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IFC-CityGML LOD Mapping Automation Using Multiprocessing-based Screen-Buffer Scanning Including Mapping Rule

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Abstract

Recently, research has been performed on Geographic Information Systems (GIS) to effectively recycle abundant Building Information Modeling (BIM). However, GIS and BIM use different schemas to describe forms. In particular, GIS defines the Level of Detail (LOD) in schema to quickly visualize numerous city-level objects. Because of schema differences, a mapping process is essential to reuse BIM in GIS. The problem is that mapping LOD models requires significant calculation time. This method reduces BIM-GIS mapping operation productivity, making it difficult to reuse BIM. In this research, we enhance mapping work productivity by developing a method that automates LOD geometry mapping using Screen-Buffer scanning-based Multiprocessing (SB-MP) including semantic mapping rule. The proposed method can dramatically improve LOD geometry modeling productivity. Finally, the developed results are evaluated quantitatively.

Keywords: *IFC, CityGML, BIM, creen-buffer scanning, multiprocessing, LOD, mapping rule*

1. Introduction

Building Information Modeling (BIM) technology has been applied extensively to the architecture, engineering, and construction sectors. In this context, there is an increasing challenge on integrating and mapping BIM object information to Geographic Information Systems (GIS). Many studies have been conducted with the aim of utilizing BIM, which can manage the entire lifecycle of facility information, and GIS, which can provide decision-making information at the state and city level (Kang and Hong, 2013). For this purpose, standard information models, such as Industry Foundation Classes (IFC), CityGML, and the Ontology model, have been used alongside technologies such as web services. IFC is an open, standardized way of storing digital building descriptions. IFC is developed by buildingSMART, and enables effortless exchange of information between various BIM software products. To date, various studies have analyzed schema characteristics with the aim of applying IFC and CityGML to industrial applications (Kolbe *et al*., 2005;Gröger and Plümer, 2012). In particular, CityGML has been optimized to manage and express city facilities information using GIS. Recently, CityGML has been applied to various use cases, such as energy management (Wu *et al.*, 2014), water and wastewater utility management (Hijazi *et al*., 2011), indoor and outdoor navigation (Hagedorn *et al*., 2009; Domínguez *et al*., 2011), and urban planning (Thompson *et al*., 2011).

The two standard model schemata have been objectively analyzed and designed. The object analysis targets for IFC and CityGML differ both in terms of building lifecycle information and GIS urban facility objects, and in the type and number of objects. In particular, when expressing shape in GIS, there is a large difference in the Level of Detail (LOD). In visualizing the 3D form of an object in GIS,LOD models according to its form description complexity must be visualized rapidly considering the camera distance at which it is observed. When numerous building objects are described in GIS, using this function can provide rendering performance that allows the user to explore an object form in real time. LOD consideration is essential for mapping object forms from BIM to GIS. In the case of IFC, however, forms are defined in terms of Boundary Representation (B-Rep) and Constructive Solid Geometry (CSG), but LOD schemas do not exist. Regarding CityGML, which is a format that differentiates external and internal surfaces, LOD schemas are divided from zero to four (Kolbe, 2006, 2007a).

When considering the conversion processing time, no significant problems are encountered during the conversion of a single facility. However, when targeting a large number of facilities, the conversion processing time adversely affects efficiency. This is due to the complex shape structure of IFC that requires a significant number of geometries computations during conversion to the LOD shape structure required by CityGML. For example, in this study, assuming there are one thousand BIM

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construction model forms in one city, we found that converting LOD forms requires approximately 100.7 days of calculations using existing methods. In this case, converting each BIM construction model to an LOD form in CityGML requires approximately 8700.3 seconds. A study related to this issue found that labor-intensive manual work is required to facilitate LOD conversion (Donkers *et al*., 2015). This method reduces the productivity of the BIM-GIS mapping operation, and makes it difficult to recycle BIM models.

In the current research, we propose an automated multiprocessor method for IFC-CityGML LOD generation. This method solves the performance problems that often occur during the conversion of IFC to the LOD model of CityGML. For this purpose, we define an automated LOD shape generation method using a Screen-Buffer scanning-based Multiprocessing (SB-MP) technique that includes semantic mapping rule.

This study aims to define the SB-MP method, which quickly extracts the surface required for each LOD of CityGML, and analyze its effects. Although the process of defining the mapping rule of LOD elements does not belong to the core range of this study in terms of semantics, it is necessary for mapping LOD elements. Hence, the semantic mapping method is briefly defined and implemented in the development stage of a prototype.

The use of SB-MP dramatically improves the performance of LOD generation compared with conventional methods. Finally, we evaluate the results given by the proposed method, and identify areas for future study.

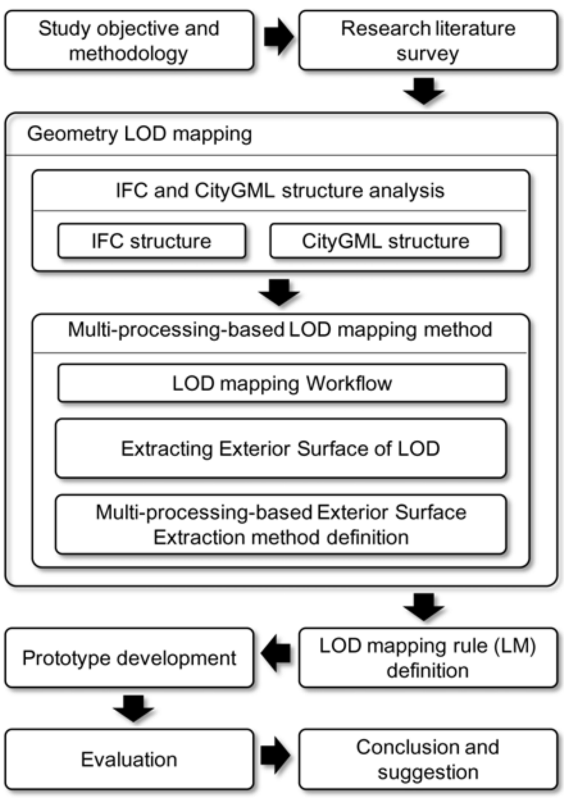


Fig. 1. Research Flow

2. Study Objective and Methodology

In this study, an automatic LOD generation method is proposed that maps object shapes from IFC to CityGML using SB and multiprocessing.

This paper is organized as follows. The points considered during this research and areas for improvement are clearly defined by reviewing related work. A geometry LOD mapping method is then defined in Section 4. We first analyze the schema structures of the standard BIM and GIS models, namely IFC and CityGML. We pay particular attention to the shape representation structure. The SB-MP-based LOD generation algorithm and related structure are also defined in this section. This study is focused on LOD mapping, but LOD mapping requires prior BIM-GIS object mapping. To address this issue, the semantics rules required to map from IFC to CityGML are defined in Section 5. The results of implementing the proposed method as a prototype are presented in Section 6. These results demonstrate the effectiveness of the proposed method in generating LODs. Finally, in Section 7, we summarize our conclusions from this research, and formulate suggestions for future work. Fig. 1 shows a schematic representation of the research method.

3. Related Work

A 3D City Model can be used as a use case in various fields such as building environment simulation, energy management, and facility management (Biljecki *et al*., 2015). It can be particularly effective for simulating, operating, and managing a city in which numerous buildings are connected to infrastructure. The LOD schema of CityGML can effectively represent a significant number of objects in GIS, including those related to transportation, urban areas, water resources, and land (Kolbe, 2007b). Several studies have considered methods for developing 3D Spatial Data Infrastructure (3D SDI) (Stoter *et al*., 2011a, 2011b). For example, some of the commercial tools used to convert IFC to CityGML include the Feature Manipulation Engine (FME) plug-in of Bentley Map; a conversion case that used this plug-in is mentioned briefly in this paper.

There have been attempts to further automate mapping from IFC to CityGML using other methods, as well as a study into the extraction of the LOD3 shape of CityGML from IFC (Donkers, 2013). In this study, the IFC and CityGML structures were analyzed, and then, to maintain geometric properties during the conversion, an LOD3 shape generation method was applied.

Donkers proposed a LOD conversion method which uses a mapping table for object elements. In his subsequent work, LOD mapping was facilitated by using the erosion and expansion operators for geometric elements (Donkers *et al*., 2015). However, the erosion and expansion operators used in this study require several geometric intersection calculations on the geometric elements of numerous building objects.

Furthermore, there have been attempts to develop an automatic IFC to CityGML conversion process using semantic mapping by focusing on the conversion of object and attribute information (Isikdag and Zlatanova, 2009). Cheng *et al*. (2013) used a semantic mapping algorithm to generate the LOD of CityGML by dividing the inner and outer surface of a given shape. In their method, to distinguish the indoor and outdoor 3D shapes that constitute the IFC model, the Even-Odd Rule (EOR) (Foley, 1990) is applied through the polygonal shape boundary, and an infinite linear cross-calculation is used. Because CityGML is a complex semantic model, visualizing large city objects on the actual GIS is a significant geometric calculation. GPUs have been employed to improve calculation performance (Jie *et al.*, 2012).

There have been various studies related to integration (El-Mekawy, 2010; El-Mekawy *et al.*, 2011, 2012) and conversion (Benner *et al*., 2005; Borrmann *et a*l., 2013; Kang and Hong, 2014) after the expansion of the standard BIM and GIS model schemata (de Laat and van Berlo, 2011; Borrmann and Jubierre, 2013), or after designing a new schema. Methods that involve schema extension, integration, and conversion do not reutilize applications or systems based on existing standard BIM and GIS models. When schemata are developed by targeting specific use cases, there is a limitation in terms of a drop in versatility. There has been research related to converting 2D and 2.5D geometry from GIS to BIM (Wu, Zarrinmehr, Rahmani, Miranda and Clayton, 2014). In the research, ArcGIS was used to extract GIS shape and Revit was used to generate BIM object. In addition, some approaches extract the information required for IFC engineering using web services, and provide a service through remote servers (Döllner and Hagedorn, 2007; Curtis, 2008; Beetz *et al*., 2010; Delgado *et al.*, 2010; Chambelland and Gesquière, 2012; Zhang *et al*., 2014). These methods must build a separate system to extract the information required for the implementation of specific use cases. Recently, a study has been conducted to generate LOD from BIM by using the GIS through the ray-tracing method and semantic mapping. This study defines the semantic elements among the IFC-CityGML LOD elements as a mapping table. The study uses a method of extracting a necessary surface based on the ray-tracing method for geometric elements (Deng *et al.*, 2016). Moreover, the local coordinate system of IFC is converted into the global coordinate system of CityGML by obtaining the global coordinate conversion matrix, a method which has been typically used in other studies, to address the accuracy issue that arises during the coordinate conversion of building object elements. However, the ray-tracing method used in this study requires significant amount of time to extract the geometric elements of numerous building elements through intersection calculation, and the method used for semantic mapping is unlikely to be user-oriented.

We have so far examined research trends related to the present research. There have been many attempts to utilize the advantages of BIM and GIS for more effective urban facility management. In this regard, there has been significant interest in integrating or mapping the information models of each area. This research is related to the mapping of BIM with a focus on GIS. In particular, multiprocessing can overcome the problem of the high computational load of mapping the LOD of GIS using a standard model. Most existing studies have focused on semantic mapping, with few approaches aiming to improve the generation of GIS LOD models from the IFC geometry model. There has been even less research on improving processing performance during LOD mapping from large numbers of high capacity IFC models to CityGML models.

4. Geometry LOD Mapping

4.1 Overview

The IFC and CityGML schemata are object models built through object-oriented principles, with various class types and properties defined for the exchange of semantic information from buildings and cities. In general, the object structure is constituted from object, property, method, and relationship components. From the object-oriented perspective, shape can be viewed as a property in both IFC and CityGML. However, because we consider a shape to be an important element, it should be classified and managed separately. Relationship scan include “inclusion”, “derivation”, and “dependency” between classes. In terms of semantics, these relationships may imply that objects are “near”, “meet”,or “connect”. With regard to all these parts, it is difficult to convert one schema to another (El-Mekawy *et al*., 2012).

The present research is limited to mapping with regard to the shape and properties of objects. Theoretically, for two schema models to have a complete mutual mapping without losses, all object-oriented elements constituted by the schemata must be mapped one-to-one. In the case of a many-to-one mapping, the manner in which the several elements are converted and mapped to one should be considered. In this case, depending on the type of mapping adopted (bidirectional or unidirectional), element type information is added during the conversion, and can be assigned to the property information. In the case of a one-to-many mapping, which is the topic of the current research (for example, the object shape of IFC should be mapped to the LODs of CityGML), we map the original source elements to the converted target elements using a process that conceptually separates the original source elements according to the type of target elements, and then performs the conversion. Furthermore, the conversion process differs for bidirectional and unidirectional mappings. It is impossible to map IFC and CityGML schemata on a one-to-one basis for the aforementioned reason.

4.2 IFC and CityGML Structure Analysis

In this section, the structures of CityGML and IFC are analyzed for object shape mapping. In particular, we focus on the geometrical structure required for LOD generation.

4.2.1 IFC Structure

IFC consists of set relationships among entire buildings, building spaces, and building members. This implies a whole/

part relationship supported by IfcRelAggregates. Because a relationship always occurs between two objects, it is defined by an aggregates/parts relationship. Aggregates are defined by a RelatingObject of IfcObjectDefinition type, and parts are defined by RelatedObjects. For example, a building is an aggregate, and each floor of the building is a part. The IFC spatial structure is divided into four concepts: IfcSite, IfcBuilding, IfcBuildingStorey, and IfcSpace. IfcBuildingStorey can include building members, such as IfcWall, IfcSlab, and IfcColumn; these building members are represented by classes generalized by IfcProduct. Space and building member objects are related to each other. For example, as shown in Fig. 2, IfcBuilding includes IfcBuildingStorey in a set relationship using IfcRelAggregates objects. Conversely, IfcBuildingStorey indicates objects, such as magnets, by an inverse relationship (INV). IfcBuildingStorey manages IfcProduct using IfcRelContainedInSpatialStructure relationship objects.

Each spatial object has its own local coordinate system that represents IfcObjectPlacement by IfcLocalPlacement. This allows shapes such as “BoundingBox”, “SurfaceModel”,“B-rep”, and “MappedRepresentation” to be formed (buildingSMART, 2008). By adopting a boundary representation method, the “B-rep” approach represents topology using IfcFace, IfcLoop, IfcEdge, and IfcVertex, which are derived from IfcTopologicalRepresentationItem objects. IfcLoop can represent the external boundary of shapes such as walls, or void-type openings such as the window of a wall. This can be seen through the connection direction of the edge that constitutes a loop.

4.2.2 CityGML Structure

CityGML defines a Geometry that represents the geometric model, Features that represent geographic features, and a Definition class that defines the data dictionary. To address many city objects, the city object class is derived from the FeatureCollection class, which is a basic feature class (Open Geospatial Consortium, 2012). FeatureCollection can manage many city objects because it uses a composite design pattern (Gamma *et al.*, 1994) as an object container. These play a role similar to the IfcRelContainedInSpatialStructure relationship of

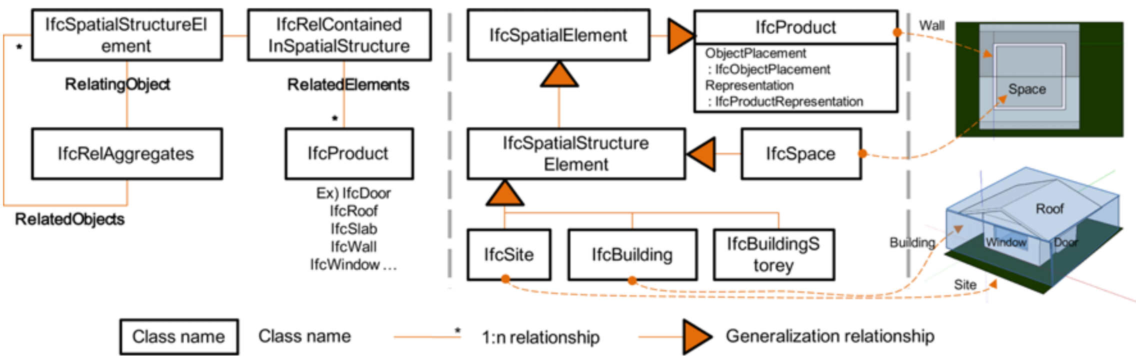


Fig. 2. IfcBuilding Information Representation

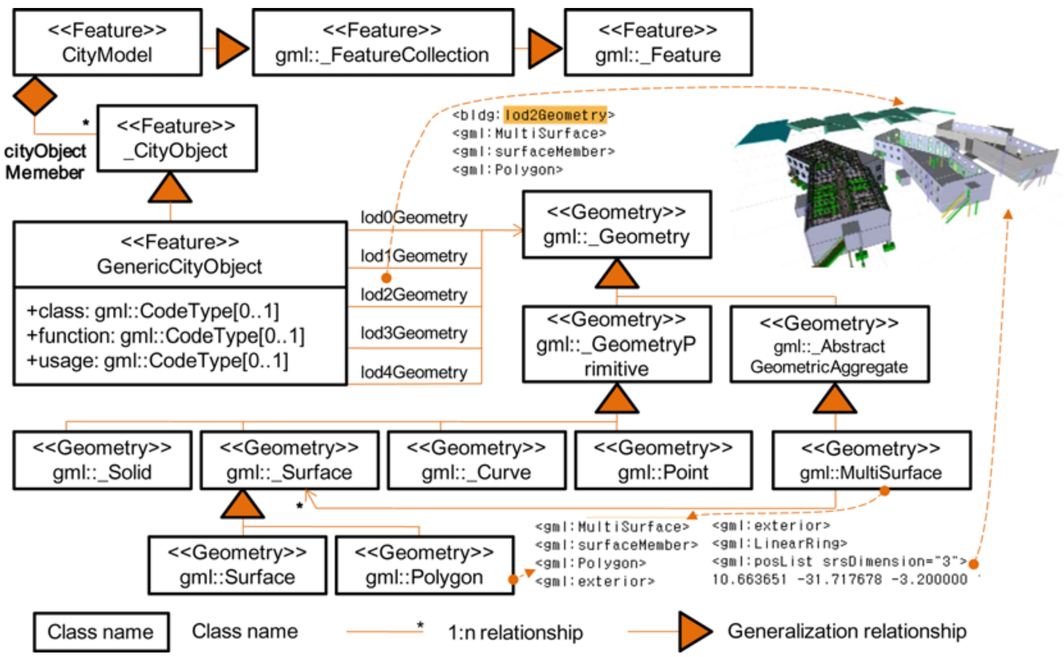


Fig. 3. GenericCityObject and LOD Representation Structure in CityGML

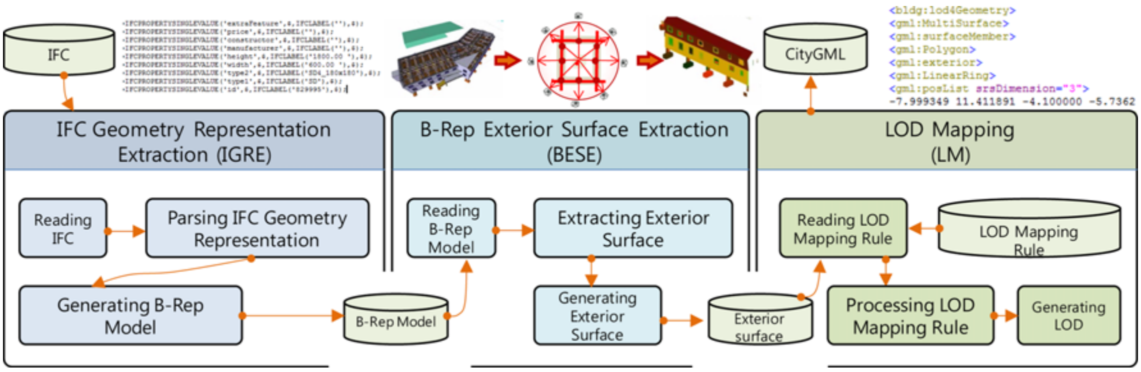


Fig. 4. CityGML LOD Mapping Flow Chart in IFC

Table 1. Definition of Each CityGML LOD Mapping Step in IFC

No	Phase	Description
1	Parsing IFC Geometry Representation	Geometry and Topology information required to generate the surface that composes the shape is derived by parsing the geometry and topology structure of IfcProductRepresentation with regard to IfcProduct.
2	Generating B-Rep Model	To convert to LOD with respect to CityGML objects, conversion is performed by the B-Rep model of the mesh structure form that can map to MultiSurface. The coordinates are accurately converted by calculating the global coordinate conversion matrix based on the local coordinate system, which is obtained through IfcLocalPlacement.
3	Extracting ES	In the B-Rep model, ES is extracted using the external surface extraction algorithm.
4	Processing LOD Mapping Rule	Based on the predefined LOD mapping rule, LOD mapping is performed after semantic mapping from the IFC object to CityGML.
5	Generating LOD	Mapped LOD is generated in CityGML format.

IFC. CityGML divides shape representation levels from LOD0–LOD4 to effectively visualize many city facilities. This point is significantly different from the shape representation method of IFC. Fig. 3 illustrates the geometry representation according to each LOD; the representations are defined from lod0Geometry to lod4Geometry, and include a GenericCityObject.

Each LOD is defined by GeometryPrimitives, such as Solid, Surface, and Curve, derived from Geometry. Because the shape is formed using these Primitives, complex shapes can be implemented through composite design pattern structures, such as MultiSolid, MultiCurve, and MultiSurface, derived from AbstractGenericAggregate (Open Geospatial Consortium, 2007). The shape structure is relatively simple compared with IFC, and cannot support topology such as IfcLoop. In this study, MultiSurface is generated based on the application rule for each LOD by extracting complex shapes from each IfcProduct object of IFC, and by automatically extracting the outer surface.

4.3 Multiprocessing-based LOD Mapping Method

4.3.1 Mapping Workflow

LODs should be mapped by considering the shape model structure of IFC and CityGML, which were analyzed in the previous sections. First, for LOD mapping, the geometric representation of IfcProduct must be converted to the simplified B-Rep structure of CityGML. B-Rep, which is converted by each IfcProduct, should extract Exterior Surfaces (ES) for LOD mapping. The LOD mapping of CityGML and IFC should occur per the semantic similarity between objects, and according to the LOD concept of CityGML. Therefore, the ES derived from each B-Rep of each IfcProduct is mapped to the LOD of CityGML using the mapping rule that defines the semantic and LOD mapping method. The LOD mapping flow of this process is shown in Fig. 4. The processing operations for each major step are listed in Table 1. Among these steps, we examine ES extraction and the processing of LOD mapping in detail.

The phases in Table 1 were divided into three categories. Parsing IFC Geometry Representation and Generating B-Rep Model are included in IFC geometry Representation Extraction (IGRE) because IFC shape information is extracted and stored in the B-Rep Model database. Extracting ES which extracts the external surface from the B-Rep Model database is included in the B-Rep Exterior Surface Extraction (BESE). The remaining phases are related to LOD information generation in the LOD mapping (LM).

4.3.2 Extracting ES Method Definition

Because IFC is a complex shape model, we convert from a mesh structure to a simplified B-Rep structure to effectively extract the external surface. Methods for external surface extraction used in existing studies include EOR (Foley, 1990), which is based on the LOD generation method (Cheng *et al.*, 2013). This method proposes a core operator in the ray-tracing method that Deng (Deng *et al.*, 2016) used for extracting LOD

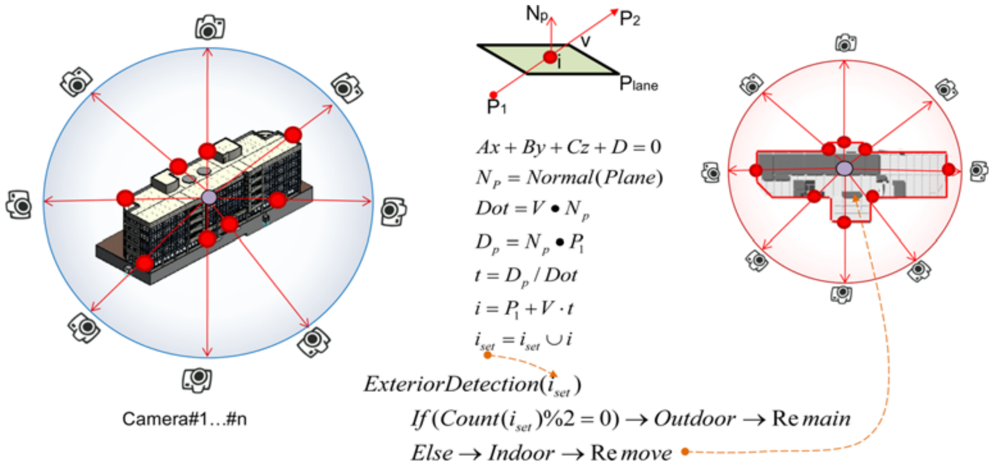


Fig. 5. EOR-based ES Extraction Concept

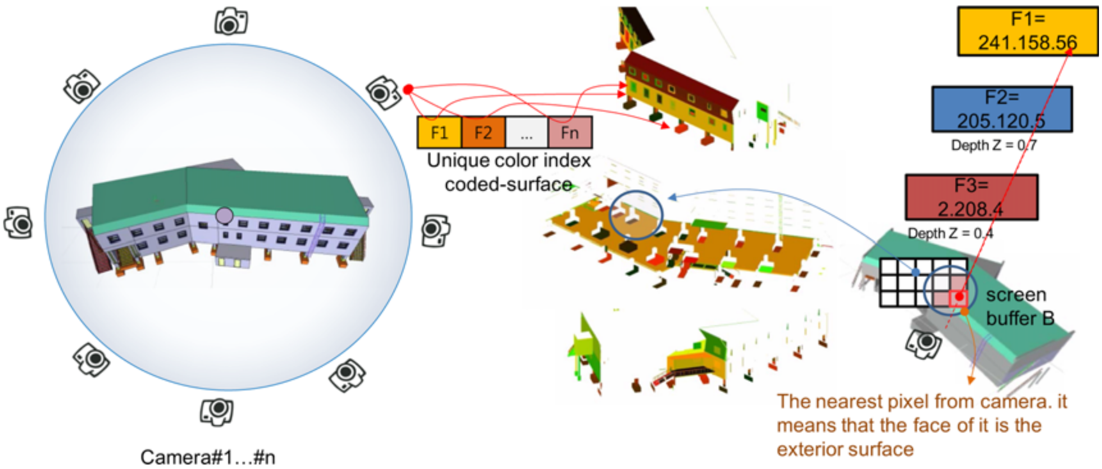


Fig. 6. SB-based ES Extraction Concept

and requires the calculation of the surface of objects that form a building as well as numerous cross calculations. EOR extracts the external surface through the cross calculation of surface, as performed in the ray-tracing method.

As shown in Fig. 5, in the EOR-based method, a camera is placed around a complex shape model used to extract an external surface, and a virtual eye ray S(P_1, P_2) is created with respect to the camera. If the number of intersection points between eye ray S and the complex shape is an odd number, the relevant constituent element is enclosed inside the other surface, and is therefore removed.

As shown in Fig. 6, the SB scanning-based method dramatically increases processing speed compared with the EOR method because it uses a Z-buffer test during rendering. In Z-buffer test algorithm, if the z-value at a pixel indicates that the surface is closer to the camera than the z-value in the z-buffer, the z-value and the intensity values recorded in the buffers are replaced by the surface's values. After processing all surfaces, the resulting intensity buffer can be displayed.

The calculation speed for the EOR method is extremely slow because the number of computations is proportional to the number of surfaces that compose the complex shape model. This is because the 3D surface-straight-line required during the EOR test demands a high real calculation cost. However, the SB method scans the buffer using a simple Z-buffer test with regard to a SB that renders the surfaces of relevant scenes per camera while testing the external surface. For this reason, only the pixel values that confirm the external surface are checked. Moreover, because the SB method uses the Z-buffer test or high-speed multiprocessing, external surfaces can be extracted at high speed. To define the pixel values that confirm the external surface, SB should be scanned after setting a Unique Surface Identifier (USI) for each surface in the B-Rep using a color code (Unique Color Index—UCI) and after rendering the relevant surfaces. Using the scanned UCI, the external surface can be found directly by the B-Rep model. Because SB is generated by capturing one surface through various cameras, the scanned UCI might be duplicated. This duplication problem can be solved using a hash-map technique. For *n*SBs with a screen image of width *w* and height *h*, the B-rep model M is defined as

$$M = \sum_{i=1}^{n} \sum_{j=1}^{w} \sum_{k=1}^{h} SB_{i,j,k} \quad (1)$$

$$SB = \{UCI, \ldots\} \tag{2}$$

i, j, k unit = pixel resolution , UCI = Unique Color Index, SB = Screen Buffer

4.3.3 Multiprocessing-based ES Extraction Method Definition

The number of facilities that require BIM in city-scale management cases can exceed one million. If extracting the outer surface of each facility shape requires considerable time, the computation time and cost of extraction can become prohibitive. To overcome this problem, we now describe a multiprocessing method based on SB scanning for extracting ES introduced in the previous section.

The SB method independently scans the screen buffer generated by each camera, and requires synchronization between each buffer. If the functions subjected to multiprocessing can access and modify the same datasets, a synchronization process is essential; in this case, it might be difficult to improve processing performance. Current multiprocessing methods include OpenMP, which utilizes the threading method of a multi-core CPU, and the Compute Unified Device Architecture (CUDA) method developed by NVIDIA. Both methods use the same algorithm for external surface extraction and parallel processing.

In the current research, two approaches can be used for parallel processing. The first divides SB for each parallel processing unit (u), and the second processes the SBs generated by each camera in parallel. To allocate the buffers to parallel processing units, the divided processed data M_e is used in each SB scan function $SB_{MP}(\ )$. The $SB_{MP}(\ )$ extracts UCIs by scanning the SB assigned to the function, and processes the duplicate UCIs. Fig. 7 and Eqs. (3), (4) describe the algorithm for this process.

$$M(u) = \sum_{e=1}^{n} M_e \tag{3}$$

$$ESM = SB_{MP}(M, e) \tag{4}$$

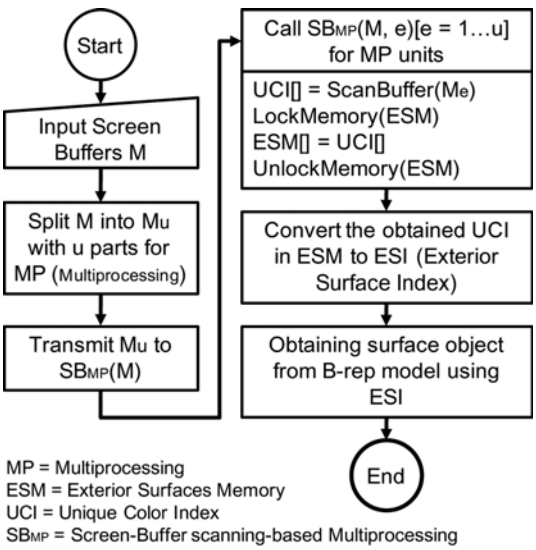


Fig. 7. Multiprocessing-based ES Extraction Algorithm

4.3.4 LOD Mapping Rule (LM) Definition

For LOD mapping from IFC to CityGML, IfcProduct objects should first be mapped to the CityObject of CityGML through a semantic-based rule. However, in the case of LOD, after simply obtaining the Footprint of a building or facility, data extruded in the height and elevation directions are processed through a cross-Boolean operation. Hence, a complex rule is required. Therefore, only the relevant operators are defined. For the LOD mapping considered here, we define the semantic mapping rule shown in Fig. 8.

During the mapping to the CityObject of CityGML, the semantic concept of IfcProduct can differ depending on whether it is inside or outside a building. The symbols of "[ ]", which indicate inter (or indoor), and |, which indicate outer (or outdoor), are used to distinguish indoor and outdoor objects. For example, IfcBeam should be mapped to IntBuildingInstallation if in an indoor space, and to OuterBuildingInstallation for an outdoor space. Therefore, special operators such as "[Int | Outer]" can be attached to the mapped CityObject element. In this case, the mapping targets should be modified to inner or outer building elements, depending on the semantics. This rule is easily represented by an XML format that can be read by the user. Fig. 9 shows an

LOD	LOD Generation Rule
1	Extrude(Product.Footprint) ∩ Extrude(Projection(Product.Elevation))
2	ExteriorSurfaceExtraction(Product) – ExteriorSurfaceExtraction(Product).Void
3	ExteriorSurfaceExtraction(Product)
4	LOD3 ∪ IndoorSurface(Product)

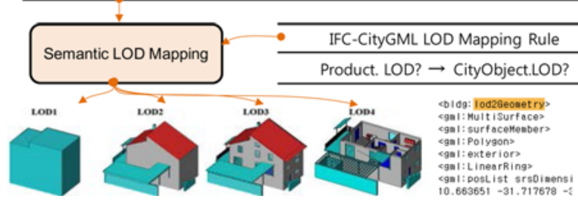


Fig. 8. IFC-CityGML Semantic LM1Definition

```
<LM>
  <LOD-Generation>
    …
    <LOD Level='3'> ExteriorSurfaceExtraction(Product) </>
    <LOD Level='4'> LOD3 + IndoorSurface(Product) </>
  </LOD-Generation>
  <SemanticLODMappingRule>
    …
  <MappingRule Source='IfcWall*.L3' Destination='WallSurface.L3'></>
  <MappingRule Source='IfcWall*.L2' Destination='WallSurface.L2'></>
  </SemanticLODMappingRule>
</LM>
```

IFC	CityGML
IFCBEAM,	IntBuildingInstallation OR OuterBuildingInstallation
IFCBUILDINGELEMENTPROXY,	IntBuildingInstallation OR OuterBuildingInstallation
IFCCHIMNEY, | IFCFLOWCONTROLLER,	IntBuildingInstallation
IFCCOLUMN,	IntBuildingInstallation OR OuterBuildingInstallation
IFCCOVERING,	CeilingSurface
IFCCURTAINWALL,	OuterBuildingInstallation
IFCDOOR,	Door
IFCFOOTING,	IntBuildingInstallation
IFCFURNITURE,	BuildingFurniture
IFCPLATE, | IFCRAILING, | IFCRAMP,	IntBuildingInstallation OR OuterBuildingInstallation
IFCROOF,	RoofSurface
IFCSLAB,	FloorSurface
IFCSTAIR, | IFCSTAIRFLIGHT,	IntBuildingInstallation OR OuterBuildingInstallation
IFCWALL,	WallSurface OR InteriorWallSurface
IFCWALLSTANDARDCASE,	Wall
IFCWINDOW,	Window
IFCSPACE,	Room

Fig. 9. IFC-CityGML Semantic LM Definition Example

example of the IFC-CityGML Semantic LM used in this study.

5. Test Case Study

We developed a prototype using the Multiprocessing-based ES extraction algorithm and the LOD mapping method proposed in Section 4. To confirm the effect of multiprocessing-based outer surface extraction, the EOR and MP algorithms were examined by implementing a CPU-based single thread and an OpenMP-based multi-thread method that ensures data structures are thread-safe and avoids the need for thread synchronization (Kuhn *et al.,* 2000). Because the IFC sample is for small and medium scales, we modeled an indoor space.

The prototype and sample results listed in Table 2 indicate that the proposed method processes the mapping for each LOD of CityGML. For comparison with other methods, the EOR-based method, which is used in the ray-tracing method, is applied in this study. EOR-based method should perform geometry intersection calculations evenly on all surfaces of the sample shape with respect to the eye ray from the camera to the center of the object. Thus, the potential for calculation errors is greater than with the SB-based method, and the phenomenon of not being able to extract the outer surfaces properly can be observed.

6. Evaluation

As indicated in Table 3, the external surface extraction processes were compared using the samples and prototype developed in Section 5.The results in Table 3 indicate that the SB-MP-based ES extraction method proposed in this study can improve computation time by a factor of up to 16,649.32 over that of the EOR-based (single-thread) approach. In particular, as shown in Fig. 10, the sensitivity of the processing performance according to data size is no greater than that for EOR, and we can confirm that the proposed algorithm is highly efficient. There is a slight difference between the single-thread, multi-thread, and OpenMP

Table 2. IFC-CityGML LOD Mapping Results

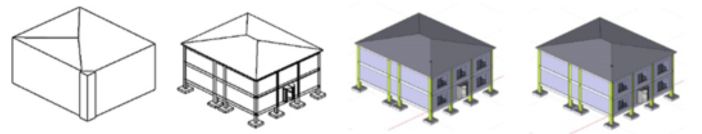
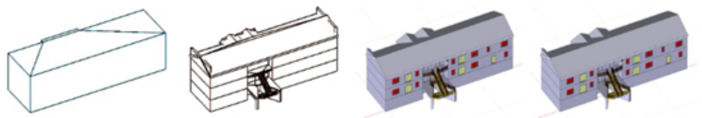
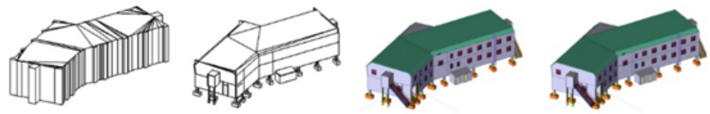
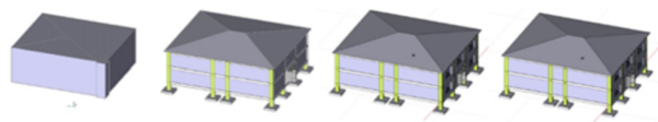
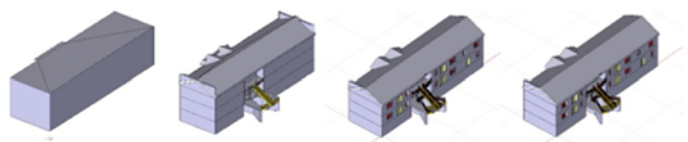
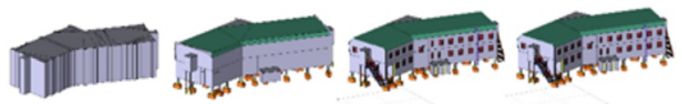
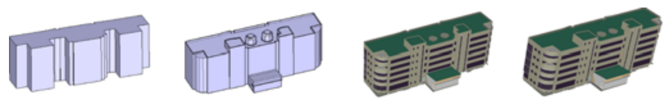
No	Algorithm	IFC Data	LOD1	LOD2	LOD3	LOD4
1	EOR	Sample#1 (Size: 0.559 Mb)				
2		Sample#2 (Size: 2.257 Mb)				
3		Sample#3 (Size: 28.188 Mb)				
4		Sample#4 (Size: 55.357 Mb)				
5	SB	Sample#1 (Size: 0.559 Mb)				
6		Sample#2 (Size: 2.257 Mb)				
7		Sample#3 (Size: 28.188 Mb)				
8		Sample#4 (Size: 55.357 Mb)				

Table 3. Performance Test Results (Seconds) Using Intel(R) Core(TM) i7 CPU Octa-core 860 2.80 GHz, 12 GB RAM, and 64-bit Operating System

No	Algorithm	Sample#1	Sample#2	Sample#3	Sample#4
#1	EOR-based (single-thread)	16.75	211.79	8,700.30	152,840.79
#2	EOR-based (multi-thread)	16.68	85.68	3,141.55	11,278.64
#3	SB-based (single-thread)	0.68	0.69	2.31	9.23
#4	SB-based (multi-thread)	0.67	0.68	2.31	9.21
#5	SB-based (OpenMP)	0.60	0.62	2.29	9.18
	Improvement ratio (#1 / #5)	27.81	342.45	3,805.76	16,649.32

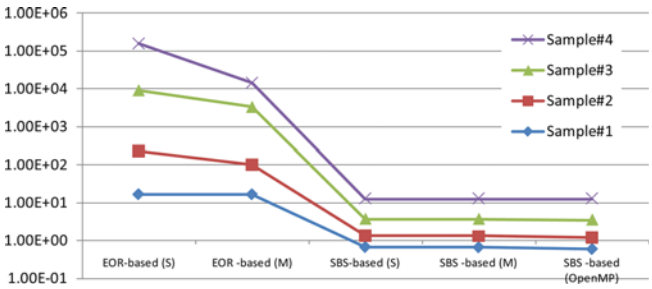


Fig. 10. SB-MP-based Exterior Surface Extraction Performance Comparison Chart (Seconds)

cases with the SB approach.

Figure 10 shows that SB-based exterior surface extraction is more effective for extracting exterior surfaces than EOR-based exterior surface extraction. If the image number were increased, the performance difference between single and multiprocessing would be greater than in the current results because the multiprocessing performance depends on the number of data that can be processed in parallel.

7. Conclusions

In this research, we defined a geometric LOD mapping method from IFC to CityGML. Furthermore, an SB-MP-based LOD generation algorithm and related structure were proposed. The proposed method was implemented and tested with a given sample. The test results showed that the proposed method could reduce the computation time by a factor of up to 16,649.32 compared with existing methods. The difference in processing performance varies according to the IFC data size and complexity. The test results show that the size and complexity of IFC have an insignificant effect on the SB-MP method, as compared to other methods. In the results, it was quantitatively proved that the proposed algorithm is more efficient than other methods. This study proposes the SB-MP method, which can quickly extract the surface required for each LOD of City GML, and analyzes its effects. However, a method of defining the LOD mapping rule, which can determine the meaning of elements to be mapped according to the aspects of LOD, is additionally needed to implement the LOD element mapping by using CityGML in IFC. The LOD mapping rule should provide the user, which can be used to facilitate the mapping of LOD elements according to the perspective of model users. The concept of definition-based rules can clearly determine the mutual semantic difference from the perspective of users during the mapping of BIM-BIS element LOD, thereby eliminating the ambiguity surrounding the mapping process.

In addition, we found that the element mapping related to heterogeneous models between IFC and CityGML is not semantically 1: 1 mapped. Also, the semantic meaning was found to depend on the application context. The rule-based semantic mapping method between the BIM-GIS model elements proposed in this research is practical because developers can design semantic meaning to be mapped to GIS from BIM according to the application context clearly.

In the current research, to interoperate BIM and GIS information models on standardized IFC and CityGML, we proposed a shape structure by semantically generalizing the method that performs LOD mapping through a multiprocessing-based SB method. The method proposed in this research can be applied to similar 3D BIM and GIS shape mappings. However, our approach has a limitation in that it considers only unidirectional mappings, and does not consider mappings related to properties and relationships. In addition, there are limited studies on defining the standard for comparing the mapping accuracy owing to the difference in the geometric representation between IFC and CityGML. Further studies will thus be conducted by considering this limitation.

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