Multi-Dimension Simulation Framework for Operating Room Construction Using Omniverse

Chia-Ying Lin[1], Lung-Hsiang Su[2] and I-Chen Wu[1]

[1] Department of Civil Engineering, National Kaohsiung University of Science and Technology, Taiwan
[2] JE MON Engineering Co., Ltd., Taiwan

cylin813@nkust.edu.tw, kwu@nkust.edu.tw

Abstract –

The construction of operating rooms involves multiple coordinated procedures. In practice, time and cost estimation are often uncertain. Additionally, project control still relies heavily on the manual interpretation of 2D drawings, resulting in inconsistencies between the design intent and on-site execution. There is one other thing that is important for the operating room. Operating rooms impose stringent requirements on illuminance and uniformity of illuminance to support long-duration surgical tasks. Inadequate lighting distribution can lead to increased visual fatigue and introduce shadows that negatively impact task performance. Therefore, this study integrates illuminance and uniformity simulation into the design workflow, allowing for the immediate evaluation of lighting performance after each layout configuration and the adjustment of lighting performance at an early stage. To address the above issues, this paper proposes a Multi-Dimension Simulation Framework based on the Omniverse platform. The proposed workflow can automatically generate the operating room interior framework (e.g., metal studs and antibacterial panels) from CAD floor plans, thereby reducing modeling time and supporting on-site installation processes. The system then placed the ceiling grid using a modular, center-out strategy, and the related attributes were recorded for subsequent quantity takeoff. At the same time, the user can place modular cabinet components, and then the system detects openings and boundaries, generating the bracing and support studs for enhancing stability. Finally, the component of the model will bind the schedule and cost data for 4D/5D simulation. Therefore, the results of this research can raise the effectiveness and efficiency of the operating room construction and project management.

Keywords –

Omniverse; Design Automation; Operating Room Construction; Illuminance Simulation; 4D/5D

1 Introduction

As a specialized interior environment defined by high sterility and process-intensive operations, the operating room demands strict adherence to specific protocols in design and construction. Guided by cleanroom design manuals, walls and ceilings must employ a modular, seamless construction integrated with a metal stud system; corners require rounded profiles to prevent dust accumulation, while openings necessitate reinforcement and edge sealing to ensure compliance with ISO Class 5–7 cleanliness standards [1]. However, current practices predominantly rely on manual interpretation of 2D schematics for modeling. This often results in inconsistent stud modularity, edge detailing, and opening-reinforcement execution, making it difficult to translate design requirements into computable parameters—such as module size and spacing, minimum clear distances, and corner radii—that serve as inputs for subsequent geometry generation and verification.

In the domain of automated configuration and digital workflows, academic research has made significant progress in recent years. Lee et al. [2] utilized Building Information Modeling (BIM) technologies to establish a template matching protocol, proposing a methodology wherein model geometry is deconstructed to allocate standard components based on rules and priorities, while defining non-configurable zones. This approach effectively illustrates the implementation path of transforming "regulation to rule to geometry." Addressing integration and collaboration across diverse data sources, Abbasianfar [3] posited that distributed construction simulation—encompassing IoT, imagery, and numerical models—relies critically on interoperability and consistency. Visualization platforms anchored by Universal Scene Description (USD) and NVIDIA Omniverse were identified as effective tools for preserving data integrity and supporting visual synchronization. Regarding the practical integration of 4D/5D dimensions, Inzerillo et al. [4] used a railway station project to demonstrate the interfacing of Revit

(3D/Quantity Take-off) with Navisworks (4D scheduling) and supplementary plugins (ArchVISION/PriMus) for cost linkage. This integration achieved real-time updates of quantities and costs in response to model changes, thereby establishing a unified management system for both schedule and expenditure.

In the domain of lighting simulation, the research focus has shifted from solely managing energy consumption to prioritizing human-centric visual comfort and optimizing illuminance distribution. Since Kennedy and Eberhart [5] introduced Particle Swarm Optimization (PSO), which employs swarm intelligence to determine global optima, this methodology has become a cornerstone of lighting control systems. Subsequently, Madias et al. [6] integrated multi-objective evolutionary algorithms into interior lighting control, demonstrating that compliance with the EN 12464-1 standard could align with the dual objectives of average illuminance and uniformity, effectively enhancing energy efficiency. Wagiman et al. [7] advanced this research by employing Multi-Objective Particle Swarm Optimization (MOPSO) alongside the Illuminance Uniformity Deviation Index (IUDI); by simultaneously minimizing power consumption and non-uniformity, their simulations achieved compliance with standards requiring a uniformity of ≥ 0.6 and an average illuminance of 500 lx. From an engineering practice perspective, Wati [8] highlighted that the Lumen Method (also known as the Zonal Cavity Method) retains a distinct efficiency advantage, enabling the rapid estimation of average illuminance and luminaire requirements, which serve as a reference for electrical configuration. In the context of operating rooms, where zoned lighting and scenario transitions (e.g., preparation, surgery, sanitation) are operational necessities, illuminance simulation must occur concurrently with geometric configuration. Only through this synchronization can the stringent requirements for shadowless illumination, uniformity, and maintenance accessibility be fully met.

In light of the foregoing analysis, three critical challenges persist within contemporary practice that demand immediate resolution. First, operating room renovation regulations remain unsystematically parameterized, rendering them unable to directly drive automated generation and verification mechanisms. Second, the integration of geometric modeling with 4D/5D data relies predominantly on manual linkage, resulting in Information not synchronized and inadequate version consistency. Third, illuminance simulation is typically introduced only in the latter stages of design, which prevents the establishment of a closed feedback loop with stud and panel configurations. To address these impediments, this study establishes an automated interior renovation workflow anchored by Universal Scene Description (USD). By implementing a rule engine using Python and Omniverse, the system translates construction principles into geometric constraints and processes. The system will generate the operating room model based on these rules. The scene utilizes the USD format to preserve readability and modification advantages, reserving metadata fields for 4D/5D integration to link scheduling and cost data simultaneously. Concurrently, the system synthesizes generated geometry for real-time assessment of illuminance and uniformity, thereby realizing a holistic workflow that unifies design, construction, and performance simulation.

2 System Framework

This study uses an operating room as the case study and targets renovation projects characterized by complex interfaces and frequent design changes. It establishes a Multi-Dimension Simulation Framework that integrates Python automation scripts with Universal Scene Description (USD). As shown in Fig. 1, the framework follows a data-driven approach and organizes the workflow into three sequential stages:

1. Drawing parsing input layer: reads 2D vector drawings, parses entities, and extracts geometric feature data.
2. Rule-based automation core: parameterizes the extracted geometry and converts it into USD assets according to predefined construction logic (e.g., opening reinforcement and light-gauge partition framing layout).
3. Simulation application layer: imports the generated model into NVIDIA Omniverse to support integrated simulations of construction sequencing and environmental performance.

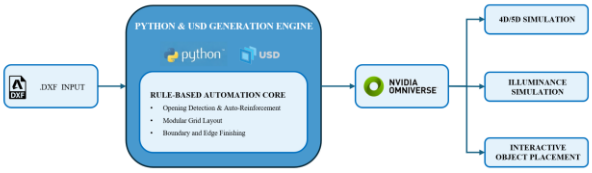

Figure 1. System framework for this research.

2.1 System design

The system design is shown in Fig. 2. The workflow is implemented by two main classes, Interactor and USDScene, and three supporting components: OmniKit_Context, JSON_Data_Source, and pxr.Usd.Stage. Interactor is responsible for UI interaction and state management. It queries OmniKit_Context (e.g., get_context() and get_selection()) to access the Omniverse editor context and user selections. It also reads the initial layout inputs from JSON_Data_Source (parsed_data.json) and stores them as baseline data (baseline_data). During editing, Interactor records user actions in a command list (cabinet_tasks) and derives the current logical state (tubes) by overlaying these commands on the baseline data, without directly editing USD geometry.

When the logical state is updated, Interactor instantiates USDScene and triggers a rebuild (Fig. 2, "Instantiates & Triggers Rebuild"). USDScene performs full-scene regeneration and writes geometry to pxr.Usd.Stage (Fig. 2, "Generates/Writes Geometry"), including floor/grid construction from wall segments (wall_segments), column placement from structural-chain data (cols_by_chain), panel and opening generation, and detailing operations such as corner correction, C-channel reinforcement, and ceiling-keel placement (create_ceiling_keels). The stage is then saved as USD-compliant outputs. In addition, Interactor reads/monitors pxr.Usd.Stage changes via a Tf.Notice listener (Fig. 2, "Reads/Monitors") to synchronize stage updates with the internal command flow.

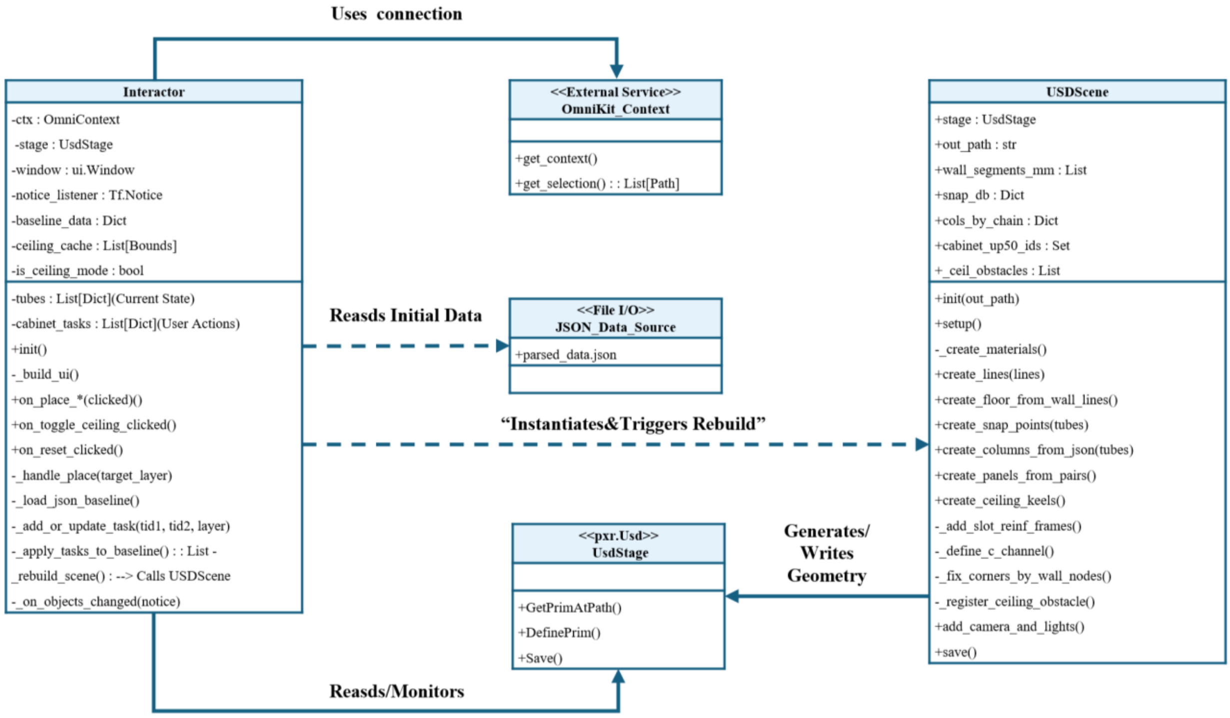

Figure 2. Schematic of the System Design.

3 Operating Room 3D Model Generation

This section outlines the comprehensive workflow for automatically generating a 3D operating room model from 2D drawings. The system divides the process into four stages. First, it parses the raw CAD data to obtain spatial coordinates. Next, it generates building components according to procedural construction rules. And then, it outputs a USD model that includes engineering information. Finally, the user can place modular cabinet components for time and cost simulation.

3.1 Layout Data Extraction

This study establishes a standardized preprocessing workflow that converts AutoCAD drawings into computable data. The program will filter out non-geometry data, such as dimensions, text, and hatches, to reduce noise, and then export only the geometry of walls and columns. The extracted coordinates of lines and points are written into the basic data as the geometric basis for subsequent automated generation and validation. The CAD drawing of the operating room layout is shown in Fig. 3.

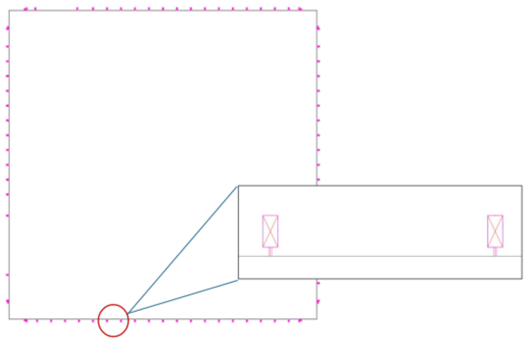

Figure 3. The CAD drawing of the operating room layout.

3.2 3D Model of Operating Room

The automated workflow in this study outputs not only 3D geometry but also a set of semantic OpenUSD assets. The resulting 3D model of the operating room is shown in Fig. 4. The assets are stored in USDA format, which features an open data structure that allows for direct access and attribute comparison, thereby improving modification and version control during the development stage. During component generation, the system writes the required metadata so that the geometry can be used as "smart objects" for engineering management. Examples include:

- Classification and model ID: bim:model (e.g., CeilKeel-3x6, Panel-<len>).
- Dimensional information: bim:length_mm, grid width, and related fields for 5D quantity takeoff.
- Construction sequence: sim:order for 4D animation and progress mapping.

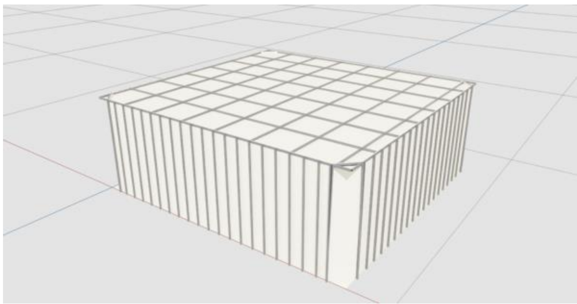

Figure 4. The results of the operating room 3D model.

To ensure consistency across tools, the scene utilizes a unified upaxis and unit definition. After importing the assets into NVIDIA Omniverse, 4D/5D binding and illuminance analysis can be performed directly without additional coordinate or unit adjustments. Overall, the USDA maintains a clear linkage among "geometry–attributes–process." This supports rule verification and change detection, and provides a stable data structure for schedule- and cost-related computations.

As shown in Table 1, this research uses the general surgery operating room as a comparison with manual modeling. The proposed system not only generates the operating room geometry but also writes the required attributes and processes the data simultaneously. This allows the generated model to be directly used for later 4D scheduling, 5D cost calculation, and illuminance simulation. In contrast, manual modeling usually focuses on geometry reconstruction, while the data needed for later simulations must be added, organized, or transferred to other platforms afterward.

Table 1. Comparison between manual modeling and system-generated modeling

Item	Manual modeling	System-generated modeling
Modeling time	1 hr 6 min	1 min
Geometry	Antibacterial panels, floor, ceiling, and equipment	Antibacterial panels, floor, ceiling, equipment, peripheral framing, and equipment reinforcement structures
Data	Additional organization or manual input required	Written automatically during generation
4D / 5D / illuminance simulation	Cross-platform integration required	Can be directly continued within the proposed system

3.3 Implementation for Rule-based Engine

This study implements a rule-based engine for modeling of operating room construction, covering four functions: geometry generation, interactive reinforcement, 4D/5D simulation, and illuminance verification. To support review and implementation, Table 2 summarizes each rule set by its trigger conditions, processing steps, and output attributes.

3.4 Modular Cabinet Components Placement

The user interface and interactive mechanism for placing and reinforcing modular cabinet components are illustrated in Fig. 5. The cabinet instances used for placement are created in Revit and exported as Revit family files (RFA), and are also converted into USD assets for interaction in the scene. When the user places a cabinet asset, the system evaluates its geometric relationship to openings and boundaries and generates the corresponding reinforcement components with associated attributes for sequence simulation and cost/schedule linkage.

Table 2. Mapping of system generation rules.

Rule Category	Trigger Condition	Algorithmic Action	Generated Components	Key Attribute
Framing Generation	Closed boundary provided	Place studs and panels along the path using modular spacing; generate edge trims at boundaries.	C-Studs, Antibacterial Panels, Edge Trims	bim:model、bim:length_mm
Ceiling Grid Generation	Geometric center defined	Expand ceiling grids outward from the center, splitting at intersections and trimming at boundaries.	Ceiling Grids, Ceiling Panels	bim:model、bim:length_mm
Interactive Reinforcement	Equipment Placement	Analyze topological relations, generate opening frames, horizontal supports, and corner stiffeners, and densify studs as required.	Opening Frames, Horizontal Supports, Corner Stiffeners, Densified Studs	bim:model、bim:length_mm
4D Simulation	Visibility Activation	Toggle visibility sequentially to reconstruct the assembly order.	Step-by-step Visualization	sim:order
5D Cost Estimation	User Initiation	Convert length to modules and cost in real time; remove duplicates by selecting the longest overlapping path segment.	Itemized / Total Cost	bim:length_mm
Illuminance & Uniformity	Manual Simulation Trigger	Run illuminance mapping and uniformity checks based on the generated scene.	Illuminance Map, Uniformity Verification Map	-

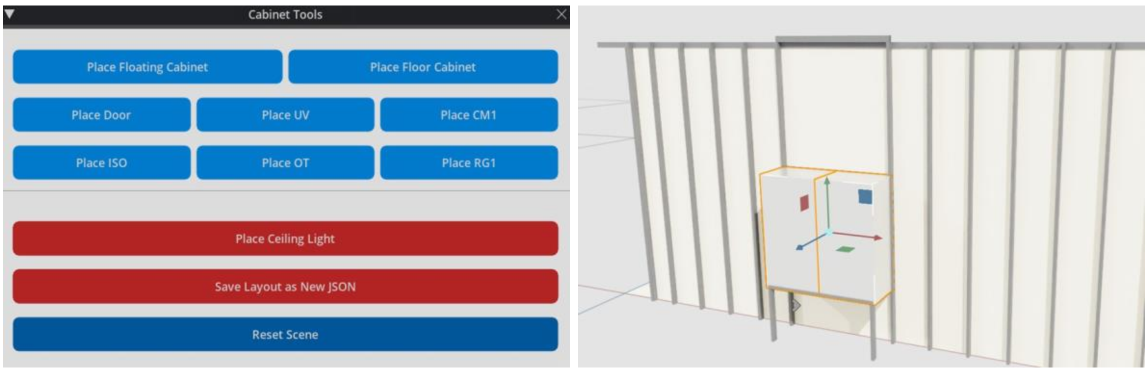

Figure 5. User interface and interactive mechanism for placing and reinforcing modular cabinet components.

4 4D/5D Data Binding and Visualization

This study proposes an integrated strategy that packages geometric models, construction schedules, and cost data into a single scene description file, thereby reducing information fragmentation in conventional BIM workflows. The system uses the USD file as the computational core, where required attributes are stored in an embedded data structure within the scene. Accordingly, 4D and 5D computations are driven by reading the schema attributes attached to each component, rather than querying a separate data store.

In terms of data structure, the system uses the component model identifier (bim:model) and geometric dimensions (e.g., bim:length_mm) as the basis for quantity measurement, and uses the sequence attribute (sim:order) to label the construction order. After parsing these attributes, both 4D reconstruction and 5D cost estimation can be performed simultaneously, as shown in Fig. 6. Each 4D event—defined as a component switching from hidden to visible and treated as "completed"—also serves as the trigger point for 5D costing. Because progress milestones and cost calculations share the same component ID and attributes, the system can accumulate costs along the timeline with synchronized data updates.

First, the 4D schedule reconstruction applies a "sequential reveal" strategy. At the start of the simulation, the entire scene is hidden, and component visibility is then switched on in batches according to sim:order to reproduce the assembly sequence and serve as the basis for computing the progress timeline. Second, 5D cost estimation is performed concurrently during the 4D animation. For components that have been revealed, the system performs real-time quantity takeoff and applies unit prices, enabling a "cost-on-completion" workflow：

1. Linear components (e.g., ceiling grids and C-channels): Quantities are accumulated using length attributes and then converted into the number of standard modules as the budgeting basis.
2. Wall panel deduplication: For the same wall-path segment, only the largest Panel-<len> is used as the calculation value to avoid duplicate counting caused by overlaps.
3. Unit-based modules (e.g., ceiling panels): The number of pieces is derived from width attributes and predefined modular rules.

These rules ensure consistency in geometry, scheduling, and cost computations within a single USD scene, facilitating tracking and comparison.

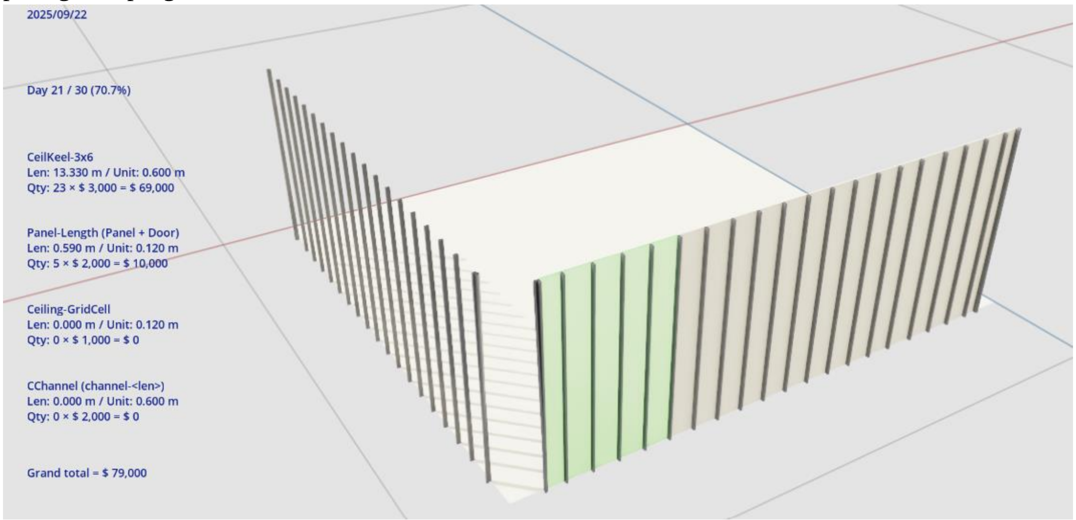

Figure 6. The Interface for 5D Process Simulation and Real-Time Cost Analysis.

5 Illuminance and Uniformity Simulation

This study undertakes a comprehensive evaluation of operating room lighting in strict compliance with the EN 12464-1 standard. Addressing the specific illuminance requirements for medical environments, the benchmark for recovery rooms is set at 500 lx, and general operating room illumination at 1000 lx. Conversely, the surgical cavity mandates an intensity ranging from 10,000 to 100,000 lx, as outlined in Table 3. Regarding the assessment of uniformity, computations are executed utilizing Equation (1):

$$U_0 = \frac{E_{min}}{E_{avg}}$$

Where U_0 denotes the uniformity of illuminance; E_{min} represents the minimum illuminance within the evaluation zone; and E_{avg} signifies the mean illuminance of the respective region. In accordance with established standards, the scope of evaluation is delineated into the task area and the immediate surrounding area:

- Task Area: Defined as the primary locus where visual tasks are executed (exemplified by the operative surface of the surgical table).
- Immediate Surrounding Area: Defined as a band-shaped zone that surrounds the task area and lies within the field of view. According to the relevant requirements, its width shall be at least 0.5 m. As illustrated in Fig. 7, the red box indicates the primary surgical task area, and the blue box represents the area expanded outward by 0.5 m. The system uses this defined range for grid discretization and uniformity verification.

In instances where the requisite illuminance upon the working plane equals or exceeds 750 lx—with this study stipulating a general operating room illuminance of 1000 lx—the objective uniformity is mandated as follows: ≥ 0.7 for the task area and ≥ 0.5 for the immediate surrounding area, as delineated in Table 4.

In the implementation, the system integrates geometric configuration with optical simulation. After the user places objects about surgical equipment, luminaires, and the surgical table in the scene, the system enables NVIDIA Omniverse Illuminance Arbitrary Output Variables (AOVs) to perform ray tracing and outputs a high-dynamic-range EXR image. At the moment the surgical table is placed, the system simultaneously detects its bounding box and defines it as the task area. The immediate surrounding area is then automatically generated by extending the task area outward by 0.5 m in accordance with EN 12464-1. The EXR data are subsequently read by a Python program developed in this study, which performs grid discretization and numerical sampling within these predefined regions for illuminance and uniformity verification. As shown in Fig. 8, a false-color map is first used to present the illuminance distribution, where red/orange indicates high illuminance, yellow/green indicates medium levels, and blue indicates low illuminance; the corresponding lx values are mapped to the color bar below, allowing designers to quickly identify hotspots and dark zones. As shown in Fig. 9, the system further performs a quantitative grid-based verification for the task area by computing illuminance values at each sampling point and checking whether the uniformity index U_0 meets the target criteria.

Table 3. Design Illuminance Specifications for Medical Environments [10].

Type of interior, task or activity	$\bar{E}_m$	Remarks
Pre-op and recovery rooms	500	
Operating theatre	1000	
Operating cavity	-	$\bar{E}_m$:10,000 to 100,000 lx

Table 4. The Relationship of Illuminance and Uniformity between the Task Area and the Immediate Surrounding Area [10].

Task illuminance (lx)	Illuminance of immediate surrounding areas (lx)	Uniformity: Task area (U_0)	Uniformity: Immediate surrounding area (U_0)
≥ 750	500	≥ 0.7	≥ 0.5

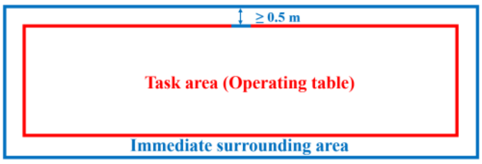

Figure 7. Schematic definition of the uniformity evaluation regions.

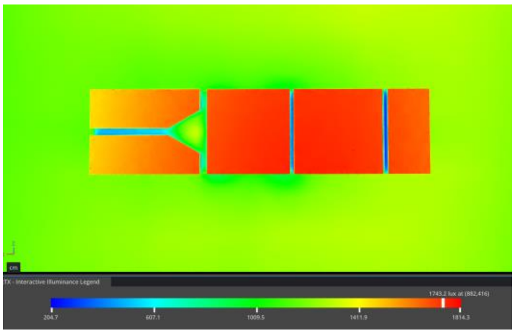

Figure 8. Simulated overall illuminance distribution for the operating table.

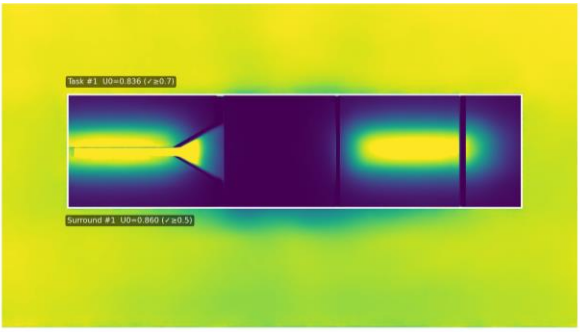

Figure 9. Analytical Diagram Verifying Illuminance Uniformity within the Task and Immediate Surrounding Areas.

6 Conclusions and Future Work

This study uses operating-room renovation as the validation scenario and develops a Multi-Dimension Simulation Framework. The framework separates computational logic from geometric data, providing a workflow from drawing parsing to multidimensional simulation. The main contributions are summarized as follows:

1. 3D Modeling: The system generates structure framing that includes metal studs and ceiling grids automatically. When the user places the cabinet components, the system updates the opening–boundary relationships and generates the required bracing and support studs. This can reduce the time and cost of 3D modeling.

2. 4D Simulation: The installation sequence is replayed by reading sequence attributes embedded in each component. This enables pre-construction checks of task precedence and supports early detection of process conflicts.
3. 5D Cost: 3D Model components are linked to a unit-price table. When wall or ceiling configurations change, quantities and total costs for panels and framing are recalculated and updated to reflect the current design state, allowing budget impact assessment without manual takeoff.
4. Illuminance and uniformity verification: Illuminance images (EXR) are generated via ray tracing. The system will calculate the average illuminance and uniformity on the operating table and verify compliance against EN 12464-1, enabling early verification during the design phase.

In summary, the results indicate that using USD as a unified data storage can integrate geometry, time, cost, and physical performance data within a single workflow, thereby reducing data discontinuities across heterogeneous tools. Future work will extend the framework to computational fluid dynamics (CFD) and human-factor evaluations, including airflow simulation for operating room ventilation, to support quantitative decision-making in healthcare space planning.

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