ARCHITECTURAL INFORMATICS SOCIETY

Classified voxel visualization to secure building occupants' EHS

Ai Kasai*[1] and Tsukasa Ishizawa[2]

[1] Project Researcher, Institute of Industrial Science, The University of Tokyo
[2] Project Associate Professor, Institute of Industrial Science, The University of Tokyo

* kasai-ai@iis.u-tokyo.ac.jp

Abstract

This study empirically investigates how differences in information presentation affect interior designers' initial understanding of Environment, Health, and Safety (EHS) design intent during the renovation phase of existing buildings, where such intent is often insufficiently shared. EHS-related spatial constraints were restructured into three action-oriented categories—prohibited placement, avoidance of fixed objects, and cautionary placement—and visualized using voxel-based representation with a hierarchical priority structure. A staged workshop was designed in which information was sequentially presented through drawings and BIM models, color-coded voxel visualization, and written explanations of design intent. The workshop was conducted primarily with architecture students. The results indicate that drawings and BIM models alone were insufficient for establishing an understanding of many EHS elements, particularly those related to ceiling-mounted equipment and operational requirements. In contrast, voxel-based color coding enabled participants to promptly identify constrained areas ("where"), while written explanations of design intent supported the understanding of underlying rationales ("why") that could not be conveyed through visual cues alone. These findings suggest that an information structure that incrementally integrates visual localization ("where") and semantic explanation ("why") is effective for connecting EHS design intent to early-stage layout decisions. This study proposes a practical framework for restructuring information to support the communication of design intent in building renovation contexts.

Keywords

Building Information Modeling (BIM); Environmental Health and Safety (EHS); spatial constraints; information visualization; design rationale

Type: Research Article

Citation: F. Author, S. Author an T. Author, "How to write a peer-reviewed paper of the Journal of Architectural Informatics Society: ver. 20231125," Journal of Architectural Informatics Society, vol. 0, no. 0, pp. a1-aXX, Nov. 2023. doi: https://doi.org/xx.xxxx/xxxx/xxxxx

Received: 15 April 2020
Revised: 29 December 2021
Accepted: 05 January 2021
Published: 10 January 2021

Copyright: © 2021 Author F et al. This is an open access article distributed under the terms of the Creative Commons Attribution License(CC BY-SA 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. If you remix, transform, or build upon the material, you must distribute your contributions under the same license as the original.

1. Introduction

The importance of architectural planning that ensures Environment, Health, and Safety (EHS) for building occupants has been widely recognized [1], [2]. To comply with EHS requirements during a building's operational phase, various spatial constraints must be considered. EHS is commonly used as a practical framework that comprehensively addresses indoor environmental conditions, occupant health, and safety. However, previous studies have reported that the building environment involves multiple interrelated factors, making EHS management and operation inherently complex [3], [4].

From a health perspective, the need to prevent the intrusion of pollutants into indoor spaces has been highlighted [5], and insufficient ventilation has been shown to affect health, cognitive performance, and safety negatively [6], [7]. In terms of safety, inadequate provision of evacuation routes during fires poses significant risks [8], [9], and obstacles that interfere with sprinkler discharge may contribute to fire spread [10]. Designers are therefore required to develop layout and placement plans that satisfy these spatial constraints under predefined design conditions [11]. Accordingly, EHS-related design intent must be appropriately carried over into the operational phase of buildings [12], [13], [14].

In practice, however, during renovations or layout modifications of existing buildings, the original design intent is often not adequately preserved. As a result, EHS requirements such as securing evacuation routes or maintaining equipment inspection spaces are frequently overlooked in the design process. Even when a layout appears functionally viable, it may fail

to meet the intended EHS standards, potentially affecting occupant health and safety [15].

This discontinuity can be attributed to the structural characteristics of the building lifecycle, in which diverse stakeholders participate intermittently from design through operation [16], [17] (Figure 1). While design information at the time of construction is typically documented in drawings, information related to mechanical and electrical systems is often fragmented by discipline and not systematically maintained through the operational phase. Building Information Modeling (BIM) has been proposed as an effective means of integrating such information [18] and as a potential vehicle for delivering EHS-related value to building occupants [19]. Nevertheless, barriers to adoption due to unfamiliarity with BIM remain [20]. In large office buildings, frequent tenant turnover further exacerbates this issue, as different interior designers may join renovation projects for short periods, increasing the risk that design intent is not adequately shared.

Under these conditions, interior designers are required to make rapid, action-level decisions from the early stages of design, such as determining where objects may be placed and which areas require special attention. However, EHS information recorded in drawings and BIM models is often fragmented and not presented in a form that directly supports such decisions. Although voxel-based representations focusing on a single design intent have been reported [21], [22], there are few examples of integrating multiple EHS factors and structuring them into decision-oriented criteria for layout planning. Previous studies have suggested voxel-based approaches for intuitively grasping EHS-related spatial constraints [23]; however, the scope of these studies did not extend to integrating multiple EHS factors into decision-oriented criteria for early-stage layout planning, nor to systematically examining how differences in presentation formats affect users' understanding in renovation contexts. In such contexts, interior designers may struggle to grasp the necessary judgment criteria during early design stages. In particular, systematic investigation into how differences in information presentation formats affect users' understanding remains limited, especially in renovation contexts.

Based on this background, this study investigates how differences in information presentation formats that combine spatial visualization of EHS-related constraints with explanatory information on design intent influence interior designers' understanding of design intent and their early-stage layout decisions in renovation contexts.

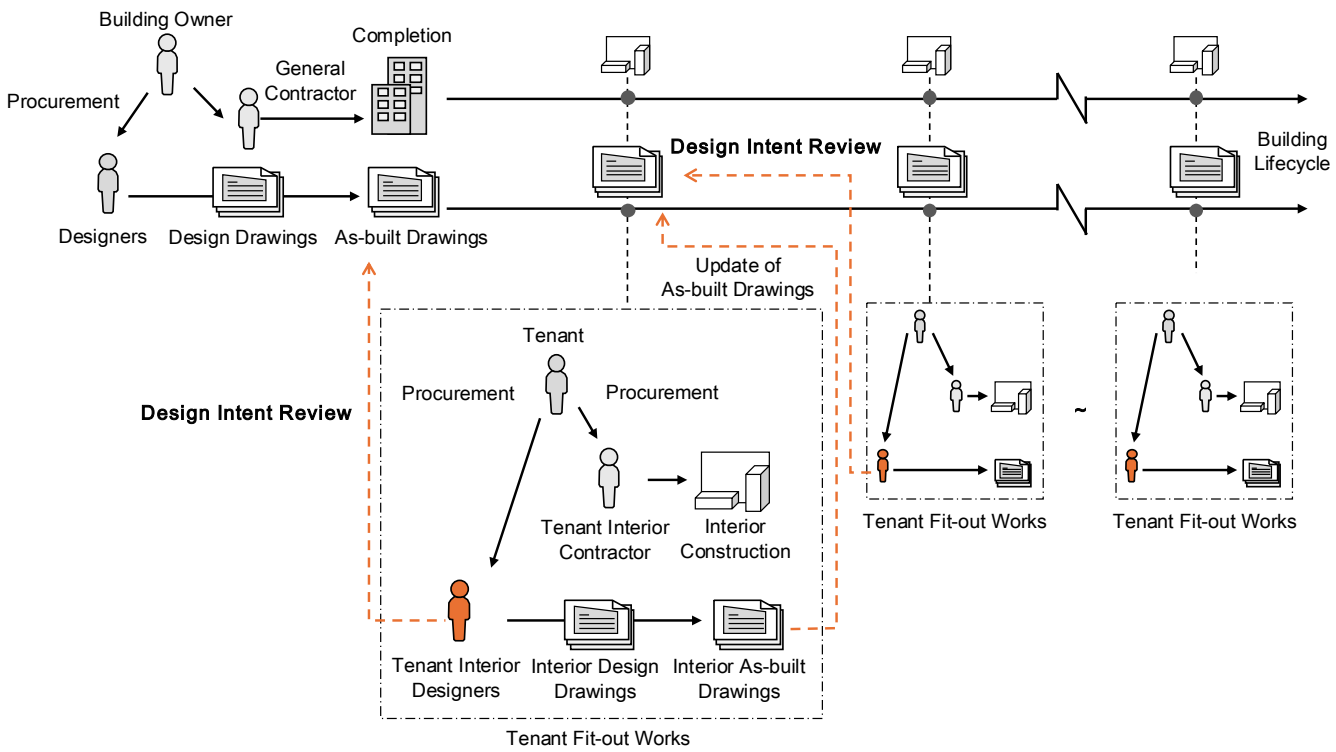


Figure 1. Stakeholders and drawing flow across the building lifecycle.

2. Methodology

2.1. Methodological framework

This study addresses the practical challenge that EHS-related spatial constraints are often insufficiently shared during building renovations and aims to compare and examine how differences in information presentation formats influence the understanding of design intent. One of the authors has professional experience in mechanical and building services design and has encountered difficulties in communicating design intent to interior designers during renovation projects. This positionality informed the problem setting of the study and motivated the need to reconstruct EHS constraints at the level of action-oriented decision making.

To achieve this objective, the study adopts the Design Science Research Methodology (DSRM) [24]. Figure 2 illustrates the research flow of this article. DSRM structures research into six steps, including problem identification, solution design, demonstration, and evaluation. This study is positioned at the second step, "Define Objectives of a Solution," as its entry point.

The Introduction corresponds to the first DSRM step, "identify problem & motivate," by outlining the background and practical impact of EHS information discontinuity. It also addresses the second step, "define objectives of a solution," by clarifying the research focus on differences in information presentation formats. Based on this problem formulation, the subsequent sections follow the DSRM flow: Methodology presents the experimental framework, design & development describes the workshop design, results report the empirical findings, and discussion/evaluation analyze and interpret the outcomes.

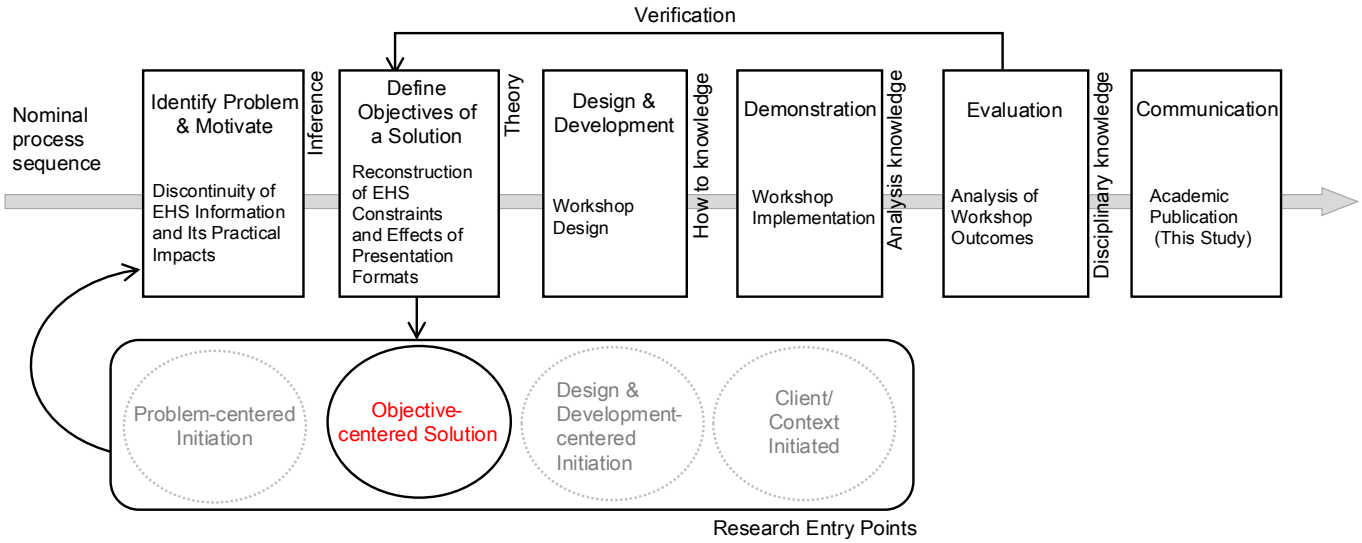


Figure 2. Research process based on the Design Science Research Methodology (DSRM).

2.2. Conceptual framework

As an existing method for visualizing design intent and EHS-related spatial constraints at the voxel level, this study refers to Indoor Voxel Visualization (IVV) [23]. IVV subdivides space into uniform voxel units and assigns constraint-related information extracted from BIM to each voxel, providing a voxel-based framework for spatially associating EHS-related constraints with building elements. It also provides a structure that links voxel identifiers to detailed explanatory documents and historical information, allowing design intent to be traceable during the operational phase after completion.

Figure 3 illustrates a reconstructed IVV configuration diagram based on one previously presented by the authors at an international conference, focusing on information flows relevant to interior designers. As the objective of this study is to evaluate the effects of presentation formats on understanding, only the visualization components referenced by interior designers were used in the empirical study. Upstream IVV processes, such as automated BIM data extraction and document generation, were excluded from evaluation to isolate the impact of visualization formats. The voxel data used in the experiment were manually constructed within the necessary scope to enable a controlled comparison of presentation effects.

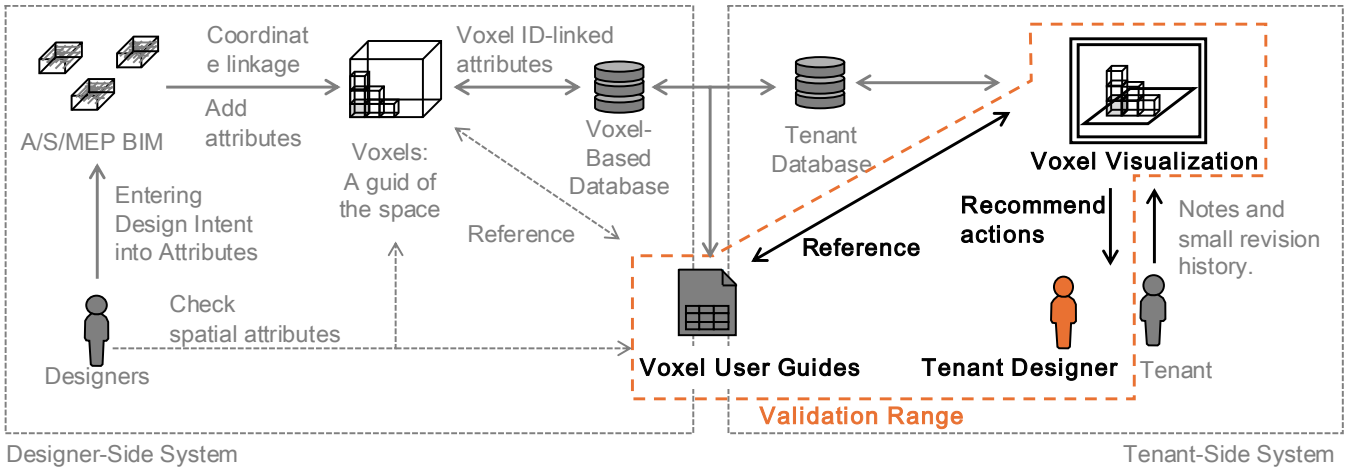


Figure 3. Conceptual diagram of the IVV framework extended to include tenant interior designers.

2.3. Theoretical framework

This study adopts the concept of scaffolding as a theoretical framework for the staged workshop design [25]. Scaffolding refers to a temporary support structure that provides information incrementally to assist learners in addressing tasks that would be difficult to handle independently, with support adjusted according to the learner's level of understanding.

Interior designers involved in renovation projects often lack sufficient prior knowledge of EHS requirements at the early stages, making staged support particularly relevant for understanding spatial constraints. The three-stage presentation structure—drawings and BIM models, color-coded voxel visualization, and combined visualization with explanatory information—aligns with the scaffolding framework by gradually shifting cognitive load from spatial recognition to comprehension of underlying rationale. This theoretical perspective is used to examine the role each presentation stage plays in the process of understanding.

3. Design & development

3.1. Conceptual design of the IVV color-coding scheme

The voxel visualization employed in this study is grounded in the IVV framework proposed in prior work, while its color-coding scheme was redesigned to support decision units relevant to tenant renovation practice directly. IVV was originally developed to voxelize BIM models and to facilitate intuitive recognition of constrained areas through color-based visualization. However, in prior studies, color categories were primarily presented as alerts linked to individual constraint rationales and were not sufficiently examined as an integrated scheme that consolidates multiple design intents into action-oriented decision making.

To address this gap, this study restructures fragmented requirements—originating from regulations, building services conditions, and safety requirements—into three integrated categories corresponding to layout actions: (1) prohibited placement (red), (2) avoidance of fixed objects with only immediately movable items permitted (orange), and (3) cautionary placement (blue). When multiple constraints overlap, a hierarchical priority structure (red > orange > blue) is applied to assign the most restrictive category. This mechanism collapses compound requirements into a single, consistent visual representation.

In addition, this study adopts a two-layer presentation structure in which color-coded constraints are paired with corresponding explanations of design intent (rationale information). This structure enables participants to quickly identify "where" constraints exist through color cues and, when necessary, to consult textual information to understand "why" those constraints apply. Whereas prior IVV implementations primarily emphasized visualization of "where," the present study introduces a staged connection between "where" and "why," informed by the scaffolding concept, by designing a presentation that supports progressive understanding.

Through the combination of (i) three-category coding, (ii) hierarchical prioritization, and (iii) rationale information, multiple EHS-related constraint elements are reorganized into decision units that interior designers can reference in early-stage layout planning. This design is positioned as a foundational visualization strategy for applying IVV to tenant renovations.

3.2. Workshop design

To compare how information presentation formats influence interior designers' understanding of EHS constraints, this study designed a hands-on workshop in which participants created layout proposals as they received information in successive stages. The session was designed to be completed in 90 minutes and to be administered under identical conditions for more than 20 participants. Workshop content and the sequence of information provision were therefore strictly standardized.

The workshop consists of three stages to enable observation of understanding processes across steps: (i) drawings and BIM models, (ii) color-coded voxel visualization, and (iii) explanatory information describing design intent. In Step 1, only 2D floor plans and the BIM model were provided to establish basic spatial understanding. In Step 2, color-coded constraints were added to examine how participants' recognition of constrained areas was updated. In Step 3, a written document explaining the design intent behind the color coding was provided to assess how much rationale information contributes to understanding. By progressively varying the abstraction level and granularity of information, the workshop enables comparison of which presentation formats support which phases of understanding.

Architecture students were recruited as participants. Even among practicing interior designers, relevant regulations and inspection requirements vary by discipline, and detailed knowledge of constraints is often not retained at the early stages of renovation planning. Therefore, for the specific process targeted in this study—initial understanding formation when receiving new EHS-related information—the baseline conditions of practitioners and students are not assumed to differ decisively. Students also provide relatively homogeneous prior knowledge, making them suitable for comparative observation of understanding processes.

Participants used a laptop computers or tablet, and Microsoft PowerPoint was required for layout work. Internet access was prepared because online materials were referenced for the color-coded visualization and explanatory information. The general background and purpose of the workshop were briefly explained; however, to preserve the staged nature of the design, the content of each step and the overall comparative intent were not disclosed in advance, so participants relied only on the information presented at each stage. Participants were informed in advance of the research purpose and the voluntary nature of their responses, and the workshop was conducted only after obtaining consent. In the pre-briefing, participants were also asked to assume the role of an interior designer with limited BIM knowledge who must make layout decisions under conditions where design intent may not be sufficiently shared.

Under these conditions, the workshop was designed to enable a controlled comparison of how differences in information presentation affect distinct phases of understanding.

3.2.1. Step 1: Layout planning based on drawings and BIM without design-intent explanations

In Step 1, participants—assuming the role of tenant interior designers—were asked to create a layout proposal without being provided any information about design intent. This step serves as the baseline condition for evaluating (i) how much spatial understanding can be obtained from drawings and BIM alone and (ii) how understanding changes after subsequent information is introduced in Steps 2 and 3. Step 1 is positioned as the starting point for capturing participants' initial interpretations and for comparing how understanding is updated across presentation formats.

Only basic operational instructions were provided (e.g., how to manipulate the drawings and submit outputs). Explanations that might affect spatial interpretation (e.g., the plan's background rationale) and information about subsequent steps were intentionally withheld. The schedule consisted of 10 minutes of instruction and 15 minutes of layout work (25 minutes total), creating a setting in which participants were required to make intuitive decisions under time constraints.

Floor plans and reflected ceiling plans were distributed as PowerPoint files. The BIM model was created using Rebro 2024 [26] and Autodesk Revit [27], converted into IFC format, and made available for viewing via Speckle [28]. Because the viewing experience could be affected by network conditions, an additional bird's-eye snapshot obtained from BIMserver.center [29] was attached next to the drawings to support understanding of the overall configuration.

Participants conducted layout work in PowerPoint. All required furniture, fixtures, and equipment symbols were provided as a legend. To ensure efficiency, participants were not allowed to create new shapes; only rotation and resizing were permitted. Participants were instructed to maintain consistency between the floor plan and reflected ceiling plan; any modification to one was required to be reflected in the other. Changes to building components such as exterior walls and major openings were prohibited, restricting work to the scope of a

plausible tenant layout modification.

The hypothetical office plan used in this experiment represents 12 meters by 12 meters (144 m^2) tenant area comprising an office zone, a guest zone, and a meeting room, with corresponding floor and reflected ceiling plans (Figure 4 and 5). The evacuation plan provides two-way egress via a stair and a balcony escape hatch, and daylight is obtained through south- and west-facing openings. On the floor, desks, chairs, shelves, and sofas were placed, along with a water dispenser and a fire extinguisher. On the ceiling, EHS-related elements were included, such as fire detectors, air-conditioning equipment, ventilation devices, lighting, fire dampers, and filter access panels. These elements were provided as symbols in the legend; where function was not obvious, minimal annotations (e.g., "for maintenance") were included. To approximate information obtainable through site verification, photographs corresponding to the legend elements were also provided to participants, though they are not published in the paper.

Tenant requests provided to participants included four typical renovation changes: reducing the number of desks, creating a new break area, partitioning a guest area, and removing the meeting room while creating two meeting booths. These requests were selected as common renovation tasks that implicitly require EHS consideration.

Accordingly, Step 1 was designed to record how participants interpret the space and arrive at placement decisions in the absence of explicit EHS design-intent information. The initial understanding captured in this step provides the basis for examining the incremental contributions of color coding (Step 2) and explanatory information (Step 3).

3.2.2. Step 2: Observing understanding updates using color-coded voxel-based constraint visualization

In Step 2, in addition to the drawings and BIM model provided in Step 1, participants were given a voxel-based visualization that color-coded constrained areas (Figure 6). This step evaluates how visual support changes participants' understanding in layout decision-making. By operationally adding color-coded constraints, Step 2 enables the extraction of the degree to which visual presentation contributes to understanding updates relative to the Step 1 condition.

The schedule consisted of 5 minutes of instruction and 10 minutes of work (15 minutes total). The color coding was generated using a pre-constructed voxel visualization model, in which the indoor space was discretized at a 600 mm pitch and constraint information was assigned to each region. The design rationale of the color coding is described in Section 3.1; in this step, only the finalized visualization output was presented. Voxel information was shown as static images in Microsoft Forms, and, as in Step 1, a 3D view was also made available via Speckle.

Participants first reviewed their own Step 1 layout proposal and compared it with the color-coded voxel visualization to identify which placed furniture or fixtures conflicted with which constrained areas. When conflicts were found, participants were asked to describe them in a free-text field in Microsoft Forms. This design enables qualitative observation of how visual constraints contribute to understanding updates, such as identifying misplacements, re-recognizing constrained areas, and clarifying decision criteria.

The voxel visualization presented in Step 2 was treated as a fixed condition based on the hypothetical office plan and was not dynamically updated according to each participant's Step 1 layout. This choice was made to support a controlled experimental format with multiple participants under identical conditions and to isolate the effect of presentation format on understanding processes.

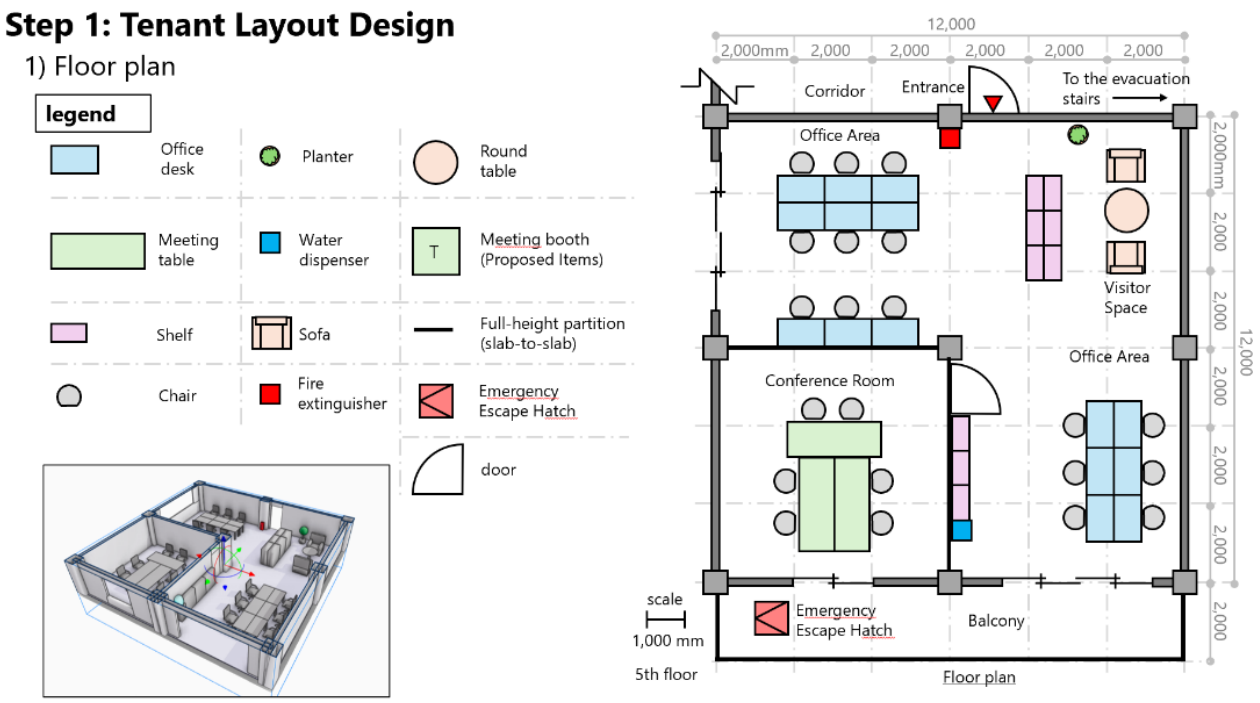


Figure 4. Floor plan of the target tenant space.

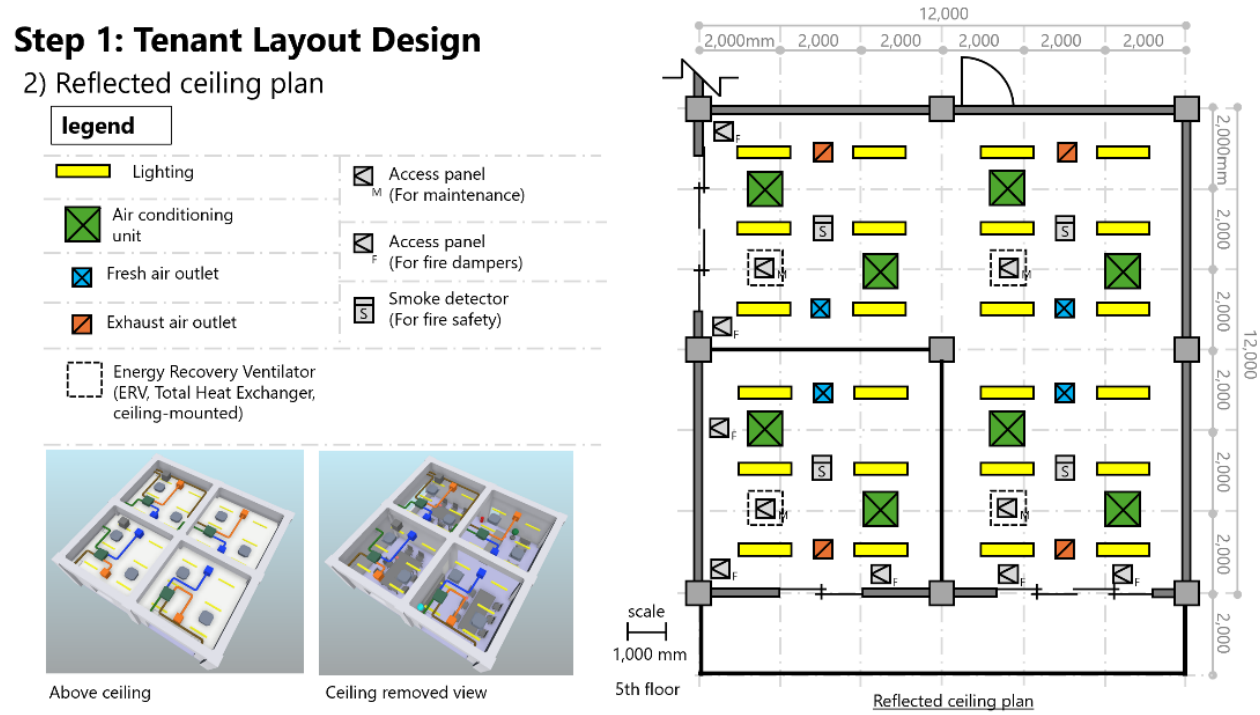


Figure 5. Reflected ceiling plan of the target tenant space.

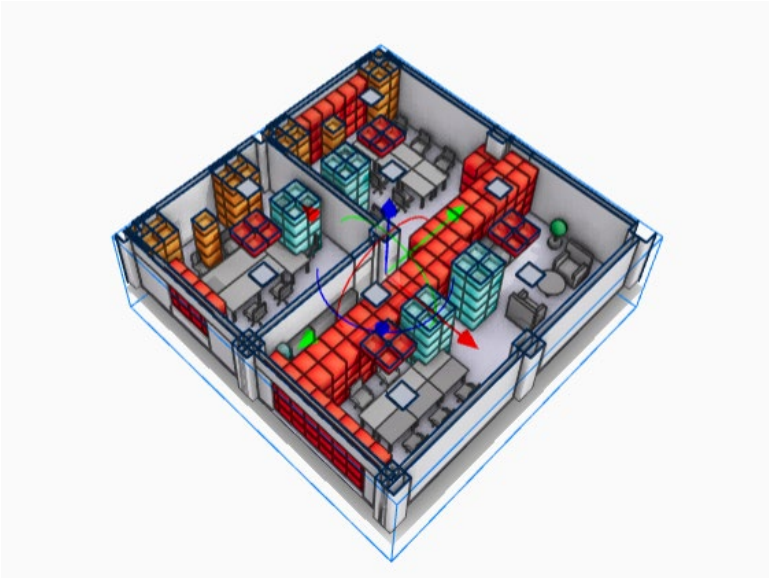


Figure 6. Step 2: Voxel-based color coding of placement constraints.

3.2.3. Step 3: Final confirmation of understanding through explanations of constraint rationale

In Step 3, in addition to the color-coded constraints provided in Step 2, participants were presented with written explanations of the design intent behind the constraints. This step evaluates how combining visual constraints with rationale information changes participants' understanding. By supplementing the background rationale that may be difficult to infer from color coding alone, Step 3 aims to measure at which stage participants reach understanding.

The schedule consisted of 5 minutes of instruction and 10 minutes of responses (15 minutes total). Microsoft Forms was used to provide the rationale information. To help participants associate each explanation with its spatial location, a perspective view of the corresponding area was placed alongside each text explanation. Presentation content was limited to text and images.

The rationale information used in this experiment was organized into seven design-intent items based on the hypothetical office plan (Figure 7). These items were reconstructed into decision units necessary for the workshop based on the author's professional experience in building services design and knowledge grounded in Japanese building-related regulations; however, the purpose is not to provide a strict legal interpretation. The seven items were grouped into three categories.

For voxels classified as red (prohibited placement), four design-intent items were defined: securing evacuation routes, securing clearance in front of fire extinguishers, securing clear space directly below smoke detectors, and securing daylight openings. Evacuation routes require unobstructed passage with a minimum of approximately 2 m above the floor. Clearance in front of fire extinguishers is required so that use is not impeded during emergencies. For smoke detectors, obstacles must not be placed around the device to maintain detection performance. For daylight openings, objects that block openings must be avoided to ensure the daylighting area required under the Building Standards Act. These items are strong constraints grounded in safety and legal requirements and were therefore defined as areas in which furniture and fixtures must not be placed.

For voxels classified as orange (avoidance of fixed objects; only immediately movable objects permitted), two rationale items were defined: filter maintenance clearance and fire damper inspection clearance. Both are intended to secure access required for periodic inspection or component replacement and were therefore treated as areas where only physically movable items are allowable.

For voxels classified as blue (cautionary placement), one rationale item was defined: avoiding seat placement directly below outdoor air intakes to reduce adverse effects from airflow.

Participants were asked, for each of the seven design-intent items, to indicate at which stage they became aware of the rationale. Response options were Step 1 (drawings/BIM), Step 2 (color coding), Step 3 (rationale explanations), or "not yet understood." This structure records the timing of understanding formation for each item. Participants also provided free-text comments on unclear points and suggestions for improvement, enabling supplementary

observation of how presentation formats affect cognitive load and the formation of decision criteria.

By introducing Step 3, the study establishes a structure for explicitly measuring how effectively rationale information—difficult to capture through color coding alone—is transmitted to participants, thereby enabling evaluation of deepened understanding across the three-stage presentation.

3.2.4. Post-workshop survey

After completing all workshop steps, a post-workshop survey was administered to capture how participants perceived the overall experience. The survey was conducted immediately after the workshop, and participation was entirely voluntary. As in the preceding steps, Microsoft Forms was used to minimize response burden.

The survey included: (i) an open-ended question asking what participants found most impressive, to identify which elements attracted attention; (ii) an open-ended question asking about unclear points and suggestions for improvement, to collect qualitative feedback on presentation formats and facilitation; (iii) a single-choice question asking whether the workshop was useful (Yes/No/Maybe), to capture subjective assessments of utility; and (iv) an overall satisfaction rating on a 10-point scale, to capture a summary evaluation of the workshop experience.

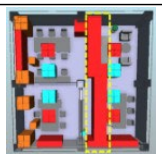
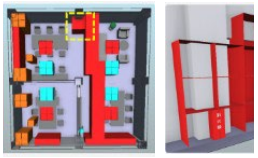
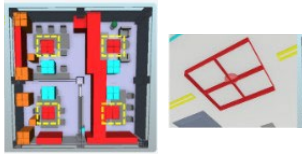
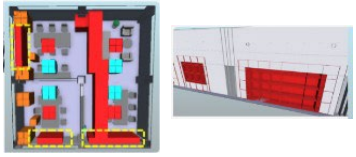
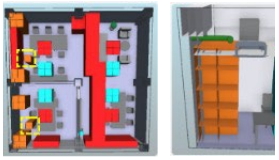
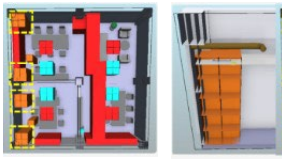
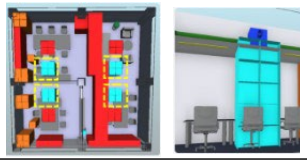
No.	Color / Restriction	Target	Key design intent	
1	Red: No placement	Evacuation route	Do not obstruct movement paths leading to exits.	
2	Red: No placement	Fire extinguisher	Always keep the frontal access space clear.	
3	Red: No placement	Smoke detector	Do not place objects directly beneath that may obstruct detection.	
4	Red: No placement	Daylighting area	Ensure the minimum required daylighting area.	
5	Orange: No fixed items	Air-conditioning filter	Ensure floor access for inspection and replacement.	
6	Orange: No fixed items	Fire damper	Ensure access for inspection and replacement.	
7	Blue: Placement with caution	Outdoor air intake	Avoid seating placement due to airflow effects.	

Figure 7. Design intent descriptions with corresponding voxel locations.

4. Demonstration

This section reports the workshop implementation designed in Section 4 and summarizes the demonstration process across steps. The workshop was conducted in person on 22 August 2025, from 14:00 to 15:30, in a meeting room at the Komaba Research Campus, The University of Tokyo. Participants comprised 22 undergraduate students majoring in architecture, civil engineering, or urban planning at a university in China, and two instructors (24 participants in total). Some participants did not specialize in architectural design or building services. Two authors facilitated the session. Participants worked on their own laptop computers using Microsoft PowerPoint, and questionnaires were administered via Microsoft Forms. The university eduroam network was used for connectivity, and PDFs and files were shared through Google Drive. While the lecture and facilitation were conducted in English, some participants translated the materials into their mother language during the tasks.

The demonstration was conducted as a non-invasive study involving an educational workshop and anonymous questionnaires. Participants were informed in advance about the research purpose and the research use of outputs and photographs, and only those who provided consent participated. Questionnaire responses were voluntary and anonymous, and the collected data were statistically processed in a manner that prevents individual identification.

At the beginning of the workshop, a 10-minute introduction outlined BIM use cases in facility management (FM) in Japan and explained how floor plans and reflected ceiling plans are read in relation to interior layout planning. Because the purpose of the demonstration was to compare understanding processes across steps, only procedural instructions were provided, and content-related information was intentionally withheld in advance.

In Step 1, participants were provided with a floor plan, a reflected ceiling plan, and a BIM model converted into Industry Foundation Classes (IFC) format and made accessible via Speckle. Participants were asked to create a layout proposal. The drawings were distributed as a PowerPoint file, and participants arranged furniture, fixtures, and equipment symbols from the legend to compose a 2D layout. The schedule initially allocated 10 minutes for instruction and 15 minutes for layout work (25 minutes total); however, because many participants did not finish within the allocated time, the work period was extended by 5 minutes, resulting in 20 minutes of work time. Layout files were submitted via Google Drive, and 23 of 24 participants submitted outputs. Questions about the content were not accepted; support was limited to technical assistance for operation.

In Step 2, voxel-based color coding was introduced as additional visual information, and participants were asked to check conflicts between their Step 1 layout and the presented constraints. The voxel data were generated by assigning color information to a cuboid grid overlaid on the BIM model at a 600 mm pitch. The three categories—red (prohibited placement), orange (avoidance of fixed objects with only movable items permitted), and blue (cautionary)—were presented in Microsoft Forms along with descriptions. Perspective views of the voxel visualization were also provided, and unconstrained voxels were hidden to improve readability. Participants reported, in free text, which elements conflicted with which colored areas. All participants submitted responses within the allotted time, written either in English or Chinese.

In Step 3, seven design-intent rationales underlying the three-category constraints were presented together with perspective views of corresponding locations: securing evacuation routes; securing clearance in front of fire extinguishers; securing clear space below smoke detectors; securing daylight openings; filter maintenance clearance; fire damper inspection clearance; and avoiding seat placement below outdoor air intakes. The rationales were presented in Microsoft Forms as text, and participants were asked to select at which stage they became aware of each rationale: Step 1, Step 2, Step 3, or “not yet understood.” Participants were also asked to describe how they understood each rationale and to provide comments on cognitive load and unclear points across presentation formats. In Step 3, 25 responses were recorded from 24 participants, indicating that one duplicated response may have occurred; accordingly, the analysis is conducted with an assumed error margin of one response.

After the workshop, a post-workshop survey was administered to capture subjective evaluations. The survey was voluntary and asked about (i) the most impressive aspect, (ii) points for improvement, (iii) perceived usefulness (Yes/No/Probably yes), and (iv) overall satisfaction (10-point scale). All participants completed the survey within the time limit, and no major confusion was observed. After completion, access permissions for Google Drive and Microsoft Forms were restricted to the authors, and all collected data were backed up.

Through these procedures, the study secured empirical data necessary to compare how the three-category color-coded visualization and design-intent explanations influence understanding, consistent with the research objective.

5. Evaluation

This section analyzes the submitted layout outputs and questionnaire responses collected after each step, including free-text comments.

5.1. Step 1

In Step 1, the authors evaluated (i) the extent to which participants satisfied the tenant requests and (ii) the degree to which EHS-related design intents were complied with, based on the layout proposals created by participants. Among the 24 submissions, one file was corrupted and could not be opened. Accordingly, the analysis focuses on 22 usable submissions among 23 accessible files.

First, compliance with the tenant requests was assessed (Table 1). The request to reduce the number of desks from 15 to 10 was met by 21 participants (91%), the highest participation rate. 17 participants (74%) successfully created a new break area, and 19 participants (83%) correctly partitioned the guest area. In contrast, the request to remove the meeting room and create two meeting booths was satisfied by 14 participants (61%), suggesting that this requirement was relatively more difficult. In addition, 15 participants (65%) followed the instruction to revise not only the floor plan but also the reflected ceiling plan.

Next, compliance with seven EHS-related design-intent items was evaluated (Table 2). When judgment was ambiguous, the evaluation was made conservatively and treated as non-compliance. 15 participants (65%) complied with evacuation routes; violations mainly occurred due to blocked corridors or insufficient clearance around exits. 13 participants (57%) complied with the clearance requirements in front of fire extinguishers, while multiple cases were observed in which fire extinguishers were not replaced after layout modifications or where furniture interfered with the required clearance. Smoke detector clearance was complied with by 19 participants (83%). Although the overall compliance rate was relatively high, cases of insufficient separation distance or missing placement were observed. Daylight openings were complied with by 16 participants (70%), while violations occurred when furniture blocked openings.

For ceiling-related constraints, 16 participants (70%) complied with filter maintenance clearance, and 14 participants (61%) complied with fire damper inspection clearance. In both cases, interference was observed when shelves or meeting booths were placed within inspection/maintenance zones. The restriction on seat placement directly below outdoor air intakes showed the lowest compliance rate, at 11 participants (48%).

These results indicate that, in Step 1, participants were generally able to produce layout proposals reflecting many of the tenant requests using the provided drawings and BIM information, but their ability to identify and comply with EHS-related constraints varied substantially across items. In particular, requirements involving ceiling-mounted equipment or airflow considerations—requiring three-dimensional and domain-specific reasoning—tended to show lower compliance.

Table 1. Degree of fulfillment of tenant layout requests in Step 1.

No.	Request description	Participants achieving (n = 22)	Achievement rate
1	Reduce the number of desks from 15 to 10	21	95%
2	Add a new break area	17	74%
3	Install partitions for the visitor area	19	83%
4	Add two meeting booths	14	61%
5	Coordinate with the reflected ceiling plan	15	65%

Table 2. Degree of compliance with design intent (EHS requirements) in Step 1.

No.	Design intent	Compliant participants (n = 22)	Compliance rate
1	Evacuation routes	15	65%
2	Fire extinguishers	13	57%
3	Smoke detectors	19	83%
4	Daylighting areas	16	70%
5	Access openings for air-conditioning filter replacement	16	70%
6	Access openings for fire damper inspection	14	61%
7	Outdoor air intake	11	48%

5.2. Step 2

In Step 2, participants compared their Step 1 layout proposals with the presented voxel-based constrained zones and reported, in free text, the furniture or equipment placed within constrained areas (Fig. 8). This question did not require exact agreement with the actual number of conflicts. Rather, its purpose was to assess whether participants could recognize what types of objects were placed within the restricted zones indicated by the color-coded voxels. Understanding of the underlying design intent (i.e., rationale) was examined in Step 3.

For the red zones (prohibited placement), 36 conflict reports were provided. The most frequently mentioned objects were “shelves” (7 reports) and “chairs” (7 reports), followed by “walls” (6 reports), “sofas” (4 reports), and “doors” (3 reports). Additional items mentioned once or twice included “break room,” “water dispenser,” “fire hydrant,” “smoke detector,” and “air conditioning.”

For the orange zones (no fixed items; only immediately movable items permitted), 14 conflict reports were provided. “Chairs” were most frequent, with nine reports. “Meeting booths” were mentioned five times, “plants” three times, and “shelves,” “water dispenser,” and “lighting” were each mentioned one to two times.

For the blue zones (cautionary placement), 21 conflict reports were provided. “Chairs” were most frequent, with 10 reports, followed by “walls” (2 reports), and “shelves” and “sofas” (1 report each).

All participants reported at least one conflict in one of the constrained zones. This suggests that the color-coded voxel visualization enabled participants, to a certain extent, to direct attention to placement constraints indicated on the layout.

5.3. Step 3

In Step 3, in addition to the color-coded constraint information provided in Step 2, textual explanations describing the underlying design intent were presented. Participants were asked to indicate, for each design-intent item, at which stage (Step 1-3) they became aware of the rationale.

5.3.1. Comparison of understanding stages across design-intent items

Figure 8 shows the distribution of the stage at which participants reported understanding each design-intent item. For evacuation routes, 18 responses (72%) indicated that understanding was achieved in Step 2, suggesting that a majority formed understanding through the voxel-based color coding. For clearance in front of fire extinguishers, 15 responses (60%) indicated understanding in Step 1, implying that the rationale was often inferred during initial planning. For smoke detector clearance, 14 responses (56%) indicated understanding in Step 3, suggesting that a majority required the explanatory document. For daylight openings, responses were split: 11 (44%) indicated Step 1 and 10 (40%) indicated Step 3, suggesting dispersion across early inference and later clarification. Among participants who did not understand the daylight rationale in Step 1, 10 of 13 (approximately 77%) reported understanding it after Step 3.

For filter maintenance clearance, 20 responses (80%) indicated Step 3. For fire damper inspection clearance, 17 responses (68%) indicated Step 3. For the avoidance of seat placement directly below outdoor air intakes, 12 responses (48%) selected Step 3, representing the most significant single share for that item.

Summarizing the most frequent understanding stage per item:

- Step 1: Fire extinguisher clearance (60%), daylight openings (44%)
- Step 2: Evacuation routes (72%)
- Step 3: Smoke detector clearance (56%), filter maintenance (80%), fire damper inspection (68%), and below outdoor air intakes (48%)

Overall, some items were correctly understood in Step 1 even without a staged presentation, whereas other items were often not recognized until Step 3. Items commonly encountered in everyday experience, such as fire extinguishers and windows/daylight openings, were inferred solely from drawings and BIM information. In contrast, evacuation routes—which emerge as a spatial consequence of connecting exits—were more readily understood when the routes were highlighted with color-coded voxels in Step 2. Furthermore, for ceiling-mounted equipment and related operational requirements that participants do not typically encounter in daily life, many participants reported understanding only after the Step 3 explanations were provided.

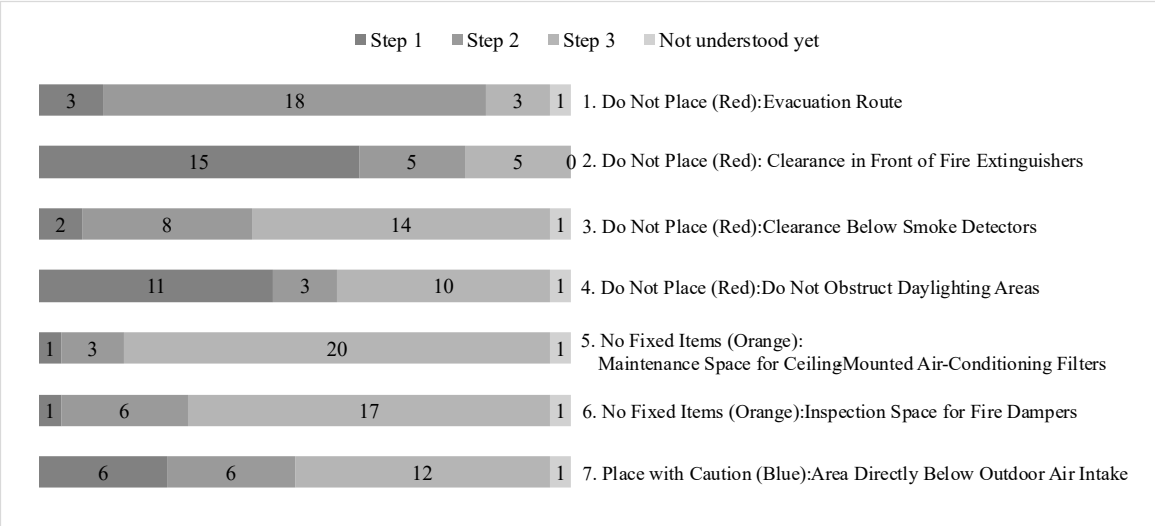


Figure 8. Level of understanding for each design intent.

5.3.2. Analysis of free-text comments

Five of the 24 participants provided free-text comments, including three substantive points. First, one comment noted that, in Step 1, the treatment of "non-movable equipment" such as ventilation ducts or air outlets was not explicitly defined, whereas Step 2 introduced voxel coloring based on the positions of ceiling equipment; as a result, the lack of linkage between the two conditions made judgment difficult. Second, a comment noted that it was challenging to consider multiple elements simultaneously within the limited time available. Third, a comment highlighted the interdependent relationship between tenant layout decisions and ceiling equipment planning. In particular, the participant noted that elements such as evacuation routes can change depending on the placement of partitions, which helped them understand why iterative coordination across disciplines is required in practical projects.

5.4. Post-workshop survey

The post-workshop survey collected responses on four items. For the open-ended question on "what was most impressive" (n = 22), comments about voxel color coding were observed in nine responses (41%), indicating that participants found it easier to visually identify prohibited and cautionary zones. Responses referring to BIM were observed in seven cases (30%), suggesting that BIM was also perceived as a memorable element in the process of understanding design intent. In addition, twelve responses (50%) referred to how design intent influences interior design decisions, indicating that the workshop contributed to increasing participants' awareness of design intent in design practice.

For the open-ended question on "points for improvement" (n = 10), responses were summarized with overlap among respondents. Three comments concerned the linkage between IVV and BIM, including inconsistencies between color coding and equipment relocation, and requests for more dynamic integration with reflected ceiling plans. Three comments concerned the decision process, such as having participants themselves determine the color coding and adding a step to detect unclear points. One comment referred to insufficient time allocated for the workshop. In addition, three comments requested more preliminary explanations of basic knowledge about building equipment and structural systems.

For the question "Was this workshop useful?", all respondents answered "Yes." Satisfaction ratings (1–10) were as follows: 10 points by 13 respondents (52%), 9 points by 4 respondents (16%), 8 points by 4 respondents (16%), and 7 points by 1 respondent (4%).

6. Discussion and limitations

In this study, the three-stage presentation format—(i) drawings and BIM, (ii) voxel-based color coding (red/orange/blue), and (iii) textual rationale—was operated under consistent conditions, and the stage at which participants reported that they understood each design intent was recorded per item. As a result, the study successfully captured, in an observable and comparable manner, how differences in presentation format shape understanding of EHS-related design intent during early-stage layout decision-making.

Building on this observation, the research question asks how a staged presentation format—

where spatial EHS constraints are reconstructed into three hierarchical action-oriented categories (red/orange/blue) and combined with rationale information—affects interior designers' early-stage understanding of design intent and their layout decisions. The discussion below interprets the evaluation results by relating each step (Steps 1-3) to the mechanisms of understanding and decision-making.

In Step 1 (drawings and BIM), participants generally produced layout proposals that reflected most tenant requests, yet compliance with EHS requirements varied across items. In particular, compliance was low for avoiding seat placement directly below outdoor air intakes, and violations were also observed for ceiling-related requirements such as fire damper inspection and filter maintenance clearances. These findings suggest that geometric information provided through drawings and BIM alone does not reliably lead to the underlying operational or maintenance-related intent, and that the decision criteria needed for early-stage layout planning are not sufficiently structured at the "action level" for interior designers.

In Step 2 (voxel color coding), all participants reported at least one conflict within constrained zones, indicating that the color-coded visualization effectively supported recognition of "where constraints exist" (i.e., the formation of spatial awareness of constrained regions). However, Step 2 was designed to elicit identification of conflicts rather than explanations of underlying intent. Therefore, the results should not be interpreted as evidence that color coding alone guarantees understanding of "why the constraint exists." This distinction becomes clearer when Step 2 is considered together with Step 3.

In Step 3 (rationale provision), the stage at which understanding was established differed by item: evacuation routes were more likely to be understood after Step 2, whereas smoke detector clearance, ceiling maintenance/inspection clearances, and avoiding seat placement below outdoor air intakes were more likely to be understood after Step 3. This pattern indicates that the three-category visualization with a priority hierarchy (red > orange > blue) is effective for integrating diverse constraints into an action-oriented unit and for communicating the presence of constraints. At the same time, for items that are difficult to infer from everyday experience—particularly those related to ceiling-mounted systems and operational requirements—rationale information is essential for establishing understanding.

Taken together, the results suggest that, to connect EHS design intent to early-stage interior layout decisions, it is effective to separate (i) visual region-based cues indicating where attention is required and (ii) semantic rationale explaining why the constraint matters, and to integrate them in a staged manner. Furthermore, the hierarchical rule that prioritizes the most restrictive category when multiple constraints overlap (red > orange > blue) likely helped maintain consistency of interpretation by collapsing compound constraints into a single actionable decision unit.

This study aimed to compare the effects of presentation formats based on IVV and, therefore, deliberately limited the scope of implementation and evaluation. The workshop employed static visualization outputs rather than assuming advanced functions such as automatic updates of constrained regions in response to layout modifications or dynamic linkage with external systems.

If the proposed approach is to be applied more extensively in practice, additional development and evaluation will be required, including mechanisms that automatically recompute constrained regions when layouts change and system-level integration that enables dynamic coordination across drawings, BIM, and other operational information sources. These extensions are positioned as future work.

7. Conclusion

This study addressed a practical challenge in tenant fit-out and renovation contexts: interior designers may not sufficiently inherit the EHS-related design intent embedded in the original building design. The study was motivated by the hypothesis that the primary issue is not the absence of EHS information per se, but the lack of restructuring of such information into units that directly support action-level decisions during early-stage layout planning. To examine this hypothesis, the study systematically investigated how restructuring EHS constraints and varying presentation formats influence the process of understanding establishment.

A central contribution of this work is the integration of previously item-specific IVV color cues into three action-oriented categories—prohibited placement, avoidance of fixed items, and cautionary placement—together with an explicit priority hierarchy (red > orange > blue). Using an empirical workshop design that staged drawings/BIM, voxel color coding, and rationale provision, the study demonstrated how differences in presentation format affect when and how participants establish understanding of design intent.

The results indicate that drawings and BIM alone support only limited understanding of

EHS-related design intent; many items involving three-dimensional relationships and operational requirements—especially those associated with ceiling-mounted systems—were difficult to understand at the early planning stage. In contrast, voxel-based color coding functioned as an effective visual cue for rapidly identifying constrained regions and for supporting awareness of where attention is required. However, color coding alone did not necessarily lead to understanding of the underlying rationale. When rationale information was added, participants tended to establish understanding even for items that were not well understood through visualization alone, particularly those related to maintenance and inspection clearances that are difficult to infer from geometry.

These findings suggest that, to connect EHS design intent to early-stage interior layout decisions, a staged information structure is effective: visual region-based cues (where) and semantic rationale (why) should be separated in function yet integrated progressively. In addition, the three-category hierarchical integration rule that prioritizes the most restrictive attribute in overlapping areas appears to support consistent interpretation by collapsing compound EHS constraints into a single actionable unit.

Overall, the proposed framework can be positioned as a practical redesign of information structure for transmitting diverse EHS design intents into action-level decision making during renovation and tenant fit-out. In practice, where design intent is prone to fragmentation across project phases and stakeholders, the findings provide a grounded direction for developing support methods that bridge design and operation and contribute to safer and healthier building use.

Acknowledgements

The authors gratefully acknowledge the students and faculty members of the College of Civil Engineering and Architecture, Zhejiang University, who participated in and supported the workshop.

ChatGPT was used for translation and grammar checking [30]. All content was subsequently reviewed and revised by the authors.

Declaration of competing interests

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.

Funding

The authors received no specific funding for this work, including the research, authorship, and publication of this article.

References

[1] W. J. Fisk, “The ventilation problem in schools: A literature review,” *Indoor Air*, vol. 27, no. 6, pp. 1039–1051, Dec. 2017, doi: https://doi.org/10.1111/ina.12403

[2] J. M. Samet and J. D. Spengler, “Indoor environments and health: Moving into the 21st century,” *American Journal of Public Health*, vol. 93, no. 9, pp. 1489–1493, Sep. 2003, doi: https://doi.org/10.2105/AJPH.93.9.1489

[3] M. Frontczak and P. Wargocki, “Literature survey on how different factors influence human comfort in indoor environments,” *Building and Environment*, vol. 46, no. 4, pp. 922–937, Apr. 2011, doi: https://doi.org/10.1016/j.buildenv.2010.10.021

[4] P. M. Bluyssen, “What do we need to be able to (re)design healthy and comfortable indoor environments?” *Intelligent Buildings International*, vol. 6, no. 2, pp. 69–92, 2014, doi: https://doi.org/10.1080/17508975.2013.866068

[5] I. Mujan, A. S. Anđelković, V. Munćan *et al.*, “Influence of indoor environmental quality on human health and productivity – A review,” *Journal of Cleaner Production*, vol. 217, pp. 646–657, Apr. 2019, doi: https://doi.org/10.1016/j.jclepro.2019.01.307

[6] C. Yu and D. Crump, “Indoor environmental quality – standards for protection of occupants’ safety, health and environment,” *Indoor and Built Environment*, vol. 19, no. 5, pp. 499–502, 2010, doi: https://doi.org/10.1177/1420326X10381106

[7] J. Zhang and K. R. Smith, “Indoor air pollution: a global health concern,” *British Medical*

Bulletin, vol. 68, no. 1, pp. 209–225, Dec. 2003, doi: https://doi.org/10.1093/bmb/ldg029

[8] P. B. Luh, C. T. Wilkie, S.-C. Chang *et al.*, "Modeling and optimization of building emergency evacuation considering blocking effects on crowd movement," *IEEE Transactions on Automation Science and Engineering*, vol. 9, no. 4, pp. 687–700, Oct. 2012, doi: https://doi.org/10.1109/TASE.2012.2200039

[9] E. A. Lim and W. C. Tan, "Simulating evacuations with obstacles using a modified dynamic cellular automata model," *Journal of Applied Mathematics*, Article ID 765270, 2012, doi: https://doi.org/10.1155/2012/765270

[10] Commercial Building Regulation Study Group, *Regulation Handbook of Commercial Building and Store Planning*. Tokyo, Japan: Shoten Kenchiku-sha, 2004.

[11] G. A. Palenske and G. N. Ornelas, "Obstructions and early suppression fast response sprinklers," *Fire Technology*, vol. 59, pp. 3157–3184, Nov. 2023, doi: https://doi.org/10.1007/s10694-021-01205-y

[12] A. Sagun, D. Bouchlaghem, and C. J. Anumba, "Building design information and requirements for crowd safety during disasters," in *Proceedings of the International Conference on Building Resilience: Achieving Effective Post-Disaster Reconstruction (i-Rec 2008)*, Christchurch, New Zealand, 2008, pp. 1–10. [Online]. Available: http://www.grif.umontreal.ca/i-rec/i-Rec2008/papers/CIB11578-sagun.pdf

[13] Facility Management Promotion Council, *The Official Guide of Facility Management*. Tokyo, Japan: Nikkei Publishing Inc., 2018.

[14] K. M. Pollack, M. M. Bailey, A. C. Gielen *et al.*, "Building safety into active living initiatives," *Preventive Medicine*, vol. 69, Supplement, pp. S102–S105, Dec. 2014, doi: https://doi.org/10.1016/j.ypmed.2014.08.010

[15] Ministry of Land, Infrastructure, Transport and Tourism (Japan). (2022, Jun.) *Guidebook for ensuring disaster prevention performance for facility managers of government buildings*. Accessed Aug. 2025. [Online]. Available: https://www.mlit.go.jp/gobuild/content/001512319.pdf

[16] K. Shide and K. Kosuge (eds.), *Managing Contemporary Construction Projects* (in Japanese). Tokyo, Japan: Shokokusha, 2022.

[17] Japan Federation of Construction Contractors, *The Japanese Building Process Illustrated*. Tokyo, Japan: Shokokusha, 2017.

[18] BIM Education Promotion Organization, *BIM Basic I: A Textbook on Architecture and BIM*, Revised ed. (in Japanese). Tokyo, Japan: Nikkan Kensetsu Tsushin Shimbunsha, 2023.

[19] J. Whyte and T. Hartmann, "How digitizing building information transforms the built environment," *Building Research and Information*, vol. 45, no. 6, pp. 591–595, Aug. 2017, doi: https://doi.org/10.1080/09613218.2017.1324726

[20] S. Durdyev, M. Ashour, S. Connelly *et al.*, "Barriers to the implementation of building information modelling (BIM) for facility management," *Journal of Building Engineering*, vol. 46, Article no. 103736, Apr. 2022, doi: https://doi.org/10.1016/j.jobe.2021.103736

[21] M. Patel, V. S. Rajus, and G. Wainer, "Software architecture for integrating DEVS simulation into BIM," in *Proceedings of the 2022 Annual Modeling and Simulation Conference (ANNSIM)*, San Diego, CA, USA, Jul. 2022, pp. 670–681, doi: https://doi.org/10.23919/ANNSIM55834.2022.9859473

[22] M. Aleksandrov, S. Zlatanova, D. J. Heslop *et al.*, "BIM-based connectivity graph and voxels classification for pedestrian-hazard interaction," *Journal of Spatial Science*, vol. 69, no. 3, pp. 699–719, 2024, doi: https://doi.org/10.1080/14498596.2023.2281923

[23] A. Kasai and T. Ishizawa, "Indoor voxel visualisation for tenant occupants' environment, health, and safety," in *Proceedings of the 30th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2025)*, Tokyo, Japan, Mar. 2025, vol. 3, pp. 255–264. [Online]. Available: https://papers.cumincad.org/cgi-bin/works/Show?caadria2025_189

[24] K. Peffers, T. Tuunanen, M. A. Rothenberger *et al.*, "A design science research methodology for information systems research," *Journal of Management Information Systems*, vol. 24, no. 3, pp. 45–77, 2007, doi: https://doi.org/10.2753/MIS0742-1222240302

[25] D. J. Wood, J. S. Bruner, and G. Ross, "The role of tutoring in problem solving," *Journal of Child Psychology and Psychiatry*, vol. 17, pp. 89–100, 1976, doi: https://doi.org/10.1111/j.1469-7610.1976.tb00381.x

[26] *Rebro* (2024), NYK Systems Co., Ltd., Accessed: Aug. 2025. [Software]. [Online]. Available: https://www.nyk-systems.co.jp/

[27] *Revit* (2024), Autodesk, Inc., Accessed: Aug. 2025. [Software]. [Online]. Available: https://www.autodesk.com/products/revit/

[28] *Speckle*, Speckle Systems, Accessed: Aug. 2025. [Online]. Available: https://speckle.systems/

[29] *BIMserver.center*, BIMserver Center, Accessed: Aug. 2025. [Online]. Available: https://bimserver.center/jp

[30] *ChatGPT*, OpenAI, Accessed: Feb. 3, 2025. [Online]. Available: https://chatgpt.com/

Appendix

This appendix presents the detailed design rationales underlying the voxel color-coding scheme provided to participants in Step 3 (Table 3). As described in the main text, these rationales were defined by the authors specifically for the hypothetical office plan used in this study. Evaluating the validity of each requirement itself is not the objective of this research.

Table 3. Design Rationales Underlying the Voxel-Based Spatial Restrictions Presented to Participants.

No.	Restriction category	Target use / Equipment	Design rationale assigned to voxels
1	Red: No placement	Evacuation route	– Secure evacuation routes leading to the emergency exits at the entrance and balcony. – Do not place any objects along evacuation routes. – When modifying the layout, evacuation routes must be maintained and their travel distance should not be excessively increased compared to the existing condition.
2	Red: No placement	Fire extinguisher	– Clearance in front of fire extinguishers must always be maintained so that they can be used immediately in an emergency.
3	Red: No placement	Smoke detector	– This device detects smoke generated during a fire and activates an alarm. – Do not place any objects within several tens of centimeters around the detector that may obstruct smoke detection. – Partitions should be arranged to avoid this area, or the position of the smoke detector must be relocated.
4	Red: No placement	Daylighting area	– A minimum required daylighting area must be secured depending on the building type. – In Japan, building regulations require a minimum total opening area relative to the floor area. – Daylighting areas must not be arbitrarily reduced.
5	Orange: No fixed items	Air-conditioning filter	– Fresh air is supplied through ducts from ceiling-mounted energy recovery ventilators (ERVs), while indoor air is exhausted outdoors. – ERVs transfer heat from indoor air to incoming fresh air, supplying it at a temperature close to room temperature. – Filters inside the unit remove dust and harmful substances and require periodic replacement; therefore, maintenance access from the floor must be ensured.
6	Orange: No fixed items	Fire damper	– Fire dampers are installed in supply and exhaust ducts to prevent flames and heat from adjacent rooms or upper floors from entering this space during a fire. They automatically shut off airflow when high temperatures are detected. – Periodic inspections are required several times a year. – Depending on their condition, replacement may be necessary every few years.
7	Blue: Placement with caution	Outdoor air intake	– Airflow directly below outdoor air intakes may cause discomfort to occupants. – To ensure thermal comfort, seating should be avoided in this area as much as possible.

抄録

本研究は、既存建築物の改修段階において十分に共有されない場合が多い環境・健康・安全（Environment, Health, and Safety：EHS）に関する設計趣旨について、情報提示方法の違いが内装設計者の初期理解にどのような影響を与えるかを実証的に検討した。EHS に関連する空間的制約を、「設置禁止」「固定物設置禁止」「配置に要注意」という行動レベルに対応させた三つのカテゴリに再構成し、階層的な優先度の構造を持つボクセル表現として可視化した。図面・BIM、色分けされたボクセルの可視化、設計趣旨を説明する文章情報を段階的に提示するワークショップを設計し、主として建築系学生を対象に実施した。

その結果、図面および BIM のみでは、特に天井設置機器や運用上の要件に関連する多くの EHS 要素について十分な理解が得られないことが示された。一方で、ボクセルによる色分けは制約領域を迅速に把握すること（where）を可能にし、さらに設計趣旨に関する説明情報を付加することで、視覚情報のみでは伝達できない背景的な理由（why）の理解が促進された。これらの結果は、空間的位置情報（where）と意味的説明情報（why）を段階的に統合する情報構造が、EHS の設計趣旨を初期段階のレイアウトへ反映させるうえで有効であることを示唆した。本研究は、建築改修における設計趣旨の共有を支援するための、実践的な情報再構成フレームワークを提案するものである。