A multi-LOD model for visualizing building information models' vagueness

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ABSTRACT

The decisions taken throughout a building's design stages steer a project's success and outcome. The early stages involve choosing between alternative designs and form the basis of the following stages. Therefore, managing the early stages is crucial in avoiding a substantial amount of rework and reduced productivity. However, the lack of adequate and accurate information impedes informed decision-making. At the same time, current model-based planning techniques require extensive input data and produce very detailed designs, which can lead to false assumptions and model evaluations. Hence, this paper discusses a meta-model approach to support a formal definition of the model information in multiple design stages, incorporating potential vagueness. Thereafter, multiple visualization techniques are proposed for conveying the specified vagueness. This approach facilitates performing subjective estimation of a building model's information at the early stages to support model analyses and decision-making.

INTRODUCTION

Throughout the design stages of a building, several experts from different disciplines collaborate to satisfy the project's requirements and objectives by exchanging building information models iteratively. In this collaboration, following common standards and specifications is essential for a project success. Using Building Information Modeling (BIM), the physical and functional characteristics of a building are digitally represented. Recently, BIM has been increasingly adopted by the AEC industry (Young *et al.*, 2009), 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 different stages of their development (BIMForum, 2018; Hooper, 2015).

The decisions taken throughout the design stages, especially the early ones, steer a project's success and results (Howell, 2016). The early design stages involve the selection between alternative designs and the determination of costs, forming the basis of the subsequent stages (Steinmann, 1997). At the beginning of the design process, the uncertainty in how the design may evolve is high due to incomplete or unknown information (Knotten *et al.*, 2015), which affects the process and outcomes of the decision-making.

The terms uncertainty and vagueness are used in various domains and application contexts (Raskin and Taylor, 2014), most commonly, uncertainty is an umbrella-term which describes the lack of knowledge or information causing the occurrence of an uncertain future state (Hawer *et al.*, 2018). On the other hand, vagueness, as a synonym for fuzziness and ambiguity, is related to a specific state of a specific object, and it refers to having imprecise or non-crisp information (Hawer *et al.*, 2018).

In the context of Computer-aided design (CAD) modeling, Steinmann (1997) described the 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. This means that they require performing fundamental changes to the proposed design, like changing the overall building's shape, adding a new storey, or changing the internal spatial structure. Vagueness is related to the reliability of the building elements' attributes and their refinement through the LODs, for example, load-bearing components' exact position and external walls' opening percentage.

The interactive visualization of 3D building models provides great support for evaluating the building designs. However, as the available model-based planning techniques require extensive input data and produce very detailed designs (Penttilä, 2007), they are inadequate for supporting the early design stages. Modeling additional information would wrongly suggest that the design is more elaborate than it actually is, which can lead to false assumptions and model evaluations, affecting the decisions taken throughout the design stages (Kraft and Nagl, 2007). At the same time, the current LOD definitions are informal, textual definitions as well as graphical illustrations, and do not include the potential vagueness, which allows multiple interpretations.

In the frame of the EarlyBIM[1] research project, 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. To provide a foundation for managing multiple LODs of BIM models, the authors have developed a multi-LOD meta-model (Abualdenien and Borrmann, 2018), which facilitates a formal specification of the LOD definitions, incorporating the component types' attributes vagueness. Accordingly, the information provided as an input for the different kinds of simulations and analyses can be estimated earlier by representing it as a range of values and a distribution function or an abstract classification rather than a fixed value.

This paper discusses the multi-LOD meta-model approach for describing the information vagueness at different design stages, demonstrating how it can support a model's analysis and decision-making. In its essence, the paper presents multiple visualization techniques, which are proposed for quantifying and conveying the specified amount of vagueness on the multi-LOD model. Representing the information reliability and explicitly describing its potential vagueness will foster improvement in planning quality and consideration of the impact on the building performance assessment in the early design

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

stages, for example, as the impact of load-bearing components' position, opening percentage, and material on the Life Cycle Assessment (LCA) and structural analysis.

The paper is organized as follows: Section 2 discusses the background and related work. Section 3 provides an overview of the multi-LOD meta-model and describes the design concepts, and in Section 4, multiple approaches for visualizing the building information vagueness are proposed and demonstrated. Finally, Section 5 summarizes our progress hitherto and presents an outlook for future research.

BACKGROUND AND RELATED WORK

Level of Development (LOD). The LOD concept describes the maturity of a building element throughout all the design and construction stages. Defining the model content using the LOD scale enhances communicating and describing its current state. In most approaches, the individual levels of development are described by means of (informal) textual definitions and graphic illustrations for various building elements. These definitions represent the required information quality, i.e. reliability, preciseness, and completeness. A good example is the definitions provided by the BIMForum (BIMForum, 2018), 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. The LOD concept facilitates defining BIM-based exchange requirements throughout the design process. The BIMForum have published the Level of Development Specification based on the American Institute of Architects (AIA) definitions from LOD 100 reaching LOD 500 (BIMForum, 2018). To benefit from an LOD definition it needs to have a formal machine-readable format, allowing the precise description of attributes and automatic integration with BIM-authoring tools, which makes it possible to automate checking the actual building elements for compliance with an LOD definition.

Uncertainty visualization. Conveying the quantity of uncertainty in the information is crucial for making rational conclusions (Griethe and Schumann, 2005). This particularly applies to the architectural design and engineering of buildings. Multiple researchers from different domains, including geospatial information (MacEachren *et al.*, 2005), navigation systems (Andre and Cutler, 1998) and architecture (Griethe and Schumann, 2005; Houde *et al.*, 2015), have suggested and applied a variety of techniques for representing uncertainty.

These techniques are grouped into two main categories: (1) intrinsic, changes the graphical variables of an object, such as color, transparency, texture, or shape, and (2) extrinsic, involves additional graphical objects, like text, glyphs, or overlay, to describe the status of an object while leaving the original component unchanged (Gershon, 1998). Furthermore, others have proposed visualizing uncertainty using interactive techniques, including animation (Hullman *et al.*, 2015), and sound (Lodha *et al.*, 1996).

Several researchers emphasized the effectiveness of visually depicting uncertainty using the color variables and attributes, including intensity, value, lightness, saturation, and opacity (Hengl, 2003; Drecki, 2002). According to the method proposed by Hengl (2003), who manipulated saturation and color value, uncertain data appear more white or pale.

MacEachren (1992) proposed that data with less certain information should use a correspondingly less saturated color, thereby, making their color hue uncertain. Drecki (2002), proposed representing an uncertain object with transparency, as it is not real, while certain objects are relatively opaque. From the extrinsic point of view, Pang (2001) suggested adding different glyphs to describe uncertainty, in the same context, Cliburn *et al.* (2002) cautioned that extrinsic visualization can be confusing or overwhelming.

MULTI-LOD META-MODEL

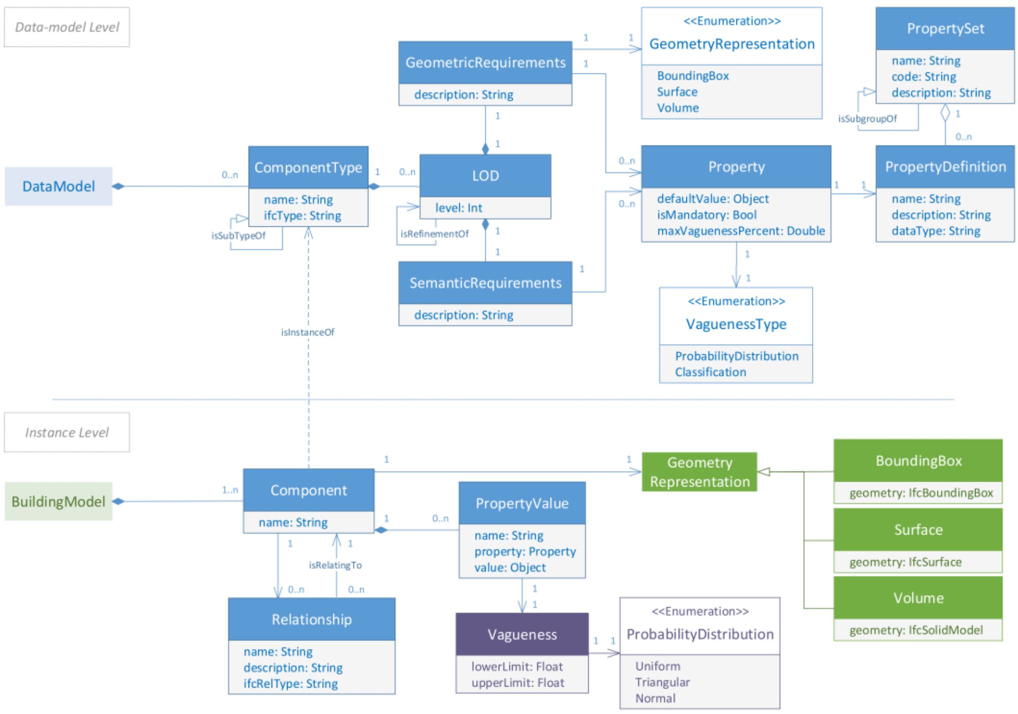


Figure 1. Multi-LOD meta-model (UML diagram).

The multi-LOD meta-model offers a high-level interface for defining component types' LOD definitions, incorporating the potential vagueness (Abualdenien and Borrmann, 2018). Accordingly, the known uncertainties are explicitly modeled, which delivers great advantages in assessing and verifying the model's consistency in the early design stages. The meta-model introduces two levels: *data-model level*, defines the component types' requirements for each LOD, and *instance level*, represents the actual building components and their relationships. In order to ensure the model's flexibility and applicability, its realization is based on the widely adopted data model Industry Foundation Classes (IFC). The IFC model specification is an ISO standard, which is integrated into a variety of software products (Liebich *et al.*, 2013).

In more detail, each component type is associated with a list of LOD definitions and linked to an IFC type, IfcWall as an example. An LOD definition is produced out of two objects, geometric and semantic requirements. Both requirements are explicitly described in the form of properties. The details of each property are determined in addition to the permissible vagueness and geometry representation. In terms of vagueness, a probability distribution function is specified and its range is automatically generated from the maximum vagueness 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 increase the limitation of the range values, such as to be between -5 and +7 cm.

Formally specifying a component's LOD definitions, incorporating the potential vagueness, assists in evaluating the performance of different design options before making a design decision. In the same context, engineers and designers work together to determine the realistic design options that fit into the project's requirements. Therefore, expressing the specified vagueness using visualizing would communicate and quantify its effect on the overall building model, and thus being aware of and account for various use-cases.

APPROACH FOR VAGUENESS VISUALIZATION

The attributes' reliability at every LOD is described by the vagueness specified at the multi-LOD meta-model. The geometric attributes represent the shape and its dimensions, and the semantics describe various aspects of a component's maturity, including its construction type and material. Visualizing components' potential vagueness on each LOD improves the engineers' awareness of the possible states in the subsequent stages. Additionally, such visualization facilitates evaluating the surrounding components' relationships, which improves the quality of the decisions taken.

In many cases, a component's geometry can be more developed than its semantics (BIMForum, 2018). Hence, we propose visualizing the information vagueness using two intrinsic approaches, one for each type of information. The geometry's vagueness is expressed via three border styles, dotted, dashed, and solid, whereas, the vagueness in semantics is represented by varying the color and opaque values to three levels, from light-opaque to dark-full. Such a transformation of the border style and color is meant to convey the reduction of the amount of vagueness; the first level indicates that the vagueness is around 50%, the second less than 25%, and the third is 0%, i.e. precise and certain.

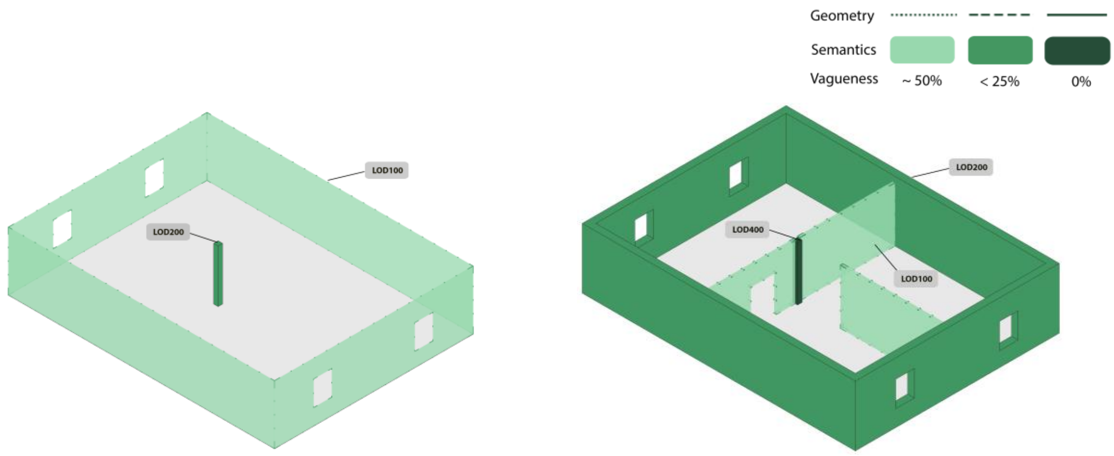
The total vagueness for a specific component is quantified by averaging its properties' vagueness, which is specified at the Multi-LOD meta-model for all LODs as shown below; unknown properties are substituted by 100% of vagueness, the known properties with a classification vagueness are substituted with 50%, and the properties associated with a distribution function vagueness use the vagueness percentage.

$$TV_{LODx}(component) = \frac{1}{n}\sum_{i=1}^{n} PV_{i,LODx}$$

where TV_{LODx} refers to the total geometric or semantic vagueness percentage, and $PV_{i,LODx}$ is a property's vagueness percentage in a particular LOD, n represents the component's total number of geometric or semantic properties in all LODs. For example, the total geometric vagueness of a wall in LOD 100 in case the *Position* (20% PV), *Thickness* (unknown), *Length* (20% PV), and *Height* (unknown), is:

$$TV_{LOD100}(Wall) = \frac{20 + 100 + 20 + 100}{4} = 60\%$$

As illustrated in Figure 2a, the position, thickness, construction type, and material layers of the external walls are still not certain as the walls are in LOD 100. Hence, they are represented by a dotted border style and light-opaque fill color. Additionally, the column's semantics are associated with some vagueness. In this stage changing the external walls' length and position strongly affects the overall shape of the building. In Figure 2b, the columns in the next stage are in LOD 400, filled with a dark green and have a solid border, meaning that their information is certain. Similarly, the geometric information of the external walls is certain as their border is solid, while their semantics are associated with some vagueness. Here, a preliminary design of the storey's internal structure can be estimated by adding inner walls with LOD 100, indicating that their geometry and semantics are uncertain.

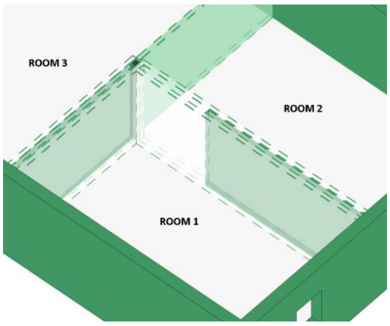


(a) stage 1 (b) stage 2

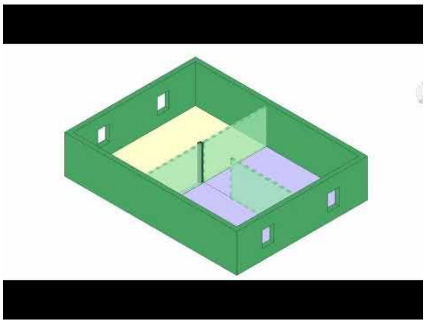
Figure 2. Intrinsic approach for vagueness visualization, showing two design stages where the building components are associated with diverse LODs

The proposed intrinsic approach provides an overview of the vagueness associated with the overall building model, showing the amount of vagueness associated with all elements. Usually, the designer considers all the possible cases when evaluating the individual component's position and dimensions. Therefore, we propose applying two extrinsic approaches to represent the possible combinations of the geometric attributes to assist the designer in choosing the most probable values. The first approach involves generating duplicate opaque instances around the original element, and the second signifies the vagueness in the form of animation. However, such techniques should be carefully employed, otherwise, they can be overwhelming. Hence, we propose confining their application to one attribute at a time and to a specific family of elements, like inner walls, or to all elements related to a specific zone.

Figure 3 demonstrates the possible positions and lengths for the inner walls. Subfigure 3a represents the vagueness related to ROOM 1 by duplicate elements whereas Subfigure 3b uses the animation approach. When visualizing the possible positions and lengths using animation, it is crucial to signify and communicate the impact of the possible values. For example, the vagueness associated with the external walls strongly affect the overall building's shape and orientation. Additionally, the vagueness in the inner walls' length influences their function, in this case from being a room-dividing to non-room dividing. Such a change modifies the storey's spatial structure, which affects the designed compartments for fire-safety regulations, life-cycle analysis, and load-distribution where the wall is load-bearing.



(a) duplicate static instances



(b) animation (available online)[2]

Figure 3. Extrinsic approach for representing the possible positions and lengths: on the left, showing duplicate instances, and on the right, using animation.

CONCLUSION

Information vagueness is a fundamental issue affecting the process and outcome in designing a building. Careful management and visualization of the information vagueness at the early design stages can improve planning quality and reduce project risks. The multi-LOD meta-model provides a high-level interface for managing the different component types' LOD definitions and describing their attributes' vagueness. Expressing the amount of vagueness using visualization techniques assists in evaluating how the model can evolve in the subsequent stages. This paper has proposed multiple intrinsic and extrinsic approaches for visualizing the information vagueness. The intrinsic approach varies the border style, color value, and opaqueness, quantifying the amount of vagueness, and the extrinsic approaches facilitate evaluating all the possible combinations of the geometric attributes by generating multiple opaque instances and animating the building elements.

The proposed approaches for vagueness visualization were evaluated by our research group. As a next step, it is necessary to perform iterative rounds of surveys for obtaining feedback from different experts and practitioners in the AEC industry in terms of simplicity, clearness, and support for the decision-making process.

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