Calculus (RCC) Representing Pairwise Relationships between Regions of Space [63]

Qualitative Spatial Reasoning (QSR) provides representational primitives, a spatial vocabulary, and mechanisms for reasoning about the spatial data. The Region Connection Calculus (RCC) theory is a well-established formal system for qualitative spatial reasoning. It is based on a primitive connectedness relation, *C*, which is a binary symmetric relation [64]. Using this relation, a set of binary relations are defined [63] (some formal definitions are listed in Table 1). Most importantly, the eight relations illustrated in Figure 9, {*DC, EC, PO, TPP, TPPi, NTPP, NTPPi, EQ*}, form a Jointly Exhaustive and Pairwise Disjoint (JEPD) set, which means that any two regions stand to each other in exactly one of these relations. These eight topological relations are known as RCC8.

Relation	**Interpretation**	**Definition of R(x, y)**
DC(x, y)	x is disconnected from y	$\neg C(x, y)$
P(x, y)	x is a part of y	$\forall z[C(z, x) \rightarrow C(z, y)]$
PP(x, y)	x is a proper part of y	$P(x, y) \wedge \neg P(x, y)$
EQ(x, y)	x is identical with y	$P(y, x) \wedge P(y, x)$
O(x, y)	x overlaps y	$\exists z[P(z, x) \wedge P(z, y)]$
PO(x, y)	x partially overlaps y	$O(x, y) \wedge \neg P(x, y) \wedge \neg P(y, x)$
EC(x, y)	x is externally connected to y	$C(x, y) \wedge \neg O(x, y)$
DR(x, y)	x is discrete from y	$\neg O(x, y)$
TPP(x, y)	x is a tangential proper part of y	$PP(x, y) \wedge \exists z[EC(z, x) \wedge EC(z, y)]$
NTPP(x, y)	x is a non-tangential proper part of y	$PP(x, y) \wedge \neg\exists z[EC(z, x) \wedge EC(z, y)]$

Table 1: Some definitions of the RCC relations [63]

6.1. Formal definition

The proposed methodology introduces a new relationship, *IsRefinedBy*, that represents the dependencies between the different BDLs. It comprises the geometric and semantic information as well as the topological relationships. Additionally, the permissible fuzziness, i.e. the fuzziness type and maximum percentage defined at the data-model level, at each LOD is taken into consideration. In order to consider a BDL refinement as consistent, it needs to at least conform to the information defined at the previous BDL. Consequently, each building component is represented by a set of components at the subsequent BDL, including their properties and relationships, which makes the BDLs interconnected and serves as the building model's refinement history.

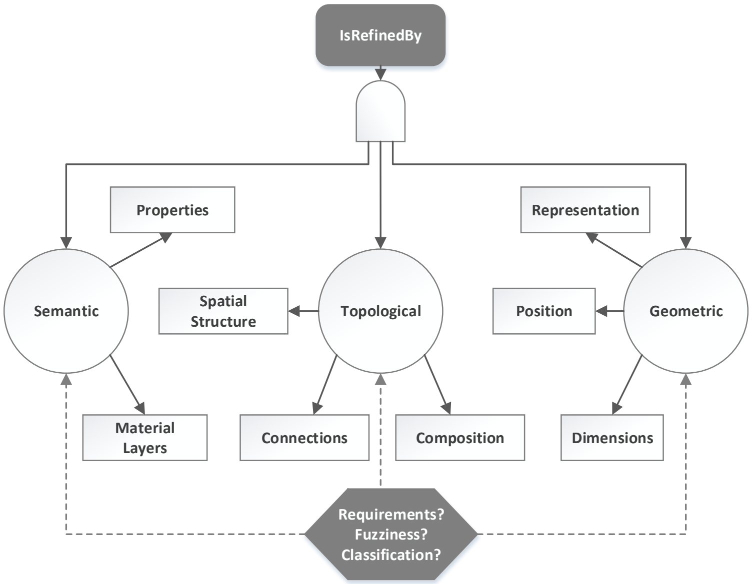


Figure 10: *IsRefinedBy* relationship composition

Figure 10 represents the information validated for checking the consistency of a building model at two different levels. A building's topology is described as a network of adjacency relationships between all components (physical elements and spaces), see Figure 13. We define two BDLs as being consistent iff:

- The topological network of the objects and spaces at BDL_x is topologically equivalent to the network at BDL_y (explanation follows).

- If there is a refinement relationship between components $a \in BDL_x$ and $b \in BDL_y$, for all components b holds: their position and size is *contained* (in the sense of TPP, $NTPP$, or EQ of RCC8) in the geometric representation of a.

- If there is a refinement relationship between components $a \in BDL_x$ and $b \in BDL_y$, for all components b holds: their semantic information (type and attributes) is a concretization of the semantic information of a.

6.2. Approach

To validate the consistency of two BDLs, multiple checks are conducted. To perform these checks, fundamental knowledge about the spatial relationships of the individual components at both BDLs is required. Thus, a pre-processing step mapping each component of BDL_x to a set of components that occupy part or all of the same area at BDL_y is performed. In this regard, qualitative spatial reasoning is applied to all the components by creating an *Axis Aligned Bounding Box* (AABB) around each component and finding the overlapping elements at the other BDL as depicted in Figure 11. Once there is a bounding box overlap, a *Ray / Triangle Intersection* [65] calculation is performed to accurately identify the mapped elements that are actually overlapping.

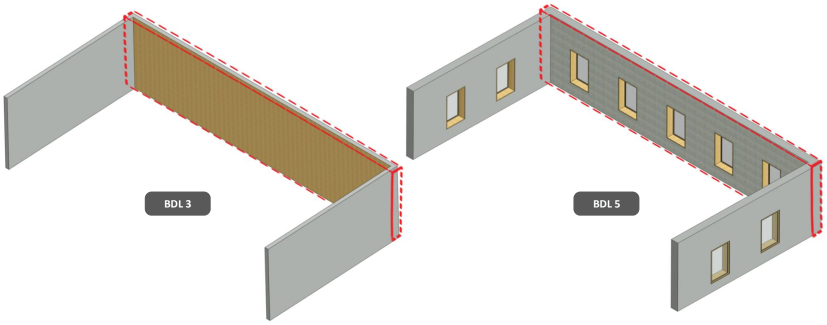


Figure 11: Pre-processing: matching components based on their position and dimensions, in this example, the wall at BDL 3 is matched with a more refined wall that has additional layers, openings, and multiple windows at BDL 5

6.2.1. Topological consistency

First, the overall model's topological relationships are investigated. As changing the position and dimensions is allowed within a ± fuzziness value, it is possible that a change results in a critical modification of the building's topology as illustrated in Figure 12. Reducing *Wall05*'s dimensions within the allowed fuzziness disconnects it from *Wall01*, which is critical, as it changes the function of *Wall05* from room dividing into non-room dividing. Such a change modifies the storey's spatial structure from two spaces into one space, which has a critical effect on various aspects, including the designed compartments for fire-safety regulations, life-cycle analysis, and load distribution in case the wall is load-bearing.

Consequently, the refined model is not considered consistent since it does not comply with the decisions made at the previous BDL. For that reason, it is necessary to maintain the building's topological relationships in a way that preserves the spatial structure's consistency. A more refined BDL can include additional / more detailed components or a more complex spatial structure, but it should at least comply with the spatial structure provided by the previous BDL.

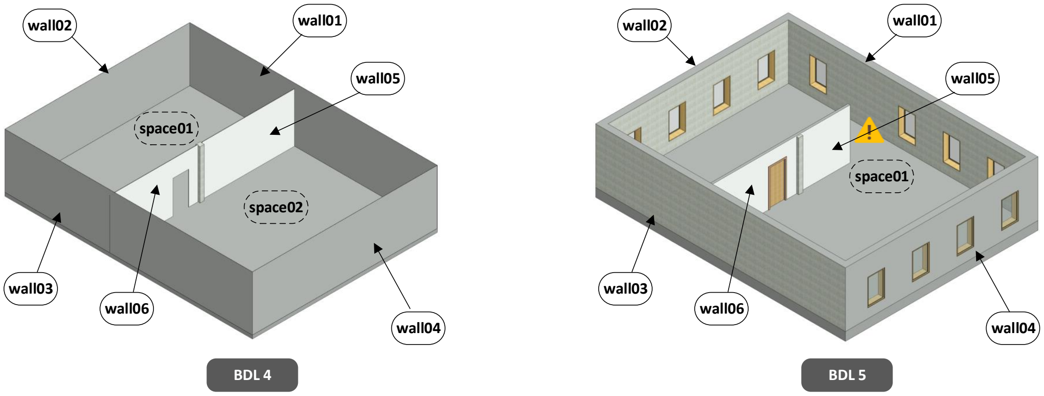


Figure 12: Demonstrating the motivation for maintaining the spatial structure's consistency across the BDLs by showing the effect of changing *Wall05*'s dimensions with the permissible fuzziness at a subsequent BDL. Consequently, the function of *Wall05* has changed from room dividing into non-room dividing at BDL 5, modifying the spatial structure from two spaces into one space

Thereby, the proposed methodology aims to construct a labeled-graph representation of the building's spatial structure by including the available spaces, their boundaries, and the relationships between them. In this way, the topological complexity is simplified into graphs, which facilitates the comparison of two BDLs.

However, although information about the available spaces and their boundaries are supported by the IFC schema, using *IfcSpace* components and *IfcRelSpaceBoundary* relationships, they are not automatically exported by the BIM authoring tools [66]. Instead, they need to be either manually modeled or computationally determined. Similarly, the connections between walls and other boundaries, such as columns, are not automatically exported. Therefore, the RCC8 relations (PO, EC, and DC) are applied to extract the connections between the geometric components. As a result, a graph is constructed of the connected components, such as walls and columns, as vertices. Next, the bounded spaces are extracted by finding all the graph cycle spaces, a graph theory technique.

> "A *Cycle Space* of a graph G, denoted $\mathrm{W}_C(\mathrm{G})$, is the subset of the edge space $\mathrm{W}_E(\mathrm{G})$ consisting of the null set (graph)ϕ, all cycles in G, and all unions of edge-disjoint cycles of G." [67]

For instance, Figure 13 exhibits two BDLs, BDL 4 at the top and BDL 5 at the bottom, including their graph representation. At BDL 4, the graph results in three closed cycles:

- Storey space (Space01 + Space02): *wall01, wall02, wall03, wall04*
- Space01: *wall01, wall02, wall03, wall06, column01, wall05*
- Space02: *wall01, wall04, wall03, wall06, column01, wall05*

As at BDL 5, more precise information about the storey's interior structure and load distribution is available, the model is refined by splitting each of *wall01* and *wall03* into two smaller walls and adding a structural load-bearing column in between. Additionally, a new internal wall, *wall07*, is added. Consequently, the constructed graph has different patterns and vertices than BDL 4. When processing the graph, five closed cycles are found:

- Storey space (Space01 + Space02 + Space03): *wall01.2, column01.3, wall01.1, wall02, wall03.1, column03.3, wall03.2, wall04*

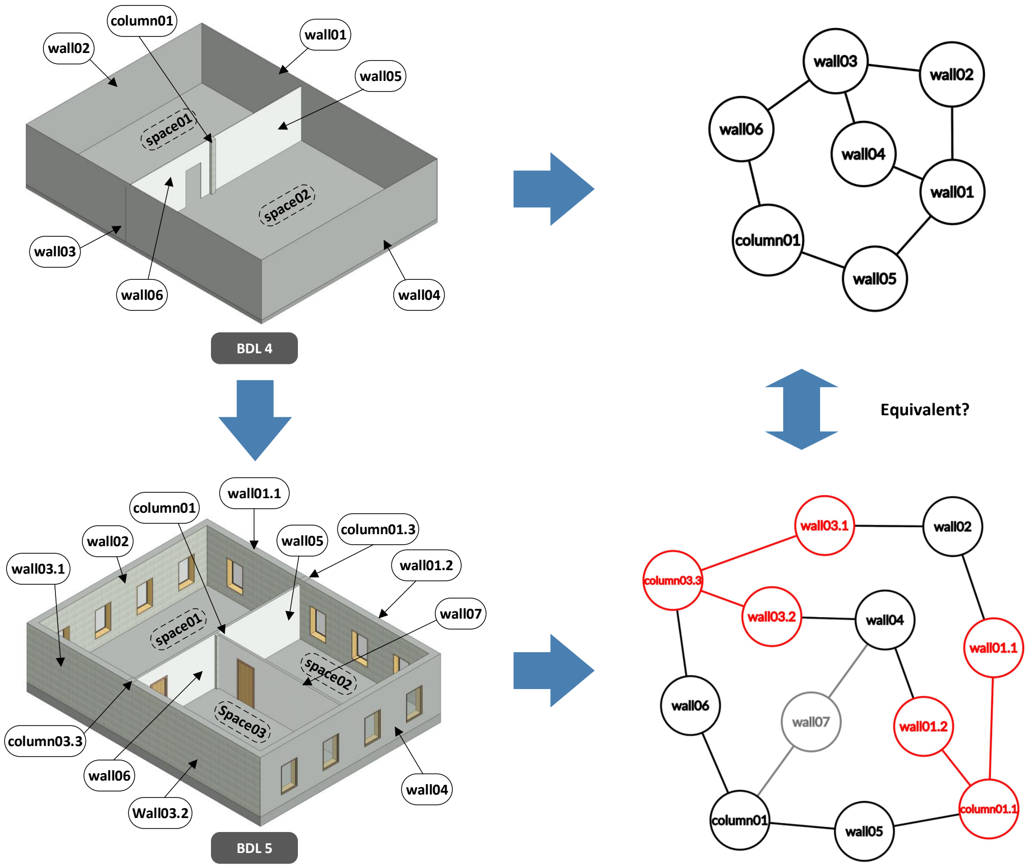


Figure 13: Labeled-graph representation of the building's spatial structure of two BDLs. The vertices represent the geometric components and the edges mean that there is a physical connection between two vertices

- Space02 + Space 03: *wall01.2, wall04, wall03.2, column03.3, wall06, column01, wall05, column01.3*
- Space01: *column01.3, wall01.1, wall02, wall03.1, column03.3, wall06, column01, wall05*
- Space02: *wall01.2, wall04, wall07, column01, wall05, column01.3*
- Space03: *wall04, wall03.2, column03.3, wall06, column01, wall07*

Next, the extracted cycles from both BDLs are compared for equivalency. In this context, the mapped components from the pre-processing step are replaced by the original component. In this example, *wall01.1*, *column01.1*, and *wall01.2* are replaced by *wall01*, and this is also the case for *wall03*. As a result, finding the exact cycles of BDL 4 as part of the BDL 5 cycles is guaranteed in case their topology is consistently refined. Finally, the relationships' correctness of the mapped components is investigated; if one wall is refined into two walls with openings, then the connections and voids relationships need to be assigned accordingly.

6.2.2. Geometric and semantic consistency

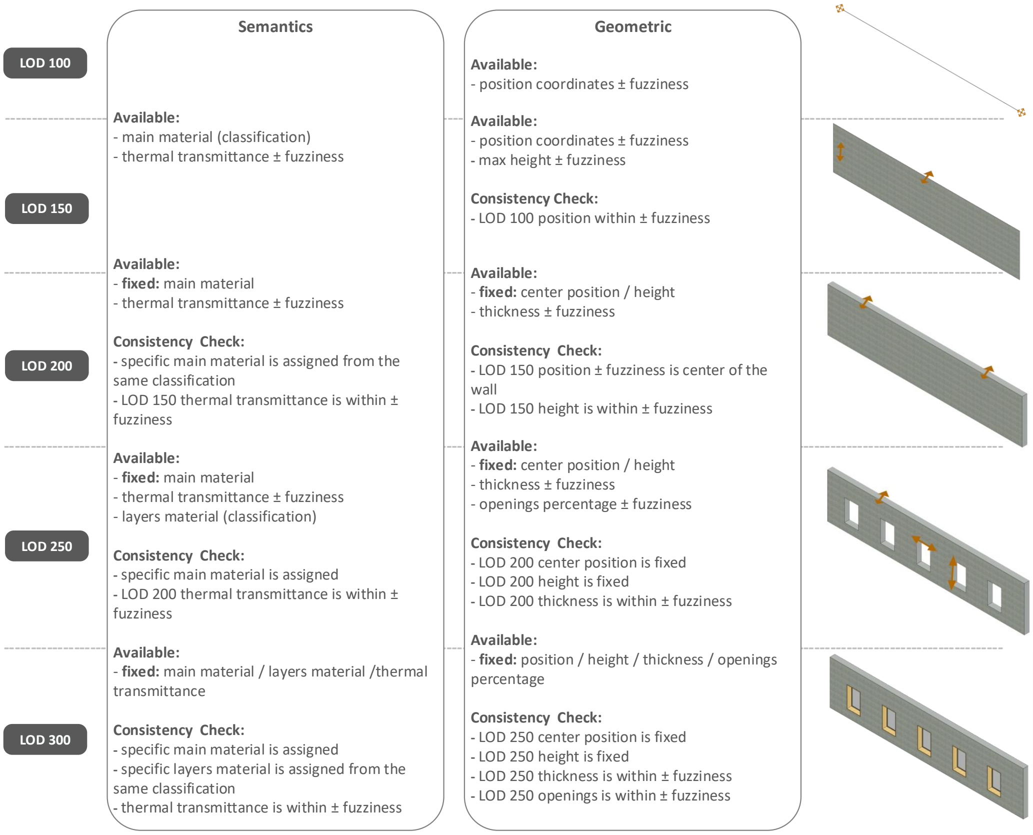
The second check verifies whether the geometric information, including dimensions and position, and the semantics, like material, of two LODs comply with each other considering the permissible fuzziness defined in the multi-LOD data model. The aim is to assure that each component refinement conforms to the decisions made at the previous LOD.

In more detail, Figure 14 demonstrates an external wall refinement, listing the available information and the consistency checks. In the beginning, information about the component's position, accompanied by fuzziness, is available, which allows for a representation of the wall by a centerline. At LOD 150, the height of the wall can be estimated, which makes it possible to represent the wall as an extruded surface. The consistency check here focuses on maintaining the centerline position defined previously ±fuzziness.

Afterwards, additional information about the wall material layers and insulation is available. Thus, the wall thickness can be estimated. In this case, checking the consistency involves verifying the wall's height and that the surface position ±fuzziness represents the center of the wall.

In terms of semantic information, the consistency is checked based on its type. Semantics can have diverse types and meanings, including material layers, openings percentage, fire rating, thermal transmittance, and much more. Therefore, making sense of this information is a prerequisite for checking its consistency. Here, the defined requirements of the multi-LOD data-model provide additional context for mapping the same property between different LODs.

The data-model explicitly defines the property type in addition to the fuzziness type and percentage, which yields a formal specification of the expected values at the refined LOD. Furthermore, mapping the defined properties to the classification systems, like *Uniclass* and OmniClass, as well as to the commonly known property sets, like *Pset_SlabCommon*, assists in validating the refinement consistency. For instance, when a *Ceramic* material



	Semantics	Geometric
LOD 100		**Available:** - position coordinates ± fuzziness
LOD 150	**Available:** - main material (classification) - thermal transmittance ± fuzziness	**Available:** - position coordinates ± fuzziness - max height ± fuzziness **Consistency Check:** - LOD 100 position within ± fuzziness
LOD 200	**Available:** - **fixed:** main material - thermal transmittance ± fuzziness **Consistency Check:** - specific main material is assigned from the same classification - LOD 150 thermal transmittance is within ± fuzziness	**Available:** - **fixed:** center position / height - thickness ± fuzziness **Consistency Check:** - LOD 150 position ± fuzziness is center of the wall - LOD 150 height is within ± fuzziness
LOD 250	**Available:** - **fixed:** main material - thermal transmittance ± fuzziness - layers material (classification) **Consistency Check:** - specific main material is assigned - LOD 200 thermal transmittance is within ± fuzziness	**Available:** - **fixed:** center position / height - thickness ± fuzziness - openings percentage ± fuzziness **Consistency Check:** - LOD 200 center position is fixed - LOD 200 height is fixed - LOD 200 thickness is within ± fuzziness
LOD 300	**Available:** - **fixed:** main material / layers material /thermal transmittance **Consistency Check:** - specific main material is assigned - specific layers material is assigned from the same classification - thermal transmittance is within ± fuzziness	**Available:** - **fixed:** position / height / thickness / openings percentage **Consistency Check:** - LOD 250 center position is fixed - LOD 250 height is fixed - LOD 250 thickness is within ± fuzziness - LOD 250 openings is within ± fuzziness

Figure 14: An example of an external wall refinement, listing the available information and the geometric - semantic consistency checks

group is specified at LOD 150, at LOD 200 an exact material that belongs to this group, such as *Brick*, *Earthenware*, and *Terracotta*, should be assigned.

7. Prototype

To evaluate the proposed multi-LOD model for practical use, it is implemented as a webserver and a client-side User Interface (UI), providing a user-friendly way to define disciplines, levels of development, property sets, component types, and building development levels.

The webserver alleviates the disciplines' collaboration by centralizing the storage of exchange requirements and building models' information and providing web-service access for all modeling, simulation, and analysis tools.

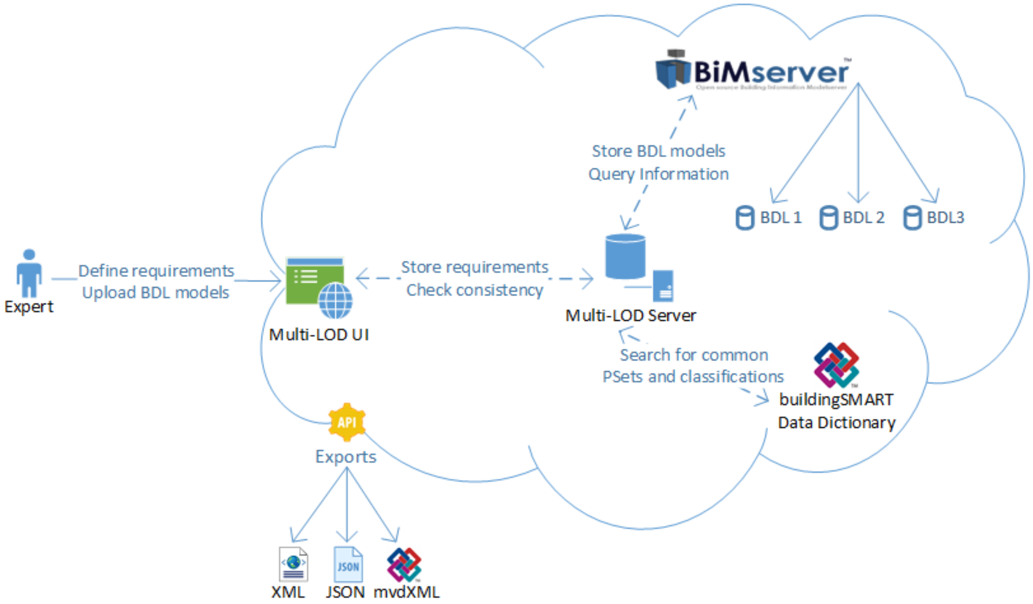
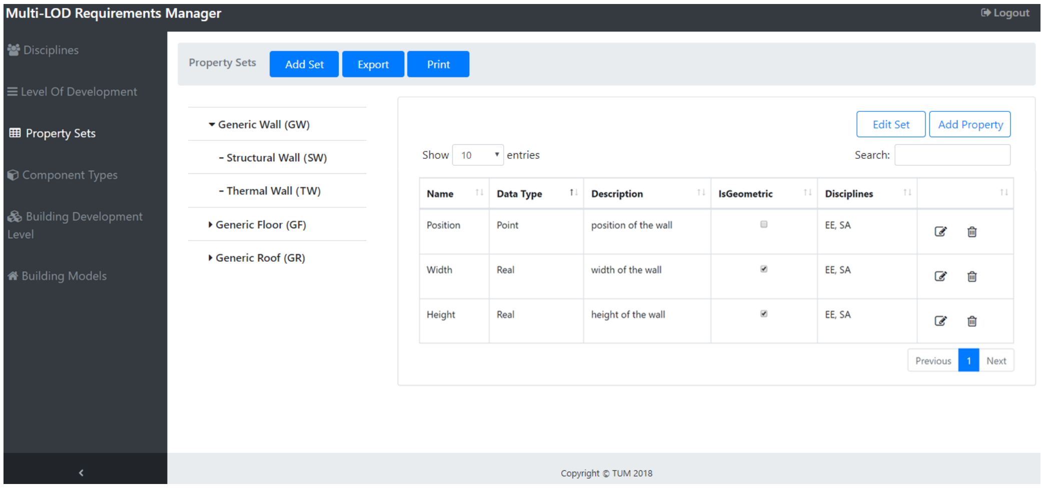


Figure 15: Overview of system design

Maintaining and managing the actual building models (at different BDLs) is realized by employing an instance of the BIMServer [52], thus functioning as a back-end. Figure 15 provides an overview of the system design.



Name	Data Type	Description	IsGeometric	Disciplines	
Position	Point	position of the wall	☐	EE, SA	
Width	Real	width of the wall	☑	EE, SA	
Height	Real	height of the wall	☑	EE, SA	

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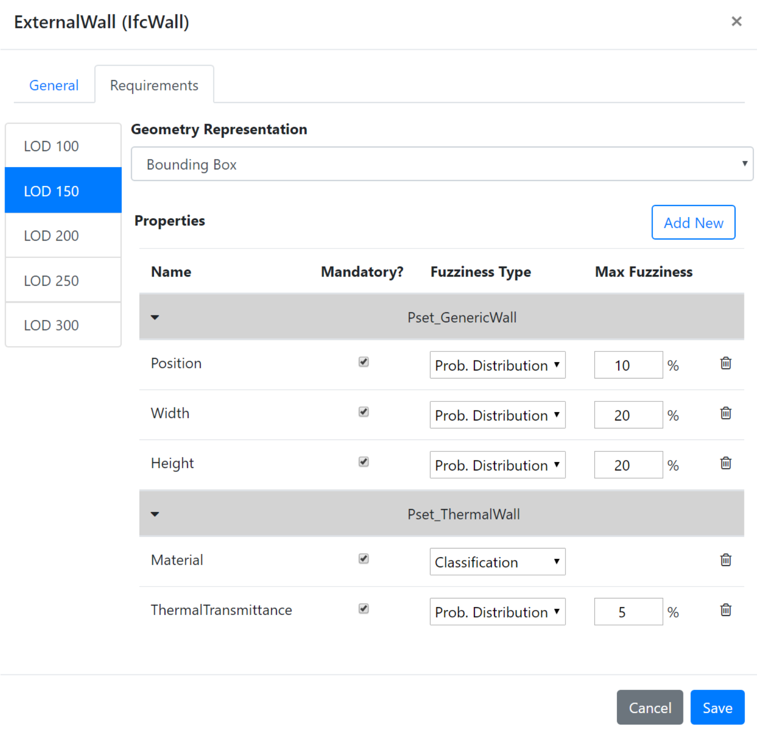
Figure 16: Property Sets management screen (UI prototype)

The main concept is that every discipline is capable of defining its own property sets and then assigning particular properties to a specific component type's LOD. The property sets' management screen is demonstrated in Figure 16. A property set can have sub-sets in order to minimize the properties' redundancy. Additionally, a property is assignable to multiple disciplines.

Afterwards, the properties are assigned to an LOD at the component types' screen. Figure 17 shows the component details screen for an *ExternalWall*. The *General* tab is for defining the component name, IfcType, description, and whether the component is external and load-bearing. The second tab, *Requirements*, facilitates the association of every LOD with properties including a specification of their fuzziness. The properties are grouped based on their *Property Set* name, following the naming scheme *Pset_**, for instance *Pset_ThermalWall*.



ExternalWall (IfcWall)

Geometry Representation: Bounding Box

Properties

Name	Mandatory?	Fuzziness Type	Max Fuzziness
Pset_GenericWall			
Position	☑	Prob. Distribution	10 %
Width	☑	Prob. Distribution	20 %
Height	☑	Prob. Distribution	20 %
Pset_ThermalWall			
Material	☑	Classification	
ThermalTransmittance	☑	Prob. Distribution	5 %

Figure 17: Component details screen of an ExternalWall; the fuzziness percentages are estimated based on an interpretation of the BIMForum's definitions and domain knowledge (UI prototype)

To improve the usability and increase the data integrity, the buildingSmart Data Dictionary's (bsDD) Application Programming Interface (API) [41] is employed. It assists the process by listing the commonly known IFC elements, properties, and classifications to the user. Consequently, this mapping to the bsDD's GUID provides additional context and meaning to each value, which improves interoperability between different disciplines and assists in the model's analysis.

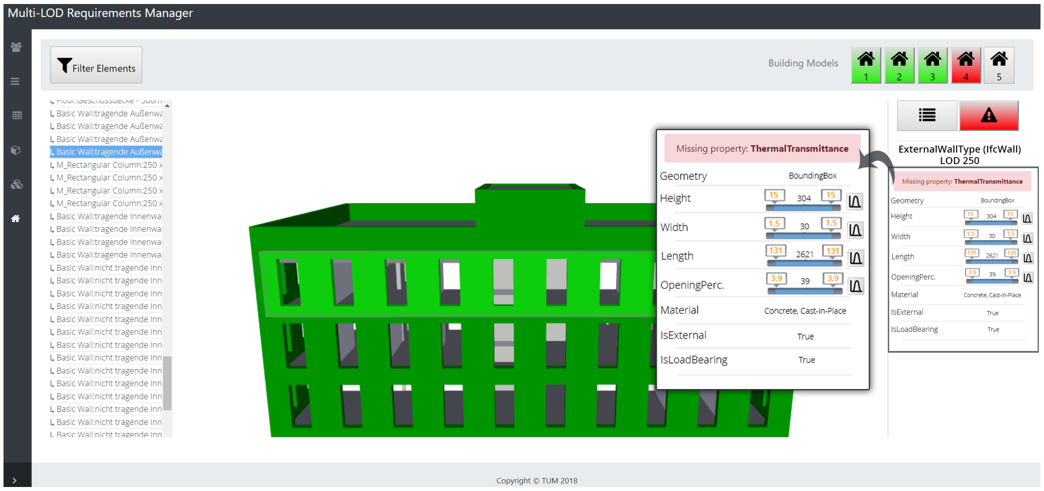
The multi-LOD webserver stores the component types' requirements into a relational database and exports them as XML and JSON formats using the REpresentational State Transfer (REST) API. To facilitate the usage of these exchange requirements and validate their existence, the webserver exports them into the common formats supported by BIM authoring tools, such as a PropertySets file provided by Autodesk Revit, and automatically generated mvdXML rules. Hereby, it is possible to use the requirements for external services, such as a Revit plugin, to automatically generate and ensure the exchanged building models' attributes completeness.

After defining the LOD requirements, the experts are able to share and validate their developed building models. As shown in Figure 18, an expert selects a particular building's BDL (from the buttons on the top) and uploads its corresponding IFC file to the system. When BDL 1 is uploaded, the multi-LOD service checks its compliance with the defined requirements, i.e. if all the mandatory properties exist and the geometry representation is as specified; in case it is valid, then it is stored at the BIMServer, otherwise, the expert is notified.

When the next BDL is uploaded, the same check regarding the defined requirements is performed, and then the information refinement consistency with the previous stage is verified using the approach described in Section 6. To retrieve the building model's information, the BIMServer provides a convenient implementation of BIMQL [68]. Additionally, to check the BDLs' topological consistency, the QL4BIM [69] is integrated into the process to query the connected components and generate a graph representation.

As demonstrated in Figure 18, the building model expects the external walls to be at LOD 250, which requires the *ThermalTransmittance* property to exist. Besides listing the component's properties and their defined fuzziness, the user interface indicates that there is a required property missing for the highlighted external wall. The multi-LOD service serves as a gate for maintaining the model's consistency when updating or adding a new BDL.

To assist in checking the building models' completeness and consistency beforehand, the generated mvdXML rules can check the IFC models locally



ExternalWallType (IfcWall)
LOD 250

Missing property: **ThermalTransmittance**

Geometry	BoundingBox
Height	15 304 15
Width	1.5 30 1.5
Length	131 2621 131
OpeningPerc.	3.9 39 3.9
Material	Concrete, Cast-in-Place
IsExternal	True
IsLoadBearing	True

Figure 18: Building models management screen; an expert selects a BDL and uploads an IFC file. The defined requirements, as well as the model's consistency, are verified. On the right side, the component's properties are mapped to the defined LOD requirements and the expert is notified when a property is missing

before uploading them to the system. For example, Listing 1 shows two mvdXML rules; the first rule checks the consistency of the *ThermalTransmittance* property value between two different LODs. The range limitation is generated by retrieving the value of the same property from the available LOD and multiply it by the allowed fuzziness percentage, while the second mvdXML rule is formed from the list of the available materials assigned to the *Ceramic* material group in the *OmniClass* classification system.

```
<TemplateRule Parameters="PSet[Value]='Pset_ThermalWall' AND PropertyName[
    Value]='ThermalTransmittance' AND PropertyValue[Exists]=TRUE AND
    PropertyValue[Value] >= 0.15 AND PropertyValue[Value] <= 0.50"/>

<TemplateRule Parameters="PSet[Value]='Pset_StructuralWall' AND
    PropertyName[Value]='Material' AND PropertyValue[Exists]=TRUE AND
    PropertyValue[Value] = 'Brick' OR PropertyValue[Value] = 'Earthenware'
     OR PropertyValue[Value] = 'Terracotta' OR PropertyValue[Value] = '
    Fired Shale' OR PropertyValue[Value] = 'Porcelain' OR PropertyValue[
    Value] = 'Vitreous China'"/>
```

Listing 1: mvdXML rules checking the consistency of *ThermalTransmittance* and *Material* between two different LODs

8. Case study: Design of the Tausendpfund building

Figure 19: *Ferdinand Tausendpfund GmbH & Co. KG* office building, in Regensburg, Germany built in 2017. It has three storeys and is 27m long, 14.7m wide, and 9.8m tall. The gross volume is approx. 3950 m^3, with a gross area of 1290.5 m^2 and a window-to-wall ratio of 25%

In this case study, the proposed approach was applied to the definition of the exchange requirements and to check the consistency across the BDLs of the real-world construction project depicted in Figure 19. The benefits of specifying the information fuzziness to reduce the uncertainty and support the decisions are presented below. The targeted type of analysis is the Life Cycle Assessment (LCA) calculation and its corresponding Embedded GreenHouse Gases (EGHG) in the early design stages.

LCA is one of the most established and well-developed methods for assessing the potential environmental impacts and resource consumption throughout a product's life-cycle [70]. As one of its applications, LCA is used to calculate the embedded energy, which is represented as the sum of non-renewable energy consumption during a building's life cycle [71]. The GreenHouse Gases (GHG) emissions resulting from the embedded energy are defined as Embedded GreeHouse Gases (EGHG). Performing the LCA calculation involves a variety of geometric and semantic information, including the building location, dimensions, number of storeys, material, and window-to-wall ratio. Additionally, custom energy-related attributes, such as the *Thermal Transmittance* (U-value), are required for each component and need to be transferred when exchanging the model.

Our research group includes architects and several engineers specialized in embedded and operational energy as well as structural analysis. At each design stage, engineers and architects need a detailed list of requirements to exchange building information models.

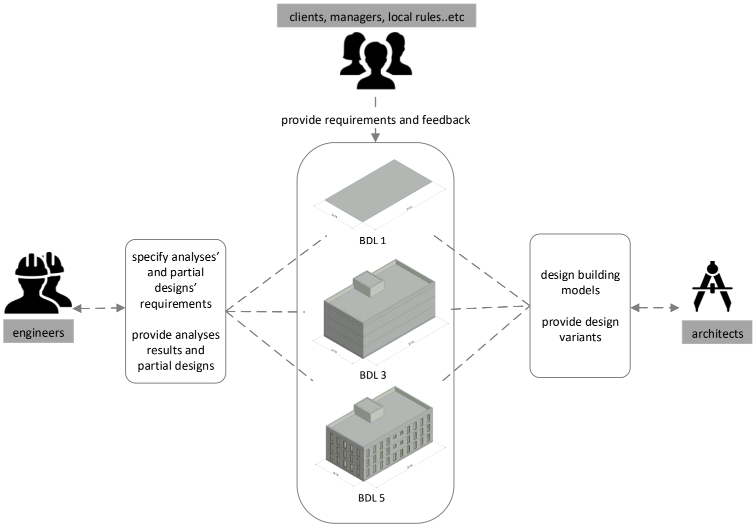
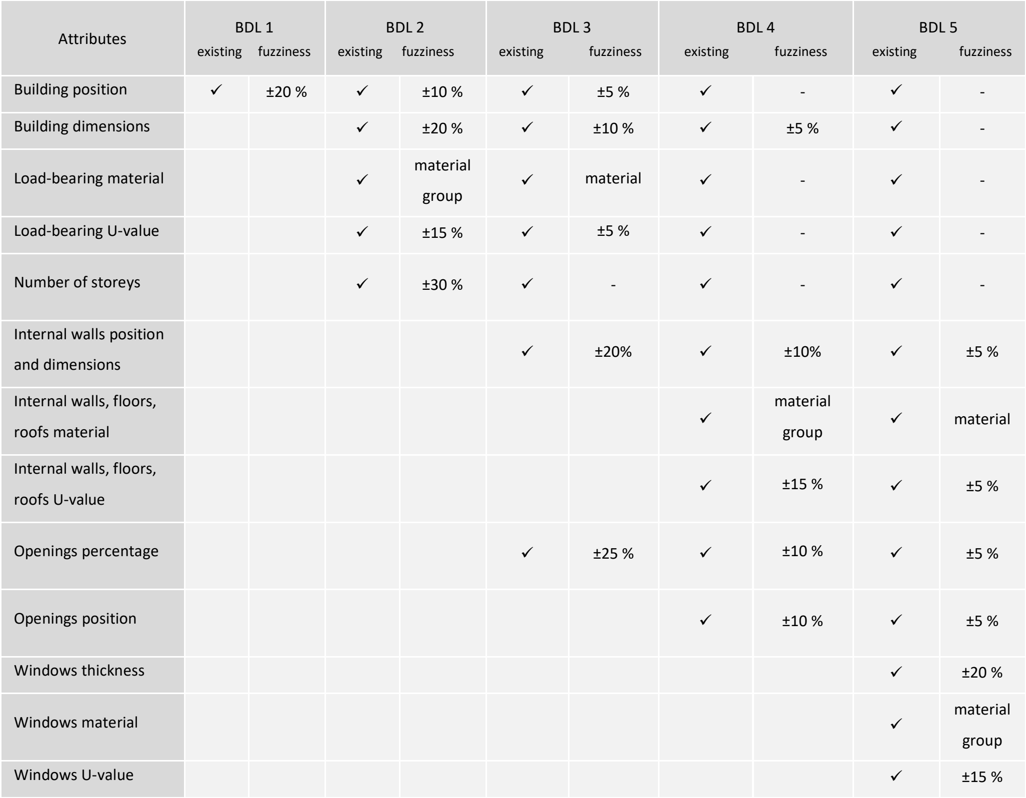


Figure 20: Collaboration between several disciplines to define a building project's requirements and objectives

Figure 20 illustrates the collaborative process between several actors when developing a building. At every building development level, each discipline requires specific information to be present in the model to perform a model analysis. Similarly, architects incorporate clients' feedback and engineers' analyses results in the building models and produce design variants. Supporting the different kinds of evaluations for the same model is a very challenging task, as the information needs to represent the attributes and types of fuzziness in a way that allows the various simulation tools to integrate them in the correct way. Here, the multi-LOD data-model comes into play, as it enables the requirements of the individual component types to be defined at every LOD.

While developing the conceptual design, the owner decided to build a sustainable building and explore multiple design variants, such as different numbers of storeys, a window-to-wall ratio for each side of the building, and different building dimensions.

Figure 21 lists the required attributes for LCA calculation in BDLs 1 – 5. The set of attributes and their associated fuzziness are estimated by the research group's engineers based on domain knowledge, interpretation of the BIMForum's definitions, and numerous studies on the required information for energy performance simulation [72, 73, 74, 75].



Attributes	BDL 1		BDL 2		BDL 3		BDL 4		BDL 5	
	existing	fuzziness	existing	fuzziness	existing	fuzziness	existing	fuzziness	existing	fuzziness
Building position	✓	±20 %	✓	±10 %	✓	±5 %	✓	-	✓	-
Building dimensions			✓	±20 %	✓	±10 %	✓	±5 %	✓	-
Load-bearing material			✓	material group	✓	material	✓	-	✓	-
Load-bearing U-value			✓	±15 %	✓	±5 %	✓	-	✓	-
Number of storeys			✓	±30 %	✓	-	✓	-	✓	-
Internal walls position and dimensions					✓	±20%	✓	±10%	✓	±5 %
Internal walls, floors, roofs material							✓	material group	✓	material
Internal walls, floors, roofs U-value							✓	±15 %	✓	±5 %
Openings percentage					✓	±25 %	✓	±10 %	✓	±5 %
Openings position							✓	±10 %	✓	±5 %
Windows thickness									✓	±20 %
Windows material									✓	material group
Windows U-value									✓	±15 %

Figure 21: Required building attributes for LCA calculation in the early design stages (fuzziness percentages are estimated based on domain knowledge and interpretation of the BIMForum's definitions)

Using the Multi-LOD user interface, the LCA requirements are defined and assigned to component types. For each BDL, a set of components and their LOD definitions, including fuzziness type and percentage, are specified. For instance, in BDL 2, the building is associated with fuzzy dimensions, position, and a number of storeys. Load-bearing components, such as *Columns*, *External Walls*, and *Foundation*, are associated with thickness, material and U-value.

Estimating the attributes with a fuzziness percentage makes performing the LCA calculation on an earlier BDL viable. In this way, the impact of each attribute on the calculation results can be assessed. This makes it possible to make better decisions that improve the building's performance during the building's life cycle and fit into the design intentions [11].

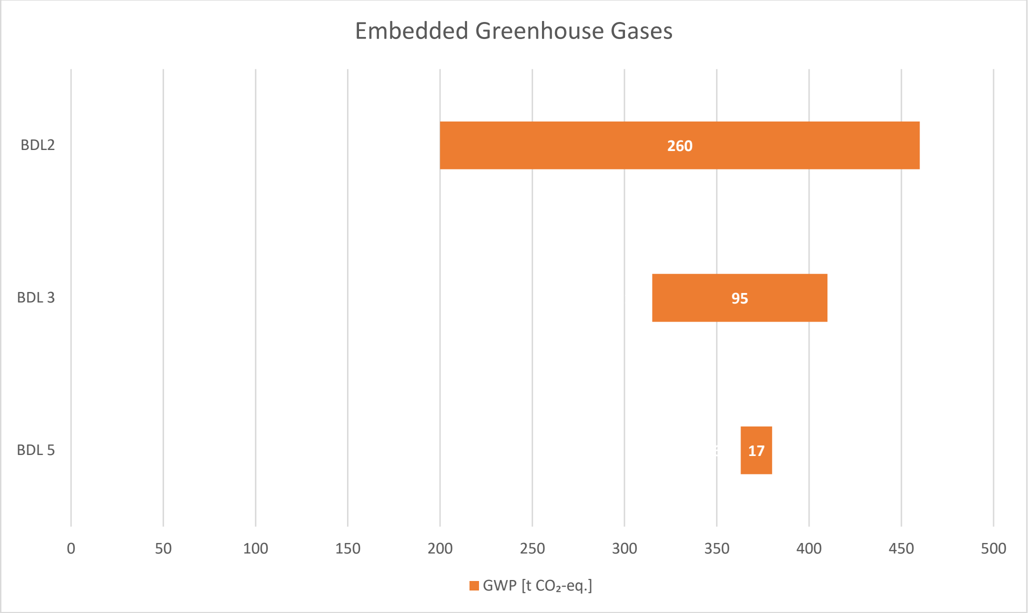


Figure 22: Comparison of the uncertainty range in EGHG results for BDLs 2, 3, and 5 [76], regenerated with permission

As part of our research group, Harter et al. [76] used the methodology proposed in this paper to calculate the EGHG for the proposed variants. Figure 22 illustrates how the information fuzziness across the BDLs influences the uncertainty in the EGHG calculation. The uncertainty of the results decreases in inverse proportion to the increase in BDL, from a difference of 260 GWP [t CO_2-eq.] in BDL 2 to 17 GWP [t CO_2-eq.] in BDL 5. Hereby, the previously performed analyses' results are still considered valid and become more accurate by including the more precise information.

With the building model in BDL 2, multiple concepts were proposed. Figure 23 compares the EGHG results of the building model in BDL 2 with the impact of varying the building's dimensions by ±10%, window-to-wall ratio to 25% and 50%, and dividing the building into two and three storeys. The simulation results act as a weighting approach for the potential fuzziness, i.e. they shed a light on which attributes have the greatest influence on the evaluation results compared to the others, which improves the designer's awareness and the quality of the decisions made.

At BDL 4, the interior structure, including the rooms' division and usage, was selected. Figure 24 depicts the floor plan layout of Level 0. At this BDL,

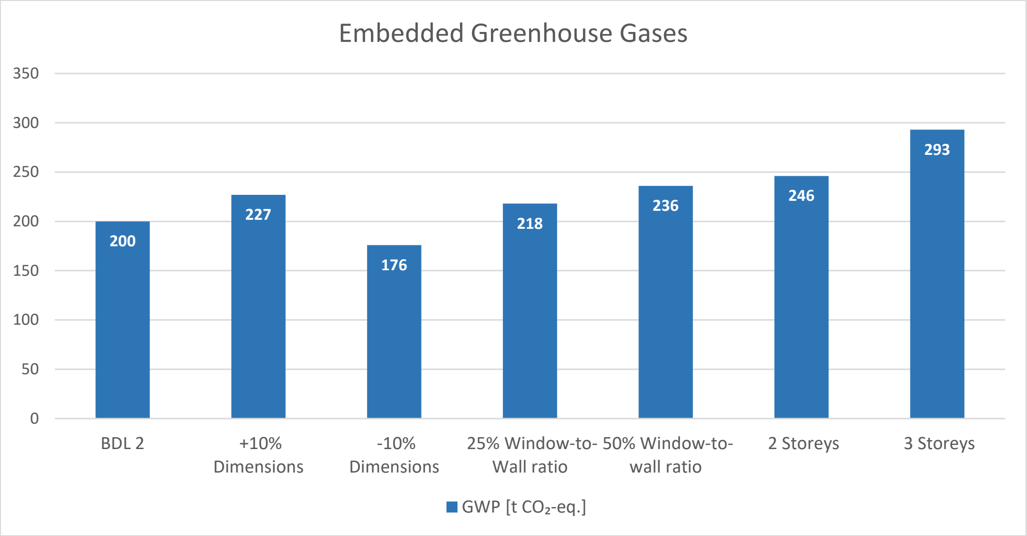


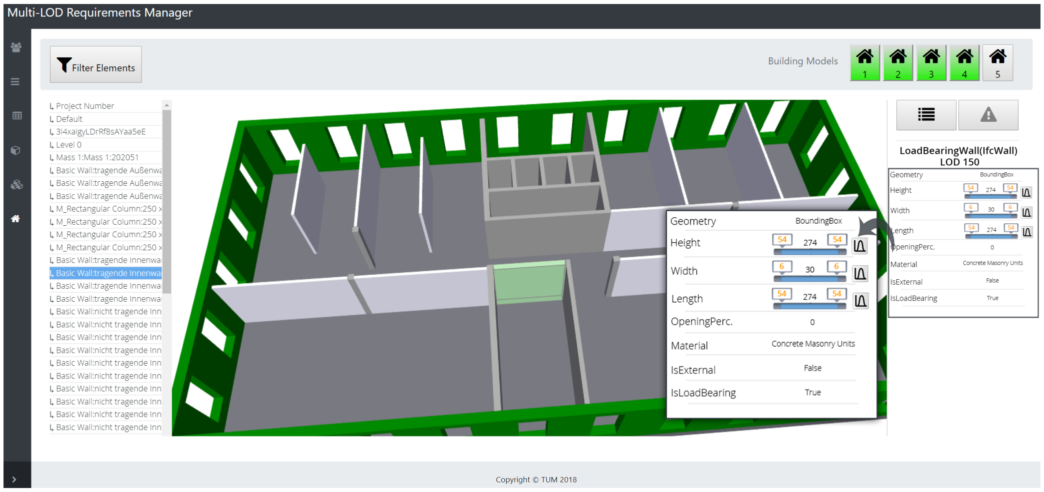
Figure 23: Impact of the information fuzziness on EGHG results in comparison to BDL 2 [76], regenerated with permission

the different kinds of analysis were performed and the results evaluated in terms of how they fulfill the project's requirements. The building model was then uploaded to the multi-LOD system. The system compared the uploaded model with BDL 3 and since the changes involved adding openings and interior walls, BDL 4 was successfully stored as a consistent refinement of BDL 3.

At BDL 5, the owner requested two design changes: (1) replacing one of the walls surrounding the staircase by one curtain wall and adding two structural columns, (2) reducing the height of one of the interior walls to allow for smooth communication between two of the offices, as their usage is similar. At BDL 4, the staircase walls are designed as load-bearing with 240mm concrete masonry units, and the offices were completely separated.

Although these changes satisfied the owner's request, they did not follow the decisions made in the earlier stages. Changing the wall's material and merging two spaces into one are major decisions that affect the different kinds of analysis and evaluations, such as EGHG, heat-flow, the structural system, and satisfying the fire-safety regulations. To guarantee that these changes did not affect the analyses performed previously and are at least equivalent to the previous design, the analyses need to be repeated.

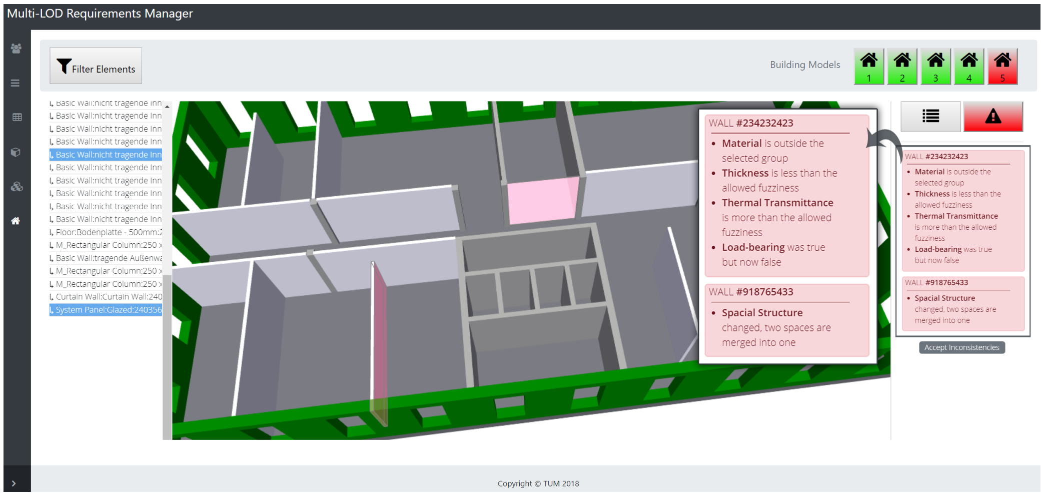
Consequently, the system considered the building model at BDL 5 as



LoadBearingWall(IfcWall)
LOD 150

Geometry	BoundingBox
Height	54 274 54
Width	6 30 6
Length	54 274 54
OpeningPerc.	0
Material	Concrete Masonry Units
IsExternal	False
IsLoadBearing	True

Figure 24: Floor plan of level 0 at BDL 4 (UI prototype)



WALL **#234232423**

- **Material** is outside the selected group
- **Thickness** is less than the allowed fuzziness
- **Thermal Transmittance** is more than the allowed fuzziness
- **Load-bearing** was true but now false

WALL **#918765433**

- **Spacial Structure** changed, two spaces are merged into one

Figure 25: Detection of inconsistent refinement at BDL 5 (UI prototype)

inconsistent and flagged a warning to the designer, as shown in Figure 25. At this point, the designer can make the decision to re-evaluate the model before approving this change or accept the changes and upload the current building model to the system as BDL 5.

Using the BDL concept to describe the building model development offered a spatial overview of the project and encouraged consideration of the different use-cases. Additionally, explicitly modeling the information fuzziness facilitated an evaluation of the impact of the different attributes on the building performance. The presented approach assisted in making informed decisions and reduced the likelihood of having to perform major changes to the model at later stages, which in turn prevented a substantial amount of rework and added expenditure.

9. Conclusion and future work

This paper has contributed a new approach for the formal specification of maturity levels of building information models, in particular for the early stages of building design. To facilitate the early integration of analyses and simulations, this paper has proposed extending the BIMForum's LOD specification by adding intermediate levels to specify the maturity levels in a more fine-grained granularity. Additionally, the *Building Development Level (BDL)* has been introduced as a means to describe the required maturity of an entire digital building at a particular stage, through the composition of component-wise LOD specifications.

To enable the precise specification of a BDL/LOD content, a multi-LOD meta-model has been introduced. It offers an interface on the meta-level for specifying and querying the BDL definitions of buildings and the LOD definitions of individual component types. The meta-model provides two levels, the *data-model level* and the *instance level*. This offers a high degree of flexibility in defining per-project BDL/LOD requirements. Most importantly, it supports the formal checking of a building model's conformance with the defined semantic and geometric requirements at a specific stage or for a specific application, such as building performance simulations or structural analyses.

In particular, the proposed multi-LOD meta-model allows to explicitly define the fuzziness of geometric and semantic information, both for defining the requirements of an LOD and for specifying information of a concrete building model. This allows to check a building model for formal conformance with the specification of an LOD, not only with respect to the existence of properties and the provision of values within a given range, but also with respect to the maximum allowed fuzziness on a given LOD. The definition of fuzziness on the instance level, on the other hand, delivers significant advantages in assessing the building's performance at the early design stages, as simulations and analyses can make direct use of the modeled uncertainties.

Finally, the explicitly defined fuzziness allows verifying the building model's consistency across different BDLs. This enables tracking whether earlier assumptions still hold after the design process has progressed and the building model has been correspondingly refined. This, in turn, gives a strong indication whether the results of simulation performed on coarser BLDs still hold.

As a proof of concept, the meta-model has been prototypically implemented in a client-server software system based on web technologies. The system provides a means for managing the component types' LOD definitions and BDLs' requirements. On top of this, the building models are maintained throughout the BDLs, where they are checked for consistency and compliance with the defined requirements. The system exports the LOD definitions into JSON, XML, and automatically generated mvdXML rules to encourage their integration in the modeling process. To check the consistency across multiple BDLs, the building's topology is evaluated for equivalency and the individual components' geometric, semantic and topological information refinement is validated.

As demonstrated in the case study, the feasibility of the proposed approach was validated on a real-world construction project. The project participants emphasized the advantage of specifying the required information along with its potential fuzziness in communicating the uncertainties in the input as well as the simulation results. Moreover, checking the building model's refinement consistency prevented a disregarding the previously made decisions and flagged up the necessity to repeat the performed analysis.

Despite its expressive power and flexibility in defining LOD requirements and checking the refinement consistency, the presented approach also has limitations. On the one hand, the refinement and detailing process remains a manual activity, i.e. the presented approach does not provide a consistency preservation mechanism, but only an inconsistency detection mechanism. On the other hand, as of now, there is no defined response in the detection of inconsistencies between different BDLs. Whether the coarser model would need to be updated or the finer one would be discarded heavily depends on the detailing work-flow and the goals associated with it.

As a next step, further research is necessary to support the specification of relative requirements for a group of components, where a condition can be defined to link a property value to another property that belongs to the same or a different component. Additionally, the quantification and communication of the information fuzziness using multiple visualization techniques can support making informed decision. In various scenarios, the properties of specific components are dependent on other components' properties, such as the position and distribution of columns. Additionally, visualization is essential for representing and simplifying the meaning of information.

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