Modeling multi-level spaces with network-based space layouts: a case study

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Abstract. Space layouts are used throughout the building life-cycle to model spaces and related objects. In building design, layouts created by architectural designers are reused by building services designers to develop lighting, heating, ventilation, and air conditioning, security, and safety systems. In previous work, the author has proposed a schema for network-based space layouts that supports space modeling in multiple domains. Operations have been defined to generate and analyze space layouts. Single-level as well as multi-level spaces, such as stairways or atriums, may be modeled in a uniform manner in order to minimize model complexity and modeling effort. By contrast, coverage of multi-level spaces in existing space modeling methods is limited. The objective of this paper is to show how multi-level spaces may be modeled based on the mentioned space layout schema and operations. This is done by means of a case study of an existing facility. At first, an architectural layout of the facility is created in a commercial BIM system. In accordance with common practice, multi-floor spaces are modeled by multiple, single-floor spaces. Layout operation expressions are developed and evaluated to automatically generate a pedestrian circulation and an artificial lighting layout. Multi-floor spaces are generated from their constituent single-floor spaces in the architectural layout. Generated layouts are assessed by visual inspection. Modifications of the original layout schema that were necessary to cover multi-level spaces are discussed.

1. Introduction

Space layouts are used throughout the building life-cycle to model spaces and related objects. In building design, layouts created by architectural designers are reused by building services designers to develop lighting, heating, ventilation, and air conditioning, security, and safety systems. Designers create layouts according to their domain-specific space views. The creation of space layouts is supported by commercial building information modeling (BIM) systems (Eastman et al. 2011). However, data structures (schemas) and hence the richness of space layouts in BIM systems are still limited compared with layout representations that have been developed by the research community.

In previous work, the author has developed a schema for network-based space layouts in order to support modeling of multiple space views (Suter 2013). The schema reuses and adapts concepts of existing space schemas, including the IFC space schema (Björk 1992, Ekholm & Fridqvist 2000, Eastman & Siabiris 1995, buildingSMART International 2010). In a network-based space layout, selected spatial relations between layout elements, such as spaces or doors, are modeled as a spatial relation network. The distinction of whole spaces and subspaces (partial spaces) allows for flexible and fine-grained space modeling. High-level operations have been developed that leverage spatial relation networks to generate and analyse space layouts for building services domains (Suter 2011, Suter et al. 2012, 2014). From a base layout that is prepared in a BIM system, designers can automatically generate lighting, pedestrian circulation, natural ventilation, thermal zone, or fire zone layouts. Graph algorithms are used to analyze spatial relation networks. For example, the shortest path may be determined between a given workplace and its nearest building exit (for evacuation planning), or windows that are near a given workplace (for natural lighting and shading control design).

The objective of this paper is to show how multi-level spaces may be modeled in a uniform manner with network-based space layouts. The benefits of this approach include minimized model complexity and modeling effort. Modeling of multi-level spaces is relevant as these spaces are found in many buildings and pose specific challenges for architectural as well as building services design. Of particular interest are spaces that span multiple floors, including elevator shafts and stairways.

2. Related work

Representations that model spatial relations between spaces and building elements as graphs or networks are useful in space planning, code compliance checking, indoor route planning, construction planning, and case-based design. Several recent efforts have shown how spatial relation graphs or networks may be generated from space data created in BIM systems.

The pedestrian circulation network developed by Lee et al. (2010) consists of horizontal and vertical access networks. Each network is derived separately from an IFC-based BIM. Spaces are organized into floors that are connected by vertical access objects, such as stairs and elevators. Whereas Lee et al. generate networks from buffered space boundary polygons, Taneja et al. (2011) use the medial axis of space boundary polygons.

Lin et al. (2013) use a similar approach to model pedestrian circulation systems. Spaces and building elements are extracted from IFC data and projected onto a planar grid for each floor. Stairways and elevators are modeled as transit nodes that connect floor grids on different levels.

Langenhan et al. (2013) retrieve space layouts from design repositories based on space access graphs. In such graphs, nodes correspond to spaces and edges to access relations. An access relation between two spaces exists if there is at least one door or opening that connects them. Compared with the previous methods, access graphs are more coarse-grained, and vertical circulation elements are not modeled explicitly.

A common characteristic of the reviewed methods is that multi-floor spaces are not modeled in whole, but rather as partial spaces on each floor. While this may be sufficient for space and path planning, the application to other domains appears limited. In lighting design, for example, it is desirable to assign luminaires to stairways that are modeled explicitly as contiguous vertical spaces. Similarly, volumes of atriums or auditoriums that span multiple floors need to be modeled for thermal or fire safety design.

3. Methodology

Modeling of multi-level spaces with the layout schema and operations is demonstrated with a case study of an existing academic facility on the campus of Vienna University of Technology. The facility has 9 floors and a gross area of 4500 m^2. Multi-level spaces include the main entrance; two stairways and elevators that provide access to faculty and administrative offices on the upper floors; a two-story auditorium with a gallery and a capacity of 392 seats on Basement and Ground floors; and access and evacuation spaces for the auditorium.

The case study is performed in four steps. In the first step, an architectural space layout of the test building is created in a BIM system for architectural design (Section 4.). The layout is used as a base layout to generate layouts of multi-level spaces for pedestrian circulation and artificial lighting. These domains are chosen because of their diverse and detailed space views.

In the second step, definitions (types) for space elements, including doors, openings, and flights of stairs, are developed (Section 5.). This step is relevant as circulation and lighting layouts are generated based on these definitions.

In the third step, layout operation expressions are defined and executed in a layout modeling system prototype to generate circulation and lighting layouts from the architectural layout (Section 6.).

In the fourth step, generated layouts are described and evaluated (Sections 7. and 8.). The connectedness of generated spatial relation networks (relevant for pedestrian circulation networks) and correct modeling of obstructions (relevant for pedestrian circulation and artificial lighting networks) are assessed by visual inspection.

4. Architectural layout

An architectural layout of the test building has been created in a commercial BIM system (Autodesk, Inc. 2011). The layout consists of (whole) spaces, windows, doors, openings, flight of stairs, ramps, landings, desks, and luminaires. It has neither spatial relations nor subspaces (partial spaces). Figure 1 shows Basement, Ground, and First floors of the layout. In accordance with common practice, each space that spans multiple floors is modeled by multiple, single-floor spaces. The auditorium, for example, is decomposed into three spaces. The main space is located on the Basement Floor, and air and gallery spaces on the Ground Floor.

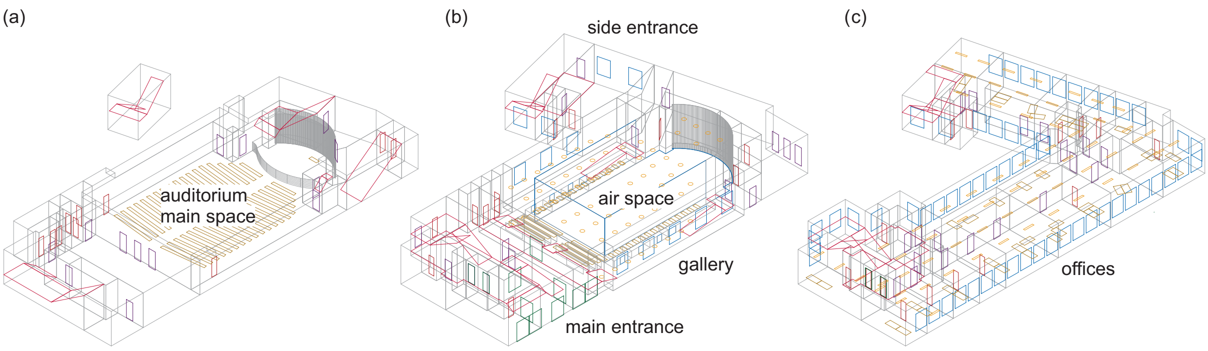

Figure 1: Architectural layout of the test building: (a) Basement Floor, (b) Ground Floor, (c) First Floor.

5. Space element types

Doors, openings, or partitions are examples of space elements. A space element may have subspaces or other space elements. The latter are generated automatically in a layout based on space element definitions or types. Figure 2 shows space element types that are used to generate circulation and lighting layouts for the test building. A door, for example, has two nearby subspaces. Based on this definition, subspaces are generated for all doors in a layout. Subspace volumes correspond to Voronoi cells (Aurenhammer & Klein 2000) that are derived from subspace positions and intersected with the volumes of whole spaces in which they are contained.

Space element types further specify if a space element must be contained in or (partially) enclose a whole space. Space elements that fail to meet this relation are considered as spatially inconsistent. Whereas a door must enclose at least one whole space, a study desk must be contained in a whole space. A door that does not enclose a whole space is removed from a layout, as is a desk that is not contained in a whole space (Suter 2013).

According to Figure 2, partitions may assume either role, dependent on their spatial context. A partition may thus enclose a whole space, while another is contained in a whole space.

Two opening types are defined. Openings that are based on the first type do not have subspaces and must enclose whole spaces. Such openings enclose the auditorium air space and are generated by flights of stairs. They are relevant for merging enclosed spaces into stairways or the auditorium. Openings that are based on the second opening type have two subspaces. They are used in the circulation layout to model access to audience cubicles on the auditorium gallery.

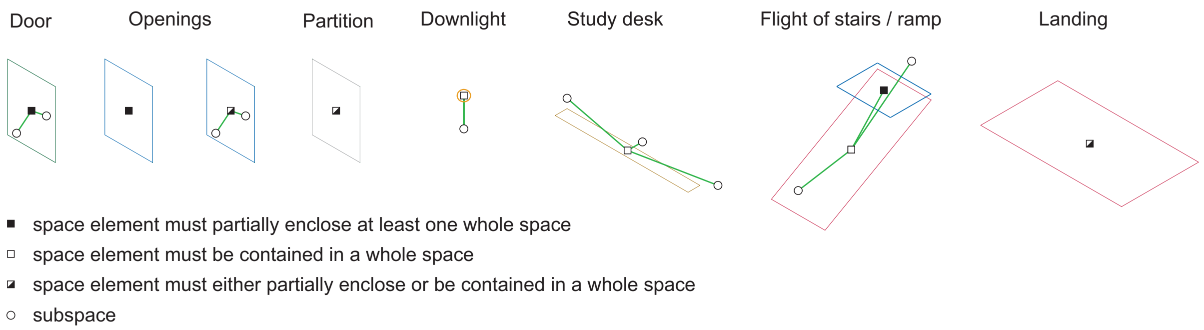

Figure 2: Space element types.

6. Layout generation

Circulation and lighting layouts of the test building are generated from the architectural layout by evaluating two layout operation expressions that consist of *select*, *aggregate*, *union*, and *insert* operations (Figure 3). Each operation accepts one or two argument layouts and returns a result layout. Operation signatures and processing are described in previous work (Suter 2011, Suter et al. 2012). The *select* operation selects whole spaces and space elements from an argument layout. The *aggregate* operation merges connected whole spaces in an argument layout. The *union* operation merges two argument layouts. The *insert* operation inserts selected whole spaces and space elements from the first into the second argument layout.

User-defined filters specify explicitly or implicitly those layout elements and spatial relations that are included in result layouts. Descriptions of filters that are used to generate circulation and lighting layouts are provided in Tables 1 and 2. The *union* operation does not require filters.

7. Circulation layout

The generated circulation layout includes multi-level pedestrian circulation spaces in the test building. Figures 4, 5, and 6 show partial layouts.

The main entrance provides access to the auditorium on Basement and Ground floors as well as faculty and administrative offices on the upper floors (Figure 4 (a)). Elevators and the main

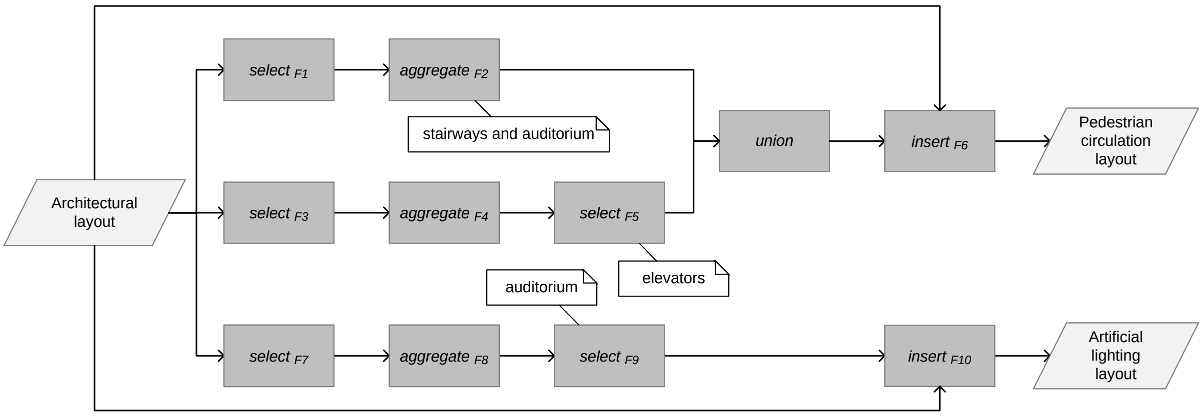

Figure 3: Layout operation expressions that generate circulation and lighting layouts from the architectural layout. Filters $F1 \ldots F10$ are described in Tables 1 and 2.

stairway are elevated by ca. $0.5m$ from the main entrance level. A ramp ensures barrier-free access to these spaces.

Office and auditorium stairways as well as elevator shafts spanning multiple floors are generated by the *aggregate* operation from spaces in the architectural layout that are connected by openings of flights of stairs (Figure 4 (b)). Stairways with U-shaped and L-shaped, two-flight stairs are generated by the same operation expression. The auditorium stairway spans two floors and encompasses the auditorium lobby. The generated volume of this space is a non-manifold solid with a pair of overlapping edges. Two elevator shafts that span, respectively, eight and nine floors are generated - only the first three floors are shown in the figures. The operation expression that generates these spaces covers situations where certain levels are not serviced by an elevator. As a result, an engine space on the Basement Floor is part of an elevator shaft.

The circulation network in Figure 4 (b) is a subnetwork of the circulation layout's spatial relation network. It consists of the subspace adjacency relation and the proximity relation between subspaces and space elements. The subspace adjacency relation is restricted by additional filters to edges that are feasible for pedestrian circulation. For example, edges that intersect with flights of stairs, landings, or other obstructions are excluded. In order to avoid visual clutter, subspace volumes, from which subspace adjacencies are derived, are not shown in the figures.

Secondary multi-level spaces in the test building include a side stairway for offices on the upper floors and evacuation spaces for the auditorium (Figure 5 (a)). Again, spaces in the architectural layout are merged into multi-floor spaces. Evacuation spaces s_1 and s_2 on the main level of the auditorium are merged with evacuation space s_3 on the street level to form space $s_{1,2,3}$, which spans two floors (Figure 5 (b)).

The auditorium consists of a main audience space on the Basement Floor and air and gallery spaces on the Ground Floor (Figure 6 (a)). It is modeled in the circulation layout because it has a multi-level circulation system with flights of stairs and ramps. The presentation stage is elevated from the main audience level and modeled with partitions. The gallery itself has several levels in order to maintain line-of-sight between study desks and the stage. Large openings enclose air, gallery, and main spaces.

Auditorium spaces in the architectural layout are merged into a single circulation space by the *aggregate* operation because they are connected by these openings (Figure 6 (b)). The openings are contained in but do not enclose the merged auditorium circulation space. They are not included in the circulation layout because they must partially enclose at least one whole space (Figure 2). Study desks, ramps, flights of stairs, and small openings that provide access to

Table 1: Filters used to generate the circulation layout.

Operation	Filter	Layout elements	Spatial relations	Comments
select	F1	Flights of stairs, ramps, external doors		Related whole spaces are selected implicitly. Openings are generated near flights of stairs and ramps.
aggregate	F2	Whole spaces, openings	*partially encloses* relation between space elements and whole spaces	
select	F3	Whole spaces, elevator doors		Whole space areas must be less than 6 m^2.
aggregate	F4	Whole spaces	*is adjacent to* relation between whole spaces	Whole space adjacency edges must be approximately vertical.
select	F5	Elevator doors		Related whole spaces are selected implicitly.
insert	F6	Doors, openings, partitions, landings, desks		Missing space elements are inserted

audience cubicles on the gallery participate in the generated circulation network. Line-of-sight between some of these space elements is restricted by horizontal and vertical partitions.

The generated circulation network of the circulation layout has a single component. That is, all doors and study desks in the network are reachable from each other. Visual inspection further suggests that all paths between doors and study desks are feasible for pedestrian movement. Restrictions due to multi-level spaces appear correctly reflected in the circulation network. Thus such a network could be useful, for example, to estimate evacuation distances for each study desk in the auditorium that consider multiple levels, or to determine study desks with barrier-free access. However, certain feasible paths in the circulation network deviate significantly from paths which people are expected to choose in reality. An example are paths from the main entrance to the first flight of stairs in the main stairway. Likewise, access to certain study desks near the stage in the auditorium is too restricted. This latter issue can be resolved by increasing the number of subspaces that are related to study desks (Figure 2).

8. Lighting layout

The generated lighting layout includes the auditorium space only. Its volume is equivalent to the auditorium volume in the circulation layout. Downlights, study desks, and partitions are modeled (Figure 7). Downlights and study desks are nodes in the generated lighting network. Similar to the circulation network, partitions obstruct line-of-sight between certain subspaces that are near downlights and study desks. The adjacency relation between subspaces is restricted to subspaces that are near downlights or study desks.

Downlights mounted in the gallery ceiling provide direct lighting to approximately half of the positions of subspaces that are near study desks at the main space level (Figure 7 (a)). These positions can be considered as approximate positions of audience seats. By contrast, the lectern receives direct lighting from downlights above the stage (Figure 7 (b)). There may be glare due

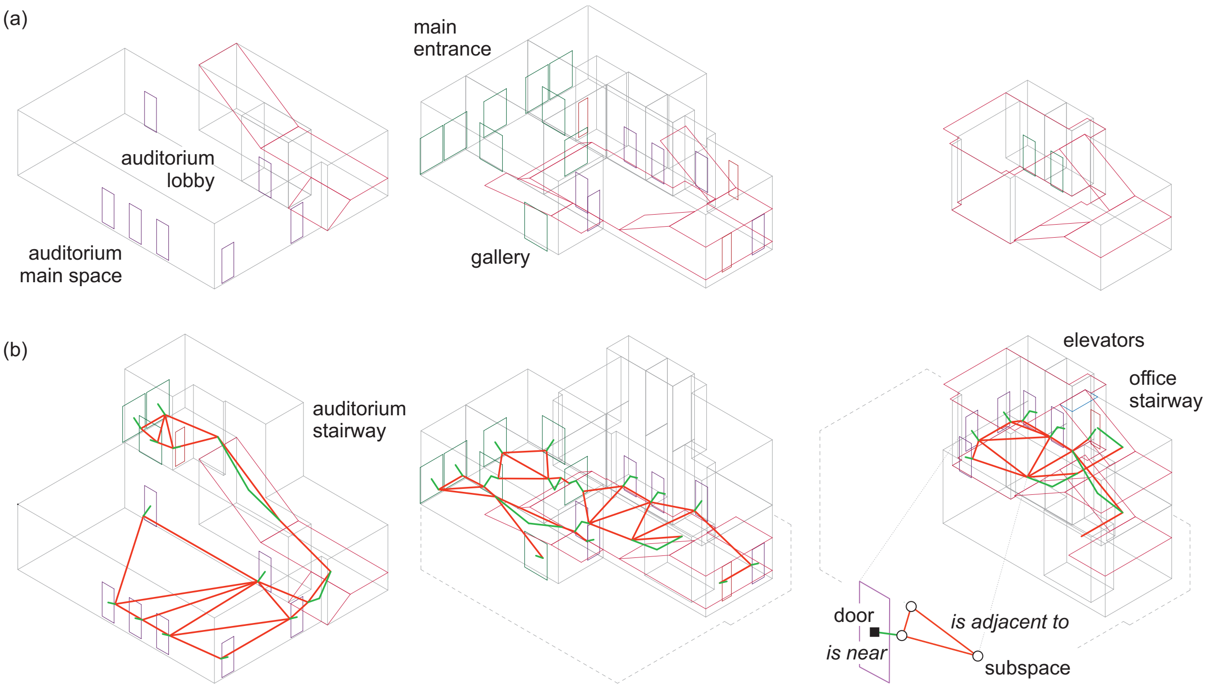

Figure 4: Main access spaces: (a) architectural spaces, (b) circulation spaces.

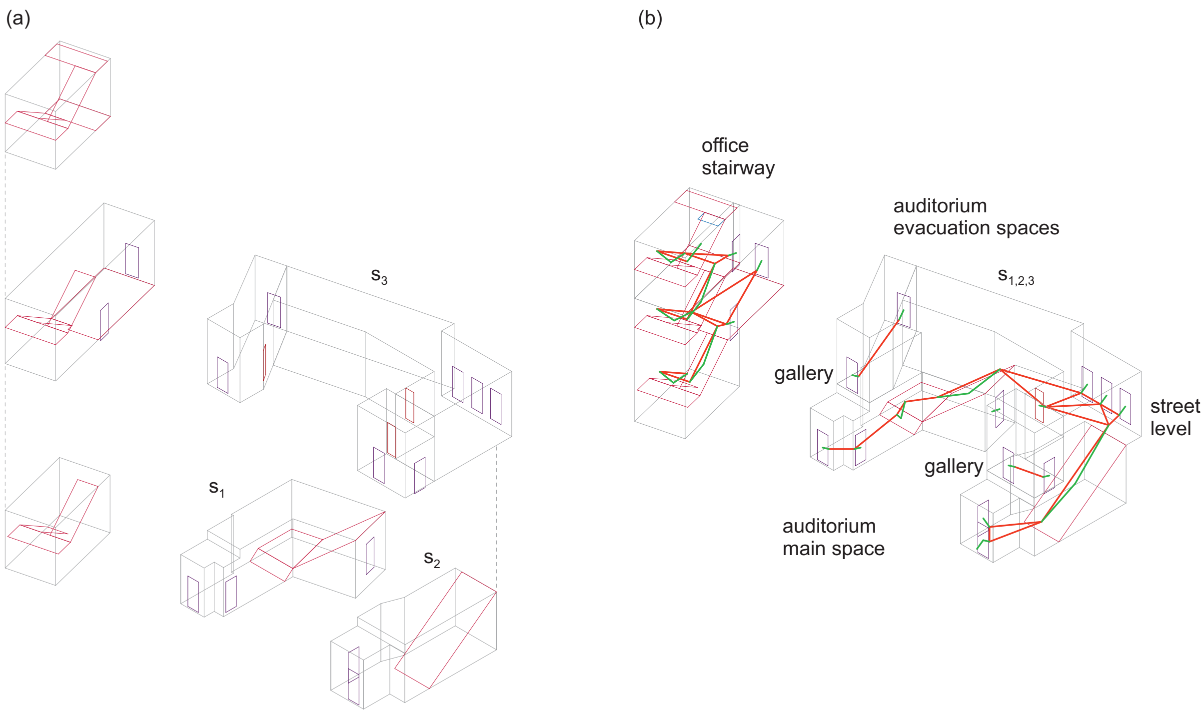

Figure 5: Side stairway and evacuation spaces: (a) architectural spaces, (b) circulation spaces.

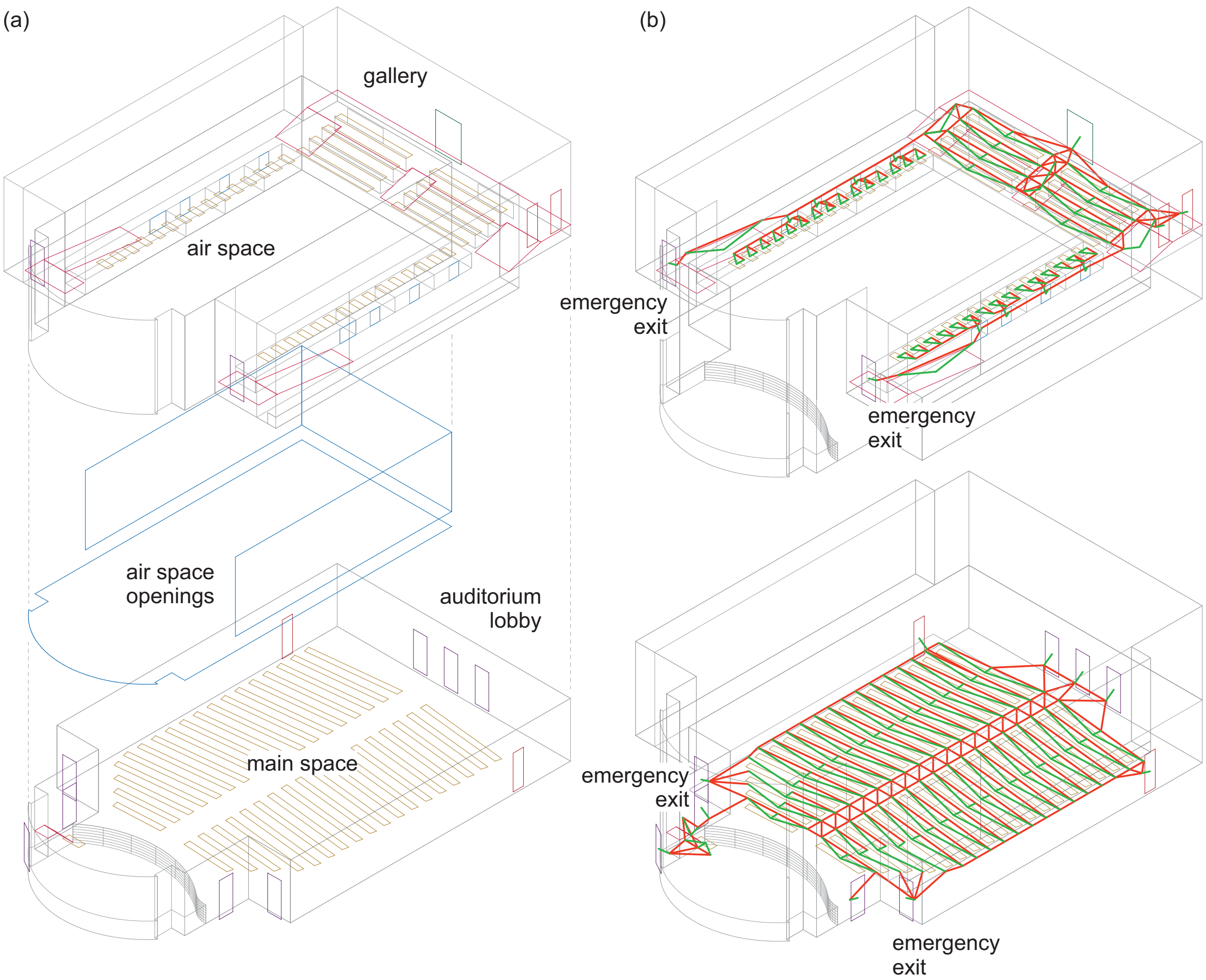

Figure 6: Auditorium: (a) architectural spaces, (b) circulation space.

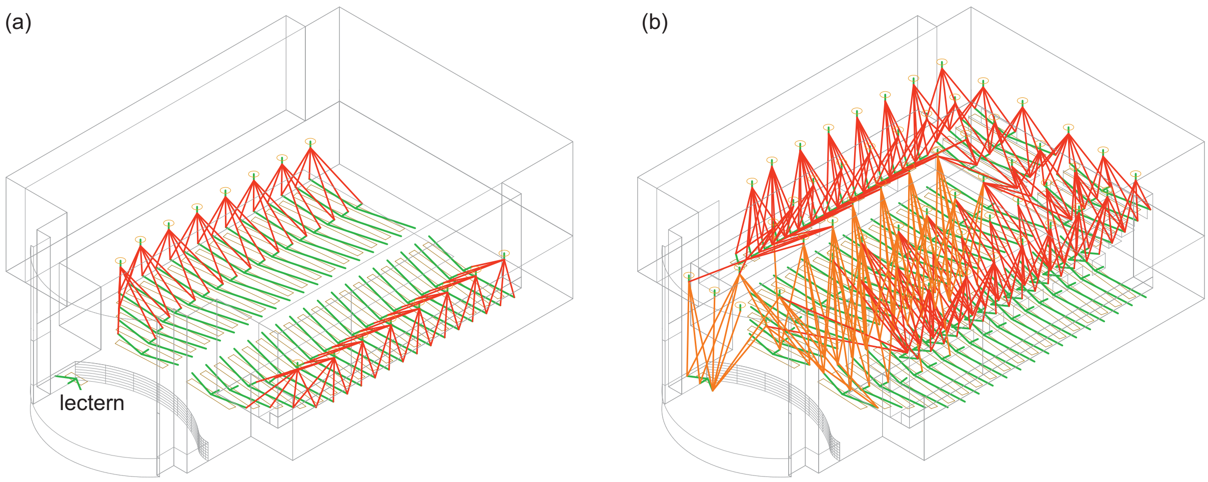

Figure 7: Auditorium: (a) lighting of study desks from downlights mounted in gallery ceiling, (b) lighting of study desks from downlights mounted in main ceiling.

Table 2: Filters used to generate the lighting layout.

Operation	Filter	Layout elements	Spatial relations	Comments
select	F7	Openings, desks		Related whole spaces are selected implicitly.
aggregate	F8	Whole spaces, openings	*partially encloses* relation between space elements and whole spaces	Large openings enclose the auditorium air space (Fig. 6 (a)).
select	F9	Whole spaces, openings, desks		Whole spaces are selected explicitly and must have at least 20 study desks.
insert	F10	Downlights, partitions		Missing space elements are inserted

to stage lighting at front row seats on main space and gallery levels. Seats on both sides of the main aisle are lit from the auditorium ceiling, as are those on the gallery. There are aisle sets underneath the gallery that do not receive direct lighting from downlights.

The generated lighting network allows for an approximate qualitative assessment of direct lighting distribution in a multi-level space. However, in order to assess e.g. the glare potential of downlights in greater detail, additional seats that are currently not considered as sufficiently close to specific downlights would need to be considered together with photometric properties of downlights.

9. Conclusion

Coverage of multi-level spaces by an existing schema for network-based space layouts and operations has been shown with a case study. In contrast to existing methods, multi-level and single-level spaces are modeled in a uniform manner, which limits model complexity and minimizes modeling effort. The academic facility that was chosen as a test building has several features that pose significant challenges for multi-level space modeling. Certain modifications of the schema were necessary to achieve desired results. These include the addition of area attributes for layout elements and spatial relation orientation attributes. Another change concerns space element types. In the modified schema, a space element type may be defined such that a space element is instantiated not only with subspaces but other space elements as well. For example, openings are instantiated together with flights of stairs.

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