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Vagueness visualization in building models across different design stages

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A R T I C L E   I N F O

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A B S T R A C T

The iterative and developing nature of designing a building involves the specification and handling of vague, imprecise, and incomplete information. A crucial factor for mitigating the impact of these uncertainties on the decision-making process is to effectively quantify and communicate them among the project stakeholders. The interactive visualization of 3D building models provides great support for evaluating building designs. However, the currently available visualization methods of the available authoring tools do not incorporate the potential uncertainties associated with the geometric and semantic information of building elements. Currently, building models appear precise and certain, even in the early design stages, which can lead to false assumptions and model evaluations, affecting the decisions made throughout the design stages. Hence, this paper presents a set of visualization approaches, including intrinsic, extrinsic, animation, and walkthroughs, that have been developed to present the uncertainties associated with the building elements' information. The efficiency of the approaches developed in this study was evaluated through an online survey and interviews. More specifically, the approaches were compared in terms of intuitiveness, applicability, and acceptance. The evaluation results positively indicated the participants' ability to understand the amount and impact of the uncertainties on the design by using the developed approaches.

1. Introduction

The comprehensive exchange of information is a key factor in supporting the design decisions involved in a construction project. The process of designing and constructing a building involves multidisciplinary domain experts, including architects as well as structural, mechanical, and fire safety engineers, collaborating to develop a holistic solution. Each of the experts contributes with specialized domain knowledge to fulfill various and sometimes contradictory requirements and objectives while fulfilling the boundary conditions, including budget, environmental impact, and structure. This process involves a set of interrelated activities that result in increasing the design solution knowledge (or reducing the uncertainty).

The design process has an iterative nature, in which the attention of domain experts oscillates between understanding the problem and developing a solution. This iterative nature is essential and beneficial to the developed design. However, as the design process is multidisciplinary, coordination and communication throughout the design stages are crucial to avoid a substantial amount of unnecessary rework (resulting from false assumptions, misunderstandings, and incomplete information) [1–4]. This kind of rework is a significant cause of problems with time and schedule overruns as well as quality deviations and added expenditure [1,3,4]. In this regard, multiple researchers monitored and analyzed the information flow in the design of numerous projects and found a direct relationship between the quality and completeness of exchanged information and the effectiveness of design documents [3,5,1].

Building Information Modeling (BIM) provides a suitable foundation for storing and sharing various kinds of information during the course of a building life cycle [6]. A well-managed BIM process relies on communicating which information needs to be included in the building model as well as assigning different responsibilities for each project participant in each design stage. This kind of coordination facilitates a seamless integration of the different partial models.

Although the early design stages (conceptual and preliminary stages) are characterized by high uncertainty due to the lack of information and knowledge [7], the decisions made during those stages significantly influence the costs and success of the project [8,9]. In the early stages, the efforts and costs required to make changes in a building model are lower than in the subsequent stages [10]. However, the lack of information affects the decision-making process and outcomes; the uncertainty of how the design may evolve is high, as many

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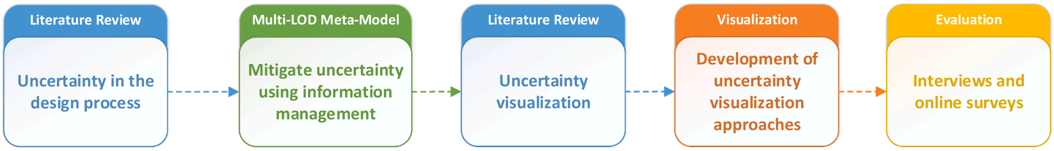


Fig. 1. The research method used during this research.

decisions have not yet been made [1]. In this paper, the term *uncertainty* is used as an umbrella term to encompass many different descriptions, including lack of definition, lack of knowledge, and lack of trust in the knowledge. On the other hand, the term *vagueness* is related to a specific state of a specific object, and it refers to having imprecise information [11].

As discussed above, a design solution is gradually refined and detailed as the design emerges. Accordingly, the quantity and quality of the available information increases as the design becomes more mature. The Level of Development (LOD) concept describes the progressive refinement of the geometric and semantic information by providing definitions and illustrations of BIM elements at different stages of their development [12,13].

To provide a foundation for managing multiple LODs of BIM models, the authors have developed a multi-LOD meta-model [14], which facilitates a formal specification of the LOD definitions, including the explicit specification of the vagueness associated with the building information. Accordingly, the individual properties are assigned to different kinds of vagueness, including a range of values and a distribution function or an abstract classification rather than a fixed value.

In the Architecture, Engineering, and Construction (AEC) industry, visualization is an essential component of the established workflows and exchange scenarios, including communicating design intent, checking the integrity of partial designs, and evaluating design variants [15]. The interactive visualization of 3D building models provides great support for many tasks related to building design and engineering. At the same time, understanding what is precise and complete and accounting for design uncertainty is critical to effectively reason about the visualized building information. However, the existing BIM authoring tools lack of methods for depicting vagueness simultaneously with building models and interacting with those depictions in an understandable way. The current visualization 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 made throughout the design stages [15,16]. Various researchers emphasized that people rely on cognitive biases when making decisions under uncertainty [17,18]. Uncertainty visualization provides high communicative efficiency by means of graphical representation, offering an easier-to-search representation that simplifies recognition and inference [19].

This paper addresses the problem of effectively visualizing the vagueness (or inversely, the reliability) associated with the geometric and semantic building information. By conveying the possibility that a position, a geometric dimension or a property value is not fixed and may vary, showing the impact on surrounding elements and spaces, uncertainty visualization enables domain experts to make informed decisions.

To the best of the authors' knowledge, there has been little research that attempts to visually communicate the vagueness of the building information in the early design stages. The contributions of this study are twofold. First, the development of multiple visualization approaches that are suitable for expressing the information vagueness in building models, including intrinsic, extrinsic, animation, and walkthroughs. Second, the evaluation of the approaches' effectiveness from three main aspects: (1) intuitiveness in expressing the information vagueness, (2) applicability on different scales (from model overview to zone/room view), and (3) users' acceptance in terms of using the visualization approaches in their practical work.

This paper is organized as follows: Section 2 describes the methodology applied for this research. Section 3 discusses the background and related work, and Section 4 provides an overview of the previously published multi-LOD meta-model. Section 5 forms the core of the paper as it discusses and demonstrates the developed visualization approaches, and Section 6 presents the results of evaluating the visualization approaches in terms of intuitiveness, applicability, and acceptance by conducting an online survey and interviews. Finally, Section 7 summarizes our progress hitherto and presents an outlook for future research.

2. Research method

This research aims to explore approaches that seek to improve the communication and collaboration among the different disciplines participating in a construction project, especially at the early design stages where architects and engineers deal with partial and uncertain information.

As illustrated in Fig. 1, the first step to achieve this goal is to identify the possible sources of uncertainty through a comprehensive literature review that is focused on understanding the uncertainty during the design process. The literature review took into account the impact of the owner's requirements, the reliability of the design decisions, the conventional approaches in developing design variants, as well as the required interaction among the project participants to make informed decisions based on model analyses and evaluations.

Through the literature review, we found that the current LOD definitions are informal (graphical illustrations and textual definitions), which leads to diverse interpretations [13,20,12]. Additionally, a major reason why buildings rarely perform as predicted is that practitioners quantify uncertainties in the building model using information from literature, experience, or default values (a well-reported gap exists between the predicted and actual building performance) [21–23].

To fill this gap and provide a framework for formally managing the information requirements and incorporating the potential vagueness throughout the design stages, the authors have previously developed a multi-LOD meta-model [14], which makes it possible to assign a vagueness definition to each of the individual properties. While evaluating the meta-model, we identified the users' need to navigate through the 3D building model and view the properties of the individual elements, because the current visualization depicts building models as precise and reliable even in the early design stages [16,15]. Additionally, as each building element can have numerous properties, in some cases even with the inclusion of the information vagueness for each property, domain experts can struggle to understand the impact of vagueness on the overall design [24,25,17,18].

Therefore, aggregating and visually conveying the overall vagueness can assist in effectively communicating the potential uncertainties and efficiently managing the design interdependencies. This paper presents a set of visualization approaches that were developed based on reviewing state-of-the-art visualization approaches from various domains. Finally, a survey and interviews were conducted to evaluate the intuitiveness, applicability, and acceptance of the developed approaches.

3. Background and related work

3.1. Drawing conventions and scales

Common graphic conventions are incorporated to describe a drawing's layout without the need to include additional explanatory text. In this context, the design reliability is represented by varying the thickness of the lines; a thicker line suggests more permanence while the thinner line suggests a more temporary quality [26].

Additionally, conventional construction planning relies heavily on the use of different drawing scales for representing geometric information on a suitable level of detail and degree of preciseness [26]. The produced drawings evolve from sketches depicting the rough shape of the building and the floor plans to detailed workshop drawings presenting the precise design of individual components, connection points, etc. Accordingly, a drawing's scale directly implies the degree of abstraction, vagueness, and maturity of the design information conveyed, and typically, specific scales are requested in specific design stages. As the concept of scale cannot be applied for digital building models, an analogue concept must be found.

3.2. Level of Development (LOD)

Several countries worldwide are promoting the research and development of BIM-based methodologies to increase the efficiency of the design, construction and operation of built facilities. As construction projects involve a large number of different parties, a fundamental pillar for integrating BIM is specifying the building elements' maturity at a particular stage. This is crucial for the overall collaboration among the project participants, because this specification acts as an agreement on *what* information should be available at what time (*when*). Based on that information, it can be decided what the model can be used for *(purpose)*, which makes it possible to decide on what model deliverables are expected from the actors involved (*who*) [27]. The exchange of BIM data within the AEC industry must be prescribed through legal agreements where the information for each specific model is specified, meaning that a common legal framework for organizing BIM data is required [28].

As a response to the need of having a consensus about what information should exist during the development of building elements, various guidelines were published to deliver a standard which practitioners can use as a basis for a common language in their projects. The first initiative involved introducing the *Level of Detail (LoD)* [29]. The LoD concept has been adopted and refined by the American Institute of Architects (AIA) to become the *Level of Development (LOD)*, referring to the completeness reliability of the building elements information [30]. Although at that time, it was new in the AEC industry, the *Level of Detail* concept is an old topic that existed in computer graphics. It is used to bridge complexity and performance by regulating the amount of detail used to represent the virtual world [31]. In computer graphics, the LoD concept is mainly concerned with the geometrical detailing, whereas in the AEC industry, the LOD represents the availability and reliability of the geometric and semantic information.

The AIA introduced a definition of the *Level of Development (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 [12].

The BIMForum specification is updated annually to provide a common understanding of the expected information at every LOD. 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 modeled 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, which 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.

In this paper, the abbreviation *LOD* represents the *Level of Development* that comprises both the *Level of Geometry (LOG)* and *Level of Information (LOI)*. The *LOG* and *LOI* abbreviations are used in the next sections for describing the total vagueness associated with the geometric and semantic information.

3.3. Information uncertainty

The assumptions made due to the lack of information or knowledge throughout the design stages is a primary cause of information uncertainty [32]. The presence of uncertainty influences the produced designs and their performance, impacting the decisions made [33]. Typically, exchanging building information between the project participants involves communicating the model's content (BIM model) and additional information describing its reliability (e.g. LOD of building elements). The LOD concept is capable of specifying which information is defined at a particular stage. However, it does not provide the ability to specify additional information that is not certain yet (imprecise or vague) to support the decision-making processes, preparing for the next stage.

Information uncertainty is complex, multidimensional, and has many interpretations. The terms uncertainty, fuzziness, and vagueness are used in various domains and application contexts [33]; most commonly, uncertainty is an umbrella term that describes a lack of knowledge or information, causing the occurrence of an uncertain future state [11]. A fundamental definition of the term *uncertainty* encompasses multiple concepts, liability to chance or accident, lack of knowledge, lack of information, or lack of trust in knowledge [34,35]. On the other hand, vagueness is related to a specific state of a specific object, and it refers to having imprecise or inaccurate information [11,36]. Fisher described uncertainty at a conceptual level as a vague or ambiguous object definition, which refers to the correct use of information [37]. In the context of Computer-Aided Design (CAD) modeling, Steinmann described fuzziness (a synonym of vagueness) as the distance from the complete and exact description [7]. In this paper, we follow the uncertainty definition provided by [38]:

> "a measure of the user's understanding of the difference between the contents of a dataset and the real phenomena that the dataset are believed to represent" [38].

Based on the authors' experience and the knowledge gained from the literature review, the design process uncertainty is categorized as follows:

- *Requirements uncertainty*: The main intentions of the building design, including its usage, environmental impact, and cost, guide the decisions being made. Understanding the client's requirements and decisions is important for an efficient design process [39]. Kometa et al. explain the client's influence on the successful execution of construction projects [40]. Additionally, the source of requirements uncertainty can be regulations and other boundary conditions.
- *Design uncertainty*: Significant decisions in construction projects are reliant on heuristic processes where assumptions are developed from past experience [41]. Typically, the process involves choosing among design alternatives and variants while fulfilling the project goals and requirements. This kind of uncertainty has a wide range of combinations at the early design stages and becomes narrower as more decisions are made in the subsequent stages. Design uncertainty and decisions have an impact on the information flow and

latency [39].

- *Interaction uncertainty*: Design decisions are built on the continuous feedback of information among the participating domain experts. The architect, as a leading discipline for the designing process, evaluates the various requirements, including functional, operational, and architectural requirements, to make design decisions. Architects are usually concerned with *what the building is*, rather than *how the building performs* [42]. Therefore, with the presence of requirements and design uncertainties, the interaction among the project participants is necessary to agree on the model content and incorporate the building performance in making subjective estimations and decisions.
- *Performance uncertainty*: Performing model analysis utilizes the design information as an input. Accordingly, the design and requirements uncertainties, such as material properties, a scenario of use or other boundary conditions, propagate into the analysis results, producing a range or a set of outcomes. This kind of uncertain results inform the architect decisions with regard to developing an optimized solution, fulfilling the project's requirements and boundary conditions.

Fig. 2 illustrates the different kinds of uncertainty and their dependencies. The project's requirements and regulations constrain the resultant design and its performance. Developing the design further requires the involvement of the project participants, since changes to the design impact the building performance. Accordingly, the design is collaboratively developed and evaluated based on the analysis results.

Making design decisions under uncertainty is driven by increasing the confidence that choosing $variant_x$ or $value_a$ will result in a better building solution. 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 in the proposed design, such as changing the overall building shape, increasing its height to add a new storey, or changing the internal spatial structure. Vagueness is related to the reliability of the building elements' attributes and their refinement throughout the LODs, for example, exact position of the load-bearing components and the percentage of the external walls' openings.

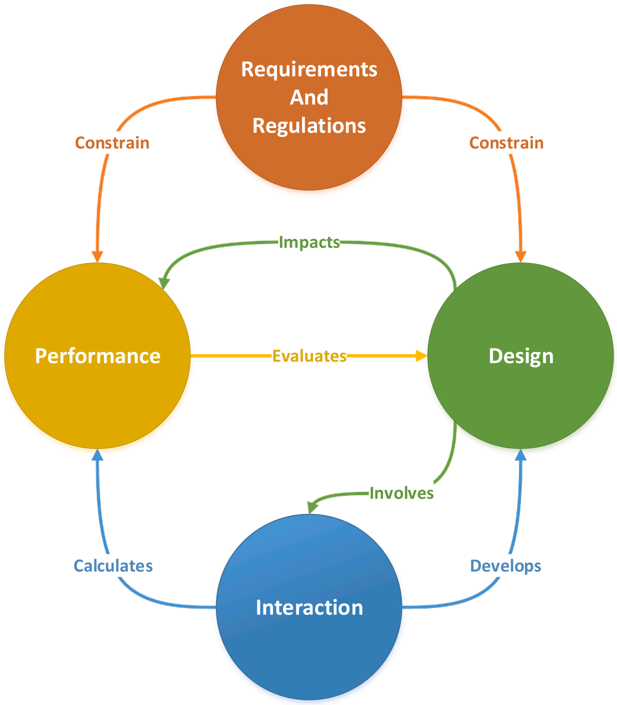


Fig. 2. Classification and dependencies of information uncertainty during the design process.

3.4. Uncertainty visualization

In the process of designing a building, each of the disciplines involved understands and evaluates the proposed design from a different perspective; for example, the architect is concerned with the building's footprint, facade, and interior layout, energy engineers look at the building from the perspective of heat loss and gain, and structural engineers are interested in the performance of the structural system. Hence, visually representing information uncertainty encourages using the domain experts' knowledge, which assists with carrying out tasks more effectively [43,44].

Conveying the quantity of uncertainty in the information is crucial for making rational conclusions [45,46]. This particularly applies to the architectural design and engineering of buildings. Visual communication of information has advantages over verbal description of it, as humans process visual information with high-efficiency [19], which can improve the estimates made [47]. Multiple researchers from different domains, including geospatial information [48], navigation systems [49], and architecture [45,50], have suggested and applied a variety of techniques for visually representing uncertainty. The most common attempts at categorizing uncertainty visualization are:

- Static vs. dynamic approaches [51]: This categorization distinguishes animation approaches from the others. In the same context, numerous researchers have investigated interactive approaches in uncertainty visualization, including animation type, duration, and rate [52–54].
- Gershon proposed two general categories: (1) intrinsic, changes the graphical variables of an object, such as color, transparency, texture, or shape, and (2) extrinsic, involves including additional graphical objects, like text, glyphs, or overlay, to describe the status of an object while leaving the original component unchanged [55].

Several researchers have emphasized the effectiveness of visually depicting uncertainty using visual variables, including intensity, value, lightness, saturation, and opacity [56–58]. Visual variables were first introduced by Bertain [59] as seven *Retinal Variables*, which were subsequently extended by Morrison and MacEachren [60,61], rendering a total of 12 variables: (1) location, (2) size, (3) color hue, (4) color value, (5) grain, (6) orientation, and (7) shape, (8) color saturation, (9) arrangement, (10) clarity (fuzziness), (11) resolution, and (12) transparency.

These visual variables received wide acceptance in the community; for example, Hengl manipulated saturation and color value to display uncertain data in a more white or pale representation [56]. MacEachren proposed that data with less certain information should use a correspondingly less saturated color, thereby making their color hue uncertain [61]. Drecki proposed representing an uncertain object with transparency, as it is not real, while certain objects are visualized in a relatively opaque representation [57]. Brown argued that the perception uncertainty using color variables alone is not high enough. Therefore, he suggested including blurring effects for depicting uncertainty [62].

In the same context, MacEachren considered that texture grain is the most appropriate approach to depict whether information is *certain enough* or *not certain enough* [61]. Davis and Keller suggested that color hue, color value, and texture are potentially the best choices for representing uncertain information using static approaches [51]. Additionally, Schulz et al. used transparency, waveform, and frequency to provide a qualitative analysis of uncertainty [63].

From a different point of view, Pang suggested adding different types of glyphs to describe uncertainty [64]. To include additional information, Finger and Bisantz examined the use of degraded icons combined with a numerical probability estimate [65]. To support the design for flood management, Ribicic et al. used error bars and range symbols over city maps for communicating the uncertainty [66]. Although the extrinsic approaches simplify quantifying the amount of uncertainty, Cliburn et al. cautioned that extrinsic visualization could be confusing or overwhelming [67].

The presented literature discusses visualizing uncertainty in diverse domains. Developing an uncertainty visualization approach for the AEC industry is a challenging task that requires understanding how the individual domain experts perceive building information. This is crucial for understanding how the knowledge of the uncertainties would influence the decisions taken.

4. Multi-LOD meta-model

In practice, it is necessary to explicitly specify which information is reliable and estimate the accuracy of the unreliable information at a specific LOD; an LOD is depicted as a milestone for making design decisions. Consequently, precisely defining the LOD requirements while incorporating their uncertainty improves the quality of the collaborative process among the disciplines.

The management of information on multiple LODs requires both representing the building elements on different LODs as well as providing the ability to specify the required information on each LOD in a formal way. The multi-LOD meta-model, presented in Fig. 3, fulfills these requirements by supporting the following activities [14]:

- Formal specification of the overall information requirements at a particular design stage.
- Formal specification of the individual elements' LOD definitions.
- Formal incorporation of the potential vagueness.
- Representation of the building models' instances at different design stages.
- Verification of building models consistency across the design stages, i.e. ensuring that the decisions made in one stage are respected in the subsequent stage.

The meta-model introduces two levels: *data-model level*, which defines the component types' requirements for each LOD, and *instance level*, which 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 [68].

In more detail, each component type is linked to an IFC type, IfcColumn as an example, and associated with multiple LOD definitions. An LOD definition consists of geometric and semantic requirements, specifying the required geometry representation and properties. The details of each property are determined in addition to the permissible vagueness. In terms of vagueness, a property can be assigned to a vagueness type (classification or probability distribution), a maximum vagueness percentage, and to whether the vagueness values are expected to be as a range.

The vagueness values at the instance level are automatically generated from the vagueness definition specified at the data-model level. For example, in case the vagueness type is a probability distribution, the vagueness percentage is 4%, and the attribute value is 250 cm, the vagueness values are generated to form a range of ±20 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.

A comprehensive explanation and evaluation of the multi-LOD meta-model approach are available in Omniclass [14]. In this paper, the meta-model is extended to support the visualization approaches presented in Section 5. More specifically, the property class at the Data-model level is now assigned to a vagueness definition which specifies the nature of the assigned vagueness, i.e. a range or a set of options.

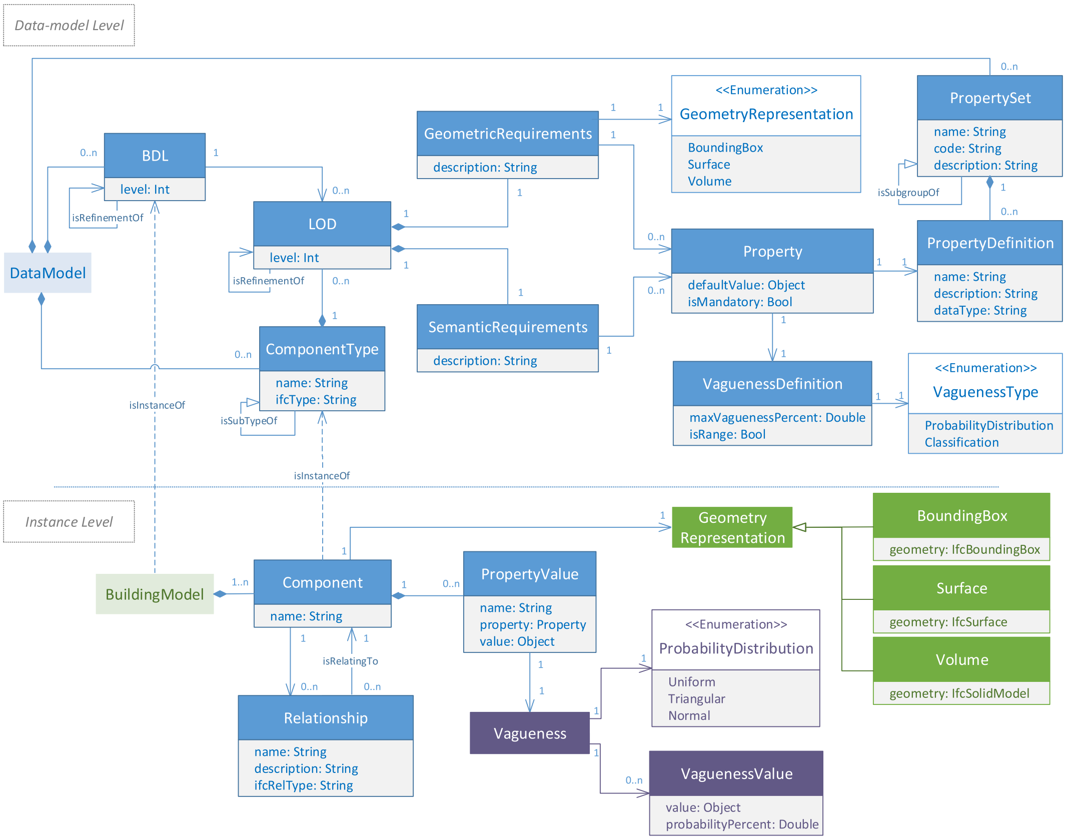


Fig. 3. Multi-LOD meta-model (UML model).

Additionally, at the instance level, the vagueness associated with each property value is now represented by a vagueness value and a probability percentage; this way, it is possible to assign a probability percentage to the individual values in case the vagueness is a set of options instead of a range.

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 architects 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 facilitate the awareness and inclusion of various use cases.

5. Proposed visualization approaches

The vagueness specified in the multi-LOD meta-model represents the reliability of attributes at each LOD. In the meta-model, there are two kinds of attributes: geometric ones, including position, shape, and dimensions, as well as semantic ones, such as construction type, material, and cost information. Visualizing the components' vagueness enhances the engineers' awareness of both the reliability of the visualized information, and how a component might evolve in the subsequent LODs. Additionally, vagueness visualization facilitates evaluating the surrounding components' relationships, which improves the quality of the decisions made.

Fig. 4 illustrates the framework used for vagueness visualization in this paper. It consists of three main steps:

1. *Preparation*, in this step, the actual building model is represented by the multi-LOD meta-model. Thereby, the individual components are mapped to component types, and their properties are assigned to the specified vagueness.
2. *Visualization*, in order to decide which visualization approach is more suitable, the intention and use-case for visualizing the vagueness need to be identified and considered. Analyzing which visualization is more suitable can be done by answering questions such as:
   - Are we interested in acquiring a rough idea about the information reliability?
   - Are we trying to make spatial or topological design decisions, i.e. designing the space program of the building?
   - Are the components' material layers, structural usage, and thermal properties crucial to the task we want to perform?
3. *Application*, the chosen visualization approach influences which view is more applicable and beneficial for understanding the impact of the information vagueness on the design. In this paper, the developed visualization approaches are applied on different scales, starting from a 3D model overview (the entire building) to the storey view, zone/room view, and finally, the walkthrough. The concept is to use the developed visualizations to highlight the potential vagueness for supporting the possible use cases.

To quantify the vagueness of a particular component (total vagueness), the average of the vagueness assigned to each property is calculated. Eq. (1) illustrates how the total vagueness is calculated for the geometric properties (TV_{LOG}) and the semantics (TV_{LOI}) at a particular LOD.

$$TV_{LOG_x/LOI_x}(component) = \frac{1}{n}\sum_{i=1}^{n} PV_{i,LOD_x} \tag{1}$$

where:

TV_{LOG_x}	total vagueness % of geometric properties at a particular LODs
TV_{LOI_x}	total vagueness % of semantic properties at a particular LOD
n	total number of geometric or semantic properties in all LODs
PV_{i,LOD_x}	vagueness % of a property (at index i) at a particular LOD

When calculating the total vagueness of a particular component based on the multi-LOD meta-model definitions, the known properties with a classification vagueness (e.g. when using Omniclass [69] and Uniclass [70] classification systems) are substituted with a percentage that corresponds to the hierarchical depth of the classification system (50% in case of two levels and 33.3% when the classification has three levels). On the other hand, the properties associated with a vagueness of *distribution function* type use the vagueness percentage. Finally, the unknown properties are represented by 100% vagueness.

For example, Fig. 5 illustrates the process of developing a wall throughout the LODs 100–300 with a selected set of properties. Per the BIMForum's specification, at LOD 100, there is no information

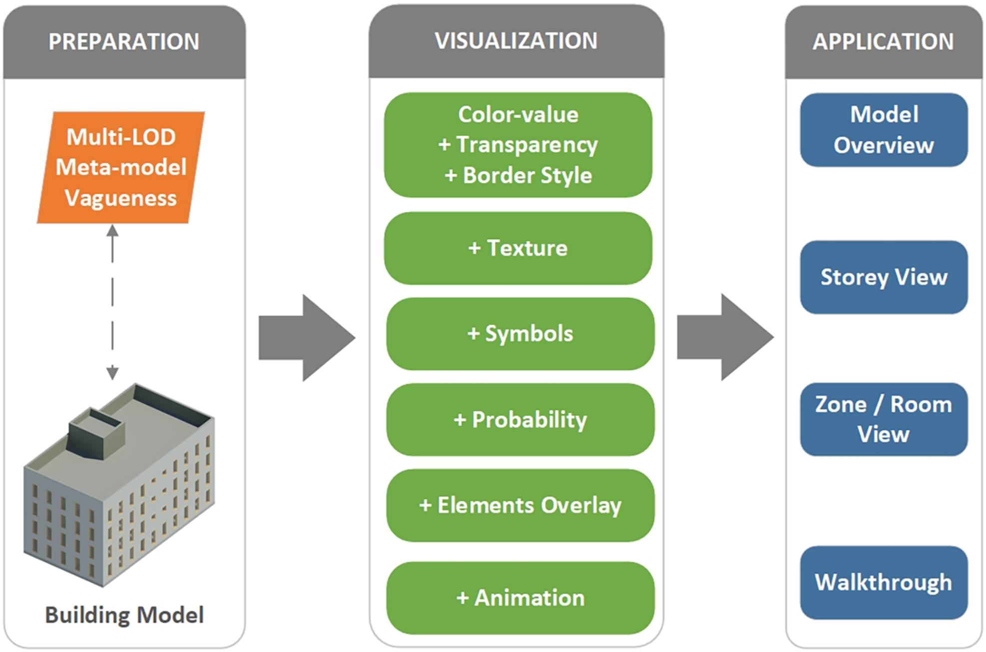


Fig. 4. Vagueness visualization framework that consists of three main steps: (1) *Preparation*, which combines the actual building information with the vagueness defined in the multi-LOD meta-model, (2) *Visualization*, which focuses on selecting a suitable visualization approach for the intended use case, and (3) *Application*, in which the information vagueness is depicted on different scales. The visualization approaches presented here are discussed in detail in this section and evaluated in Section 6 in terms of their user intuitiveness, acceptance, and application v.iew suitability.

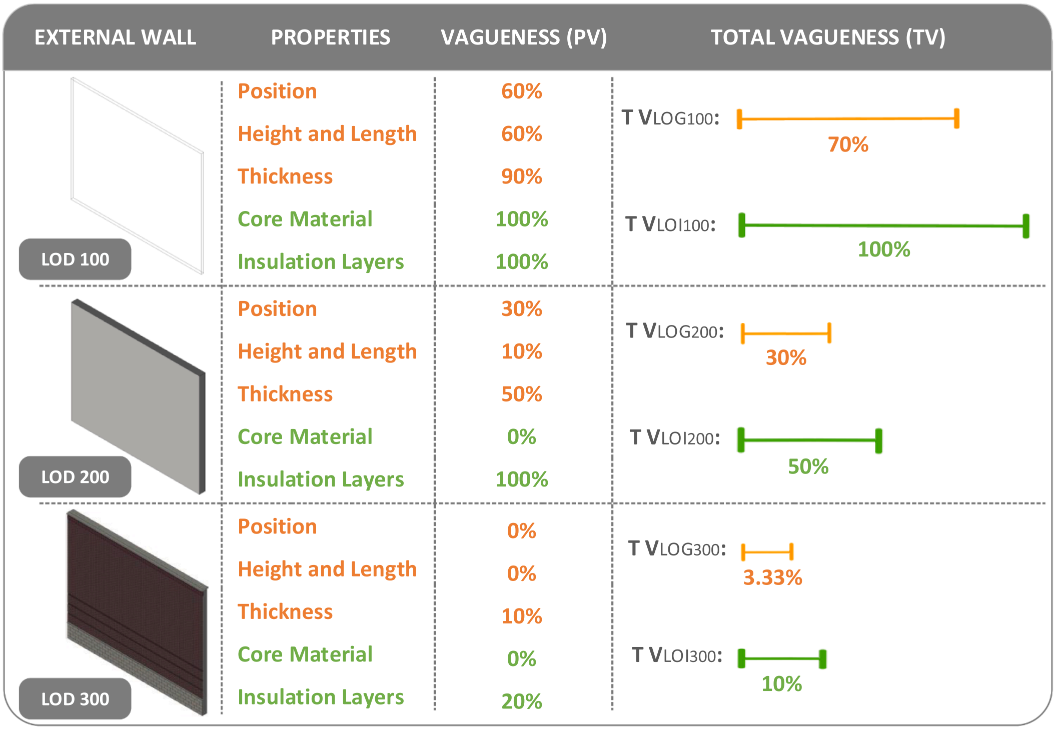


Fig. 5. Total vagueness calculation: external wall example with a selected set of properties throughout the LODs 100–300. The main idea is that the total geometric and semantic vagueness decreases with incrementing the LOD. The percentages provided are based on the authors' interpretation of the BIMForum's specification and practical experience. These estimated percentages describe the potential change in property values in the subsequent stage.

regarding a wall's material layers, and the position, dimensions, as well as the thickness are still flexible. In this case, based on the authors' estimations, the $TV_{LOG_{100}}$ equals to 70%, as it is calculated by averaging the vagueness of all the geometric properties, and the $TV_{LOI_{100}}$ equals to 100%, since information about the main material and insulation layers is not known at this level (completely unreliable). Next, at LOD 200, the main material is defined and the vagueness of the geometric information is reduced. Similarly, at LOD 300, the position and dimensions become fixed, while the material of the insulation layers and their corresponding thickness are still uncertain.

5.1. Static intrinsic approaches

The LOD requirements for the component types can vary from one project to another [12]. Accordingly, in many cases, a component's geometry can be more developed than its semantics. Hence, we propose visualizing the information vagueness for each type separately, using two intrinsic approaches. The first approach aims to express the geometry's vagueness by varying the components' border style in four styles. When the vagueness is high ($>50\%$), it is visualized without a border. Subsequently, when the vagueness is reduced, the border style appears as dotted, dashed, and solid at the end when the vagueness is equal to zero, i.e., the geometry is precise and certain. Similarly, the second approach conveys the semantics vagueness by changing the color value and its transparency in four levels, from light-transparent to dark-opaque.

Fig. 6 illustrates applying the proposed approaches on a simple storey. At LOD 100, walls represent the overall volume, but information regarding the material or construction type is missing. Additionally, thickness and position are still flexible. Therefore, the wall's geometric and semantics vagueness is more than 50%, i.e., represented by no border and light-transparent fill color. At LOD 200 and 300, walls are depicted with dotted and dashed borders because their position and dimensions become more certain.

Additionally, as the walls' main material is known at LODs 200 and 300, their fill color is darker and less transparent than for LOD 100. As described in the BIMForum's LOD specification [12], the walls at LOD 350 have fixed and reliable geometry, $TV_{LOG_{350}}$ equals to zero. Therefore, a solid border style is used. Finally, at LOD 400, the semantic information also becomes certain, as the case for the column in the middle, where the building element is visualized in a solid border style and a dark fill color.

Expressing the vagueness associated with the components' geometry and semantics using two separate approaches is helpful with regard to a variety of decisions, especially for the geometric information, as it is specifically describing the component's shape and position. However, in some cases, when evaluating the structural system or compliance with fire safety regulations, the vagueness associated with the components' structure, including material layers as well as thermal and structural properties, is more important than the other semantic information.

In such situations, employing one indicator for the semantic vagueness might not be sufficient to assist the decision-making process, especially because semantics can include additional diverse information, including vendor, brand, cost, etc. Therefore, a more specialized visualization approach that can depict the vagueness of the components' structure would be beneficial when making design decisions or carrying out different simulations. Accordingly, Fig. 7 shows, an additional indicator representing the elements' structure using four levels of texture grain, starting from no texture when the vagueness is high and then becoming more condensed when the vagueness is reduced.

5.2. Static extrinsic approaches

The proposed intrinsic approaches in the previous section provide an overview of the vagueness corresponding to the entire building model, showing the amount of vagueness associated with all elements. Usually, when designers detail the building model, they evaluate the individual component's positions and dimensions while considering all the possible cases. Therefore, in this section, we propose applying two extrinsic approaches to represent the impact of vagueness on the

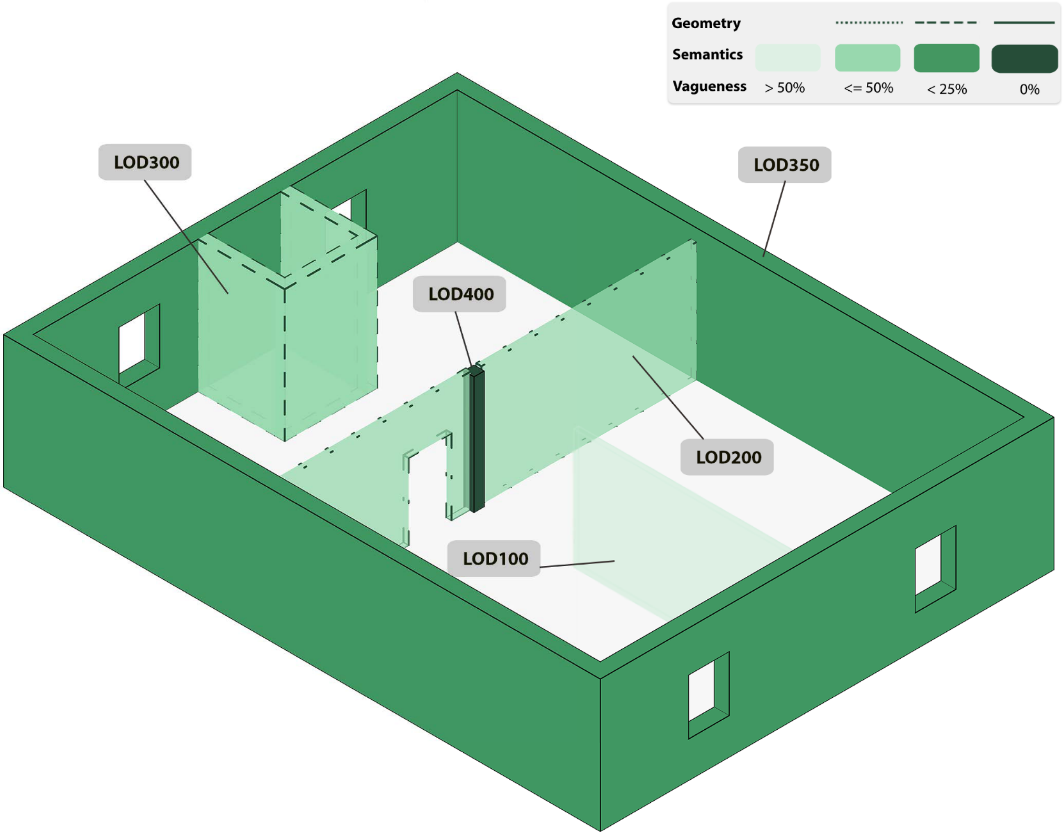


Fig. 6. Intrinsic approach – Border style, color value, and transparency: visualizing vagueness in four levels, >50%, <=50%, <25%, and 0%. Geometric vagueness is represented by a border style ranging from no border to solid style, and semantic vagueness is represented by varying the color and transparency values in four levels, from light-transparent to dark-opaque. Additionally, to make the concept understandable, the LODs are assigned to the different walls based on the definitions available in the BIMForum's specification [12] and in Abualdenien and Borrmann [14]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

possible positions and dimensions.

The first approach includes adding the combination of *property symbols*, *bars*, and *text* with a tilde (~) symbol (showing the possible values as an approximation). The property symbols convey two position types, one for the element's *center position* (a circle) and another for the *surface position* (a rectangle). As discussed in Section 4, the vagueness assigned to a property at the multi-LOD meta-model can be in the form of a continuous range assigned to a probability distribution function

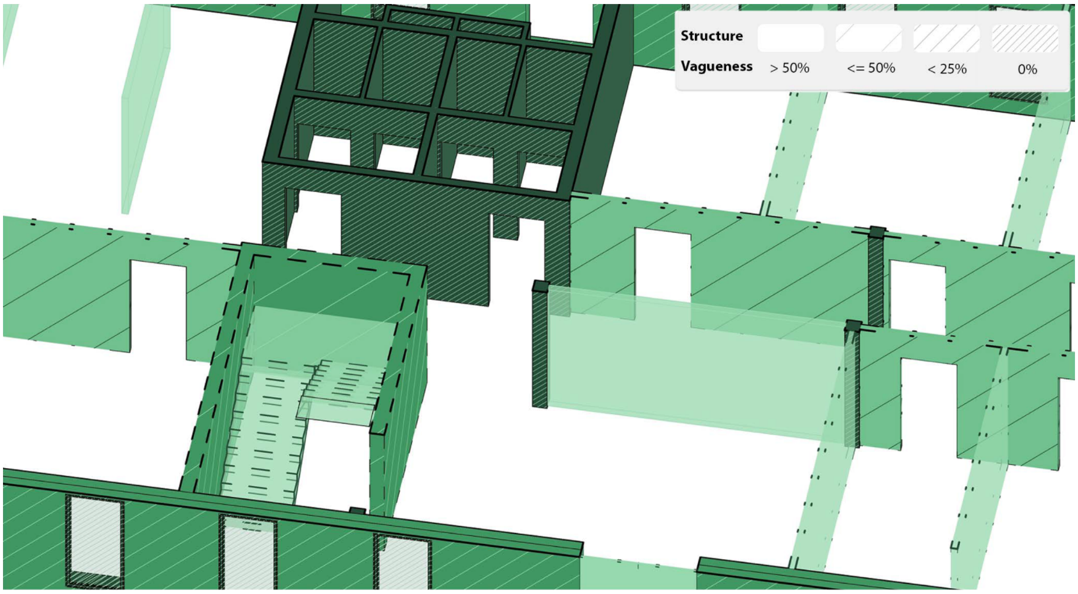
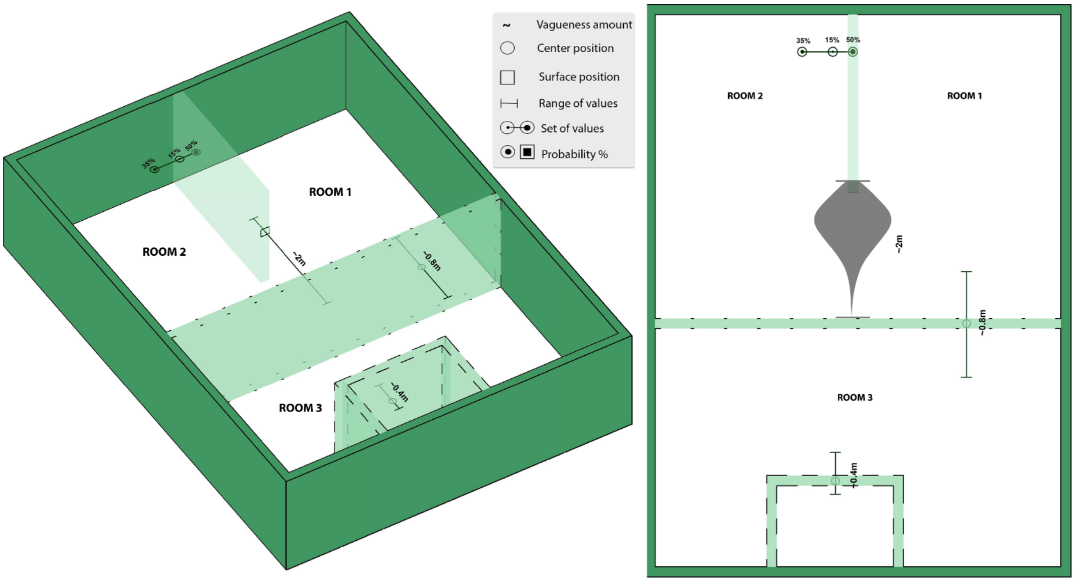


Fig. 7. Intrinsic approach – Texture grain: visualizing vagueness in four levels, >50%, <=50%, <25%, and equals to 0%. This is an extension to the approach illustrated in Fig. 6 where it represents the vagueness associated with the elements' structure, including material layers as well as thermal and structural properties. The approach varies the texture grain in four levels, where the texture becomes more condensed when the vagueness is reduced.



(a) (b)

Fig. 8. Static extrinsic approach – Symbols: 3D and 2D views of expressing the vagueness associated with the surface and center positions using symbols (rectangle and circle, respectively). In the 3D view, the bars are assigned to a rectangular probability distribution function, and the text with a tilde (~) symbol shows the possible values as an approximation. Whereas in the 2D view, an example of depicting a different distribution function is presented. In both views, the possible position options of the wall that separates Room 1 and 2 are shown as circles filled according to the specified probability percentage, the more the circle is filled, the higher the probability.

bounded by an upper and lower limit, or a set of options, in which each is assigned to a probability percentage. If the specified vagueness is *range*, then it is represented by a bounded bar, where the distribution function is depicted over it. Whereas in case of vagueness *options*, each option is shown as a circle or rectangle that is filled according to the specified probability percentage; the more it is filled, the higher the probability. The selection of the symbols is based on an extensive evaluation [71].

Fig. 8 demonstrates the approach through 2D and 3D views. The 3D view shows possible position options for the wall separating Rooms 1 and 2 with circles filled according to the specified probability percentage at the multi-LOD meta-model. Additionally, since the possible values of the length and position can be a continuous range, the vagueness of the other elements is depicted using bars, where the vagueness amount is shown as a descriptive text. Here, we can notice the difference between the symbol used for the center position and the surface position (a circle and rectangle, respectively). Additionally, the bars shown in the 3D view are assigned to a rectangular probability distribution function, while the 2D view demonstrates adding a different probability distribution function. Both approaches were evaluated on two reference projects in Section 6.

The second extrinsic approach signifies the vagueness by generating an overlay over the original element. In this approach, the main focus is to depict the possible changes in the interior layout (room dimensions), which impact the rooms' usage and their available space. Fig. 9 illustrates two examples of the proposed approach to communicate the possible room dimensions due to the vagueness of the interior walls. The 3D view illustrated in Fig. 9a depicts the possible changes in the dimensions of Room 1. Additionally, the vagueness in the inner walls' length influences their function, in this case, from being a room divider to non-room divider, causing Room 1 and Room 2 to be separate. Such a change modifies the spatial structure of the storey, which affects the designed compartments for fire safety regulations, life cycle analysis, and load distribution, where the wall is load-bearing. Fig. 9b shows a different example. The focus here is on indicating that the area of Room 1 can be increased from two directions, towards Room 2 and the corridor; Room 1 can expand to almost half of Room 2, and the position of the wall containing the room door is still flexible in both directions.

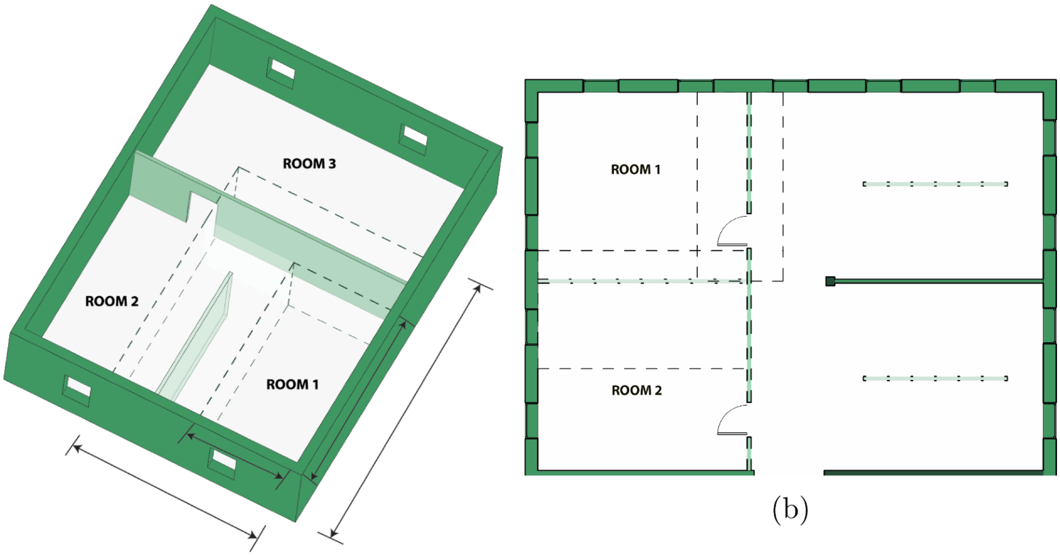
5.3. Animation as vagueness indicator and 3D Walkthroughs perspective

The effectiveness of vagueness visualization approaches is evaluated by measuring the participants' ability to seamlessly perceive and interpret the amount of vagueness in a presented context. In this regard, animation can highlight the differences in the visualization parameters [72–74]. For instance, Lundström et al. introduced probabilistic transfer functions that assign probabilities to different materials. The probabilities are visualized through an animation, where each material is shown for a duration that is proportional to its probability [73].

In this paper, animation is utilized to signify and communicate the impact of the possible positions and lengths of elements. For example, the vagueness associated with the interior walls strongly affects the story's layout and the designed functions. Additionally, when visualizing vagueness using animation, it is crucial to take into account the different topological constraints and relationships, for example, respecting the position of the external walls and door openings.

Fig. 10 illustrates the proposed animations as a video. Here, the interior walls are animated with a speed corresponding to their defined vagueness. In Fig. 10a, the position of the wall functioning as a separator changes more quickly than the other walls because it has higher vagueness, whereas Fig. 10b highlights the impact of changing the storey's topology due to the vagueness assigned to the wall's length, causing the room to be separated and disconnected. Fig. 11 shows an example of applying the proposed animations on a reference project during the conducted surveys and interviews. First, the interior walls separating the rooms are animated relatively faster and with longer distance than the stairs, since walls are associated with higher vagueness. Then, the possible separations of the offices on the other side of the model are depicted by highlighting the change in the interior layout (more details are provided in Section 6).

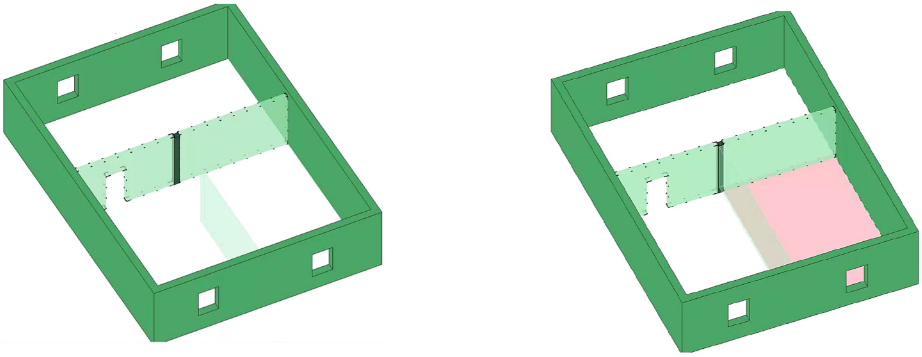
Additionally, Fig. 12 applies animation using the vagueness bars in a way that uses the animation speed to communicate the probability



(a)

(b)

Fig. 9. Static extrinsic approach – Overlay: depicting the possible changes in the interior layout (room sizes and separation) due to the currently defined vagueness. The 3D view, b, expresses that the size of Room 1 can still be reduced or expanded, this can be due to unspecified room usage (e.g., a kitchen vs. a living room). Additionally, Room 1 can be separated from Room 2. In a, the 2D view depicts the possible change in areas assigned to Room 1; its size can be expanded further into Room 2, reducing the size of Room 2. Furthermore, the position of the wall containing the room door is still flexible and can move in both directions.



(a)

(b)

Fig. 10. Animation as vagueness indicator: two techniques for quantifying vagueness by animating the building elements. a utilizes the animation speed to communicate the amount of vagueness; higher speed implies higher vagueness, whereas, b depicts the impact of the elements' vagueness on the interior layout by highlighting the floor of the changing room. The animation is available online (a) https://youtu.be/sCJEsRlSECo — (b) https://youtu.be/NlK6FailauM.

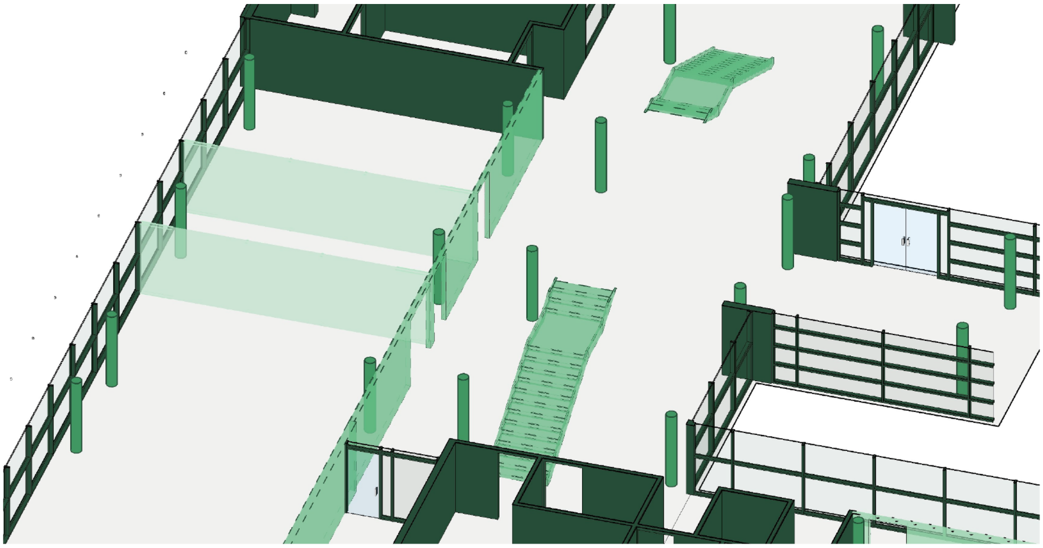
percentage of each value. The assigned distribution function in Fig. 12a is rectangular, and thus the animation speed is the same for all values (the wall stays in each position for the same duration). However, as shown in Fig. 12b, the animation speed increases when the probability gets lower and decreases when the probability is higher, giving the impression that the wall is more likely to be in those positions because it stays in those positions for a longer duration. Based on our evaluations when developing the concepts, using animation can be overwhelming to users, as many aspects might change simultaneously. Therefore, we propose carefully applying animation by confining its application to an individual element and one attribute at a time.

Representing the building in 3D facilitates understanding the relationships between objects. Numerous approaches were investigated and evaluated in the AEC industry to improve the project participants' experience [75]. Walkthrough is one of the most common extensions of 3D visualization; it offers a more realistic depiction of the relationships between elements and fosters a better spatial understanding of the proposed design [75]. The experience resulting from this kind of visualization can highlight essential aspects and provoke detailed discussions, which can lead to the discovery of unexpected conflicts and safety issues when collaboratively working with the different domain experts (in a design review meeting, for example) [76]. Hence, as Fig. 13 demonstrates, the developed visualization approaches were implemented and evaluated from a walkthrough perspective.

6. Evaluation

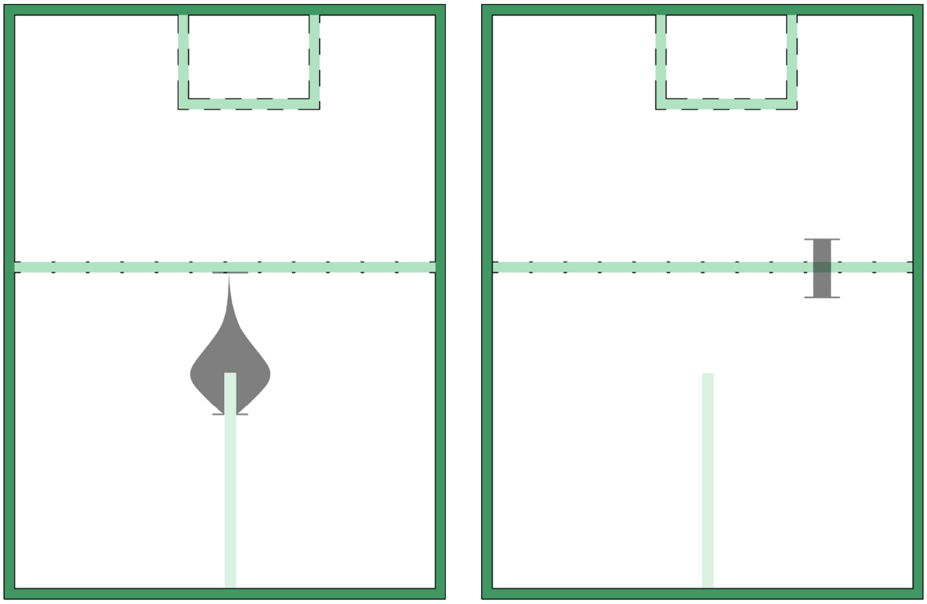
The main focus when evaluating the approaches developed for vagueness visualization is to compare the accuracy of the user's subjective judgment against a ground truth [48]. The approach used in expressing vagueness has a significant influence on visualization effectiveness and usefulness [77]. Performing a user evaluation requires the consideration of multiple aspects, including the user knowledge, visualization type (2D, 3D, or walkthrough), method of depiction (intrinsic, extrinsic, or animation), and the target use case. The evaluation of the approaches presented in this paper took into account accuracy and response time. We conducted an online survey with 60 participants from the industry as well as from research/education and performed interviews with domain experts from three different subcontractors (architecture and engineering offices).

The evaluation utilized the information available from a real project, an office building in Germany (depicted in Fig. 14), and an



(a)

Fig. 11. Animation as vagueness indicator – Example: an example of applying the proposed animations on a reference project during the conducted surveys and interviews. The animation was used to indicate the amount of vagueness associated with the interior walls and stairs. Additionally, the change in the interior layout (possible separations of offices) was highlighted. More details are provided in Section 6. The animation is available online https://youtu.be/TyytLIMzHqE.



(a) (b)

Fig. 12. Animation as vagueness indicator – Probability: including probability distribution and using animation speed to emphasize on the most probable position, the longer the wall stays in a particular position, the higher the probability. The animation is available online (a) https://youtu.be/PXgc1qO7xas — (b) https://youtu.be/WotYEXyn_Hw.

Autodesk sample project[1] (illustrated in Fig. 15).

6.1. Proof of concept

To evaluate the proposed visualization approaches, a proof of concept was implemented as an Autodesk Revit[2] plugin and Unity[3] 3D walkthroughs. While the capabilities of Unity are well known in visualization and animation, it was also feasible to apply different coloring, textures, border styles, as well as symbols, change element dimensions, and change element positions to realize the proposed animations using the Revit Application Programming Interface (API). Both prototypes provide interactive interfaces for users to navigate and review the different aspects of the building design.

6.2. Online survey design

The proposed visualizations and the prototype were evaluated by conducting an online survey. The approaches were presented to the participants gradually to assess the influence of each. First, varying the *Color Value* to represent the geometric and semantic information was evaluated. Next, the other approaches, *Border Style*, *Transparency*, *Texture Grain*, etc. were included step by step.

The survey was designed using a framework called *LimeSurvey*,[4] which makes it possible to capture the time participants took to answer

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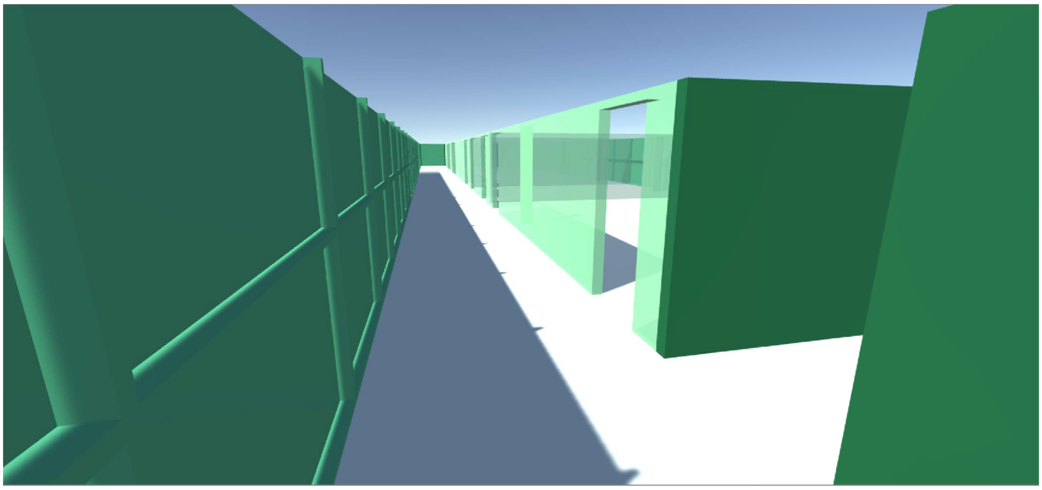
[1] https://autode.sk/2qLXiVV.

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

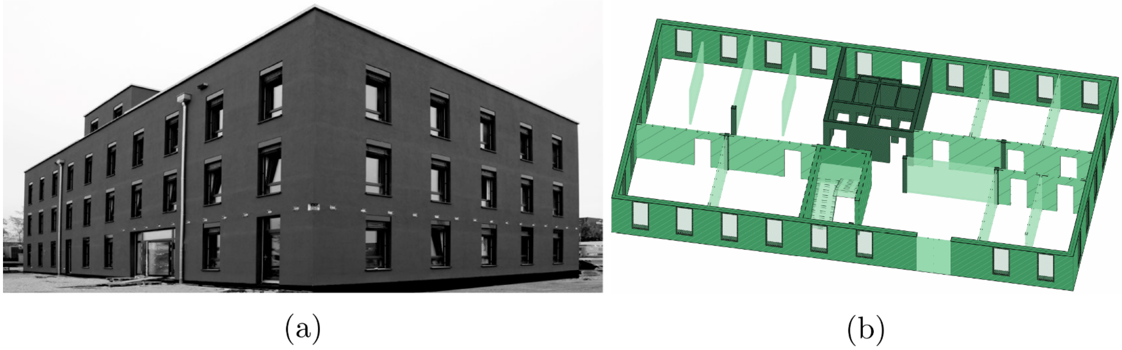
[3] https://unity.com/.

[4] https://www.limesurvey.org/.



(a)

Fig. 13. Walkthrough perspective: an overview of the implemented use cases. The user can walk through the building model and review the different aspects. The walkthrough is available online https://youtu.be/x6GsGSbzFSs.



(a) (b)

Fig. 14. Evaluation of reference project #1: Ferdinand Tausendpfund GmbH & Co. KG office building, in Regensburg, Germany, built in 2017. (a) is a picture of the actual building, and (b) is a snapshot depicting the first storey of the BIM model, including an application of the proposed visualization approaches.

each of the questions. The survey aimed at identifying extent to which participants understood each of the proposed visualization approaches and measuring the intuitiveness of each approach. A set of 22 required questions examined the participants' understanding using single and multiple-choice options. The expected answer (100% correct) for each question consists of one or multiple options, where the 100% distributed equally over the number of correct options. Additionally, at the end of the survey, participants ranked the acceptance of each visualization approach on a scale of one to five, with one being strongly disagree and five being strongly agree. Additionally, they were asked to choose which visualization approach is more applicable for each of the application views (model overview, storey view, zone/room view, and walkthrough).

The survey began with a descriptive overview of the purpose of the visualizations, and then specific explanations were provided for each question. The answers and response times were automatically collected in a database through a functionality provided by LimeSurvey. An invitation to participate in the survey was sent to multiple subcontractor offices as well as to graduate students (masters and doctorate levels) from diverse but relevant domains of the Technical University of Munich (TUM).[5] A majority of the students attended lectures in which the motivation for the visualizations was explained. Fig. 16 presents the list of participants grouped by domain. In total, 60 participants took part in the survey.

6.2.1. *Online survey: results*

Survey responses were evaluated and ranked in terms of accuracy by taking into account the expected answers and the corresponding response times.

Fig. 17 presents a comparison of the intuitiveness and response time of the developed approaches. The values shown represent the average and standard deviation for each approach. First, *Color Value* (varies the fill color value from light to dark green) attained an acceptable level of intuitiveness and response time. Then, adding the *Border Style* improved the intuitiveness and reduced the differences among the participants' response times. Including *Transparency* to the fill color value as well as adding *Animation* made a noticeable improvement in the intuitiveness and the response time.

Although the results of using *Texture Grain* to represent the building elements' structure and *Symbols* to communicate the possible positional values were relatively lower than the others, the results were acceptable. However, the *Overlay* approach as well as adding *Probability* were not ranked as intuitive; intuitiveness was drastically lower in this case than the other approaches and the participants' response time was longer.

As the order of the survey questions started with evaluating the *Color Value* first, followed by adding *Border Style*, *Transparency*, etc., an improvement in the participants' performance is reflected in the results; response times became shorter and more consistent and intuitiveness increased. This indicates that the developed approaches entail a learning step for the participants, making the developed approaches

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[5] https://www.tum.de/.

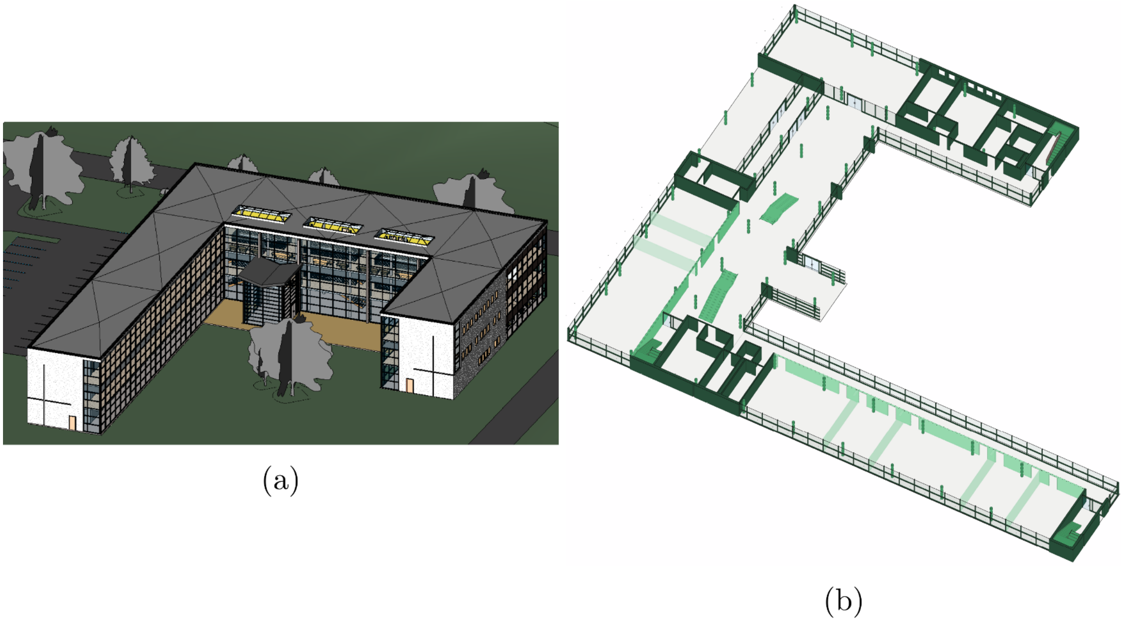


Fig. 15. Evaluation of reference project #2: Autodesk sample project. (a) is a picture of the actual 3D model, and (b) is a snapshot of the first storey, including an application of the proposed visualization approaches.

Participants	Count			
Domain	**Education /Research**	**Industry**	**Total**	
Architecture	12	5	**17**	**28.3%**
Civil Engineering	18	3	**21**	**35%**
Environmental Engineering	3	1	**4**	**6.7%**
Computer Science	7	3	**10**	**16.7%**
Graphic Design	3	2	**5**	**8.3%**
Other / Not Specified	3	0	**3**	**5%**

Fig. 16. Online survey: list of participants grouped by domain. Each domain is split into two categories: *Education/Research*, for masters and doctorate students, and *Industry* for the employees working in subcontractor offices.

easier to understand with time and practice.

In a different set of survey questions, the participants were asked to select which visualization approaches are applicable for each application view, including *Model Overview*, *Storey View*, *Room/Zone View*, and *Walkthrough*. As shown in Fig. 18, using *Color Value* + *Transparency* was ranked the highest among the other approaches for communicating the vagueness of the overall building model, storey view, and walkthrough. For the room view, five out of seven approaches yielded equivalent results and received over 80% of the votes. Although the *Color Value* approach is highly similar to *Color Value* + *Transparency*, it was not ranked as highly acceptable for any of the evaluated views (received a maximum ranking of 68% for storey view), which means that adding transparency and border style assisted in making the approach more understandable and suitable.

Considering a different visualization approach, varying the *Border Style* also received relatively high votes with both views, storey view

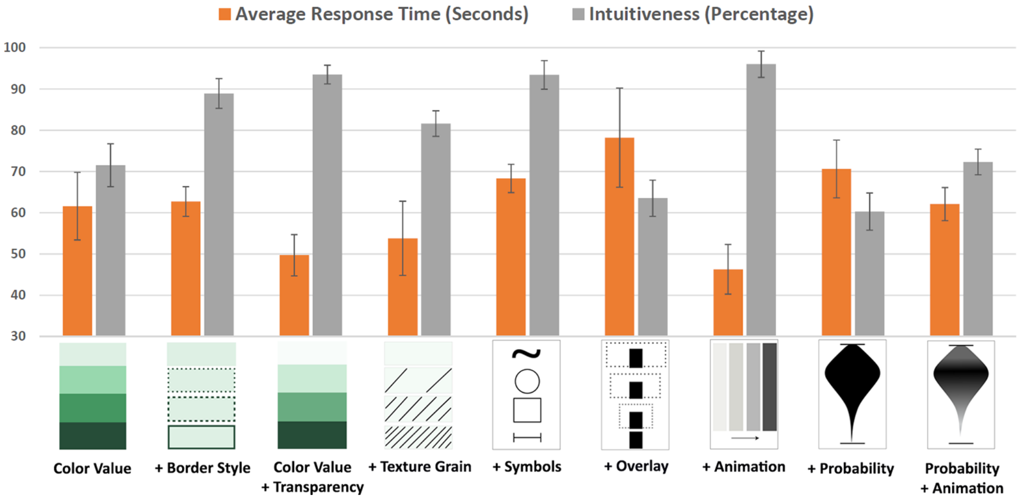


Fig. 17. Survey results – intuitiveness: the developed approaches were evaluated in terms of intuitiveness, taking into account the expected answers and the corresponding response time. The values shown here represent the average and standard deviation for each approach.

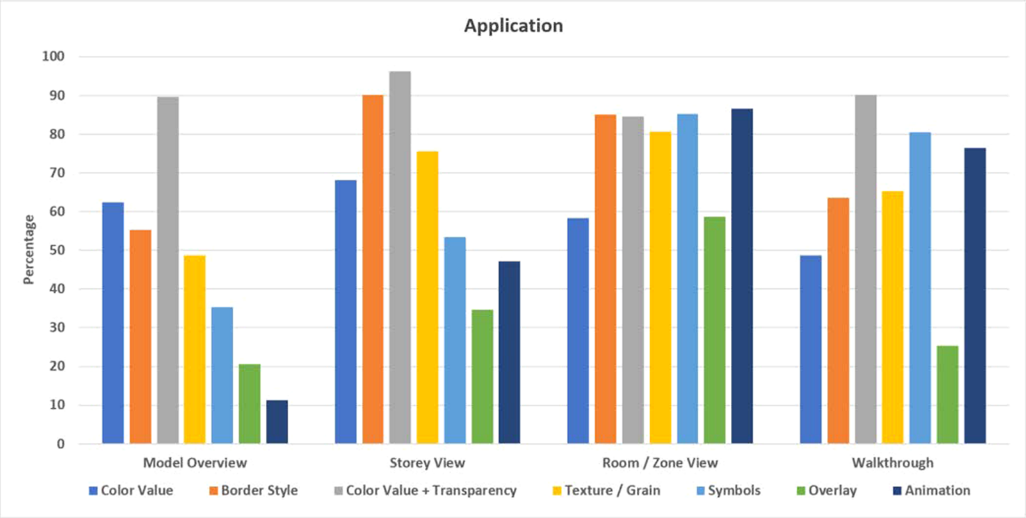


Fig. 18. Survey results – Application View: participants were asked to choose which visualization approaches are suitable for each application view, including *Model Overview*, *Storey View*, *Room/Zone View*, and *Walkthrough*.

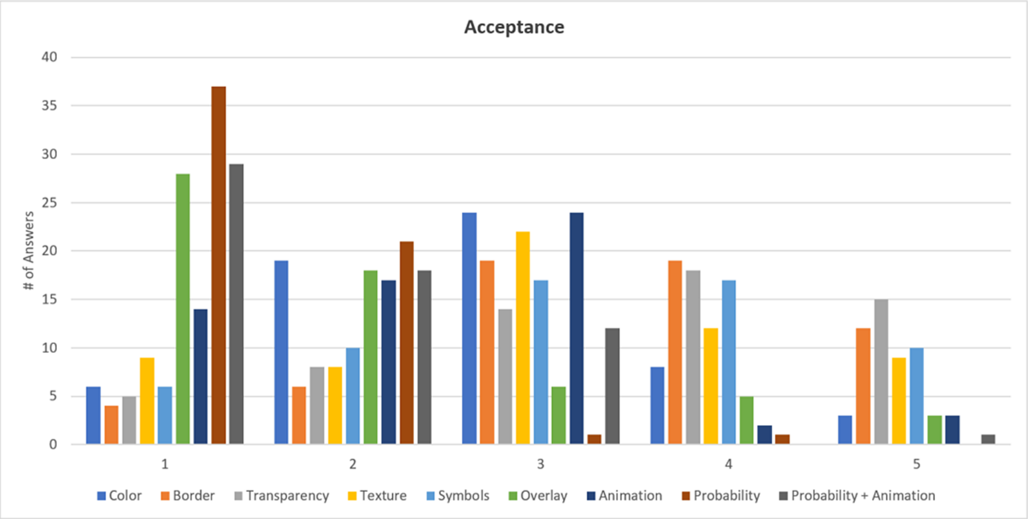


Fig. 19. Survey results – Acceptance: participants were asked to compare the visualization approaches by specifying the degree to which they would accept to use them in their practical work. The question allows participants to rank each approach in terms of acceptance, using a scale from 1 to 5 (strongly refrain from using, rather not, neutral, accept, and strongly accept).

and room view, in comparison to others (with a rank of 90% and 82%, respectively). The *Texture Grain* approach was ranked more applicable for the storey and room views than the other views (with 76% and 81%, respectively). The *Symbols* and *Animation* approaches attained a similar acceptance pattern; they received high applicability rankings for the small-scale views (room view and walkthrough) and low applicability for the large-scale views (model overview and storey view). Finally, the *Overlay* approach did not perform well in any of the views. The reason can be deduced from the results presented in Fig. 17, low intuitiveness and long response time.

Finally, the participants were asked to compare the visualization approaches by specifying the degree to which they would accept using the approaches in their practical work. The questions allowed participants to rank each approach on a scale from 1 – 5 (strongly refrain, rather not, neutral, accept, and strongly accept).

As Fig. 19 illustrates, the majority of the participants decided not to use *Probability*, *Probability + Animation*, or *Overlay*, where the 80%, 78.3% and 76.6% values, respectively, represent the percentage of the votes for *strongly refrain* from using and *rather not* use these approaches. On the other hand, varying the *Color Value + Transparency* and *Border Style* performed the best with 55% and 52%, respectively, representing the percentage of votes for *accept* and *strongly accept* to use the approaches. In the end, if all the votes for the *neutral* option are also included in the percentage of votes, the *Color Value + Transparency* and *Border Style* approaches received 78.3% and 83.3%, respectively, as the ranking of voters who did not choose to refrain from using them.

The other approaches, *Symbols*, *Texture Grain*, and *Animation*, received lower acceptance rankings (45%, 35%, and 9%, respectively) and higher neutral rankings (28.3%, 36.6%, and 40%, respectively). According to the intuitiveness results presented in Fig. 17, animation is well suited to represent positional uncertainty, as more participants interpreted the animation correctly, compared to the static visualizations. However, contradictory to those results, the acceptance results make it evident that participants showed a clear preference for the static visualizations over animation.

After compiling the survey results, we tried to deduce a relationship between the participants' results (intuitiveness, applicability, and acceptance) and their domain knowledge or familiarity with 3D models. The hypothesis assumed that the visualizations would be more intuitive and acceptable with more familiarity or relevant experience. However, the results did not reveal any pattern that would positively support this hypothesis.

6.3. Interviews

First, the interviews were conducted with subcontractors

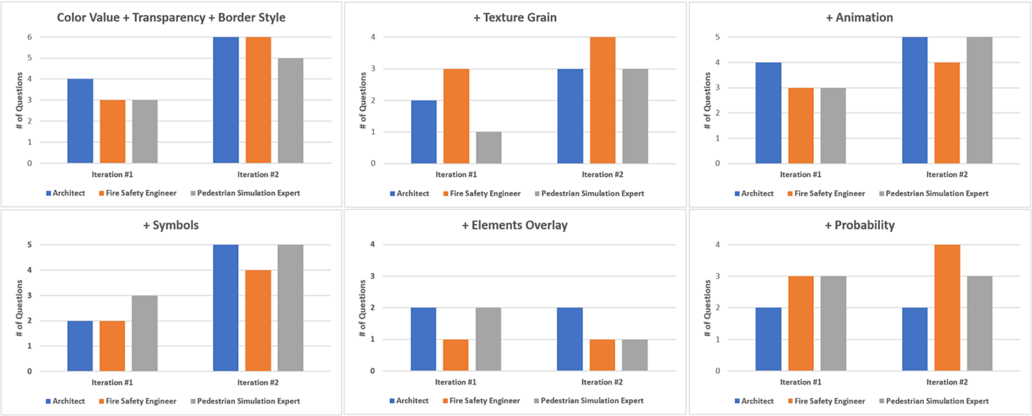


Fig. 20. Survey results – Interviews: the developed approaches were evaluated through two iterations in terms of intuitiveness. The y-axis represents the number of questions asked for each approach, and the x-axis depicts the intuitiveness results of both iterations.

experienced in either architectural designs, fire safety simulations, or pedestrian flow simulations. The interviews were conducted in two iterations, where the feedback obtained from the participants in the first iteration, regarding possible use cases, was considered in the second iteration. Each iteration consists of a series of questions, including identifying elements with a particular geometric or semantic vagueness, as well as carrying out tasks from the subcontractor perspective, for example, accounting for the impact of vagueness while performing analyses or making a change in the design. The questions and tasks included in each iteration were designed to evaluate the intuitiveness of the approaches. After each iteration, the responses were reviewed and assessed.

6.3.1. *Interviews: analysis of responses*

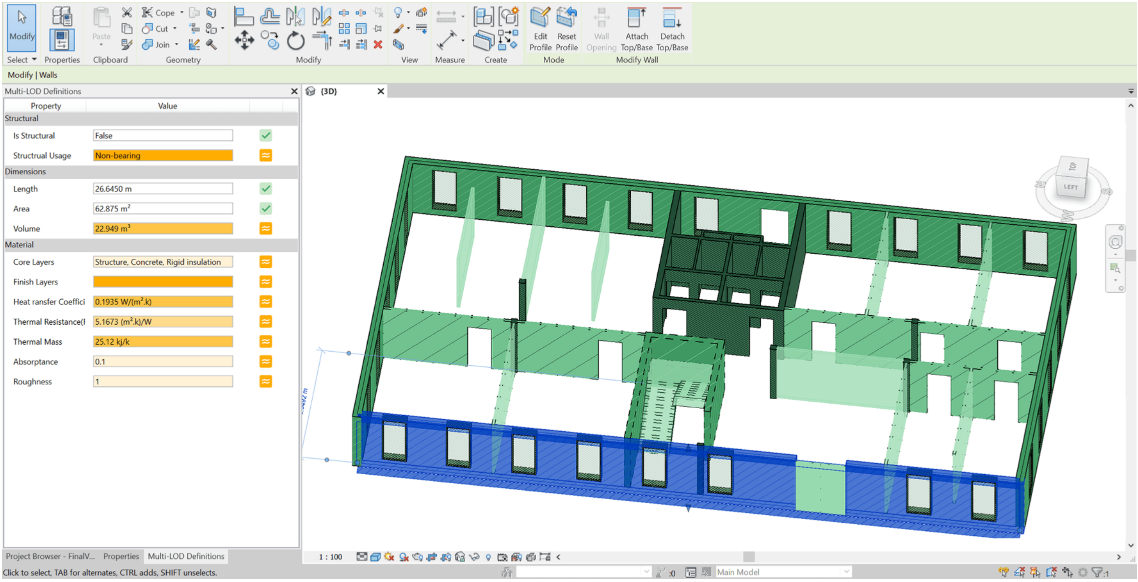
Fig. 20 presents the results of both interview iterations. The y-axis represents the number of questions asked for each approach, and the x-axis depicts the intuitiveness results of both iterations. Except for the *Overlay* approach, the intuitiveness of the approaches noticeably improved in the second iteration; the participants correctly interpreted the information vagueness in most of the approaches. However, similar to the online survey results presented in Fig. 17, the results of the *Overlay* approach showed relatively low intuitiveness in both iterations.

At the end of the interviews, participants were asked to propose new approaches or extensions to the developed approaches. Two subcontractors proposed extending the BIM authoring tools by including additional indicators over the elements' properties, as illustrated in Fig. 21. In this case, when the orange color is darker, it implies that the vagueness is higher, and when there is a check mark beside the property, it implies that it is fixed and certain.

7. Conclusions and future research

Information vagueness is a fundamental issue affecting the process and outcome of 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 facilitates managing the building information throughout the different stages. It makes it possible to formally specify the required information, including a description of the potential vagueness. Additionally, it represents the individual components of the actual building model and verifies information consistency across the design stages.

Expressing the amount of vagueness using visualization techniques assists in evaluating how the model can evolve in the subsequent stages. This paper contributed multiple visualization approaches for depicting vagueness associated with building information models. The



Multi-LOD Definitions

Property	Value	
Structural		
Is Structural	False	✓
Structrual Usage	Non-bearing	≈
Dimensions		
Length	26.6450 m	✓
Area	62.875 m²	✓
Volume	22.949 m³	≈
Material		
Core Layers	Structure, Concrete, Rigid insulation	≈
Finish Layers		≈
Heat ransfer Coeffici	0.1935 W/(m².k)	≈
Thermal Resistance(I	5.1673 (m².k)/W	≈
Thermal Mass	25.12 kj/k	≈
Absorptance	0.1	≈
Roughness	1	≈

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Fig. 21. Interviews – Proposed extension: extending BIM authoring tools by the inclusion of additional indicators over the elements' properties. When the orange color is darker, it implies that the vagueness is higher, and when there is a check mark beside the property, it implies that it is certain.

approaches developed here aim to address the problem of communicating the information vagueness among the project participants, especially at the early design stages, to support the decision-making process.

The developed approaches were evaluated through an online survey and interviews. The evaluation results positively indicated the participants' ability to use the developed approaches to understand the amount and impact of the vagueness associated with the geometric and semantic information. More specifically, varying the building elements' border style for representing vagueness of the geometric information, and using the combination of color value and transparency for quantifying the reliability of the semantics resulted in relatively high intuitiveness and acceptance by the participants. Hence, using those approaches as a basis for the other approaches assisted in expressing the vagueness associated with more specific use cases, such as including texture for describing the structure reliability as well as animation and symbols for depicting the potential lengths and positions. Additionally, although the participants took relatively less time to solve the survey tasks correctly when animation was included, they preferred the static approaches more.

Based on the experience gained from this research, attempting to communicate the vagueness of multiple building elements or properties simultaneously can be overwhelming to users. In the same context, some domain experts preferred managing the information vagueness solely through attaching it to the individual properties rather than relying on the visualization approaches. In this regard, the visualization approaches presented in this paper can express the information vagueness on various scales, from the overall building model (where the properties' vagueness are aggregated) to the individual elements (where the properties' vagueness are presented as they are), like position and length. Furthermore, the extension proposed by the conducted interviews, shown in Fig. 21, depicts the associated vagueness information on both the 3D representation as well as the individual properties. Typically, reluctance in using new visualization methods can be reduced through the users' practical evaluation in real-world projects. Certainly, more research is required to advance uncertainty visualization methods further, refine our findings, and provide more evidence.

The developed visualization approaches were evaluated on building models. As a next step, further research is necessary to collect and support infrastructure use cases, such as bridges and tunnels. Accordingly, these approaches can be refined and extended to convey specific and relevant indicators for each particular case. Finally, the exploration and evaluation of the benefits that additional visualization approaches, such as virtual and augmented reality, could support more advanced use cases, such as accounting for the condition and context of construction site by establishing early feedback on the constructability of the developed design.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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