A multi-level space unit framework for 3D buildings to facilitate the development of digital twin

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Key words: 3D geographic information, CityGML 3.0, 3D building, Digital twins, SDI, multi-level, space units

SUMMARY

In recent years, the development of digital twins and smart cities has received wide recognition. The introduction of 3D geospatial technology overcomes the limitations of 2D geographic information and makes many innovated applications possible. Building data has been considered as an essential type of 3D information for urban development. The integration of cross-domain data about buildings, however, is an extremely complicated issue due to the variety of perspectives and demands from related stakeholders. Despite there have been web-based applications providing realistic illustration of 3D buildings, many of them are nonetheless restricted to visualization only. We argue an effective strategy to facilitate cross-domain integration of building data must be based on the common geospatial reference of meaningful 3D spatial building units with unambiguous specifications and unique identifiers. The multiple representation approach based on the LOD concept of CityGML 3.0 further increases the modelling capabilities of the proposed common geospatial reference. To determine the primitive set of spatial units for buildings, this study examines the building laws and specifications of Taiwan and proposes a primitive set of spatial units of buildings from the legal perspective. For every selected type of spatial unit, its distinguished semantics, roles, characteristics and the relationships with respect to the other types of space units are further analyzed. The 3D geometric representation (including LOD) and thematic attributes are then formally defined according to the surveying technology used and the source data provided by the stakeholders. A hierarchical identifier system is developed to enable the unique identifications of individual space units and the links between different space units as well as the multiple representation of the same space units. This integrated common geospatial reference framework hence provides a feature-based mechanism not only used for illustrating the 3D buildings, but also facilitating the management and selection of building information according to the government legal requirements and the chosen applications. For the development of digital twins, the most significant impact for the common geospatial reference is to provide a reliable and consistent reference to spatially enable the 3D representation of domain data via standardized identifiers. This design tremendously expands the inter-connection of data from different sources and supports the development of 3D analysis and applications. As the framework comprehensively considers the various aspects of descriptions for meaningful spatial units of buildings and provides enabling mechanism to expand the development of 3D applications, it provides the advantages of interoperable integration and flexible expansion for the GIS-based digital twins.

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1. INTRODUCTION

With the rapid development of the Internet of Things technology, digital twin has been recognized as one of the top ten technological trends in the world(Panetta, 2017). Digital twin can be applied to a variety of domains, such as industry, healthcare, construction, and freight. However, digital twin lacks of a common understanding and concepts regarding the extensive research and applications(Liu et al., 2021). Therefore, when developing digital twins, it is important to construct a basic common understanding framework for cross-domain data. In spatial planning fields, the concept of digital twins with geographic information has been widely discussed, which leveraging the characteristics of geographic information system as a tool to integrate, analyze, and visualize the spatial data for developing digital twin. In Norway(Major et al., 2021), the government integrates geographic information, dynamic population data, and Internet of Things data, such as traffic, meteorology, telecommunications and power equipment data. High-quality 3D digital twins were developed with the GIS platform to help urban development. In the urban disaster management(Ghaith et al., 2022), GIS is used to integrate historical and real-time data can combine with disaster simulation models for decision support. This integration forms a digital twin of urban disasters that prevents urban disasters from occurring and predicts their impact. Using the concept of simulation and interoperability of digital twin, we can develop an integrated platform as the foundation for developing digital twins of cities. Therefore, combining spatial data and digital twins is essential for future urban development.

The development of 3D geospatial technology brings many benefits to the applications of urban digital twin(Patrick, 2018). By adding vertical dimensions, it conquers the limitations of 2D geographic information in the past and make simulation and display of spatial data more realistic. The concept of multi-source, multi-scale, and multi-physical can expand the applications of digital twin and help to integrate and analyze cross-domain spatial data. 3D building data is highly discussed in the development of urban digital twin because of their wide applications in urban planning. If these data can be successfully and effectively linked, it will bring innovative applications for urban development. Also, it will become an important foundation for the development of urban digital twins. In Taiwan, various types of 3D building models have been developed following different purposes, quality, specifications, and sources. Each building can be regarded as an objectized space unit at a specific level. Because there are many different construct purposes and data representations from various sources, handling heterogeneous data and cross-scale data becomes difficult.(Wagner et al., 2019). Lack of the consistent specifications and standards exposes digital twins to interoperability issues and cross-domain integration challenges (Fuller et al., 2020). These have caused the difficulty of data integration, management, and share to increase, making digital twins less useful for cross-domain collaboration. From 3D building data perspective, the challenge may widely include issues about multiple geometries, semantic objects, thematic attributes, and level of details. Hence, a well-organized framework is essential for integrating the spatial data and digital twin (White et al., 2021), and this framework can ensure the quality and accuracy of spatial data during cross-domain collaboration. Spatial data collaboration requires the cross-domain experts to provide expertise and techniques in different fields. The different requirements for spatial data cause the diversity of spatial data types. Therefore, spatial data collaboration needs to develop common data standards and enhance semantic interoperability technologies to ensure seamless interoperability of data in different fields. In order to achieve these objectives, there are at least 3 issues that must be considered. The first is that there are no clear specifications for the basic space unit, and each domain has their own methods to define space units. Second, each space unit may have multi-sources, multi-representations, and multi-versions. Last, space units do not have unique identifications that can be used across classes and scales.

To solve the above issues, the aim of this research is to establish a multi-level framework of space units with semantic consideration for Taiwan's 3D building data. After examining the Taiwan's building regulations and specification, a meaningful set of space units were chosen. By further exploration from related perspectives, the 3D geometric representation, LOD and thematic attributes of each type of space units are summarized and proposed. With unique identifications, not only the multiple representations of the same space unit can be uniquely identified, the multiple level relationship among building space unit can be also formally defined. A set of 3D building reference framework with consensus specifications is then used to facilitate the development of GIS-based digital twins to enhance cross-domain data collaboration and 3D application development.

2. SPACE UNIT BASED ON BUILDING LAWS AND SPECIFICATIONS

2.1 Analysis of relevant building laws and regulations in Taiwan

Taiwan has established well-structured building regulations and laws. Most of them are textual descriptions of space units with semantic considerations, but unfortunately lack of clear geometric definitions. As a result, the integration with GIS is not straightforward and these two are often processed separately. To facilitate a solid foundation for 3D building data, we propose to summarize the content of building regulations and suggest a set of meaningful space units with semantics that can be used to construct the representation of 3D building data. In this research, the discussion is restricted to the exterior space units of the building.

2.1.1 <u>Building Act</u>

The building Act(MOI, 2022) is the highest level of law about constructions in Taiwan. The article 1 of chapter 1 states its purpose is to manage building and maintain public security, traffic, and health, and to improve the appearance of cities. While the building act mainly focuses on the building permit, site, and borderlines, it also includes regulations about the building's life cycle, from construction to demolition. In this act, two major types of space units are defined, namely, the “buildings” and “main structure of buildings”. The difference between the two is that “building” referred to the regulations about the whole building, and the “main structure” is about the actual and more detailed structure. The term “buildings” in this act refers to the construction or works that are installed at the surface or underground, including ceilings, beams, columns, walls, etc. The “main structure of buildings” in this act refers to the structure of foundation, main beams, and columns, bearing walls, floor slab, and roof structures. The “miscellaneous works” is part of the building, it refers to the building additions, such as water towers, billboards, erected advertisement, warehouses, chimney stacks, bounding walls, mechanical amusement facilities, swimming pools, central air conditioning equipment, elevating equipment, parking facilities, air shelter facilities, and waste disposal facilities. This act defines a building as a space unit and lists the objects that may be attached to the exterior of the building. Nonetheless, the sizes and details of the space units at the exterior of the building are not defined accurately.

2.1.2 Building Technical Regulations

One branch of the building act is known as building technical regulations, which outlines the required technical specifications, including general principles, building design and construction, structure, and equipment. Among them, the design and construction sections are more related to the appearance of the building, so the following will focus on these two sections. This regulation outlines the overall design guidelines that should be considered when designing and constructing buildings. The section of technical terms defines the sizes and area of some space units. The material, construction, and fire protection design for different equipment and building types are then defined for particular purposes. As some of the content is not relevant to the space unit, we will primarily focus on the definition of terms and general design rules. According to the technical terms, we can divide them into several types of space units, such as building blocks, buildings, storeys and households. Buildings included roof-top installations for features like water towers, hoist ways, staircases, and power substations, as well as exterior wall installations like balconies, terraces, and planter boxes. Furthermore, the technical regulations clearly limit the specifications of doors, windows, and arcades.

2.2 Generalization of common space units

The space units discussed in section 2.1 can be summarized into twelve categories related to the exterior of buildings. To conceptualize the space units mentioned in previous discussion, we further explore whether these categories of space units can be implemented via surveying technology. Two types of survey works are considered in this paper, outdoor and indoor mapping. Outdoor mapping refers to the use of 2D polygon-based building data from existed maps, e.g., Taiwan E-map and 1/1000 topographic maps. Indoor mapping is generated from 2D drawing of building floor plan and building survey from cadastral registration.

Taiwan E-Map is an electronic map specifically designed for GIS-based applications. Its content includes transportation, administration boundaries, blocks, buildings, landmarks, control points, building numbers, and colored orthophoto map. The map could be applied in disaster prevention, transportation, hydraulics, economic development, tourism, academic research, and business analysis, also for meeting governments and the public’s demands. The

building layer is represented as a polygon with a planar position accuracy of 1.25m and the boundary is depicted by the outer boundaries of the building. If a single building is more than 5 meters length or width, it must be drawn. According to its mapping specification, adjacent buildings will be mapped as individual polygons, meaning a building polygon may be associated with a number of street addresses .
On the other hands, large scale topographic map is a significant geo-spatial data in Taiwan and has been applied in varied domains. To meet the accuracy of large-scale maps, the 1/1000 topographic maps have strict specification(MOI, 2022). The specification classified the building as an artificial structure in the detail surveying section. The first paragraph specifies that the building primitive should be closure polygon. It also defines the space unit boundary with the drip line of the outer edge of the building. In the attribute fields, buildings should contain the type of structure and the number of floors. Paragraph three to six defines the roof superstructures. Rooftop superstructures of a size greater than 2 x 2 square meters need to be surveyed, such as staircase, hoist way, power distribution room, etc. Furthermore, it also needs to depict linear structures which is larger than 5 meters. Temporary planter boxes and awnings on the roof should not be painted. In addition, the lines of the buildings in the townhouse must also be contained in 1/1000 topographic maps.

The above two data sources are 2D data. When converting to 3D data, Taiwan E-Map uses the difference between DSM and DEM as the height of the building. In the 1/1000 topographic maps, the building height is established by the number of floors multiplied by the average floor height 3.3 meters. It is important to emphasize the storey and household space units. There are no representation of storey features on the 1/1000 topographic maps, only the number of storeys in building features. For the household space unit, the cadastral map must be employed to separate single households. However, it is not feasible to divide buildings with more complex property rights, for example, an apartment with multiple households.

The indoor mapping is composed of building floor plan and building survey result(MOI, 2023). The original purpose of these two types of data is to support business operations and ensure ownership of legal buildings. Unlike topographic maps, the building survey focuses on the internal space units of the building The operational agencies of building survey are the land administrations. Converting 2D drawings into 3D space units by the building survey results and the floor plans. Therefore, it will be close to reality and more in accordance with the law description of the space unit. From modelling perspective, they use single building number as an identification of space unit. For example, the entire building of the house is a space unit. Some apartments will contain multiple building numbers, and each building number can identify household space unit. The space unit contains the main building and auxiliary buildings such as balconies and canopies. Therefore, they do not always include building and storey space units and require additional integration to construct the space units. Building floor plans can cover most of the space units defined by building acts and building technical regulations. The building survey is designed to match the demands of the land administration, so it won't cover every space unit. According to the cadastral survey implementation regulations, they limit the properties of the data based on business demands. For example, the cadastral survey implementation regulations canceled the canopy, roof overhangs and other components to ensure the actual living space area. Corresponding to business requirements, they record land numbers, building numbers, and addresses as identification in the attribute fields.

In general, outdoor mapping has significant limitations in the representation of space units. For example, Taiwan E-map and topographic map only represent the maximum projected area of space units. In the table below, we list the space units summarized from the regulations. Among all the space units, the Taiwan E-map can only provide information about the building space unit. The 1/1000 topographic maps can provide information about the visible large roof superstructure space units. Indoor mapping related to building floor plans can provide information about smaller space units. The building floor plans can be fully adapted to the listed space units, including doors and windows. Due to the demands, building survey cannot include all the space unit. Table 1 shows a significant difference for space unit that can be represented by indoor or outdoor mappings. Therefore, the following section will take the characteristics of space units discussed in this chapter and use them to analyze and provide specification suggestion for each type of space unit.

Table 1. Association between the semantic space unit of building regulations and surveying technology.

LAWS AND REGULATIONS		**INDOOR MAPPING**		**OUTDOOR MAPPING**	
Building Act/ Building Technical Regulations		Building Floor Plan	Building survey	1:1000-scale topographic maps	Taiwan E-map
Building blocks		•			
Building		•	-（not always）	•	-
Storey		•	-（not always）	-（number of storey）	
Household		•	•	-	
Roof-top installation	Roof superstructures（staircase, hoist way, power distribution room, etc.）	•	•	•	
	Water tank/ water tower	•	•		
	Roof details（plumbing system, chimney, lighting protection system, ridge decoration, etc.)	•	•		
	Parapet, firewall	•	•		

Exterior wall installation	Balcony	•	•		
	Terrace	•	-		
	Roof overhangs	•	-		
	Canopy	•	-		
	platform	•	-		
	planter box	•	-		
Stair		•	•		
Bridge way		•	•		
Parking space		•	•		
Arcades		•	•		
Door		•			
Window		•			

3. LOD DESIGN OF SPACE UNITS

We designed the level of detail for each spatial unit mainly following the specifications of CityGML 3.0. Two perspectives are considered, one is the definition of a single class of LODs, and another is the difference of the same unit in different LODs.

3.1 Requirements for a Single Class LOD

The CityGML 3.0 requirements and building laws were taken into consideration when designing the levels of detail for each space units of 3D buildings. According to CityGML 3.0, each LOD are defined with constraints on position accuracy, minimum size constraint, roof form and constructure, etc. In addition, some space units in Table1 are defined by regulations with restrictions on the position and size of the object, too. For example, roof-top installation are outbuildings that protrude from buildings and other miscellaneous work, and the total height of the two must not exceed limited to 6~9 meters. There are also regulations that the height of the parapet should be within 1.5 meters. Some space units will involve the constraint on the exact position of the wall, like balconies, which must be measured from the centerline of the exterior wall more than 2 meters.

Considering the building act and LOD specifications, we propose a process to determine LODs for a single class of space units. According to outdoor mapping‘s limitations, the smallest space unit size that can be represented in the topographic maps is roof superstructures. Therefore, we define the building blocks and buildings as LOD1 space units. The storey and roof superstructure are optional, but if the source contains one of them, it can be represented in LOD1. The requirement of LOD2 specification is higher than LOD1 in terms of minimum object size and position accuracy. Many detailed space units are added, such as water tanks, water towers, balconies, terraces. The household space unit is also added in LOD2 because indoor mapping is mainly based on a single household mapping. In CityGML specification, LOD3 features have the highest level of details and include many types of space units. For the exterior wall installation, we add roof overhangs, canopies, planter box, and platform. The roof details include lightning rods, wind headers, etc., and they cannot directly measure in both indoor and outdoor mapping, which makes them regarded as optional.

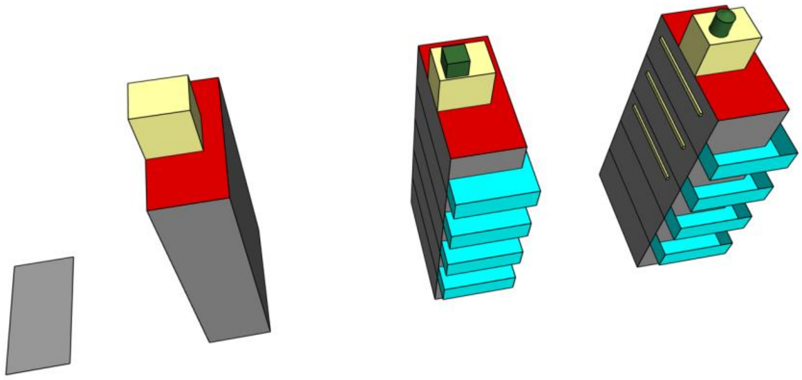
In CityGML, an individual object can be represented by different LODs. Therefore, we considered regulations and practical applications and simplified some space units from higher LODs to lower LODs. For example, smaller space units such as roof overhang, canopy, planter box, and platform are defined as the space units in LOD3. These space units can be simplified to LOD2（is shown in Table 2 arrows. Some of the space units defined in LOD 2 conform to the minimal object size of LOD 1, therefore they are simplified to LOD 1 and described as a block model.

Table 2. Semantic space unit arrangements for each LOD

LAWS AND REGULATIONS	**LOD**			
Building Act/ Building Technical Regulations	LOD0	LOD1	LOD2	LOD3
Building blocks	•	•	•	•
Building	•	•	•	•
Storey	+	+	•	•
Household	+		•	•
Roof superstructures		+	•	•
Water tank/ water tower		←	•	•
Balcony		←	•	•
Terrace		←	•	•
Bridge way			•	•
Arcades			•	•
Roof overhangs			←	•
Canopy			←	•
Planter box			←	•
Platform			←	•
Stair			←	•
Parapet, firewall				•
Roof details				+
Door				•
Window				•

3.2 Linking space units in different LOD

According to our definition, the same space unit can be represented in different LODs. LOD0 needs to be represented by 2.5D points, lines, and surfaces. LOD1 is represented by a point or volume model. LOD2 presents the main appearance and structure of the building, including the actual bumpy structure, the roof shape, and the position of the wall. LOD3 needs to represent all the real appearance and the internal structure. As shown in Figure 1, the balcony in LOD2 is made up of multiple surfaces to reflect the real world. Nevertheless, because of the constraints of the LOD1 geometric representation, the balcony could only be depicted by the block model. In the exterior wall installation, LOD3 is more realistic, whereas LOD2 is represented by multi-surfaces with lower level of detail. In addition, the space units of buildings and building blocks can be represented by LOD0~3. Figure 1(b) represents a building composed of LOD1 building space units, and (c) represents a building composed of LOD1 storey space units. This figure indicated that different space units can compose of different LOD1 buildings. However, household can only be represented in LOD0, LOD2 and LOD3. It means that a building cannot be composed of LOD1 household space units.



(a) (b) (c) (d)

Figure 1. (a)LOD0 (b)LOD1 (c)LOD1 with LOD2 generalization (d) LOD2

4. ATTRIBUTES DESIGN AND RELATIONSHIPS BETWEEN SPACE UNITS

4.1 Relationships across space unit categories

There will be corresponding relationships between different types of spatial units. The commonly used types of spatial relations are direction, distance and topology. The spatial relations can further be categorized into disjoint, contains, inside, meet, cover, cover by, distance, composition, above, below, etc. For example, the water tower needs to be installed above the roof and above the superstructure and the canopy and planter box will be counted from the center line of the wall. The spatial units will also have a hierarchical relationship among them.

The hierarchical relationship of buildings is more meaningful in the representation of large space units. We simplify the space units into building blocks, buildings, storeys, households and other building structures. Building blocks can be composed of multiple building space units, and buildings can be composed of multiple storeys and contain building structures. Storeys also can contain multiple building structures. In this research, we do not discuss indoor space units such as rooms, otherwise each storey can also be composed of many rooms.

The household space unit motioned in this article corresponds to the logical space, which is a type of dwelling unit distinguished by the house registration's building number. A building number will contain both the main building and the auxiliary buildings. And auxiliary buildings contain balconies, canopy, roof overhangs, etc. In Taiwan, single-family houses are common housing types and represented one building with one property right. Each of them is identified by individual house number. Condo and apartments belong to a multi-family building, and a building has multiple building numbers. So, it might be challenging to think of a relationship between different types of space units.

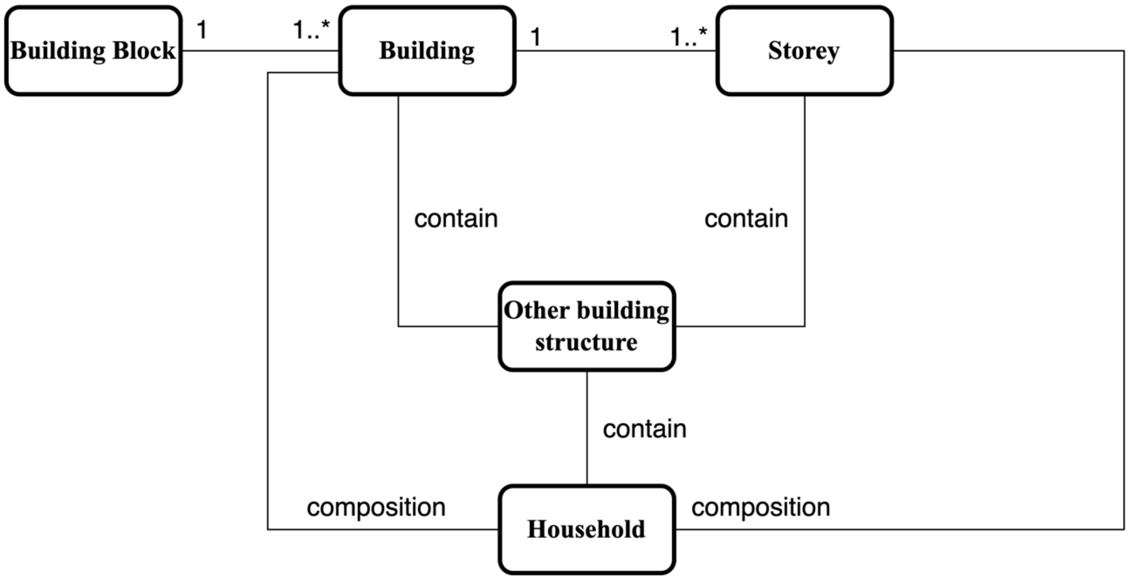


Figure 2. Construction of 3D building space units

4.2 Identification codes and attribute

In Taiwan E-map, 32-bit code conversion is used to convert the center point coordinates of the building feature to an unique identification number, for example (187658.315, 2599366.865) is converted to 1R8K75NV65. Because this is a common coding rule in Taiwan's building models, we continue to use this unique identification number as the BuildID of the building space unit. Since not all buildings have building block space units, we counted the space units and assign serial number BB01_1R8K75NV65. Take the two building in the same building block as example, these two buildings will have the same building block ID, but different BuildID. Therefore, we can query all the buildings in a building block, by using building block identification. The storey space unit is identified with the code of BuildID and "storey number". The ID of other building structures is based on the storey ID, plus the type of space unit name. After counting the same type of structure, we give them a serial number. However, the household space unit differs from others since it lacks a specific hierarchy. One building may be associated with one or more households. The building number can be seen as the identificatoin of the husehold space unit, thus we have devised the unique identification with the combination of BuildID and the 8-code building number.

In the thematic attribute part, the storey space unit records the storey height and the number of storey. The attributes of building record the types and building numbers to link household space units with the same building number. Building structures such as balcony, canopy, roof overhang, etc., will also serve as the auxiliary buildings in the household space unit. Household space units are realized through building registration, so the thematic attributes include building number, address, registration date, usage, building materials, and building completion date from the building registration documents.

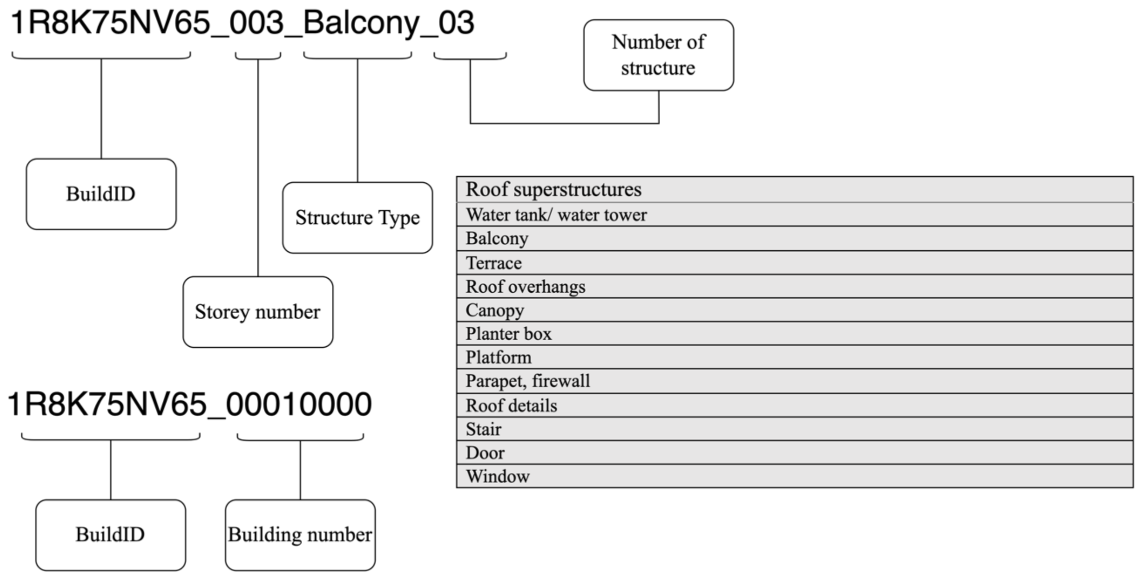


Figure 3. Example of unique identification

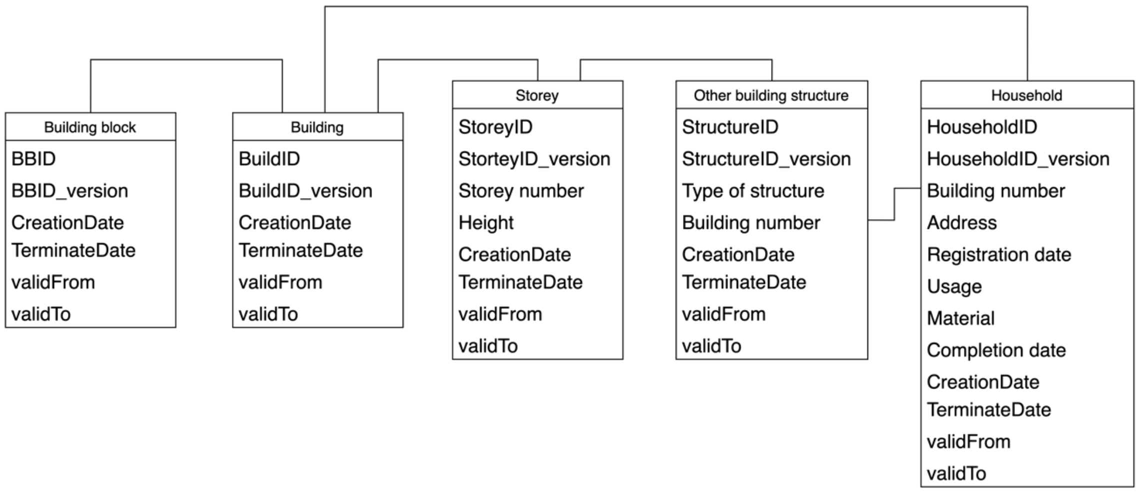


Figure 4. 3D building space units thematic attribute

The attribute will contain ID, ID_version, creationDate, terminateDate, validFrom and validTo. In CityGML 3.0, creationDate and terminateDate are used to track the feature's creation and termination time in the database. The validFrom and validTo determine the lifespan of the feature in the real world. The information that is easier to collect is the creation and termination time of the feature. When the feature is no longer used, its terminateDate will be recorded. Conversely, the currently used feature will not have a terminateDate, and the currently suitable version of the feature can be queried through this attribute. For example, the BuildID 1R8K75NV65 is stored in the database on 2023-01-01 and terminated in the database on 2023-

02-20. Therefore, the BuildID_version of the model is stored as 1R8K75NV65_001 and the new model of 1R8K75NV65 will be stored as 1R8K75NV65_002.

5. CROSS DOMAIN APPLICATION

According to our definition and hierarchical system, three things can be achieved. First of all, we can individually represent the space unit summarized from the related law and specification by a geographic feature at a specific LOD, e.g., the LOD1 balcony space unit in Figure 5. Secondly, different LODs of the same space unit can be related to each other, as shown in the figure below. LOD1 and LOD2 balcony space units have the same StructureID but their tag of LOD are different. Third, we can associate different levels of space units through the hierarchical identification framework. For example, 1R8K75NV65_005_Balcony_01 can be associated from 1R8K75NV65_005 storey space units to the 1R8K75NV65 building space unit. In addition, it is possible to aggregate multiple storey space units into a single building by using the BuildID. In this way, the two buildings in different representations can be regarded as multiple representations of the building space units.

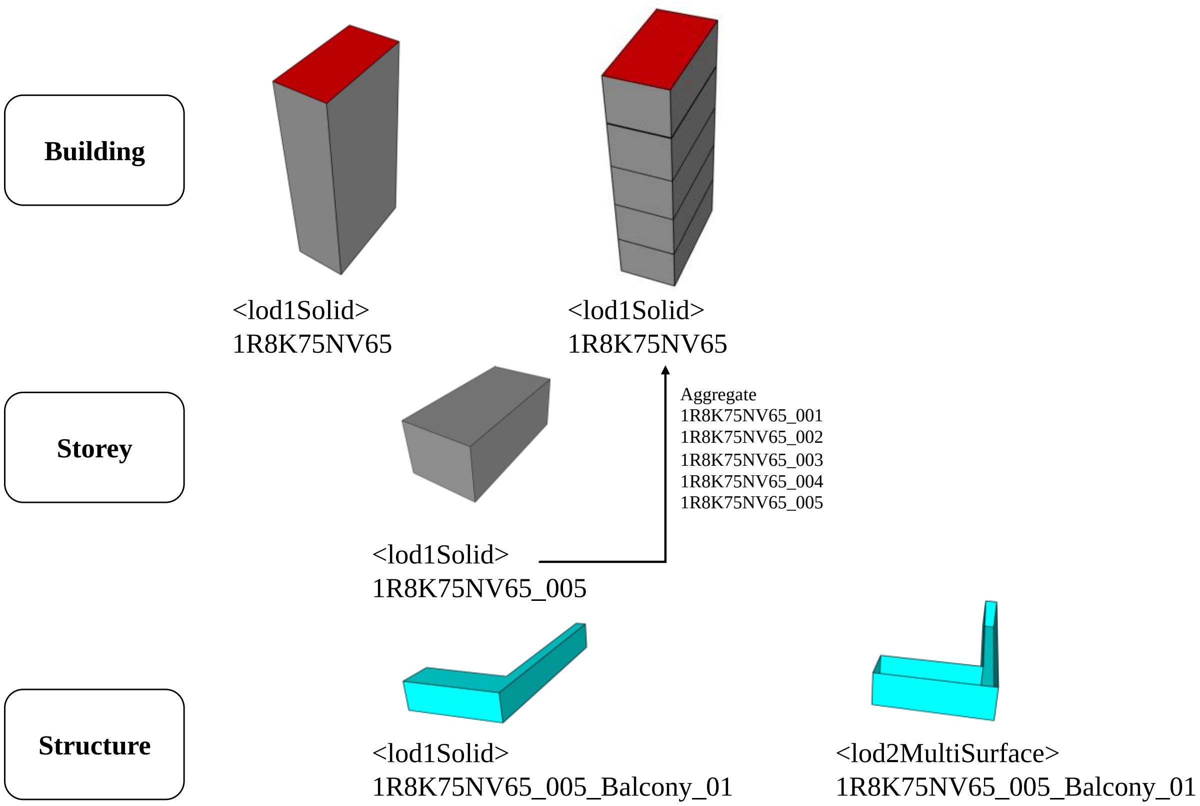


Figure 5. Example of multi-level space unit framework

Based on the building space unit defined above, we can successfully establish the cross-domain associations. In Taiwan, we usually use address and building number as identification to link cross-domain data on the basis of individual household. Based on the proposed approach, business registration and company registration data can be associated with 3D household and building space units via their addresses and becomes 3D data (Figure 6). This not only allows to visually present its geographic distribution, but also serve to determine if the type of business violates the housing regulations. Linking the tax registration data to the address of the space unit help to easily acquire the price of the building, total area, and other information.

In a 3D environment, we define multi-level spatial units based on building laws and regulations. Therefore, it can also be used as a tool for real estate agents and builders to display building information. Levels above LOD2 can represent the actual floor area of the house, and also include auxiliary buildings such as roof overhangs, canopies, and balconies to safeguard the property rights of the people.

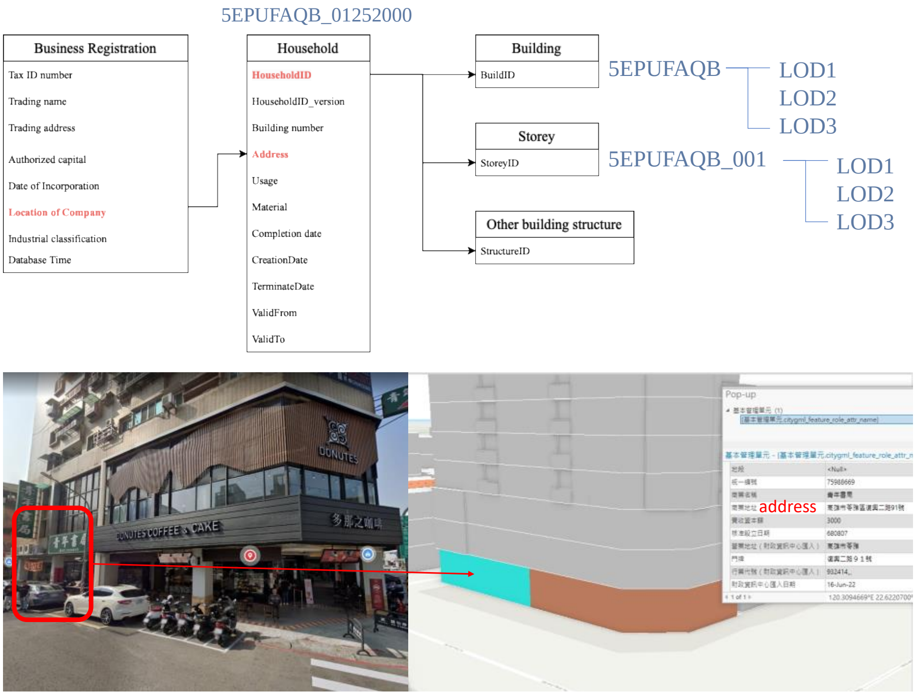


Figure 6. Business registration link with household space unit

6. CONCLUSION

Building data is an important type of 3D information for urban development. However, various demands lead to the issues of multi-scale, multi-source, and multiple representations of 3D building data, and make cross-domain building data integration a crucial challenge. By establishing a space unit primitive framework based on identifiable criteria from current building specification, we present strategies to promote the integration of building data across domains. Three contributions are summarized. First, we define a set of primitive space units based on Taiwan's building regulations and specification and explore the semantics, characteristics, and LODs of space units. By combining different mapping techniques and multi-source data, we construct 3D geometric representations in different LODs and design related thematic attributes. Second, we create a hierarchical identification framework, through the specific identification of a single space unit, and the link between different type of space units and multiple representation of the same space unit. Finally, a feature-based mechanism actually links the data in different domain, increases data interoperability and cooperates with different domain data. It is very beneficial for the development of GIS-based digital twins.

Although the results are still preliminary, this study establishes clear specifications for space units and unique identifications based on regulations and practices, and improve the complexity of integrating cross-domain building data. There's still a lot of progress to be made in the future. First, more test with real data is necessary to improve the data processing strategies. Secondly, an application environment for multi-source data shall be developed to test the linkage issue. Finally, the core of 3D framework should be further examined to facilitate more cross-domain data integration for developing an effective digital twins.

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BIOGRAPHICAL NOTES

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