Sensors and Materials, Vol. 38, No. 1 (2026) 243–264
MYU Tokyo

S & M 4297

Automatic Generation of Level of Detail for National Digital Twin Building Using Industry Foundation Classes

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(Received September 30, 2025; accepted November 25, 2025)

Keywords: geospatial information, digital twin, IFC, CityGML, LOD, building, BIM to GIS, conversion

In this study, we propose a methodology for the automatic generation of building models from level of detail (LOD) 0 to LOD 3 that comply with KS X 6808-1, the national digital twin (NDT) building data model standard of South Korea, using industry foundation classes (IFC) data. This methodology enhances the utilization of 3D data derived directly from sensor-based spatial information acquisition technologies such as light detection and ranging (LiDAR) and photogrammetry. Previous studies have been limited to a specific LOD or remain at city geography markup language (CityGML) 2.0-based conversion. In contrast, we establish an integrated conversion framework optimized for the KS X 6808-1 standard based on CityGML 3.0 and we develop the IFC2NDTBuilding generator to evaluate the proposed methodology. Through the visualization verification of the converted data, we confirm that the structural consistency of the original model is maintained, and semantic preservation validation demonstrates a high preservation rate exceeding 98% in the experimental data. The results provide a practical method for efficiently constructing a national digital twin using IFC data and ensuring the consistency of 2D/3D geospatial information, thereby maximizing the utility of data obtained from advanced geospatial sensors. This methodology is expected to serve as a new approach to building information modeling (BIM)–geographic information system (GIS) integration.

1. Introduction

Digital twins are applied across various domains, such as manufacturing and construction, and the concept of the national digital twin (NDT) has also emerged in the field of geospatial information.(1–3) The NDT is defined as a system for the efficient operation and management of national territory by linking physical and virtual spaces to enable analysis, prediction, and simulation of land and cities.(4) To interconnect and integrate the vast amount of information generated in the physical space of an NDT and enhance its utility, the 3D city model plays a

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https://doi.org/10.18494/SAM5956

ISSN 0914-4935
https://myukk.org/

crucial role as the foundation of virtual space.[5,6] In particular, 3D building models are indispensable when building an NDT, as they constitute a large proportion of urban-scale data and offer high utility.[7]

3D building models have thus far been constructed either through direct methods using geospatial information acquisition technologies, such as photogrammetry and LiDAR, or indirect methods, by converting building information modeling (BIM) from the architecture, engineering, and construction (AEC) domain into spatial data within a geographic information system (GIS) environment.[8] While direct methods are suitable for building lower level of detail (LOD) models, such as 2D footprints or block models of existing buildings, they require considerable time and cost for higher LOD model construction; thus, indirect methods, which convert industry foundation classes (IFC) data—the international BIM standard—into GIS models, are generally preferred.[8,9] Recently, many countries, such as the United States, the United Kingdom, and South Korea, have established mandatory BIM policies to enhance collaboration and efficiency in new construction and civil infrastructure projects, and for this reason, BIM models are expected to become a critical data source in GIS environments in the future.[10,11]

Generally, BIM and GIS apply different standards. Thus, conversion is essential to use BIM models within a GIS environment.[7,11–13] To date, BIM-to-GIS model conversion studies have typically focused on extracting specific information from the IFC model, which is the source model, and converting it to fit the structure of the target model, such as CityGML, shapefiles, or CityJSON, with IFC-to-CityGML conversion studies accounting for the largest share.[12,13] This is because the Open Geospatial Consortium's (OGC's) CityGML not only provides a standardized method for the integrated management of multiple geospatial information layers of a city but also has high potential for broad applications across diverse domains.[5,6,13] However, in previous studies, differences in modeling aspects, such as geometry, semantics, and LOD between IFC and CityGML, have led to conversion being limited to specific LOD models, or there have been ongoing issues, such as geometric information loss due to complex conversion procedures, processing inefficiency, and the semantic loss of building elements, such as windows and doors in IFC.[11–13]

In response to changing technological environments, such as smart cities and digital twins, the OGC extensively revised the existing CityGML 2.0 to ensure interoperability among heterogeneous models, such as IFC, IndoorGML, and LADM, establishing the CityGML 3.0 standard.[14–17] Several countries, including Singapore, Finland, and Japan, have already actively adopted CityGML 2.0 to build NDTs using 3D city models, while exploring transformative changes in spatial data infrastructure to align with changes in future trends in geospatial information.[18–20]

In this context, the South Korean government has been developing national standards based on international standards, such as OGC's CityGML 3.0, to ensure interoperability among NDT data, while implementing various policies and projects.[21] In domestic NDT projects, constructing NDT data at the large urban scale requires substantial cost, time, and complex procedures, which is why most domestic institutions continue to face challenges in constructing and maintaining 3D data.[3,21] Moreover, although pilot projects have been conducted for NDT data model standards in the building, transportation, indoor space, and terrain domains, they have remained at LOD 0–LOD 2 for buildings using existing 2D geospatial information, whereas constructing LOD 2 models for windows and doors as well as LOD 3 models representing detailed building objects remains an unresolved challenge.(21) Therefore, there is a need for a method that automatically generates LOD-specific 3D building models using BIM data containing detailed building information in an efficient and consistent manner to ensure the recency of pre-existing geospatial information as well as consistency between 2D and 3D geospatial information. Against this backdrop, in this study, we propose a method for the automatic generation of LOD models that comply with South Korea's NDT building data model standards using IFC data.

2. Related Works

2.1 IFC

IFC is an open BIM standard developed by BuildingSMART International for the exchange and sharing of BIM data in the AEC domain.(7,11) This IFC standard is a vendor-neutral model that is not dependent on the type of BIM software, such as Revit or AutoCAD, enabling interoperability across multiple systems, and it adopts an object-oriented storage approach using the EXPRESS description language.

In IFC, a 3D building model consists of spatial structure elements, such as IfcBuilding, IfcBuildingStorey, and IfcSpace, as well as building elements, such as IfcWall, IfcSlab, and IfcDoor, related to individual spatial structure elements. As shown in Fig. 1, parent and child

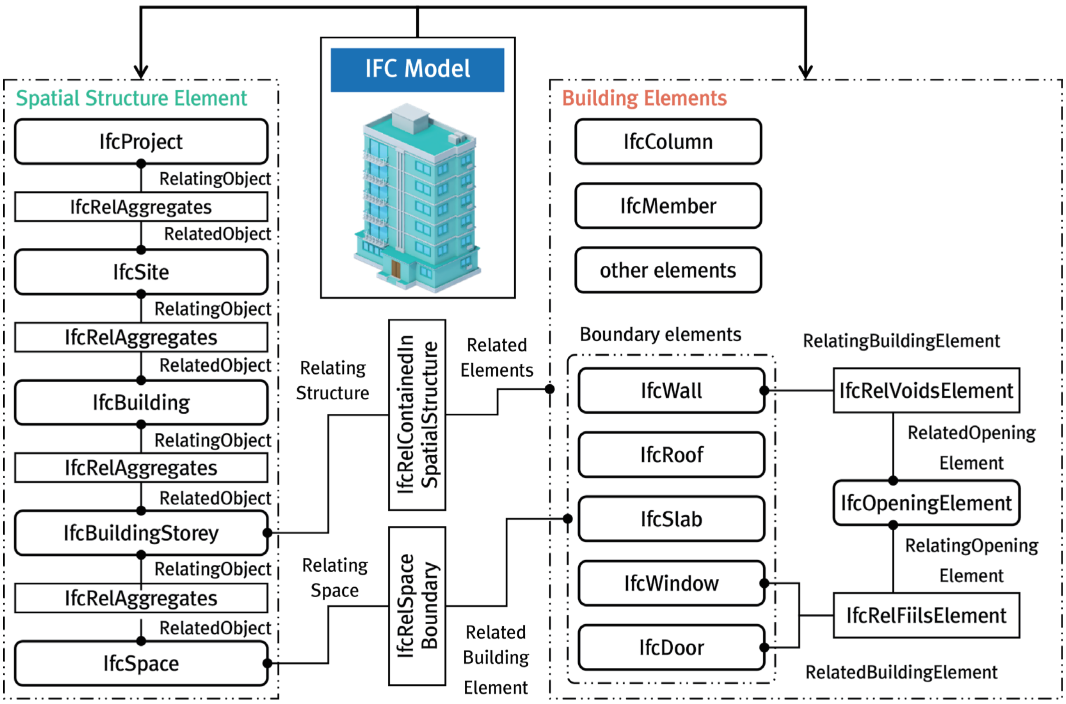


Fig. 1. (Color online) Hierarchy structure of IFC model. Source: modified from Zhu and Wu.(7)

objects are connected within the hierarchical spatial structure through relationship attributes (e.g., IfcRelSpaceBoundary and IfcRelAggregates). Spatial structure elements are classified on the basis of the IfcRelAggregates attribute, which defines a parent class grouping and includes its child classes, whereas the IfcRelContainedInSpatialStructure attribute defines the inclusion of building elements within a specific spatial structure element. Moreover, the IfcRelSpaceBoundary attribute defines the boundaries between a building's spatial structure elements and building elements, providing semantic information, such as indoor–outdoor distinction and the relationships between walls and windows. This individual geometric information of IFC objects is represented using boundary representation (B-rep), constructive solid geometry (CSG), or sweep solids. Geographic location information is defined, depending on the IFC version, in the local coordinate system using either IfcMapConversion (e.g., Easting, Northing, and Orthogonal Height) or IfcSite (e.g., RefLatitude, RefLongitude, and RefElevation).

Since the adoption of IFC 2×3 as the International Organization for Standardization (ISO) international standard ISO 16739-1[22] in 2005, IFC has evolved through various versions, including IFC 4.0 and IFC 4.3, focusing on buildings. IFC 5.0 currently under development is undergoing continuous standardization efforts with the goal of enabling a paradigm shift toward dynamic digital twins in the AEC domain by supporting large-scale infrastructure, such as ports and airports, and enabling real-time data integration.

2.2 CityGML and NDT building data model

2.2.1 CityGML 3.0 building module

OGC's CityGML is an international standard that serves as an open data model for storing, managing, and sharing 3D city models, while also defining the specifications for encoding implementation using Geography Markup Language (GML).[17] Since its establishment as CityGML 1.0 in 2008 and CityGML 2.0 in 2012, CityGML has recently evolved into CityGML 3.0, adding new modules, such as Construction and Dynamizer, and improving CityGML Core and Building modules to align with the newest technological environments.[14–17] Among the major revisions in CityGML 3.0, the modules relevant to this study are CityGML Core, Construction, and Building modules, which are specified through spatial hierarchy relationships, as illustrated in Fig. 2.

A detailed examination of the building module reveals that the adoption of spatial concepts in the CityGML Core module from a geometric perspective has led to significant improvements in LOD. Here, LOD is used as a criterion to assess how similar various real-world features, such as buildings and roads, are to objects and geometric types defined in UML diagrams.[15] In CityGML 2.0, LOD is divided into five levels (0–4), whereas CityGML 3.0 simplifies this into four levels (0–3), as shown in Fig. 3. This change resolves the issue of the redundant definition of geometric information for thematic features, such as buildings, roads, and bridges of the city, and allows indoor and outdoor objects of the building to be represented across all LODs, thereby enhancing model flexibility and usability in various application domains.[13,17]

From a semantic perspective, the adoption of the construction module and improvements to the building module have facilitated the conversion of 3D building models using other models,

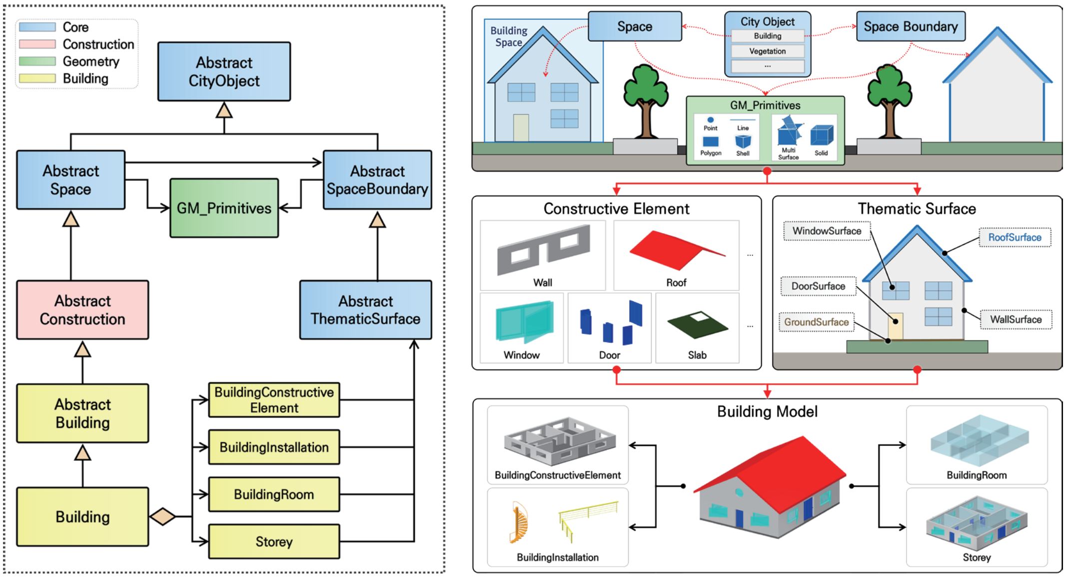


Fig. 2. (Color online) Example of spatial hierarchy relationship in CityGML 3.0 and building module.

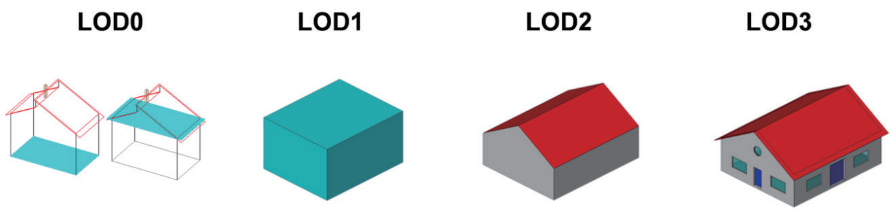


Fig. 3. (Color online) Four different levels of detail in CityGML 3.0. Source: OGC[15]

such as IFC and IndoorGML. On the basis of the spatial concepts of the CityGML Core module, information on thematic surfaces and constructive elements, which are commonly defined across objects, such as buildings, bridges, and tunnels, has been modified for integrated management within the construction module, enabling individual constructive elements to be represented simultaneously using both B-rep and volumetric models. In addition, the building module automatically inherits the concept of space from the CityGML Core, enabling buildings and individual features to be recognized and classified as physical/logical spaces and as occupied/unoccupied spaces; and feature classes, such as Storey and BuildingConstructiveElement, have been added for semantic mapping from IFC-to-CityGML. This allows the spatial and architectural elements of IFC to be converted into CityGML 3D building models through direct mapping on CityGML 3.0.[13,17]

2.2.2 NDT building data model

The NDT national standards of the South Korean government comprise 21 standards in total, including a reference model standard that defines common NDT concepts and structures, and data standards for individual domains (Data Model, Data Quality, Metadata, and Data Product

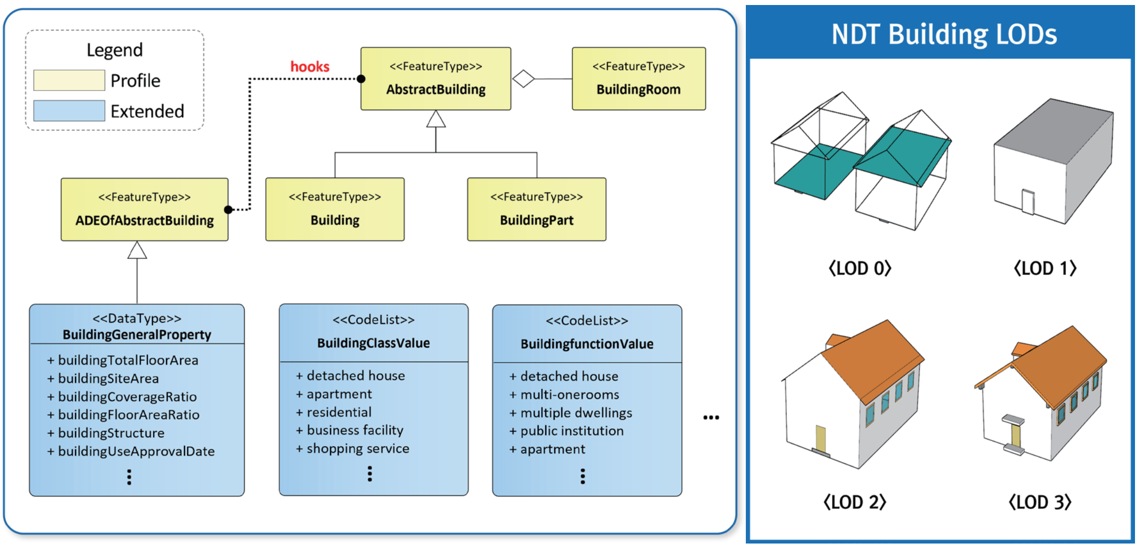
Specification) covering buildings, indoor spaces, terrain, transportation, and other areas.[20,21] Among these, KS X 6808-1 (Geographic Information – National Digital Twin Building – Part 1: Data Model) was developed by extending CityGML 3.0 using profile and application domain extension (ADE) techniques to align with domestic conditions.[23] KS X 6808-1 is a conceptual model that standardizes geometric and semantic classes, LOD, and other aspects of NDT building data using unified modeling language (UML) diagrams. Since its establishment as a national standard in 2022, KS X 6808-1 has been undergoing revisions to address redundancies between building and other domain standards (e.g., transportation, indoor spaces, and terrain) and to resolve issues encountered during construction. The UML diagram of the most recently revised KS X 6808-1[21] is illustrated in Fig. 4(a).

The newly revised KS X 6808-1 defines LOD on the basis of the geometric representation types specified in the CityGML Core module, as shown in Fig. 4(b). First, LOD 0 represents the building's exterior in a planar form, whereas LOD 1 represents the building's external shape in a block form. LOD 2 allows for a 3D representation of not only the building's roof structure but also constructive elements, such as doors and windows. Finally, LOD 3 refers to a model in which the building's exterior and interior spaces are represented as architectural models, such as BIM at a level similar to reality.

2.3 IFC-based 3D building model generation research

Recently, there has been active research on constructing 3D building models using IFC, which comprise BIM data. Representative studies on the IFC-to-3D building model conversion include IFC-to-shapefile and IFC-to-CityGML. Existing studies are summarized in Table 1.

Research on IFC-to-shapefile conversion has focused on converting the complex geometric information of IFC buildings into formats usable within GIS. While the shapefile format is typically used in GIS software, such as ArcGIS and QGIS, it does not directly support IFC's



(a) (b)

Fig. 4. (Color online) (a) UML diagram and (b) levels of detail of revised KS X 6808-1 standard. Source: NGII[21]

Table 1
Brief summary of studies on IFC-to-3D building model conversion.

Previous research	Source model	Target model	LOD support	Content	
IFC-to-shapefile conversion research	Zhu *et al.*[24] and Zhu and Wu[7]	IFC 2×3	shapefile	LOD 1–2	Enhances mass IFC-to-shapefile conversion efficiency using computer graphics techniques, but is limited by semantic information simplification and CityGML attribute support constraints
	Zhu *et al.*[12]	IFC 4	shapefile	s-LOD 1–4	Strengthens GIS usability through BIM attribute reduction via s-LOD definition, but suffers information loss due to semantic reduction
IFC-to-CityGML conversion research	Donkers *et al.*[25]	IFC 2×3	CityGML 2.0	LOD 3	Successfully achieves high-precision CityGML LoD3 interior/exterior conversion through automatic algorithms, but faces computational complexity and performance degradation with large datasets
	Stouffs *et al.*[9]	IFC 2×3	CityGML 2.0	LOD 0–2	Proposes a TGG-based bidirectional conversion framework, but is limited by lack of LoD3 support and complex geometry processing constraints
	Kang and Hong[26]	IFC 2×3	CityGML 2.0	LOD 0–3	Improves conversion efficiency through parallel processing-based LoD mapping, but accuracy degrades when handling complex IFC models
	Sani *et al.*[27]	IFC 2×3	CityGML 2.0	LOD 2	Verifies urban planning applicability through coordinate transformation and semantic mapping, but is limited by lack of LoD3+ support
	Harshit *et al.*[8]	IFC 4	CityGML 3.0	LOD 3	Generates low-cost, high-quality CityGML LoD3 using Apple LiDAR+UAV, but is limited by automation level and scalability for highly detailed IFC data

CSG and clipping representations, leading to geometric loss and quality errors during the conversion process. Accordingly, Zhu *et al.*[24] and Zhu and Wu[7] developed a conversion algorithm based on an open source for converting the geometric information of IFC into shapefile, addressing such issues as conversion failures and inefficiencies in geometric processing that occur in commercial tools, such as Data Interoperability Extension for ArcGIS and Feature Manipulation Engine (FME). Zhu *et al.*[12] developed a semantic level of detail (s-LoD) concept and conversion framework, demonstrating the potential to partially reflect IFC's semantic information even in such formats as shapefile. However, because shapefile has a simple data structure consisting only of geometry and attributes, it has fundamental limitations, such as the loss of information on building windows and indoor spaces, as well as the lack of interoperability with international standards.

In contrast, the IFC-to-CityGML conversion focuses on the geometric and semantic mapping of IFC objects and the stepwise conversion of LODs. Donkers *et al.*[25] presented an open-source solution for automatically converting IFC into a CityGML 2.0 LOD3 building model. Stouffs *et al.*[9] proposed a conversion framework based on triple graph grammars (TGGs) for converting IFC-to-CityGML, whereas Kang and Hong[26] presented an automated framework that applies a screen-buffer scanning-based multiprocessing method to efficiently convert large-scale IFC models into CityGML 2.0 LOD 1–LOD 4 building models. Moreover, Sani *et al.*[27] proposed an automated conversion procedure that includes coordinate system conversion and semantic mapping, converted IFC data into CityGML 2.0 LOD 4 models, and verified their GIS applicability, such as for urban planning and energy analysis. Recently, Harshit *et al.*[8] have proposed a workflow for generating CityGML 2.0 LOD 3 models based on surveying equipment, such as Apple LiDAR and UAVs. This semi-automated approach converts integrated indoor–outdoor point clouds into IFC and subsequently into CityGML 2.0 LOD 3 through FME. While it provides a practical alternative to traditional high-cost equipment, it still faces limitations, such as manual alignment requirements and information loss during conversion.

A review of previous studies shows that although IFC-to-shapefile conversions enhance the usability of geometry in GIS environments, semantic information loss is inevitable, and although IFC-to-CityGML studies support LOD representation and semantic mapping, relational information, such as IfcSpace, IfcRelSpaceBoundary, IfcDoor, and IfcWindow, is only partially preserved or lost. Moreover, semantic inconsistencies are not fully resolved in most studies, as they have been limited to CityGML 2.0, and the conversion process also involves intermediate formats, such as OFF, OBJ, and Nef Polyhedra, leading to geometric information loss and processing inefficiencies.

To overcome these limitations, CityGML 3.0 not only provides a standardized approach for the integrated management of heterogeneous models, such as IFC and IndoorGML as well as various dynamic information, but is a standard that can be widely applied across multiple application domains.[13,17] However, research on IFC conversion targeting CityGML 3.0 remains at an early stage; in particular, no automated conversion framework optimized for NDT standards currently exists.[7–9] Accordingly, this study makes a novel contribution by proposing a methodology for automatically converting LOD 0–LOD 3 levels in a consistent manner, fully aligned with South Korea's KS X 6808-1 standard based on CityGML 3.0, to address existing BIM–GIS integration issues.

3. Materials and Methods

In this section, we present the methodology for automatically generating NDT building LOD models based on the KS X 6808-1 standard using IFC data. To this end, the necessary IFC data were collected for the IFC-to-NDT building LOD model conversion, and an LOD framework was defined. Next, geometry transformation was performed to construct the NDT building LOD models, and semantic mapping was carried out by defining the conversion rules between IFC and KS X 6808-1. Finally, a methodology for the automated generation of NDT building models by LOD was proposed, utilizing the preprocessed geometric and semantic information from IFC, and a prototype was developed for evaluation. The detailed procedures for overall research are summarized in Fig. 5. The following subsections provide detailed descriptions of each step.

3.1 Data collection

Open source BIM data and R&D data from South Korea were collected for the automatic generation of the IFC-to-NDT Building LOD model, as shown in Table 2. Open source BIM data include FZK Haus and Smiley West data provided by the Karlsruhe Institute of Technology

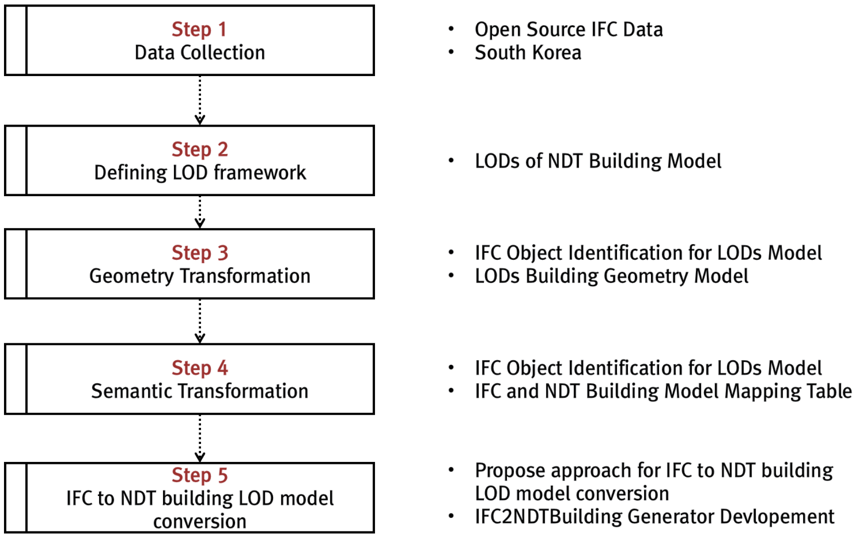
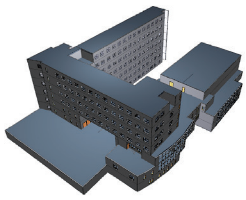
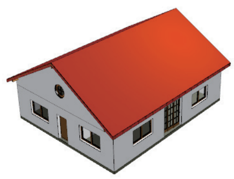
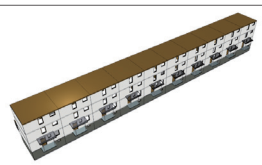


Fig. 5. (Color online) Overall framework for generation of NDT building LOD model.

Table 2
(Color online) IFC dataset used in conversion process and its citations.

Classification		Title	Provider	Schema version
1		The 21st Century Building	Busan National University BIM Data	IFC2×3
2		FZK Haus	Karlsruhe Institute of Technology (KIT) Open Source	IFC4
3		Smiley West	Karlsruhe Institute of Technology (KIT) Open Source	IFC4

(KIT) website,[28] which comply with the IFC schema and are used for experiments and validations in various studies on coordinate transformation and 3D building model conversion using IFC datasets.[7,25] Moreover, to evaluate the actual applicability in the South Korean context, the IFC model of The 21st Century Building at the University of Seoul was obtained; it was constructed as part of the project for developing and demonstrating world-class low-cost, high-efficiency indoor geospatial information core technologies.[29]

The key characteristics of the IFC datasets are that they consist of various types of building, such as residential, commercial, and educational facilities, and include not only spatial structure elements, such as buildings, stories, and spaces of IFC, but also various building elements, such as doors, windows, walls, and roofs. In addition, to enable the automated conversion of several IFC schema versions into NDT building models, the datasets include IFC 2×3 and IFC4 versions with high applicability, as well as coordinate information for geometry and coordinate transformations.

3.2 Defining LODs in NDT building model

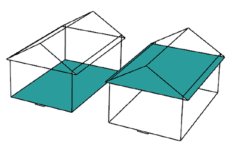
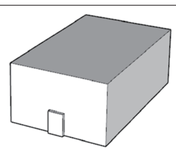
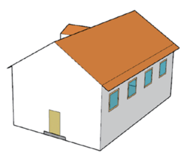
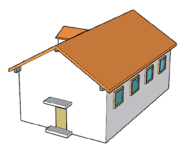
The LOD in KS X 6808-1 is defined in four levels (LOD 0–LOD 3) on the basis of OGC CityGML 3.0.[21,23] However, converting all information in IFC data into each individual LOD model requires much time and cost while reducing benefits; thus, it is important to identify the LODs that are practically applicable.[24] To this end, wey redefined the LOD framework for IFC-based KS X 6808-1 LOD model conversion. As shown in Table 3, the LOD framework was redefined in terms of geometry, semantics, and level of information by comparatively analyzing the characteristics of IFC models and KS X 6808-1, while excluding unnecessary details to ensure that each individual LOD model can be converted in a consistent manner.

3.3 Geometry transformation for NDT building LOD models

3.3.1 LOD 0 NDT building geometry modeling

The LOD 0 model of the NDT building is represented as a 2.5D polygon that simplifies the building's footprint or roof edge. Figure 6 illustrates the detailed procedure of the geometry

Table 3
(Color online) LOD definitions for NDT building models.

Classification	LOD 0	LOD 1	LOD 2	LOD 3
Generalization	2.5D Multilayer (footprint or roof edge)	3D Block Model	3D model with exterior and facilities	Detailed realistic 3D model
Semantic	Building, BuildingPart, GroundSurface, RoofSurface,	LOD 0 Object, WallSurface	LOD 1 Object, All ThematicSurface, Window, Door BuildingInstallation	LOD 2 Object, BuildingConstructive Element, Storey, BuildingRoom, All Building Object
Geometry	lod0Point lod0MultiSurface	lod0 geometry lod1MultiSurface lod1Solid	lod1 geometry lod2MultiSurface lod2Solid	lod2 geometry All Geometry Type
Example	 ⟨LOD 0⟩	 ⟨LOD 1⟩	 ⟨LOD 2⟩	 ⟨LOD 3⟩

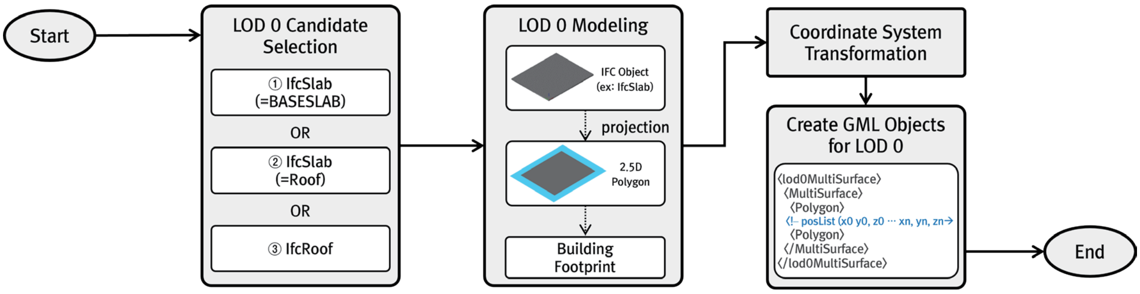


Fig. 6. (Color online) Diagram for NDT building LOD 0 geometry modeling.

transformation for the building's LOD 0 model from an IFC model. To this end, whether geometric information was represented was recursively explored through the IfcProductDefinitionShape attribute of the foundation slab (e.g., IfcSlab=BASESLAB) or roof (e.g., IfcRoof, IfcSlab=ROOF) in the IFC model, thereby selecting the candidates for LOD 0 conversion objects. Next, the conversion objects were projected onto the *XY* coordinate plane, and the outermost building polygon was extracted using a union operation[25] of a 2D Boolean algorithm. Finally, we performed coordinate transformation on the building objects of the LOD 0 model by applying the coordinate system transformation (CST) algorithm[12] and created GML objects corresponding to lod0MultiSurface in KS X 6808-1.

3.3.2 LOD 1 NDT building geometry modeling

The LOD 1 model of the NDT building was created as a 3D block model by combining the building footprint generated in the LOD 0 model with building height values. Figure 7 shows the detailed procedure for performing the geometry transformation of the LOD 1 model. In general, the extrusion technique is widely used, because it facilitates the efficient and easy construction of LOD 1 building models in a short time by utilizing 2D building data and height information for large-scale urban areas.[20,21,30] Because the IFC model does not define the overall building height as an explicit class, the maximum building height was derived by either summing the elevation attributes of IfcBuildingStorey or calculating the difference between the roof and the base slab. The calculated height values were then applied to the LOD 0 model using the extrusion technique[30] to create an LOD 1 block model with horizontal surfaces (e.g., roof and floor) and vertical surfaces (e.g., walls). Finally, we performed coordinate transformation on the building objects of the LOD 1 model using the CST algorithm,[12] and created GML objects corresponding to lod1Solid, which is the geometry class in KS X 6808-1.

3.3.3 LOD 2 NDT building geometry modeling

The LOD 2 model of the NDT building provides a detailed representation of the building's exterior shell and incorporates doors and windows on the walls. The exterior shell and openings of the building were generated from the IFC model and merged to create the LOD 2 model,

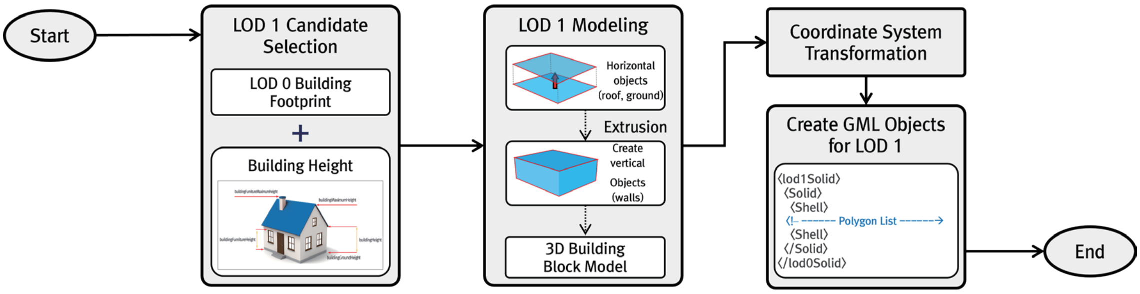


Fig. 7. (Color online) Diagram for NDT building LOD 1 geometry modeling.

performing the geometry modeling process. Figure 8 illustrates the detailed procedure for performing the geometry transformation of the LOD 2 model.

First, in the process of generating the building's exterior shell, as candidates for conversion, we selected IFC elements in which the IfcExternal value is set to True among the elements representing the building's external boundary, such as IfcWall, IfcRoof, and IfcSlab objects. These IFC objects are defined as solid models (e.g., IfcExtrudedAreaSolid), and to implement GML instance objects in KS X 6808-1, information about the surfaces enclosing the IFC solids is required. To this end, an open cascade technology (OCCT)-based boundary surface conversion method[7] was applied to decompose the solid models into B-reps consisting of faces and point lists, and the segmented faces on the same plane were merged to reconstruct a watertight exterior shell.

Next, in the opening generation step, opening elements attached to the exterior walls (e.g., IsExternal=True), such as windows (IfcWindow) and doors (IfcDoor), were extracted, and their association with IfcWall was utilized via IfcOpeningElement. Specifically, the surface-based difference operation proposed by Zhu *et al.*[12] was applied to ensure geometric accuracy and consistency between the wall and the opening elements. In other words, we projected the geometric information of the opening elements onto the exterior wall, subtracted the corresponding areas to reflect the openings, and inserted the geometric information of the doors and windows into the building's exterior shell. Finally, we performed coordinate transformation on the building objects of the LOD 2 model using the CST algorithm,[12] and the exterior shell and opening elements were generated as GML objects corresponding to lod2MultiSurface and lod2Solid.

3.3.4 LOD 3 NDT building geometry modeling

The LOD 3 model of the NDT building reproduces not only the building's exterior but also its interior spaces in a manner closely resembling reality. It must encompass all objects, such as the spatial elements, building facilities, and opening elements of IFC. To achieve this, the IFC model's spatial structure elements were sequentially explored, and individual objects, such as building space elements, openings, and building facilities, were processed step by step.

First, in generating the building's spatial elements, the hierarchy of IfcBuilding → IfcBuildingStorey → IfcSpace was traversed, and constructive elements (e.g., IfcWall, IfcSlab,

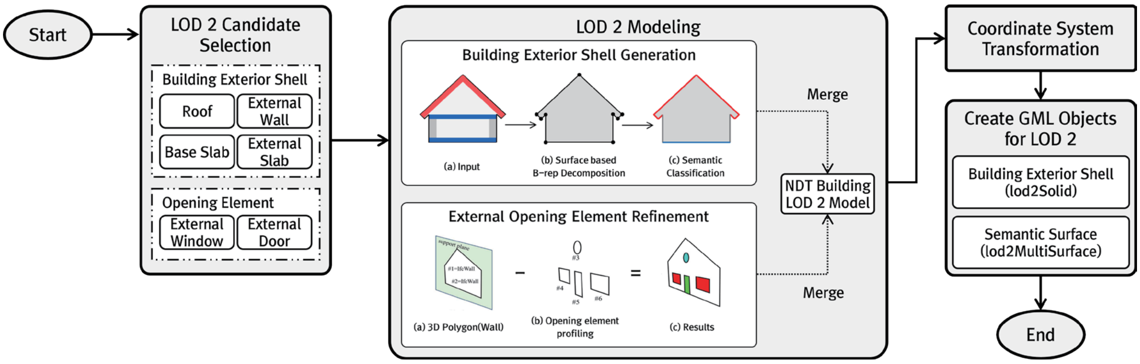


Fig. 8. (Color online) Diagram for NDT building LOD 2 geometry modeling. Source: Chetverikov *et al.*(31)

and IfcBeam) and indoor spaces (e.g., IfcSpace) associated with the building's interior and exterior boundaries using the IfcRelContainedInSpatialStructure relationship attributes included in IfcBuildingStorey were extracted as conversion objects. These objects were represented not only as solid models but also as B-rep models, and an OCCT-based boundary surface conversion method(7) was applied to convert the solid models into B-reps consisting of face and point lists.

Next, in the opening element processing step, doors and windows on the building's interior and exterior walls were simplified and integrated. In the IFC model, IfcDoor and IfcWindow are associated with building elements, such as IfcWall and IfcSlab based on IfcOpeningElement. On the basis of this concept, Chetverikov *et al.*(31) proposed a Boolean difference algorithm for processing the building's interior and exterior walls and opening elements, as shown in Fig. 9. Building on this approach, we applied Boolean operations to the building's interior and exterior walls and opening elements using the IfcRelVoidsElement attribute of IfcWall, and inserted doors and windows to the walls according to the IfcRelFillsElement relationships to concretize the LOD 3 model.

Lastly, in generating building facilities, IFC objects corresponding to facility objects, such as IfcStair, IfcRailing, and IfcCovering, were selected. Because the geometric information of these objects is represented as B-rep models, the OCCT-based B-rep method used for LOD 2(7) can be applied to directly convert them into KS X 6808-1's lod3MultiSurface. Finally, we performed coordinate transformation on the building objects of the LOD 3 model using the CST algorithm(12) and created GML objects with building spatial elements represented as lod0MultiSurface, interior spaces as lod3Solid, building facilities as lod3MultiSurface, and opening elements as lod3MultiSurface. Figure 10 illustrates the detailed procedure for performing the geometry transformation of the LOD 3 model.

3.4 Semantic transformation for NDT building LOD models

3.4.1 Semantic-based approach for class mapping

To convert IFC models according to the LODs of KS X 6808-1, it is necessary to define a mapping table analyzing the semantic correspondences between the source and target

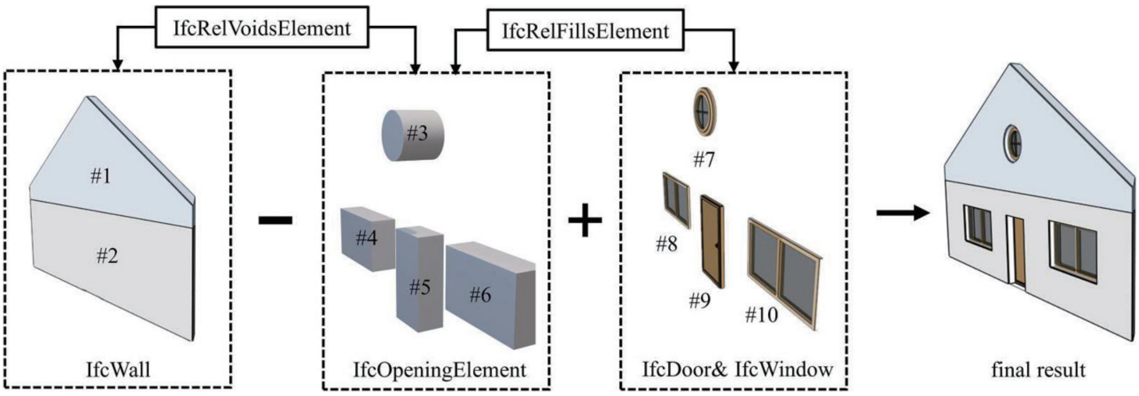


Fig. 9. (Color online) Schematic diagram illustrating the 3D modeling process of integrating door and window building elements into wall elements in IFC. Source: Chetverikov *et al.*[31]

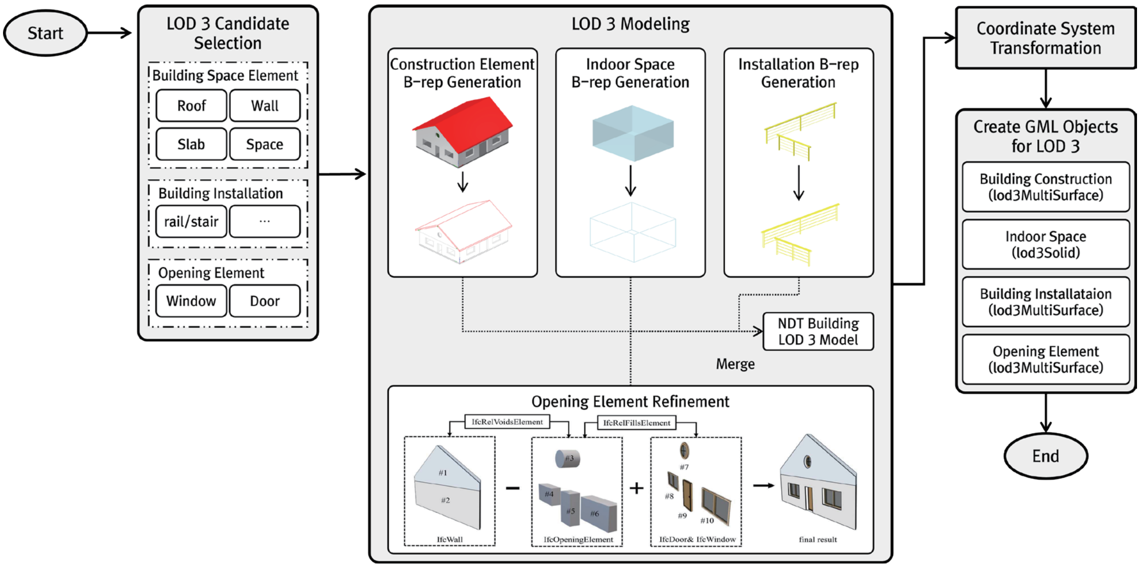


Fig. 10. (Color online) Diagram for NDT building LOD 3 geometry modeling. Source: modified from Chetverikov *et al.*[31]

models.[25–27] The source model, the IFC schema, contains over 900 object and attribute classes, which include information that is unnecessary (e.g., owner, process, and material, etc.) when converting to KS X 6808-1—the target model in GIS. Thus, previous studies have defined mapping tables between the original model and the target model prior to performing the KS X 6808-1 conversion in IFC, and have developed conversion tools. Accordingly, to specify conversion rules for each LOD, the LOD-specific mapping tables were defined as shown in Table 4 by comparatively analyzing the collected IFC data items, IFC, and the KS X 6808-1 at the schema level.

Table 4
LOD mapping between IFC and NDT building model.

Classification	Source Model			Target model	Applicable LODs			
	Entity	Criteria		Class	LOD 0	LOD 1	LOD 2	LOD 3
Building space element	IfcProject	–	→	CityModel	•	•	•	•
	IfcBuilding	–	→	Building	•	•	•	•
	IfcBuildingStorey	–	→	Storey				•
	IfcSpace	–	→	Building room				•
Building element	IfcRoof	–	→	Roof surface	•	•	•	–
	IfcSlab	PredefinedType = ROOF						
	IfcSlab	PredefinedType = BASESLAB	→	Ground surface	•	•	•	–
	IfcWall, IfcCurtain Wall, IfcWallStandardCase	IsExternal = TRUE	→	Wall surface	–	–	•	–
	IfcBuildingElement Proxy	–	→	Building installation	–	–	–	•
	IfcCovering	–						
	IfcRailing	–						
	IfcStair	–						
	IfcRoof	All Type	→	Building constructive element	–	–	–	•
	IfcWall, IfcCurtain Wall, IfcWallStandardCase	All Type						
	IfcSlab	All Type						
	IfcBeam, IfcColumn, IfcMember, IfcPlate	–						
Opening element	IfcWindow	IsExternal = TRUE	→	Window surface	–	–	•	–
	IfcDoor	IsExternal = TRUE	→	Door surface	–	–	•	–
	IfcWindow	All Type	→	Window	–	–	–	•
	IfcDoor	All Type	→	Door	–	–	–	•

3.4.2 Semantic-based approach for attribute mapping

The attribute information in IFC data plays a key role in enhancing the semantic information of NDT building models and improving their usability. The target model, 6808-1, includes the ADE extension schema of the NDT building, which includes the CityGML 3.0 encoding schema,[16] and mapping rules between the IFC and KS X 6808-1 schemas are required to convert IFC attributes appropriately into KS X 6808-1 attributes according to meaning. Usable attribute items were extracted by distinguishing between direct and indirect approaches using IFC data and mapping was performed for attribute conversion.

The direct extraction method refers to using attributes explicitly defined in the IFC schema without converting them. For example, such attributes as GlobalId and Name, which are automatically inherited by subclasses of the abstract class IfcRoot (e.g., IfcBuilding and IfcBuildingElement), are mapped to the featureID and name attributes. In addition, SiteCoverageRatio and FloorAreaRatio, defined in the Pset_SiteCommon attribute of IfcSite, directly correspond to buildingCoverageRatio and buildingFloorAreaRatio in KS X 6808-1. This method enables the utilization of IFC attributes without additional processing.

By contrast, the indirect extraction method refers to attributes that require processing derived from IFC objects. For example, because the height of AbstractBuilding is not directly defined in IFC, it can be calculated by summing the elevation attribute, which is the IfcBuildingStorey attribute, or by computing the geometric difference between the top and bottom floors. Moreover, buildingTotalFloorArea can be estimated by aggregating the GrossPlannedArea values of IfcBuildingStorey. Table 5 presents some examples of mapping rules for attribute values defined in the IFC and KS X 6808-1 schemas. While directly extracted attributes allow explicit one-to-one correspondence, indirectly extracted attributes are converted through calculations and combinations of internal attributes of IFC.

3.5 Overview of proposed IFC approach to NDT building LOD model conversion

In this subsection, we present the overall framework for the automatic generation of NDT building LOD 0–LOD 3 models in compliance with the KS X 6808-1 standard based on IFC data. The detailed procedure consists of three phases, as shown in Fig. 11: (1) IFC processing, (2) semantic and geometry transformation, and (3) the generation of the NDT building LOD model. Phase 1 parses the IFC model to verify the schema version, the existence of building objects, and the usability of coordinate information by version, and then sequentially explores the entities, attributes, and geometry information of the input IFC model according to the hierarchical structure. Phase 2 identifies the IFC objects required for each LOD and performs preprocessing tasks, such as semantic and geometry transformation. In the semantic transformation, IFC

Table 5
Attribute mapping between IFC and NDT building model.

IFC		NDT building model	
Entity	Attribute	Attribute	Class
IfcRoot	GlobalID	featureID	AbstractFeature
	Name	name	
Area calculation of LOD 0		area	AbstractSpace
Volume calculation of LOD 3 solid models		volume	
Pset_BuildingCommon	YearOfConstruction	dateOfConstruction	AbstractConstruction
	YearOfLastRefurbishment	dateOfDemolition	
Cumulative sum of IfcBuildingStorey.Elevation or Calculation of geometric height difference between the highest and lowest floors		height	
Pset_BuildingCommon	OccupancyType	class	AbstractBuilding
Pset_BuildingUse	MarketCategory	function	
	MarketSubCategory	usage	
Calculation of above-ground floor count in IfcBuildingStorey		storeysAboveGround	
Calculation of below-ground floor count in IfcBuildingStorey		storeysBelowGround	
IfcBuilding	BuildingAddress	address	
Cumulative sum of IfcBuildingStorey.GrossPlannedArea		buildingTotalFloorArea	BuildingGeneral Property
Pset_SiteCommon	TotalArea	buildingSiteArea	
	SiteCoverageRatio	buildingCoverageRatio	
	FloorAreaRatio	buildingFloorAreaRatio	

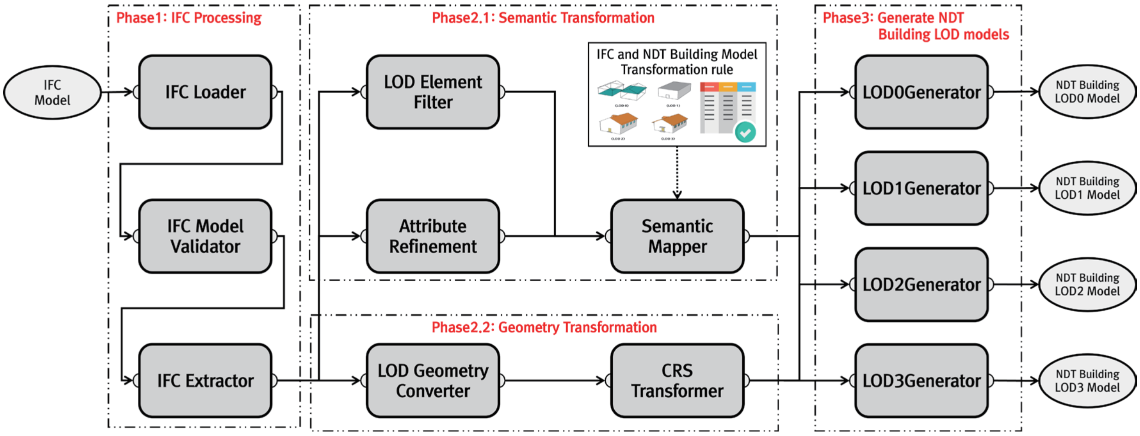


Fig. 11. (Color online) Overview of proposed approach for IFC-to-NDT building LOD model conversion.

objects necessary for generating the NDT building LOD model are filtered according to the LOD framework (e.g., Table 3); the attributes of IFC are refined directly or indirectly and then converted, and the entities and attributes of IFC are then converted according to the CityGML 3.0 and the NDT Building ADE schema based on the mapping table. In the geometry transformation process, the complex geometries and parameters of IFC objects are used to perform LOD-specific geometric modeling, followed by coordinate transformation to generate GML objects, such as lod0MultiSurface and lod1Solid. Finally, in Phase 3, the preprocessed geometric and semantic information is merged in accordance with the hierarchical structure between features and geometries in the KS X 6808-1 schema, and GML instance documents of NDT building models by LOD are generated.

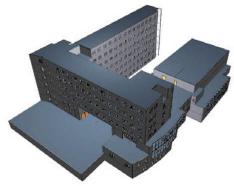
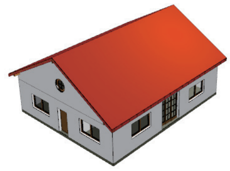
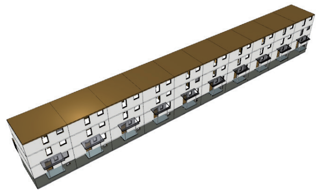
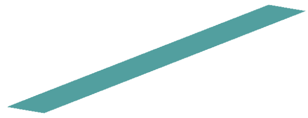
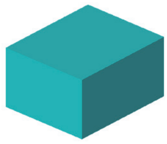
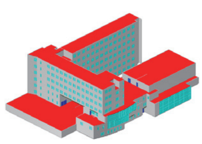
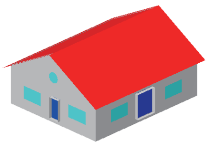
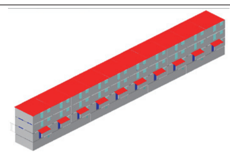
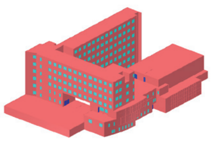
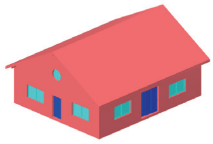
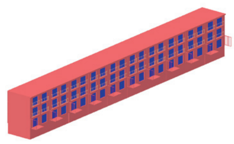
To evaluate the proposed framework, an IFC2NDTBuilding generator was developed, and key tools for IFC processing and validation, geometries and coordinates, and semantic transformation were implemented in a Python 3.8.20 environment using libraries, such as ifcopenshell, lxml, GDAL/OGR, Sympy, and PythonOCC.

4. Results

In this section, the IFC2NDTBuilding generator developed for evaluating the proposed methodology is used to convert the experimental data into LOD 0–LOD 3 models of NDT buildings. The converted results are then visualized using the open-source visualization tool KIT ModelViewer version 7.4, as shown in Table 6. The converted NDT building LOD models are confirmed to accurately reflect the geometric and semantic elements of individual LODs defined by the conversion rules, and are implemented in accordance with the schema structure defined in KS X 6808-1.

Moreover, to verify the validity of the NDT building models converted from IFC, semantic preservation validation and visualization validation were performed on the LOD 3 model, which is similar in level to the IFC model. For semantic preservation validation, we conducted an analysis on the LOD 3 model similar to the level of the IFC to quantitatively assess whether any

Table 6
(Color online) Converted NDT building LOD models.

Div.	The 21st Century Building	FZK Haus	Smiley West
IFC model			
LOD 0 model			
LOD 1 model			
LOD 2 model			
LOD 3 model			

semantic information was lost before and after the conversion of the experimental data. Table 7 shows that semantic preservation was generally high, exceeding 98%, and for open-source datasets, such as FZK Haus and Smiley West, spatial structure elements, such as IfcBuilding and IfcBuildingStorey, and various building elements were confirmed to have been fully converted at 100%. By contrast, The 21st Century Building showed some semantic information loss in IfcMember and IfcPlate. This is attributed to the fact that, among the experimental data, The 21st Century Building has a complex structure, resulting in a number of IFC data objects larger than those of other experimental data. In particular, IfcPlate objects, which are in plate-like structures represented as thin curved surfaces, encountered a zero-thickness issue and were processed as empty objects during conversion. IfcMember objects, whose geometric boundaries were not closed, caused processing errors due to geometry errors during conversion. Furthermore, during the extraction of NDT building elements by traversing the hierarchical structure of IFC objects, some IFC objects were omitted in the conversion owing to missing relationship attributes, such as IfcRelContainedInSpatialStructure, or geometric quality issues, such as not being watertight or lacking geometric information. Thus, the quality of IFC data is crucial for the automatic conversion of 3D building models in IFC. Although the proposed framework reliably preserved

Table 7
Results of semantic preservation validation before and after conversion.

IFC Class	The 21st Century Building			FZK Haus			Smiley West		
	Before	After	Accuracy	Before	After	Accuracy	Before	After	Accuracy
IfcProject	1	1	100%	1	1	100%	1	1	100%
IfcBuilding	1	1	100%	1	1	100%	1	1	100%
IfcBuildingStorey	8	8	100%	2	2	100%	5	5	100%
IfcSpace	380	380	100%	7	7	100%	140	140	100%
IfcRoof	–	–	–	–	–	–	–	–	–
IfcSlab	17	17	100%	4	4	100%	120	120	100%
IfcWall	787	787	100%	13	13	100%	281	281	100%
IfcCurtainWall	36	36	100%	–	–	–	–	–	–
IfcWall StandardCase	785	785	100%	13	13	100%	270	270	100%
IfcBuildingElement Proxy	–	–	–	–	–	–	–	–	–
IfcCovering	–	–	–	–	–	–	–	–	–
IfcRailing	–	–	–	2	2	100%	120	120	100%
IfcStair	–	–	–	1	1	100%	30	30	100%
IfcBeam	–	–	–	4	4	100%	10	10	100%
IfcColumn	–	–	–	–	–	100%	20	20	100%
IfcMember	1067	1032	96.7%	42	42	100%	–	–	–
IfcPlate	398	367	92.2%	–	–	–	–	–	–
IfcWindow	382	382	100%	11	11	100%	80	80	100%
IfcDoor	320	320	100%	5	5	100%	170	170	100%
Total	4182	4116	98.4%	106	106	100%	1248	1248	100%

semantic information, there is a need for further refinement in the process of simplifying complex geometric objects.

Visualization validation was performed on the LOD 3 NDT building GML instance of The 21st Century Building. The results of visualization using KIT ModelViewer 7.4 are shown in Fig 12. By examining the Element Toolbar in Fig 12(a), we analyzed whether the IFC objects reflected the LOD-specific semantic objects and attribute items defined in the KS X 6808-1 schema according to the rules defined in the mapping table. Specifically, the IFC spatial structure elements were classified into the core schema, such as CityModel, and the bldg schema, such as Building, BuildingRoom, and Storey, while individual IFC building elements and openings were classified according to the bldg schema, such as BuildingConstructiveElement, and the con schema, such as Window and Door. In addition, by examining the Property Toolbar in Fig 12(a), it was confirmed that key attribute information, such as spaceType and area, was added in the Core domain, and height, address and other attributes corresponding to Construction and Building were well reflected. Furthermore, the ADE attributes of KS X 6808-1, derived from the extraction of IFC attributes, were accurately converted according to the defined mapping rules, such as buildingFloorAreaRatio and buildingTotalFloorArea, into BuildingGeneralProperty, a sub-element of adeofAbstractBuilding.

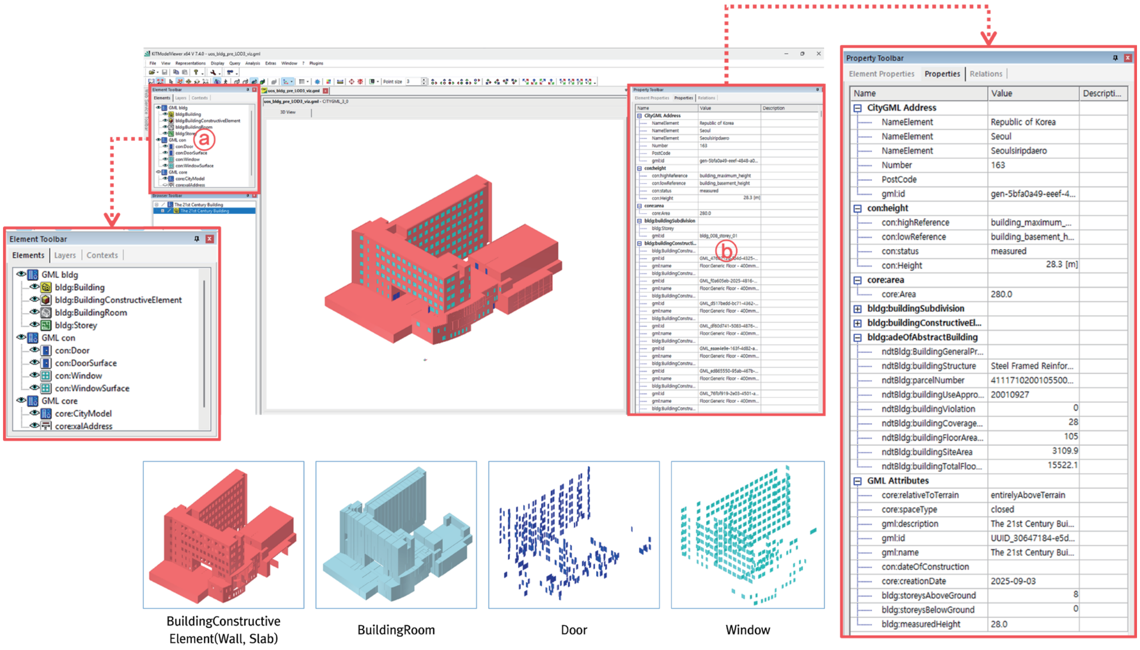


Fig. 12. (Color online) Visualization validation results for the LOD 3 NDT model of The 21st Century Building.

5. Conclusions

In this study, we proposed a methodology for automatically generating building models from LOD 0 to LOD 3 that comply with KS X 6808-1, the NDT building data model standard of South Korea, using IFC data. This methodology enhances the utilization of 3D data derived directly from sensor-based spatial information acquisition technologies such as LiDAR and photogrammetry. Unlike previous studies, which were limited to specific LOD levels or merely developed conversion models based on CityGML 2.0, we established an integrated conversion framework optimized for the KS X 6808-1 standard based on CityGML 3.0 and we developed the IFC2NDTBuilding generator for its evaluation. The conversion results achieved through the proposed methodology demonstrated a high level of semantic preservation of more than 98% and confirmed that the methodology can comprehensively transform building elements from spatial structure elements to openings and facilities. This is significant in that it enhances the efficiency of NDT construction by leveraging existing BIM data and provides a solution for ensuring consistency between 2D and 3D geospatial information, thereby maximizing the utility of data obtained from advanced geospatial sensors.

This study has the following limitations. First, there is a consistency issue when integrating the converted NDT building models with existing large-scale, city-level 2D geospatial information. Because the proposed method focuses on transforming individual buildings, it has certain limitations in achieving automatic consistency with real-world coordinate systems, and manual adjustments may be required for such aspects as LOD model rotation and terrain alignment. Second, the proposed framework considers only one-way transformation, such as

BIM to GIS; thus, to ensure interoperability between BIM and GIS, further research is needed on bidirectional transformation approaches that can bring GIS data back into the BIM environment. However, as there are fundamentally diverse perspectives and approaches depending on the application purposes of BIM and GIS, a technical review that considers the ongoing BIM/GIS standardization efforts by the ISO, OGC, and buildingSMART International may be needed. Finally, to establish a robust interoperability framework for future NDTs, it will be necessary to gradually expand the scope of research beyond buildings to include various domains, such as roads, terrain, and bridges. In the future, we plan to conduct research on spatial database solutions that can effectively store, manage, and utilize heterogeneous information, such as national base maps, administrative data, and sensor data established in the GIS environment, along with the proposed approach. The findings of this study are expected to address key issues faced by BIM–GIS integration technologies and lay a foundation for the implementation of NDTs and smart cities, while also being usefully applied as an important measure in future standardization initiatives.

Acknowledgments

This work is supported by a grant from the Korea Agency for Infrastructure Technology Advancement (KAIA) funded by the Ministry of Land, Infrastructure and Transport (Grant No. RS-2022-00143804).

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