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An Indoor Space Model of Building Considering Multi-Type Segmentation

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Abstract: Indoor space is a core part of supporting indoor applications. Most of the existing indoor space models are expressed from three space scales: building, floor, and room, and the granularity is not fine enough, lacking the expression of each functional subspace inside the room. In this study, we first analyzed the spatio-temporal segmentation characteristics of indoor space, and proposed a multi-level indoor space model framework that takes into account multiple types of segmentation. As well, based on the IFC (Industry Foundation Classes) standard, the extension of the indoor functional subspace was realized. The experimental results showed that the indoor space model proposed in this paper can effectively support the expression of functional subspace under the multi-type segmentation based on indoor elements, especially from the aspects of semantics, geometry, relationship, and attribute. This study enriches the granularity of existing indoor models and provides support for refined indoor navigation and evacuation applications.

Keywords: indoor space model; multi-type segmentation; IFC; functional subspace; extension

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1. Introduction

Indoor space is an important part of the interior of the building, and it is the main place where people live their daily life. The life and work of modern residents are mostly in the indoor space of the renovated building, and the time spent has reached 80–90% of the whole day [1]. With more and more environmental simulation and application analysis of indoor scenes, the spatial organization of buildings, floors, and rooms is difficult to meet the needs of refined and diversified indoor space analysis. It is mostly because some types of information required by certain applications do not exist in the current models and standards, for example, a more detailed subdivision information of the indoor space model framework is required in indoor navigation analysis [2–4]. Describing and expressing these micro-scale indoor spaces is the core issue of current indoor GIS research, which is conducive to assisting in sophisticated social management and application analysis of human settlements [5,6].

With the acceleration of urbanization, many scholars and institutions in the fields of geographic information and building information engineering have done a lot of research on the indoor space model of buildings [7]. Several specifications for building spaces have also been widely concerned, and the most prominent are considered include CityGML, IndoorGML and IFC4.3 [8–10]. In this study, we summarize related studies and specifications into two categories: focusing on the expression of entities and focusing on the expression of spaces themselves. The first category is the indoor space model which focuses on the

expression of entities. The defined various component entities are used to represent the actual building structure and its indoor entities, which mainly include building components, indoor furniture, home appliances, and other components [11]. The components are all tangible things that exist physically in the real world and are used to create an enclosed function space for use. CityGML supports the description of city objects from semantics, geometry, and topology. As one of the most detailed themes defined in CityGML 3.0, the building extension module allows building elements to be represented with four levels of detail from LOD0 to LOD3. The current version of CityGML 3.0 only regards the smallest granular indoor space type as the feature (Room), and internal facilities such as furniture can be represented in all LODs 0–3.

As the indoor environment for human activities becomes more and more complex, the inadequacies of CityGML's building model in expressing indoor elements are more obvious. Therefore, researchers have developed a series of indoor extension models ADE to support these indoor applications [12–16]. Tang et al. (2018) proposed an extended indoor multiple levels of detail (ILOD) specification, especially for indoor spaces. ILOD takes advantage of the two existing international standards (IFC and IndoorGML) to extend the existing LOD4 of CityGML 2.0 into a more accurate indoor ILOD0-ILOD4. Dutta et al. (2017) developed CityGML ADE for indoor routing and positioning. It adds indoor elements related to this application field and enriches BuildingInstallation elements to support indirect connections between floors, such as stairs and elevators. CityGML focuses on the element model rather than the spatial model. Kim et al. (2013, 2014) are committed to enhancing the expression of indoor elements of CityGML 2.0 and developed Indoor ADE, which extends the indoor element models of two building modules: indoor facility element models and indoor space element models. The former includes tables, chairs, and interior components such as fire hydrants, while the latter is functional space elements such as offices and conference rooms. At the same time, the ADE is only based on CityGML LOD4, and the main feature is that it can support the description and expression of the building story.

The second category is an indoor data model that focuses on the expression of spaces [17–25]. The space elements are used to represent the actual or theoretically bounded area or volume and provide certain specific functions in the building [26,27]. Spaces are a generalization of all spatial elements that can be used to define a spatial structure or spatial region. In the IndoorGML standard, indoor space is defined as a space composed of architectural components in one or more buildings. IndoorGML defines four types of indoor spaces: General Space, Connection space, Anchor Space, and Transition Space. The current version of the standard is mainly for indoor navigation applications, focusing on expressing the semantic and topological information of indoor spaces, ignoring the space occupied by indoor furniture and other components [27]. The spatial element in the IFC standard is a generalization of all spatial objects that can be used to define an indoor spatial structure or area. IFC divides the spatial elements into three levels: building (IfcBuilding), floor (IfcBuildingStorey), and space (IfcSpace) from large to small granularity. Among them, the smallest granular space (IfcSpace) represents the actual or theoretically bounded area or volume, which is directly related to the building floor. However, due to the placement of indoor furniture in the interior space, a smaller-grained functional space is formed, which is ignored by the current space model. Some researchers have developed several frameworks to further refine the indoor space granularity [19,28–33]. Zlatanova et al. (2014) propose to divide the indoor space into free sub-spaces and inert sub-spaces. Diakité et al. (2016, 2017) proposed a flexible space subdivision framework (FSS) for indoor navigation, which divides indoor space into object spaces, functional spaces, remaining free space, and agent spaces based on the ability of indoor objects to change their positions autonomously.

The indoor space model that takes into account the space segmentation has an important influence on indoor navigation, indoor map service, and indoor space facility management. For example, fine navigation based on functional subspace division, payment management based on household space, etc. However, from the perspective of the

semantic hierarchical classification of indoor space, the current standards and related research mostly focus on the three scales: building, floor, and room space. The semantic, relationship, and attribute information related to the household space and the functional subspace are missing from the current standard. Focusing on the expression of a single space, and lacking a description mechanism for multi-level complex indoor spaces under considering spatio-temporal segmentation. At the same time, without the subdivision of the room space by the furnishing components, most models lack the expression of the functional subspaces within a single space. Indoor furniture such as bookshelves will also subdivide the function of the indoor room, dividing a single room into two parts: the meeting function area and the office area. How can the existing IFC specifications be extended to include the expression of household space and functional subspace, so that it can support refined analysis and management applications, is the research question that this article needs to focus on.

In view of the above-mentioned problems existing in the existing indoor space model, the contribution of this paper was to propose a multi-level unified expression indoor space data model considering the multi-type segmentation, which covers household space and indoor functional subspace. From the perspective of indoor space characteristics and cognition, with a focus on indoor space segmentation characteristics, the indoor space elements were analyzed in terms of semantic hierarchical structure, classification system, attributes, and relationships. Based on the construction of the conceptual framework, the indoor space model was gradually improved based on the multi-level expression of the IFC standard.

The organizational structure of this paper is as follows: In Section 2, we discuss the conceptual framework of a multi-level indoor space model based on segmentation. In Section 3, we analyzed the information contained in the indoor space in detail and proposed a multi-level indoor space model based on IFC extension. In Section 4, the case and analysis are given, and the advantages of the space model proposed in this paper are discussed in Section 5. Section 6 of the article provides conclusions and future research directions.

2. Conceptual Framework of Multi-Level Indoor Space Model

Indoor space has different characteristics from outdoor space, and the particularity is mainly reflected in small spatial scale, strong closure, and high complexity. At the same time, the indoor space is separated from the outdoor natural environment by building components and has different use functions in the interior of the building. The premise of building a multi-level indoor space model framework is based on studying the characteristics of spatio-temporal segmentation and summarizing the multi-type segmentation strategies of indoor space.

2.1. Spatio-Temporal Segmentation Characteristics of Indoor Space

Indoor space segmentation is to gradually separate the internal space of an independent building into subspaces by components to meet different functional requirements. Therefore, there are significant segmentation characteristics between rooms. Describing and expressing the temporal and spatial segmentation characteristics of indoor space is the premise of recognizing multi-detail level indoor space. From the perspective of geography, this paper further explains the temporal and spatial segmentation characteristics of indoor space.

The spatial segmentation characteristics specifically refer to the geometric division of the indoor space by the components. According to different spatial segmentation characteristics, indoor space segmentation can be divided into:

(1) Entity segmentation. Entity segmentation refers to the use of objectively existing building components, furniture components, and other entities to segment the geometry of indoor space. By spatially limiting the boundaries of indoor space objects, the enclosure forms an objective physical boundary that meets the needs of specific user functions. The components will block people's sight and walking route, so

through physical segmentation, a relatively closed space will be obtained, thereby ensuring the privacy characteristics of the indoor space.

(2) Virtual segmentation. Virtual segmentation refers to the use of "empty" boundaries provided by imaginary boundary components to separate two adjacent indoor spaces. The geometry of the imaginary boundary components serves as the boundary between two adjacent spaces. Fictitious boundary components are usually not displayed, and there is no other attribute information (such as materials). The virtual partition of the indoor space is not completely closed on the boundary, forming a relatively open space (semi-indoor space).

The temporal characteristics of indoor space segmentation mainly refer to the time sequence of the division of indoor space by components. According to the temporal segmentation characteristics, indoor space segmentation can be divided into:

(1) The first segmentation process is to partition the indoor space from the natural environment by building components, as shown in Figure 1. The space boundary can be constrained by building component entities such as walls, columns, and floor slabs, which separate the indoor space from the natural space. The building shell component separates the internal space of the building from the external natural environment, and the floor component divides the internal space of the building into different story spaces in the vertical direction. Inside each story space, building internal components continue to divide the story space into a single room space with different functions.

(2) The second segmentation is the space division within a single space using indoor furnishing components. The room is divided into several areas through the arrangement of indoor furnishing components, each area being a subspace with different activity functions. The first segmentation process is essentially the construction process of the main structure of the building, and the second segmentation corresponds to the process of interior decoration.

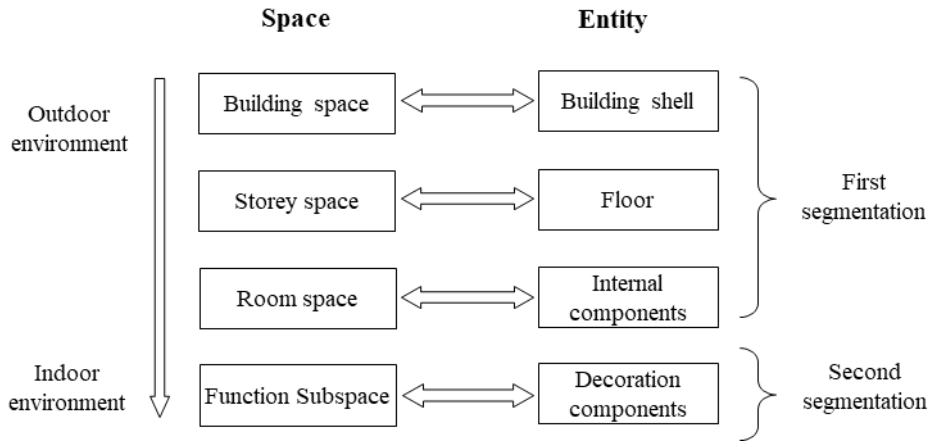


Figure 1. Indoor space and segmentation components.

2.2. Multi-Type Segmentation of Indoor Space

The interior scene of a building can be divided into two parts: component and space. The boundary of space is defined by the component, and the component is in the space. Two parts are the premise of each other and coexist in unity. From the perspective of indoor space cognition, the essential difference between space and component is that component will block people's line of sight or route, while space will ensure an unobstructed line of sight. When people are active in indoor space, they first pay attention to the differences between components and space, and mainly guide them to avoid components through sight. This guiding rule determines the scope and path of people's activity in the free indoor space. In space syntax, line-of-sight accessibility analysis is usually used to express whether there is occlusion of the line of sight between two points in space. Therefore, in the process of cognition of indoor space, firstly pay attention to the sight accessibility

of the space, and use components to divide the space into subspaces. However, due to the different visibility and mobility of components, the segmentation intensity of indoor space is also different. As shown in Figure 2, according to the characteristics of component entities from strong to weak, this paper divides the segmentation type of indoor space into the following four types:

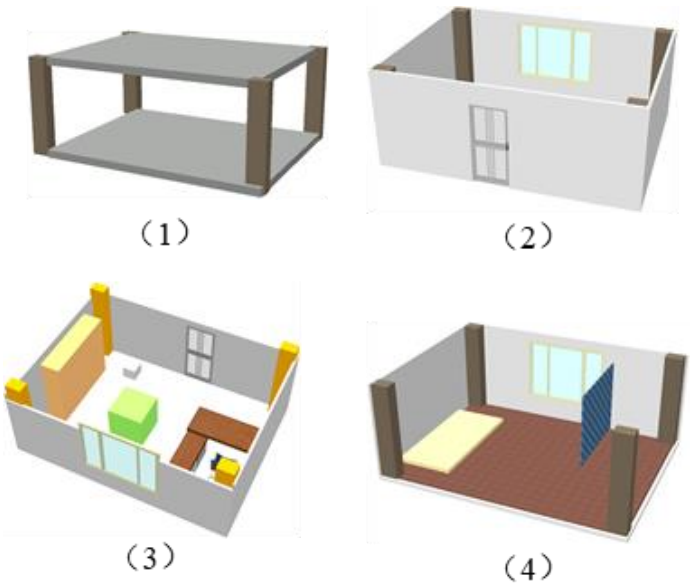


Figure 2. The four segmentation types of indoor space based on components (1–4).

(1) Segmentation of load-bearing building components (Figure 2(1))

The load-bearing components of the building mainly include structural components such as a load-bearing wall, load-bearing column, floor, beam, and so on. The load-bearing structural components not only directly bear various external forces of the building, but also play a role in enclosing the indoor space to a certain extent. Once the segmentation is completed, it is permanent and cannot be changed. Therefore, the division of the load-bearing components is the first-level division.

(2) Segmentation of common building components (Figure 2(2))

An indoor space is enclosed by ordinary building components and load-bearing structural components. Ordinary walls are used to completely block the external line of sight, sound, and light, forming an independent indoor space with good privacy. However, these walls can be removed and changed. The division of the non-load bearing ordinary building components is the second-level division.

(3) Segmentation of furniture solid components (Figure 2(3))

Every piece of furniture should be used to divide the empty interior space of the room. The segmentation of indoor space by furniture entities can be divided into vertical division and horizontal division. Vertical division refers to the use of furniture to subdivide the indoor space in a vertical direction. The division entities mainly include partitions, screens, furniture, and other components. As shown in Figure 3, partitions refer to the façades that are used to separate indoor spaces. They are more flexible in application, including fixed partitions and movable partitions. As an important part of traditional furniture, screens are placed indoors to block the wind and line of sight, which also plays a role in dividing the indoor space. The indoor space is divided by transparent high cabinets, shelves, etc., and the lines of sight can see through each other, emphasizing the fluidity and connectivity between adjacent indoor subspaces.



(a) Partitions (b) Bookshelf

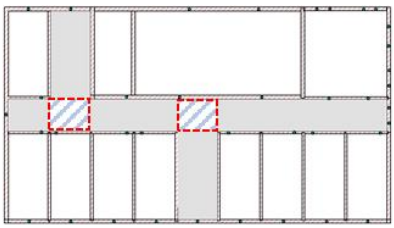
Figure 3. Vertical division components.

Horizontal segmentation refers to the subdivision of the indoor space in the horizontal direction. This segmentation mostly uses relatively short furniture, such as sofas, counters, tables, and chairs. These items of furniture usually occupy a certain space on the horizontal plane, by themselves or in combination with other furniture, forming a functional area with a specific boundary in the indoor space.

(4) Virtual segmentation of indoor space (Figure 2(4))

When it comes to open spaces such as pavilions, canopies, and empty corridors, the boundary of indoor space cannot be completely defined only through line of sight barrier and guidance. This is mainly because there is a virtual segmentation of indoor space in the design process. Without blocking the line of sight, in order to meet people's spiritual feelings and aesthetic requirements, the space virtual segmentation based on visual perception has provisions on the material, height, and arrangement of components, so as to further divide the functions of indoor space.

Spatial virtual segmentation mainly includes three categories (Figure 4): 1. Structural virtual segmentation is caused by different visual areas of corridor space. As shown in Figure 4a, the visible area at the intersection of the corridor is larger, thus forming a virtual boundary segmentation of the corridor. 2. Virtual segmentation is formed by the different heights, materials, and textures of interface components (such as the floor, ceiling, etc.). 3. Column segmentation: the columns are set up to meet the load-bearing requirements of the structure in the vertical direction. However, in order to enrich the levels and changes of indoor space, columns are sometimes used to divide indoor space (Figure 4c). The closer the columns are to each other, the stronger the sense of segmentation.



(a) Different visual areas of corridor space



(b) Different height



(c) Column

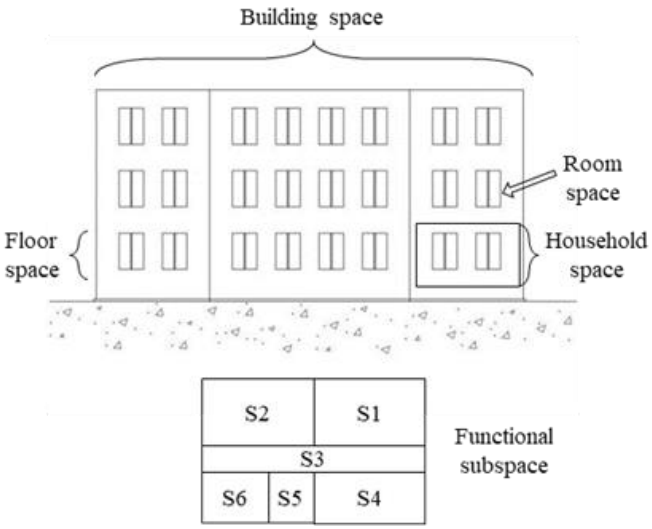
Figure 4. Spatial virtual segmentation.

Characteristics of virtual segmentation: the segmentation of indoor space is not clear, the boundary limits of components to indoor space are weak, and there is no tangible entity barrier in the line of sight. However, through symbolic segmentation, we can rely on the changes in some physical characteristics of components to give enlightenment, and divide a connected indoor space into two different indoor subspaces at the psychological level.

2.3. Semantic Framework of Multi-Level Indoor Space

The research of the indoor space data model follows the principles of geographic space cognition and segmentation methods and treats indoor spaces of different scales as specific functional, hierarchically nested complexes. This paper divides indoor space objects into five levels: building space, floor space, household space, room space, and functional subspace according to different abstract levels, and provides related definitions and descriptions, as shown in Table 1.

Table 1. Hierarchical level of indoor space.

Level	Name	Define	Illustrates
1	Building space	A place with a certain structure that provides shelter for residents or internal things	
2	Floor space	In the vertical direction, the number of sub-regions divided into the building space	
3	Household space	A set of room spaces with the same users	
4	Room space	The internal space area of the building formed by the boundaries of walls, columns, floors, virtual components, etc.	
5	Functional subspace	Indoor functional area formed by dividing a single room space with indoor components such as screens and furniture	

(1) Building space

A building space is a place that has a certain structure and provides shelter for residents or internal things. It is located at the top of the indoor scene, including the above-ground and underground spaces, divided by building components. According to the purpose of the building, the space types of the building can be divided into residential, industrial storage and transportation, commercial and financial information, education, medical and health research, entertainment, military, and others [34]. According to the specific use function, the type of building space can be further divided. For example, houses can be divided into complete sets of residential buildings, non-sets of residential buildings, and collective dormitory buildings.

(2) Floor space

Floor space is a number of sub-areas obtained by dividing the building space in the vertical direction. Floor space is the object used to organize the household space and the single indoor space. It is the second-level indoor space, including several household spaces or directly composed of all the room spaces on the same floor.

Floors include standard floor, natural floor, equipment floor, false floor, mezzanine, attic, overhead floor, structural conversion floor, refuge floor, basement floor, and semi-basement. The standard floor is the floor with the same plane structure layout. The equipment floor is the space floor of the building dedicated to setting HVAC, air conditioning, water supply and drainage, electrical and other services indoor equipment. The overhead

floor is an open space floor with only a supporting structure but no enclosure structure. When the building is more than 100 m high, refuge floors need to be set to ensure fire safety [35]. The basement floor is generally the floor where the indoor ground level is lower than the outdoor height and exceeds 1/2 of the indoor net height.

(3) Household space

A household space is a set of room spaces with the same users. It is usually used to organize a family or group by aggregating a set of spaces with specific functional combinations. Each household space must belong to a certain floor or building, and cannot be independent of the floor or building space. In addition to referring to the private housing tenants, the household space also includes the indoor space formed by the aggregation of common areas other than the housing households on the first floor.

(4) Room space

Room space is the internal space area of the building surrounded by boundary components such as walls, columns, floors, virtual components, etc. It is the fourth-level indoor space and is composed of several functional sub-spaces. The room space is enclosed by the top surface, the ground, and the wall. The presence or absence of top surface shielding (such as the roof) is considered to be the main sign distinguishing the indoor space and outdoor space of the building (Figure 5). In this kind of closed building interior space, in order to meet the requirements of the private living environment, the internal closed rooms satisfying different functions are further defined [36].

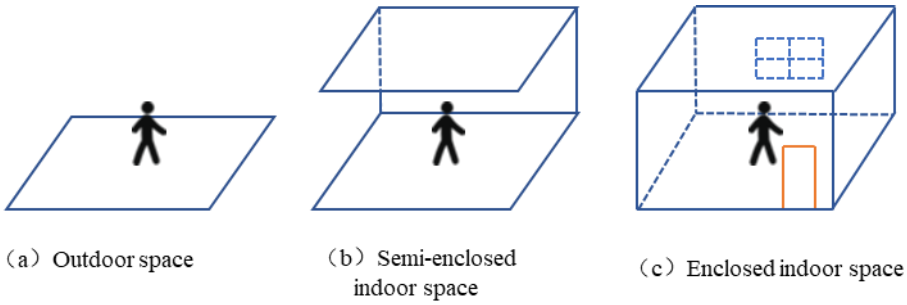


Figure 5. The distinction between indoor and outdoor spaces based on the top surface.

Room space is the basic unit that constitutes a building. In the process of architectural design, the building components divide the indoor space for the first time to form a group of room spaces. The function of space is often used as the classification basis, and the single room space is divided into four categories: equipment space, connecting space, control, and management space, and use space. Due to the lack of vertical segmentation of the floor slab, an indoor space spanning multiple floors is formed in the building, that is, a cross-floor space. As the internal structure of buildings gradually becomes more complex, cross-floor spaces are becoming more and more common. If only relying on the classification method of space function, the cross-floor and segmentation characteristics of indoor space will be ignored.

Therefore, this article will classify the room space in a combination of space segmentation features and functions. According to whether the room space has the characteristics of spanning multiple floors, first divide the indoor space into single-floor space, split-level space, and cross-floor space, as shown in Figure 6. Then, it is divided into closed space and semi-closed space according to the division degree of the boundary members of the single-floor space. The semi-enclosed space is divided into balconies, canopies, pavilions, etc. according to the use function, and the enclosed space is divided into indoor spaces such as ordinary corridors, offices, bedrooms, kitchens, and living rooms according to different functions. The split-level space is formed by the different floor heights of the same indoor space. This type of space is a special case of the indoor single-floor space. Depending on whether the space contains transitional components such as stairs and ramps, the split-level

space can be divided into sudden changes in split-level space and gradual transition spaces. The cross-floor space is divided into air duct wells, flue wells, elevator shafts, duct wells, atriums, halls, and other spaces according to different functions.

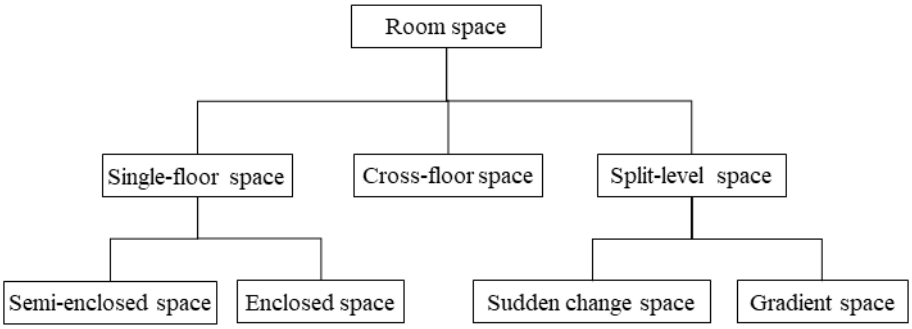


Figure 6. Classification of room space.

(5) Functional subspace

A functional subspace is the indoor functional area formed by dividing a single room space by indoor components such as screens and furniture. The lowest-level space in the indoor scene no longer includes the lower-level space. On the basis of the semantics of indoor space, according to the characteristics of indoor space segmentation, this paper continues to analyze the semantic hierarchy of single room space in more detail. As shown in Figure 7, according to different aesthetic and functional requirements, the space occupied by interior components will be subdivided into a single room space and divided into a group of sub-spaces with different functions.



（a）Living room space （b）Bedroom space

Figure 7. Schematic diagram of indoor functional subspace.

The room space is composed of several indoor functional subspaces, which are divided into interface subspace, free navigation subspace, and activity functional subspace (Figure 8). The interface subspace is the space occupied by the interface entities in the indoor space, which mainly includes the top surface subspace, the wall subspace, and the ground subspace (Figure 7a). The free navigation space is a free space used for indoor navigation and wayfinding, which does not contain indoor component entities. The activity functional subspace is a regional space that satisfies people's indoor leisure, office, entertainment, and other activities, usually including indoor furniture, home appliances, and other activities-related component facilities. As shown in Figure 7b, the bedroom can be divided into four basic functional areas: sleep, dressing, storage, and audiovisual. The living room functional space can have a dining area, tea room area, reading area, audio-visual area, entertainment area, rest area, and other functional subspaces.

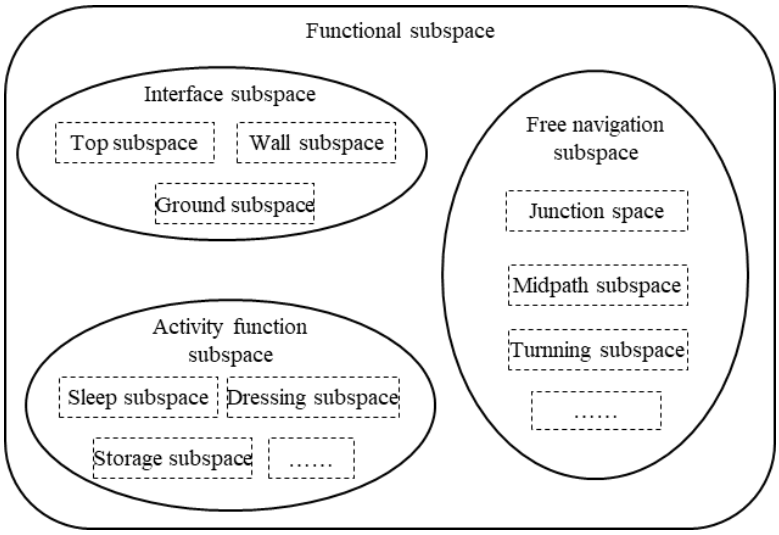


Figure 8. Classification of indoor functional subspaces.

3. Indoor Space Extension Model Based on IFC

The international IFC (Industry Foundation Classes) standard can be used to express the indoor space model, including space objects such as rooms, floors, buildings, and sites. The IFC specification can also well support the expression of space semantic description, spatial geometry, attribute characteristics, and element relationship in the model. The reason why this paper chooses to expand based on the existing IFC standards is that compared with other standards, IFC has more indoor space objects and relationships than CityGML and IndoorGML. However, the segmentation of room space by furniture discussed in Section 2.2 is ignored, and the contents of the entity, relationship, and attribute information of function subspace in the multi-level indoor space framework are imperfect in the version of IFC4. Therefore, it is necessary to add new space entity types and its attribute, relationship, and other information to IFC Standard.

3.1. Entity Extension

Due to the diversity of components and spatial complexity of indoor scenes, it is necessary to perfect the spatial entity types of the current IFC4 standard to meet more complex indoor space expression and information exchange. The granularity of indoor space objects proposed in this work can be divided into five levels: building, floor, household, room, and functional subspace. Establishing the mapping relationship between the indoor space in this article and the entities in IFC, it can be seen that there are some indoor space objects that cannot use the entity description provided in IFC, as shown in Table 2.

Table 2. Mapping relationship between indoor space objects and entities defined in IFC.

Indoor Space Objects		IFC Spatial Structure Entities
Build space		IfcBuilding
Floor space		IfcBuildingStorey
Household space		/
Room space	Single-floor space	IfcSpace
	Split-level space	/
	Cross-floor space	/
Functional subspace		/

The IfcSpatialStructureElement class defines the common attributes of all spatial structure units in IFC. It is often used to organize indoor spatial structures. It includes four hierarchical units: IfcSite, IfcBuilding, IfcBuildingStorey, and IfcSpace. IfcSite is a defined area of land in IFC4, on which the building project construction is to be completed.

This paper focuses on the multi-level indoor space framework based on the IFC standard. Therefore, the IfcSite element is not mentioned specifically. As well, the mapping relationship between indoor space objects in this study and IFC spatial structure entities are shown in the table. Among them, the single space (IfcSpace) does not distinguish between single-floor space, split-level space, and cross-floor space. At the same time, household space and indoor functional subspace objects cannot adopt the description of space objects provided in IFC.

The method of new entity extension based on the current release of IFC mainly depends on the IfcProxy class. The extension based on proxy entity uses the existing IfcProxy entity in IFC to extend the space model. The IfcProxy is an instantiable entity type which is intended to be a kind of container for wrapping objects. According to the needs of different users, the entity is instantiated, and the newly defined entity information is described by the attribute Name, Tag, ProxyType, and attribute set, so as to extend the IFC data model. Therefore, this article adopts the agent entity-based extension method to expand the indoor space.

The IFC standard uses the EXPRESS language (ISO 10303-11:2004) to describe the entity. The example of the EXPRESS definition of the indoor functional subspace extended by the IFCProxy entity is as follows:

```
ENTITY IfcProxy
SUBTYPE OF IfcProduct;
PredefinedType: OPTIONAL IfcSubSpaceEnum;
BoundedBy: OPTIONAL IfcRelSpaceBoundary;
ElevationOfFloor: OPTIONAL IfcLengthMeasure;
END_ENTITY;
TYPE IfcSubSpaceEnum = ENUMERATION OF (
RECEPTIONAREA,
STORAGEAREA,
SLEEPAREA,
USERDEFINED,
NOTDEFINED);
END_TYPE;
```

3.2. Relation Extension

3.2.1. The Relationship Involved in the Indoor Space

There are three relationships between components and indoor space: containment relationship, boundary relationship, and segmentation relationship.

(1) Containment relationship

The containment relationship refers to the relationship between the indoor space and the indoor furniture, home appliances, and facilities inside. Example: The relationship between the sofa, potted plants, and the living room (Figure 9).

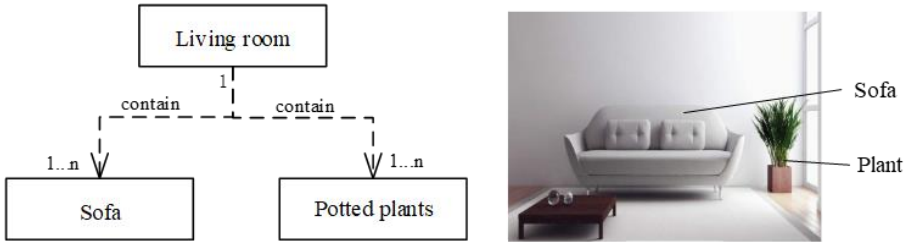


Figure 9. Containment relationship diagram.

(2) Boundary relationship

A boundary relationship is a relationship between different indoor spaces and indoor components. As the boundary element that defines the indoor space, the internal

components play the function of enclosing the indoor functional subspace. For example, the screen is the boundary between the hall space and the living room space (Figure 10).



Figure 10. Boundary relationship diagram.

(3) Segmentation relationship

The segmentation relationship is the association relationship between indoor components and indoor space. Indoor components play a role in the physical or virtual division of indoor space, dividing a single indoor space into several lower-level indoor subspaces. Such as the division of single room space by light partition wall; Virtual segmentation of different functional areas by floor and ceiling.

There are decomposition, aggregation, adjacency, and connectivity relationships among different indoor space objects.

(1) Decomposition relationship

The decomposition relationship is the relationship between the indoor compound space and the single space, and it is an expression of the relationship between the whole and the part. For example, the relationship between floor and room space, and the decomposition relationship between building space and floor space.

(2) Aggregation relationship

It is the relationship between the room space and the different functional subspaces. For example, the aggregation relationship between the living room and the meeting area, leisure area, audio-visual area subspace, etc., and the aggregation relationship between the bedroom and the sleeping area, dressing area, storage area, audio-visual area, and other sub-spaces.

(3) Adjacency relationship

This relationship refers to the adjacent relationship between different functional subspaces in the room. For example, the meeting area has an adjacent relationship between the screen and the porch.

(4) Connectivity relationship

Connectivity relationship refers to the interconnection relationship between different indoor spaces in the room. For example, the meeting room is connected through the door and the corridor.

3.2.2. Relationship Extension

IfcRelationship is an abstract summary of all objectification relationships in IFC. Objectization relationships are the preferred method for dealing with relationships between objects. There are six types of relationships, including IfcRelAssigns, IfcRelAssociates, IfcRelConnects, IfcRelDeclares, IfcRelDecomposes and IfcRelDefines. Most object relationships in indoor scenes can be described by the combination of the above six types of relationships and their sub-relationships. Among them, the IFC connection relationship includes ConnectsElements, CoversSpaces, ContainedInSpatialStructure, CoversBldgElements, Aggregates, and SpaceBoundary. However, IFC does not include the adjacency relationship, the connectivity relationship between indoor space objects, and the segmentation relationship between components and functional subspaces, as shown in Table 3.

The adjacency and connectivity relationships between spaces can be inferred from the space boundary relationship, which is an implicit expression of those types of relationships. However, when we pay more attention to the spatial model, we need to express the relationship directly and explicitly, so that it can be easily and quickly applied to indoor analysis [37].

Table 3. Indoor relationship and IFC defined relationship mapping.

Indoor Relationship	IFC Relationship
Aggregation	IfcRelAggregates
Adjacency	/
Connectivity	/
Segmentation	/
Containment	IfcRelContainedInSpatialStructure
Boundary	IfcRelSpaceBoundary

The attribute set is a collection of multiple attributes used to describe BIM model information. The attribute set based extension mechanism needs to customize attributes according to its own needs without adding new entity types. This extension mechanism has the advantages of low difficulty and high compatibility. It is suitable for simple situations such as IFC data element relationship information and attributes information that needs to be extended. Therefore, this paper adopts the spatial relationship extension method based on adding attributes to make the IFC element connection relationship support the adjacency relationship and connectivity relationship.

3.3. Property Extension

3.3.1. Attribute Information of Indoor Space

Attribute information is also called a non-spatial feature, which is an expression of the nature of the entity itself. The attribute information of indoor space is the description of the inherent characteristics of indoor space objects in indoor scenes through qualitative or quantitative methods. From different perspectives, the indoor space attributes that people pay attention to are different. For example, house builders pay attention to the property information, cost, and completion date of the indoor space, and house managers pay attention to the useful life, energy consumption, and capacity of the indoor space. The actual users of houses are more concerned about chemical attributes such as formaldehyde content and physical attribute information such as noise which influence indoor comfort.

Therefore, this paper summarizes the attribute information of indoor space into three aspects: physical attributes, chemical attributes, and social attributes (Figure 11). Among them, the physical attributes are noise, electromagnetic field, hardness, and other attributes of the indoor space. Chemical properties are the properties of space in chemical changes, such as acidity, alkalinity, oxidation, and the content of other compounds such as hydrogen sulfide and formaldehyde. Social attributes are descriptions related to social and economic characteristics such as the area, volume, property rights, price, capacity, and energy consumption of the space.

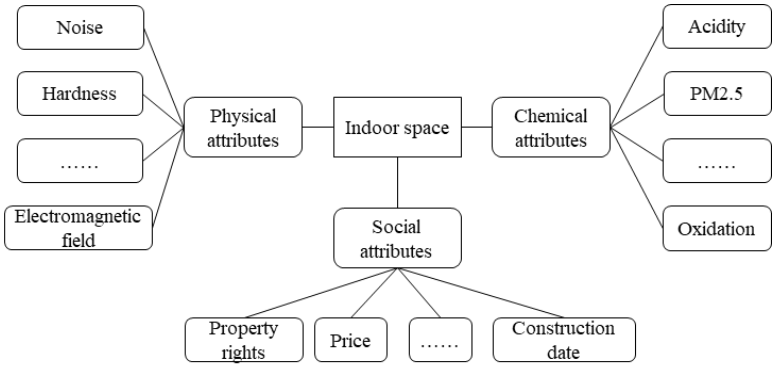


Figure 11. The attribute information of indoor space.

3.3.2. Attribute Extension Method

The physical, chemical, and social attribute information of the indoor space is expanded through the extended attribute set, as shown in Table 4. The entity type applicable to the extended attribute set is IfcSpatialStructureElement, which is used to describe the general attributes of subclass entities of IfcSpatialStructureElement. The physical property set of indoor space Set_PhysicalProperty and the chemical property set of indoor space Set_ChemicalProperty respectively define the content related to the physical and chemical properties of indoor space. The definition of the social property set of indoor space Set_SocialProperty is shown in Table 5.

Table 4. Definition of the attribute set of indoor space.

Extended Attribute Set	IFC Type	Attribute
Set_PhysicalProperty	IfcPropertySet	The noise, electromagnetic field, hardness, and related physical property information
Set_ ChemicalProperty	IfcPropertySet	Acidity, alkalinity, oxidation of space
Set_ SocialProperty	IfcPropertySet	The area, volume, property rights, price, and energy consumption of the space

Table 5. Set_ SocialProperty.

Attribute Name	IFC Type	Attribute Value Type
Number	IfcPropertyEnumeratedValue	IfcText
PropertyArea	IfcPropertySingleValue	IfcDouble
Lifetime	IfcPropertyBoundedValue	IfcDateTime
EnergyConsum	IfcPropertySingleValue	IfcDouble
Function	IfcPropertySingleValue	IfcText
Owner	IfcPropertyEnumeratedValue	IfcText
Other	IfcPropertySingleValue	IfcText

3.4. Multi-Level Indoor Space Model Considering Segmentation

The hierarchical structure of IFC's existing entities and the extended entities associated with the multi-level indoor space model of this paper is shown in Figure 12. Figure 10 illustrates the IFC class diagram that integrates the entities/relations/properties extended from the indoor space model to existing classes of IFC. In the figure, blue represents entity class, yellow represents relationship class and orange represents property class. Among them, the IFC classes with the red font are extended in the description of the previous sections.

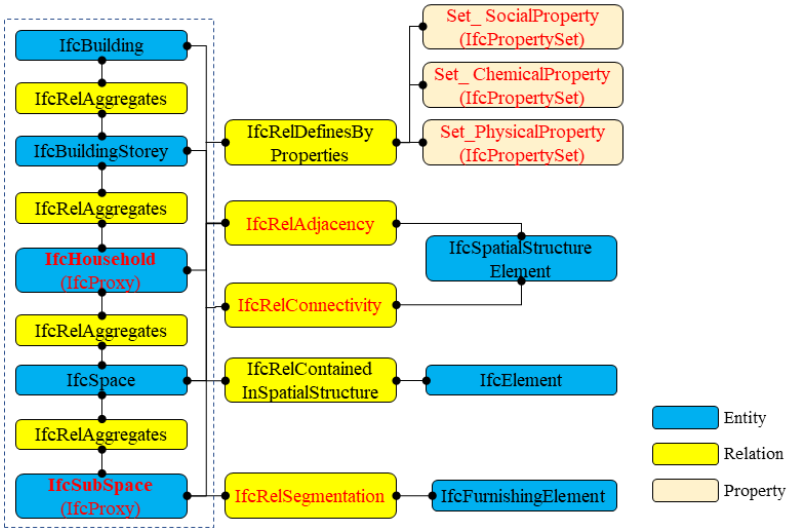


Figure 12. Multi-level indoor space model based on IFC.

4. Case Studies

In order to verify the applicability of the proposed multi-level indoor space data model, this paper uses a residential building to carry out experiments. The multi-level indoor space data model designed in this study includes five levels of building space, floor space, household space, room space, and functional subspace. Based on the building of the experiment, this article shows the indoor space models of each level in turn.

As shown in Figure 13, the indoor space of each level of the indoor space data model is displayed separately. Among them, Figure 13a shows the space of the building. The internal space of the building is expressed as a whole, and the internal space of the building is separated from the external space. Figure 13b expresses the floor space. According to the division of the building space by the floor, the building space is divided into several floors. The household space is shown in Figure 13c. It can be seen that there are several household spaces on a single floor of a residential building. Figure 13d is a display of indoor space from the level of room space, which is the smallest unit enclosed and divided by building components. The functional subspace combines the room space, which is divided by the interior decoration components and is the smallest granular indoor space (as shown in Figure 13e).

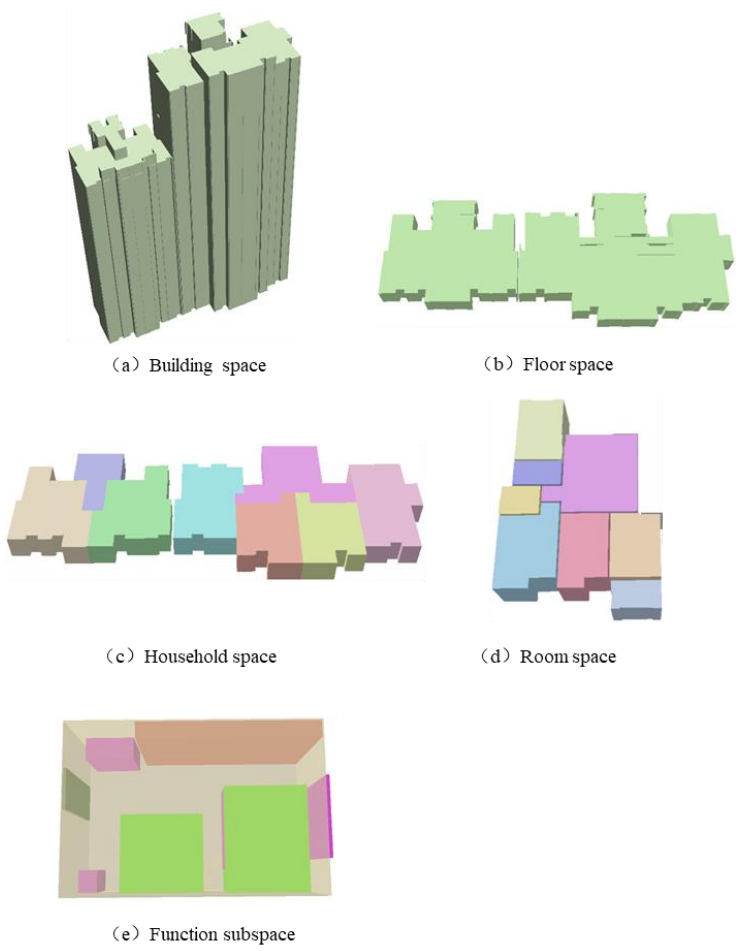


Figure 13. Demonstration of each level of indoor space.

Figure 14 illustrates the intercepted data fragments about the IFC file corresponding to the indoor space model in this paper to show that they are based on actual tests of the model. The #29 to #32 lines of the entity extension part describe the household space and function subspace entities extended in this paper, the #97 to #109 lines of the attribute extension part give the relevant attributes of a single function subspace, and the relationship extension part shows the aggregation and adjacency relationship of the extended function subspace.

Entity extension

```
#28=IFCBUILDINGSTOREY('0wnCJjVzzAvPLyLFtxXbJC',#2,'Default storey',$,$,$,$,$,$,0.);
#29=IFCPROXY('2CFCKI3Uj0qhti7zpihGhy',#2,'houseHold',$,$,$,$,.PRODUCT.,$);
#30=IFCSPACE('1nC2SttXL4e8NEqKohtp0D',#2,'space',$,$,$,$,$,$,$,$);
#31=IFCPROXY('1MLt0BYofF2e1tdkmen7Hc',#2,'subspace',$,$,$,$,.PRODUCT.,$);
#32=IFCPROXY('3Xq3TGKVz9PQIn7Scfjwsu',#2,'subspace',$,$,$,$,.PRODUCT.,$);
```

Property extension

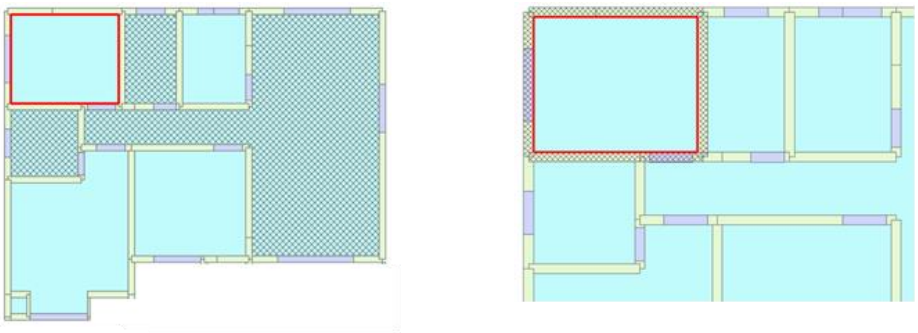
```
#97=IFCPROPERTYSINGLEVALUE('Number','',IFCLABEL('407'),#98);
#98=IFCSIUNIT(*,.TIMEUNIT.,$,.SECOND.);
#99=IFCPROPERTYSINGLEVALUE('PropertyArea','',IFCLABEL('12.00'),#100);
#100=IFCSIUNIT(*,.AREAUNIT.,$,.METRE.);
#101=IFCPROPERTYSINGLEVALUE('EnergyConsum','',IFCREAL(2000.),#102);
#102=IFCSIUNIT(*,.AREAUNIT.,$,.METRE.);
#103=IFCPROPERTYSINGLEVALUE('Function','',IFCTEXT('SleepArea'),$);
#104=IFCPROPERTYSINGLEVALUE('Owner','',IFCTEXT('Yueyong Pang'),$);
#105=IFCPROPERTYSINGLEVALUE('Other','',IFCTEXT('Normal'),$);
#106=IFCPROPERTYSINGLEVALUE('Lifetime','',IFCDATETIME('2075-02-14T12:01:01'),$);
#107=IFCPROPERTYSET('2a4XXQfzX68hPx_u_8LuYt',#2,'Set_PhysicalProperty','Property Set',());
#108=IFCPROPERTYSET('1wSQpnkHL5wuTOOghc$cRI',#2,'Set_ChemicalProperty','Property Set',());
#109=IFCPROPERTYSET('0UXXBRFpD5Ae_YVRHWQKRT',#2,'Set_SocialProperty','Property
Set',(#97,#99,#106,#101,#103,#104,#105,#96));
```

Relationship extension

```
#96=IFCPROPERTYLISTVALUE('IfcRelAdjacency',$,(IFCLABEL('1MLt0BYofF2e1tdkmen7Hc'),IFCLABEL('3Xq3TGKVz9PQIn7Scfjwsu')),$);
#116=IFCRELAGGREGATES('3tpMI8vi51ova22rxWQ0Cd',#2,'subspace Aggregates','subspace associated to space',#30,(#31));
```

Figure 14. Data fragments of the ifc file about the extension model.

The relationship involved in the indoor space expanded based on the attribute set is added to the model. Figure 15 shows the relationship between the expanded indoor space objects. The red box in the figure is the space that needs to be queried, and the objects covered by the shadow are the query results. Among them, Figure 15a shows the expanded spatial adjacency relationship, and Figure 15b shows the boundary relationship between the indoor space and the indoor components.



（a）Space adjacency relationship （b）Space boundary relationship

Figure 15. Query and visualization of relationships involved in indoor space.

As shown in Figure 16, the warehouse and office in the building are used as a case to analyze the necessity of taking into account the indoor functional sub-space model in the evacuation of indoor crowds. Among them, Figure 16a is a three-dimensional model of the warehouse, and Figure 16b is a three-dimensional model of the office. Through the indoor space modeling method, the modeling results of the indoor functional subspaces can be achieved (Figure 16c,d). Figure 17 is a classification system developed with xBIM project and displays a suits additional use case. This procedure is used to demonstrate the multi-level indoor space model proposed in this study.

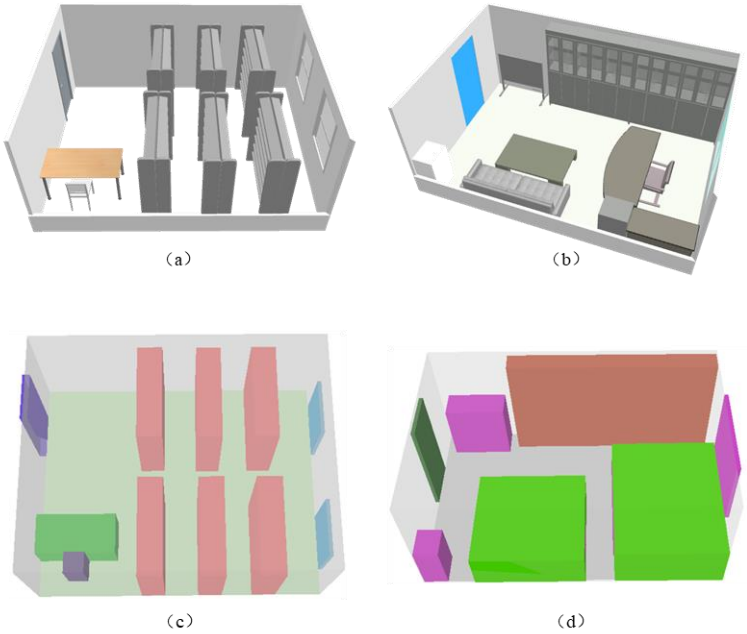


Figure 16. Functional subspace model:(**a**) a three-dimensional model of the warehouse. (**b**) a three-dimensional model of the office. (**c**,**d**) the modeling results of the indoor functional subspaces.

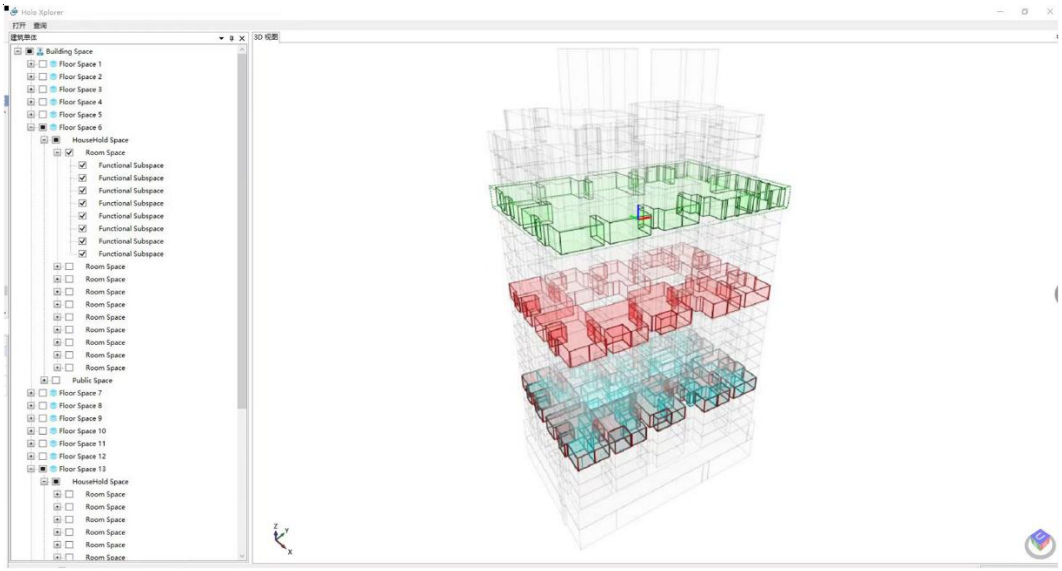


Figure 17. Indoor space classification system.

5. Discussion

5.1. Integrity of Indoor Space Model

In terms of semantics, the indoor space model proposed extends the expression of two levels: household space and indoor functional subspace. In terms of the relationship between space objects, the expression of adjacency and connectivity between indoor spaces is expanded. At the same time, the physical, chemical, and social characteristics related to indoor space characteristics are expanded into an attribute set that can describe the characteristics of indoor space objects. As shown in Table 6, the multi-level indoor space data model proposed in our study divides indoor space objects into five levels, namely, building space, floor space, household space, room space, and functional subspace. Compared with the CityGML model and the IFC standard, it increases the level expression of the household space, and at the same time extends the smallest granular indoor space to the level of indoor functional subspace.

Table 6. Granularity comparison of indoor space models.

This Paper	IFC	CityGML
Building space	IfcBuilding	Building
Floor space	IfcBuildingStorey	Storey
Household space	/	/
Room space	IfcSpace	Room
Functional subspace	/	/

For the single space, the indoor space data model has been further semantically extended, and the room space is divided into single-floor space, cross-floor space, and split-level space according to whether it has cross-story and split-level features. According to the enclosure degree of the boundary components, the single-floor space is further divided into closed space and semi-closed space. The multi-level indoor space model proposed in this paper has richer and more complete indoor space information, which provides support for processing indoor application analysis in a complex architectural environment.

5.2. Support for Indoor Navigation Applications

In the process of indoor navigation, whether to consider the segmentation characteristics of indoor furniture, the navigation path selection strategies can be divided into the following three situations:

(1) Without considering the partition of furniture in the room, the entire indoor space is regarded as a freely navigable space. At this time, the pedestrian's navigation path is the position where the pedestrian is direct to the door space.

(2) When taking into account the indoor functional subspace, the normal navigation path generation will avoid obstacles in a functional subspace such as furniture, and only select the path in the freely navigable space, as shown in Figure 18a. The green dashed line represents the path of pedestrians in a free navigation space.

(3) When disasters such as fires and earthquakes occur, people need to evacuate from their indoor locations to the outdoors in the shortest possible time. Part of the functional subspace can also be used as a traversable path. According to the attributes information of the furniture, the indoor subspace can be divided into a cross-functional space and a non-cross functional space, and the cross-functional space can be used as an evacuation path. As shown in Figure 18b, people can cross the table directly to the doorway (the red solid path).

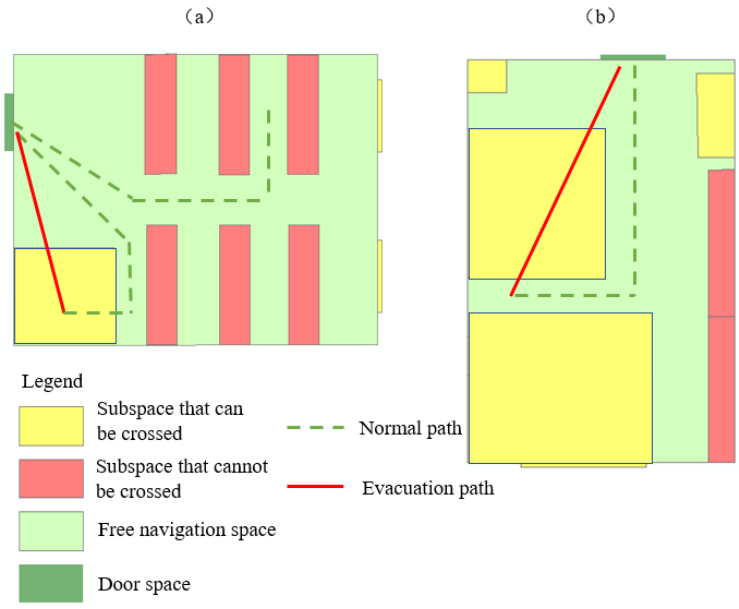


Figure 18. Indoor path selection strategies under different space models.

6. Conclusions

In view of the lack of indoor functional subspace, we proposed a multi-level representation of the indoor space data model that takes into account multiple types of space segmentation, covering five levels of indoor space: building space, floor space, household space, room space, and functional subspace. We analyzed the spatial-temporal segmentation characteristics of indoor space and gave the semantic framework of multi-level indoor space. Based on the extension of IFC's entities, relationships, and attributes, the multi-level indoor space expression model is finally constructed, and the feasibility of the indoor space data model proposed in this study is verified by the experimental data of residential buildings.

The indoor space data model proposed in this paper extends the minimum granularity of indoor space to indoor functional subspaces and provides refined indoor space model support for intelligent indoor analysis and application.

The multi-level indoor space model can be used to generate indoor navigation paths, which verifies its reliability and practicability. Nevertheless, the proposed indoor space model needs to be extended to other application analyses. Therefore, future work will study the methods of coupling the indoor space model constructed in this work with other applications.

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