Extraction of Exterior Building Envelopes from Building Information Models

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1 Introduction

The Architecture, Engineering, and Construction (AEC) industry continue to seek a higher level of digitization. In this process, building information modeling (BIM) plays a crucial role. Building information modeling refers to the concept of using data models throughout the buildings' different stages, and a building information model refers to the corresponding facility's detailed and in-depth digital representation (André Borrmann 2018). Building information modeling has been widely applied within the AEC industry for decades (Costin et al. 2018), and it has become increasingly important with different software and project implementations (Jaud et al. 2020). One goal of building information modeling is to accelerate information exchange between one building project's various stakeholders. For the purpose of smooth communication, achieving data interoperability is not only necessary but also of vital importance (Ozturk 2020). To guarantee building information models' re-usability and interoperability, common BIM standards are established. Among the open BIM standards, the Industry Foundation Classes (IFC) is well-known, it contains building assets' detailed geometric and semantic information, in addition, the topographic information between buildings' elements can be readily extracted from IFC models (Liu et al. 2021).

As aforementioned, The IFC format is currently the main open BIM standard in the AEC industry. However, in the Geo-information science (GIS) domain, buildings' data are stored according to a set of different standards. In the GIS domain, buildings are usually stored in 3D city models. A 3D city model is a city's digital representation, it contains different urban objects' geometries, including but not limited to buildings, bridges, roads, rivers, and vegetation (BILLEN 2014). In the 3D city models, the buildings play a crucial role (Ledoux et al. 2019). Previously, 3D city models are predominately used for visualization purposes (Biljecki et al. 2015). Currently, 3D city models are applied across wider domains, for instance, urban planning, environment simulations, and disaster management (Yao 2018). The international standards for 3D city models are CityGML and shapefile. CityGML is authorized by Open Geospatial Consortium (OGC) (Gröger et al. 2012), with XML and CityJSON encoding format (Ledoux et al. 2019). Before BIM models can be used in the GIS domain, conversion needs to be carried out (Zhu, Wu, and Anumba 2021).

The differences between BIM models and 3D city models create difficulty when data exchange is needed across the two domains. Converting BIM models to CityGML models is widely researched (ibid.). Considering the fact that BIM models contain highly detailed building information, making use of the building information in BIM models when constructing 3D city models will be able to avoid redundant modeling (Ohori et al. 2018). Another problem that exists in the conversion process of BIM and GIS integration is: the BIM models can possibly contain too much detailed information in the context of GIS applications (Volk, Stengel, and Schultmann 2014). This unnecessary information can occupy more storage space and make the related processes more computational-expensive (Zhou et al. 2019), and make the output GIS model less useful in real-world applications (Ohori et al. 2018). In conclusion, it is necessary to develop methods that are able to transform BIM models into 3D city models. Ideally, the outcome of the conversion should not only in a GIS-friendly format (CityGML), but also adequately simplified and suitable for potential GIS applications.

The goal of this study is to develop a method that can extract buildings' exterior envelopes from building information models, and output them as 3D city models in the GIS domain. Before generating the building envelope, necessary simplification will be carried out on IFC models to remove unnecessary data, thus speeding up the process and improve the performance. After the simplification process, 3D shape generalization method will be implemented and applied to the simplified models to extract the buildings' exterior envelopes. The ideal outcome of this study will be a tool that can produce 3D city models from input IFC models, and the output will potentially be suitable for real-world applications, including but not limited to automatic-check of building permits, or building energy modeling simulations.

1.1 Problem Statement

BIM models contain detailed and in-depth information for building assets, and the building is an important component of the 3D city models within the GIS domain. Converting BIM models to buildings in 3D city models reduces redundant modeling, but usually for 3D city models, only partial information from BIM models is required. In many use cases for the 3D city models, only the exterior part of the buildings are used, including but not limited to visualization, automatic check for building permits and urban energy modelling. In conclusion, it is necessary to develop a method that has the ability to extract building envelopes from BIM models, and the output 3D city model should potentially be suitable for real-world applications.

2 Related work

This section is divided into three subsections. Since the goal of this research is to extract information from BIM models and output the building envelopes that can be used in the GIS industry, the first subsection will cover previous research done on BIM and GIS integration. The second section summarizes previous efforts on building envelope extractions. In the end, 3D alpha shapes will be introduced, and its applicability for the building exterior envelope extraction process will be explored.

2.1 BIM and GIS integration

As aforementioned, this study aims at bridging the gap between BIM and GIS industries and outputs 3D city models from BIM models in a meaningful way. Thus, investigating research within the BIM and GIS integration domain is of great necessity to this study. This section will be divided into two parts: the first part will be about integration on the data level, and the second part will address integration on the application levels.

Up until today, there is plenty of research done on the data level of BIM-GIS integration, most of which is on the BIM-to-GIS conversion. In the research done by Rafiee et al. (2014), the geometries and the semantic data are extracted from BIM models and output as geo-referenced models Zhu, Wu, Chen, et al. (2020) developed an algorithm that has the ability to automatically convert IFC clipping representation into ESRI shapefile format. There are also different software tools that are able to convert BIM models to CityGML models, including ModelServer, IfcExplorer, safeFME (Ohori et al. 2018). However, it is worth noting that when converting BIM models to the CityGML models, most previously done approaches preserve all the geometries, making the results overly detailed for GIS applications (ibid.).

In addition to the data-level integration, attempts have also been made on the application level, i.e. exploring the possible use cases for the BIM-to-GIS integration. For instance, after converting BIM models to vector geographic format,Rafiee et al. (2014) makes shadow and view analysis on the converted data models , which can help urban planners with house pricing and energy simulations. A conceptual BIM-CityGML Data Integration (BCDI) approach has been proposed by Zadeh, Puyan A and Wei, Lan and Dee, Arianne and Pottinger, Rachel and Staub-French, Sheryl (2019), with two practical examples of where this approach can be of use: operation and maintenance, and energy center design.

2.2 Extracting Building Envelopes

This section presents a review of previous attempts for extracting building envelopes. For each method, an overview will be covered, the results will be evaluated, and the applicability for this study will be investigated.

2.2.1 Extracting exterior shell from LoD3 cityGML models

Fan, Meng, and Jahnke (2009) proposed a method that has the ability to extract building's exterior shells from IFC models.

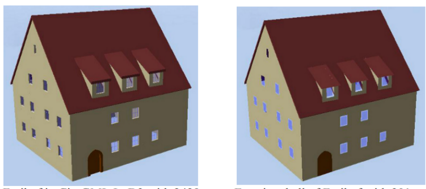
- Method Overview

The method proposed is divided into the following steps.Firstly, the walls in the cityGML models are converted to point clouds. After the conversion, the centroid and the adjusting plane for each wall is computed, and the average point of all walls' centroids is viewed as the building center.

In this study, whether a wall or roof surface belongs to the exterior or interior is determined by the distance between itself and the building center. The windows and doors are also projected onto the exterior shell to preserve the details.

- Result Evaluation

The following figure 1 shows one example result from this method.



Freihof in CityGML LoD3 with 2429 polygons (from the city model of Et tenheim in Germany)

Exterior shell of Freihof with 301 polygons

Figure 1: An LoD3 model and its exterior shell (Fan, Meng, and Jahnke 2009)

This method is relatively simple and straightforward. It produces viable results for testing buildings.However, it has limited use range: only produces viable results with buildings that have convex shapes.

- Potential Applicability to thesis

This method is about extracting the building exterior shell from a LoD3 CityGML model, but since the core of the method is about extracting vertices and evaluating polygons based on their positions, this method is applicable for extracting building envelope from IFC models as well.

As aforementioned, the main problem of this method is that it can only work with convex shape buildings, and since this drawback comes from the fact that the core evaluation condition for distinguishing building exteriors and interiors is to measure the distance between the facade and the building center, it is difficult to overcome this limitation by making improvements on this method.

However, the step that turns walls into point clouds may be applicable to the extracting points process from IFC models before feeding them to the shape generalization method.

2.2.2 Ray-tracing method for extracting building envelopes

To make extracting building envelopes from complex-shape buildings possible, the ray-scanning method is proposed and applied in various studies.

- Method Overview

In the study of Deng, Cheng, and Anumba (2016), a scanning method for extracting building envelopes from IFC models is proposed. This method got inspiration from the traditional ray-tracing algorithm. The scanning algorithm test every surface of the IFC model against all other surfaces, thus determining whether it is an exterior surface or it is an interior surface.

In the study of Karydakis (2018), the building's exterior is extracted using Python and CGAL library. It also follows the ray-casting method to extract a precise version of the building's exterior envelopes. In this study, rays are sent from one viewpoint to the target IFC model. Only the surfaces that intersect first with the rays are identified as "observable surfaces". The non-observable surfaces are removed from the IFC models. After the ray-casting method, the following steps are taken for the extraction of the building envelopes. Firstly, the bounding box around the building is created. After this, the ray-casting process is carried out. For complicated buildings, the buildings are split before feeding into the ray-casting algorithms. In addition, the result of the ray-casting process is enriched by semantic isolated projects.

- Result Evaluation

The resulting building envelopes from ray-casting process is shown in figure 2 and 3 below. Comparing to the previous method, this ray-casting method has the ability to process buildings with complex and non-convex shapes. However, this method can produce buildings with small holes and gaps, in addition it is computationally expensive and thus slow.

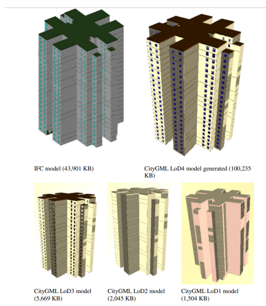


Figure 2: Exterior envelopes outputted as CityGML format (Deng, Cheng, and Anumba 2016)

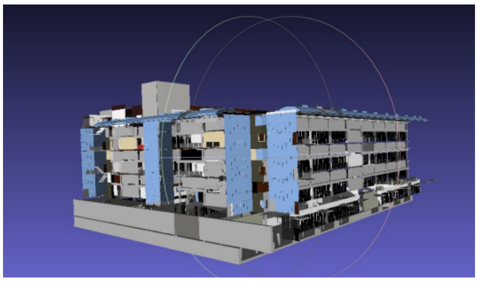


Figure 3: Exterior envelopes outputted as CityGML format (Karydakis 2018)

- Potential Applicability to thesis

The simplification method from Karydakis (2018) has the potential to be applied in this study. The conversion between IFC models and cityGML models in the study of Deng, Cheng, and Anumba (2016) is also potentially applicable to this study.

2.2.3 Boolean Operation method

- Method Overview

Donkers et al. (2015) perform Boolean set operations on selected building objects to generate the building's outer shape. First, the IFC models are filtered and transformed into solids, and the solid's boundary surfaces have been assigned to semantics.

After this step, they construct the space partitioning to extract the building's exterior envelopes. Firstly, the 3D Euclidean space is divided into non-overlapping geometry volumes. Then Boolean union operations are performed on all pairs of solids that are face-adjacent. In the end, they remove all the geometries inside the outer boundaries. Figure 4 shows this method intuitively.

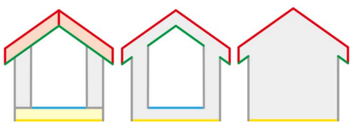


Figure 4: Extracting Building envelopes from IFC solids(Donkers et al. 2015)

- Results' evaluations

This method often fails in practice due to the geometrical or topographical errors present in the IFC files, for instance, the utilities that penetrate building exteriors, and small gaps between geometries (Donkers et al. 2015). It prevents holes in the resulting 3D city models, but it introduces artefacts, and the semantic data is lost, thus semantic-recovering methods needed to be applied, making the method complex (Ohori et al. 2018).

- Potential Applicability

The filtering method for the IFC objects is potentially useful for this study. The errors in IFC files mentioned in this study may also lead to future problems in this study.

2.2.4 Other potential methods

In order to extract the building's outer envelope, Noardo et al. (2020) proposed four potential methods: using story attributes[1], 2D alpha shapes, 3D alpha shapes, and voxelization.

2.3 3D Alpha Shape

3D alpha shape is a shape generalisation algorithm developed by Edelsbrunner and Mücke (1994), with implementation available in CGAL [2]. The alpha shape family are polytopes that can be used to represent the "shape" of a point set in the R^3 space, and the detail levels of the generated shapes are defined by the parameter α Edelsbrunner and Mücke (ibid.).

Consider R^3 space is filled with foam, and the input points are solid points. Remove all the foam without touching the solid points with a spoon with a radius of α, and the remaining foam shape will be a α-hull Edelsbrunner and Mücke (ibid.). Straighten all the curves of the α-hull, the result will be the eventual alpha shape.

3D Alpha shape has the ability to work with both convex and non-convex shapes. Extracting points from IFC models and feeding them into the 3D alpha shape algorithm can potentially produce the target building's exterior envelope.

3 Research Objectives

3.1 Objectives

This thesis's main research question is:
From IFC models, how to generate building envelopes that are suitable to potential GIS applications?

[1] https://gist.github.com/aahoo/c97248816510bf9892a2e8bdf90d1626
[2] https://doc.cgal.org/latest/Alpha$_{s}hapes_{3}/index.html$

The goal of this thesis will be to develop a software tool that has the ability to extract a building's outer envelope from BIM models, attempting to make this method applicable for complex models, and output the building envelope's in a format that can be used in the geospatial industry, e.g. CityGML. To answer the main question, four three-questions needed to be answered:

- Before putting the data into the shape generalization method, should IFC models be simplified? If the necessity is proven, what are the IFC elements that can be excluded, and what are the IFC elements that are needed to persevere?
- How can a building envelope extraction method be developed, that can generate accurate building envelopes efficiently?
- What are the factors that can potentially affect the quality of the output building envelopes?

3.2 Scope of Research

The goal of this thesis is to develop a software tool that is able to extract buildings' exterior envelopes from BIM models. Before the building envelope extraction, the necessity of IFC model simplification will be investigated. If necessary, irrelevant IFC elements will be removed before the building envelope extraction. After this, the building exterior shapes will be extracted using suitable 3D shape generalization algorithms, possibly 3D alpha shapes. The research will be done on investigating the factors that affect the quality of the results (e.g. holes, gaps, or invalid geometries). In the end, the potential applications for the generated building envelopes will be investigated e.g. energy simulations, visualizations, and checking for building permits.

4 Methodology

As aforementioned, the final goal for the thesis is to develop a software tool that is able to extract buildings' exterior envelopes. The output should be in a GIS-friendly format and applicable to possible GIS applications. To achieve this goal, the following steps need to be followed:

1. Simplification of the IFC files. IFC files will be parsed and irrelevant elements in files will be filtered. The aim of the simplification process is to speed up the following shape generalization processes.
2. Extraction of building envelopes. The simplified IFC models will be put into different 3D shape generalization algorithms to generate the building's exterior envelope. Which shape generalization algorithms will be used is yet to be decided.
3. Evaluations of possible factors that affect the output building envelope's quality. Evaluations and algorithm developments will be carried out recursively, with the aim of producing ideal results.
4. Exploration for the potential use case for the building envelopes, e.g. visualization, checking for building permits, and building energy simulations. Similarly, this exploration process will be carried out parallel to the building envelope extraction process, in order to produce outputs that can be

The flow chart below shows the general workflow for this study.

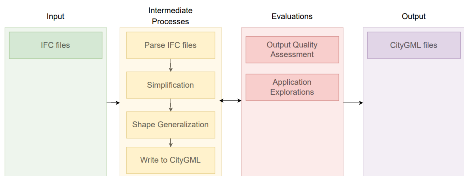


Figure 5: Flow Chart

4.1 Simplification of the IFC files

As aforementioned, IFC files contain very detailed information about the corresponding buildings. The IFC files are organized in a hierarchical structure, with different entities at different levels (Atazadeh, Kalantari, and Rajabifard 2016). The following image shows the structure of the IFC format.

However, it is worth noting that not all the IFC entities contain information relevant to the building's exterior envelope. A large proportion of the IFC objects are non-static and non-geometry objects. There are also IFC entities that represent the building interiors (Karydakis 2018). Another concern is that many IFC files contain errors, for instance, geometry self-intersection (Ohori et al. 2018).

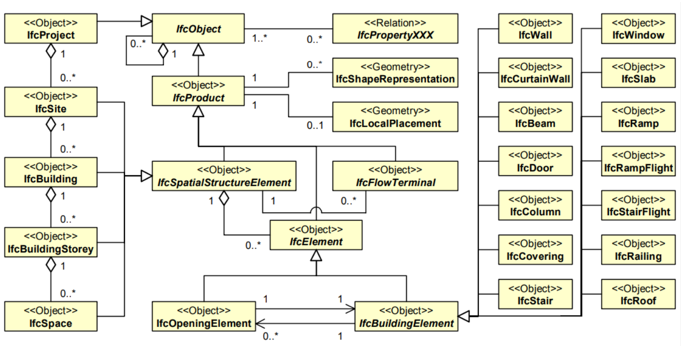


Figure 6: IFC Data Structure (Nagel, Claus and Stadler, A and Kolbe, T 2007)

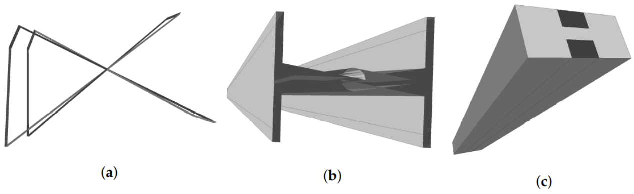


Figure 7: Geometric Errors in IFC formats (Ohori et al. 2018)

In order to avoid the aforementioned irrelevant information slowing down or bringing unnecessary mistakes into the building envelope generalization process, simplification of the IFC files may be required.

To exclude the unnecessary IFC entities, this study will generally follow an object filtering approach proposed by Donkers et al. (2015). The general filtering procedure is described in figure 8. Based on the outcomes, the

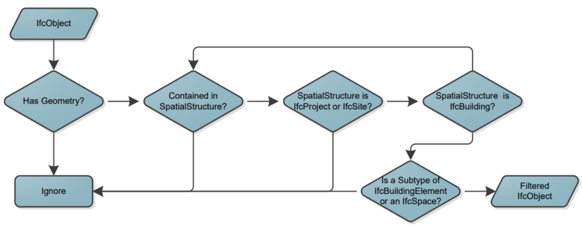


Figure 8: Workflow of filtering IFC objects (Donkers et al. 2015)

4.2 Extraction of building envelopes

To generate the exterior building envelopes, the 3D alpha shapes (Edelsbrunner and Mücke 1994) are used. As aforementioned, the 3D alpha shape algorithm can output a shape that describes the input point sets. Figure 9.

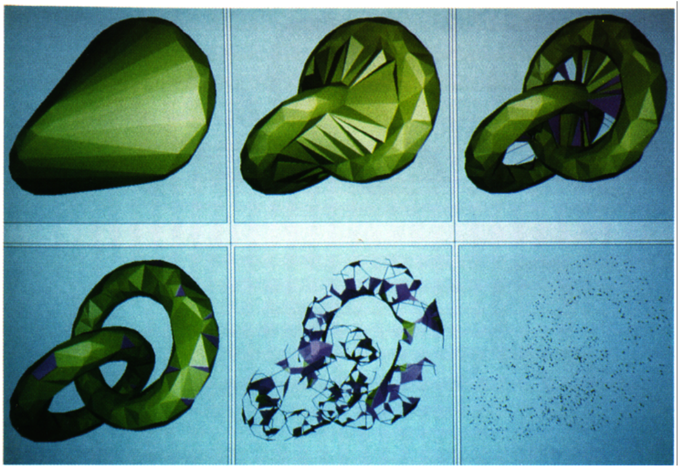


Figure 9: 3D Alpha Shapes from a point set (Edelsbrunner and Mücke 1994)

In this study, the IFC files are firstly read and parsed using IfcOpenShell [3]. Then the helper class from Vaart (2022) is used to extract the points from IFC files. The extracted points are then put into the 3D alpha Shape class provided in CGAL to generate the building's outer envelope.

[3]https://ifcopenshell.org/

5 Preliminary Results

Figure 10, figure 11 and figure 12shows some preliminary results.

The results show that the 3D alpha shape has the ability to generate a building envelope that roughly represents the building's outer shape, but there are still irregular geometries present, especially on the roof part.

The cause for this needs to be further investigated. One possible cause for this may be that only vertices from the IFC model are not detailed enough for the output. Iterating through the surfaces instead of vertices of the input IFC models, and sampling the exterior surfaces can output more points. Feeding these sampled points into the 3D alpha shape algorithm can potentially improve the results.

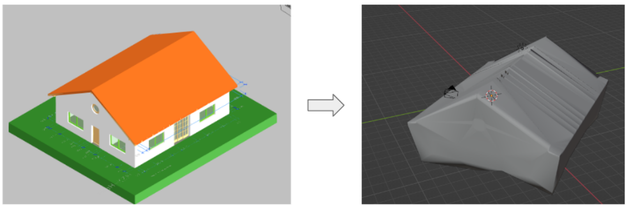


Figure 10: Building Envelope Generalization Result from AC20-FZK-Haus.ifc

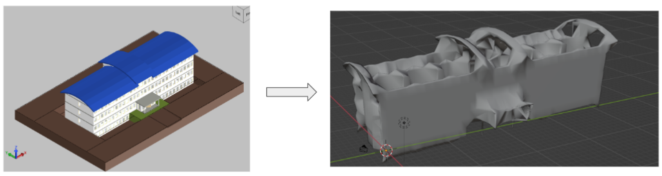


Figure 11: Building Envelope Generalization Result from AC20-Institute-Var-2.ifc

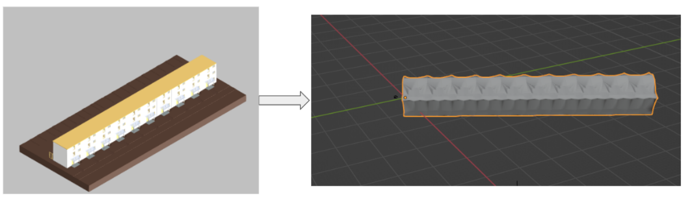


Figure 12: Building Envelope Generalization Result from AC-20-Smiley-West-10-Bldg.ifc

6 Time planning

The following is the schedule for this thesis project:

start	end	Activity
20 Oct	31 Oct	Explore the Graduation Topics
		P1 -Progress Review Graduation Plan
01 Nov	31 Dec	Literature Study
06 Nov	15 Dec	Research existing shape generalization algorithms
15 Dec	20 Dec	Research IFC file simplification methods
20 Dec	2 Jan	Research output formats
2 Jan	13 Jan	Writing Research Proposal
13 Jan	23 Jan	Preparing P2 presentation
		P2 -Formal Assessment Graduation Plan
01 Feb	16 Mar	Implement existing IFC simplification methods
16 Feb	24 Mar	Extract building envelopes
		P3 - Colloquium midterm
24 Mar	12 May	Write final implementation
01 May	12 May	Thesis writing
		P4 -Formal Process assessment
12 May	15 June	Finalize thesis
15 June	22 June	Prepare final presentation
		P5 -Public presentation and final assessment

7 Tools and datasets used

7.1 Tools

During the project, several tools will be used in different stages of this study. The tools used will be specified below:

IfcOpenShell: IfcOpenShell [4] is an open-source library available in both C++ and Python, it provides a wide range of functionalities to read and process the IFC files, with extensive geometric support. In this study, the IfcOpenShell will be used to parse the input IFC files, process different IFC elements, and extract relevant geometries.

CGAL The Computational Geometry Algorithms Library (CGAL [5]) is a C++ open-source software project that provides a variety of geometric algorithms, e.g. triangulation and Boolean operations. In this study, the 3D alpha shape from the CGAL library will be used to extract building envelopes.

OpenIfcViewer: The OpenIfcViewer[6] is a professional-grade IFC viewer developed by Open Design Alliance. In this study, it is used to visualize the input IFC files.

Blender: The Blender [7] is a open-source 3D computer graphics tool. In this study, it is used to visualize the 3D alpha shape in obj format in the intermediate process of extracting building envelopes.

7.2 Data

In this study, different open-source IFC files in IFC 4 or IFC 2*3 format will be used to test the implemented software tool. The following figures show some examples of used IFC files.

[4] https://github.com/IfcOpenShell/IfcOpenShell
[5] https://www.cgal.org/
[6] https://openifcviewer.com/
[7] https://www.blender.org/

References

André Borrmann, Markus König (Sept. 2018). *Building Information Modeling: Technology Foundations and Industry Practice*. Springer-Verlag GmbH. 584 pp. ISBN: 3319928627. URL: https://www.ebook.de/de/product/34302331/building_information_modeling.html.

Atazadeh, Behnam, Mohsen Kalantari, and Abbas Rajabifard (2016). "Comparing three types of BIM-Based Models for managing 3D ownership interests in multi-level buildings". In: URL: http://resolver.tudelft.nl/uuid:7ec46879-e6f8-4cef-83ab-a36c38ceccc9.

Biljecki, Filip et al. (Dec. 2015). "Applications of 3D City Models: State of the Art Review". In: *ISPRS International Journal of Geo-Information* 4.4, pp. 2842–2889. DOI: 10.3390/ijgi4042842.

BILLEN Roland, et al. (2014). *3D city models and urban information: current issues andperspectives - European COST Action TU0801*. EDP Sciences. DOI: 10.1051/tu0801/201400001.

Costin, Aaron et al. (Oct. 2018). "Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations". In: *Automation in Construction* 94, pp. 257–281. DOI: 10.1016/j.autcon.2018.07.001.

Deng, Yichuan, Jack C.P. Cheng, and Chimay Anumba (July 2016). "Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison". In: *Automation in Construction* 67, pp. 1–21. DOI: 10.1016/j.autcon.2016.03.006.

Donkers, Sjors et al. (Sept. 2015). "Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings". In: *Transactions in GIS* 20.4, pp. 547–569. DOI: 10.1111/tgis.12162.

Edelsbrunner, Herbert and Ernst P. Mücke (Jan. 1994). "Three-dimensional alpha shapes". In: *ACM Transactions on Graphics* 13.1, pp. 43–72. DOI: 10.1145/174462.156635.

Fan, Hongchao, Liqiu Meng, and Mathias Jahnke (2009). "Generalization of 3D Buildings Modelled by CityGML". In: *Advances in GIScience*. Springer Berlin Heidelberg, pp. 387–405. DOI: 10.1007/978-3-642-00318-9_20.

Gröger, Gerhard et al. (2012). *OGC City Geography Markup Language (CityGML) Encoding Standard*. en. 2.0.0. Open Geospatial Consortium.

Jaud, Štefan et al. (Oct. 2020). "Georeferencing in the context of building information modelling". In: *Automation in Construction* 118, p. 103211. DOI: 10.1016/j.autcon.2020.103211.

Karydakis, Panagiotis (2018). "Simplification Visualization of BIM models through Hololens". MA thesis. Delft University of Technology.

Ledoux, Hugo et al. (June 2019). "CityJSON: a compact and easy-to-use encoding of the CityGML data model". In: *Open Geospatial Data, Software and Standards* 4.1. DOI: 10.1186/s40965-019-0064-0.

Liu, Liu et al. (Jan. 2021). "Indoor navigation supported by the Industry Foundation Classes (IFC): A survey". In: *Automation in Construction* 121, p. 103436. DOI: 10.1016/j.autcon.2020.103436.

Nagel, Claus and Stadler, A and Kolbe, T (2007). "Conversion of IFC to CityGML". In: *Meeting of the OGC 3DIM Working Group at OGC TC/PC Meeting, Paris (Frankreich)*.

Noardo, F. et al. (Sept. 2020). "GEOBIM FOR DIGITAL BUILDING PERMIT PROCESS: LEARNING FROM A CASE STUDY IN ROTTERDAM". In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* VI-4/W1-2020, pp. 151–158. DOI: 10.5194/isprs-annals-vi-4-w1-2020-151-2020.

Ohori, Ken Arroyo et al. (Aug. 2018). "Processing BIM and GIS Models in Practice: Experiences and Recommendations from a GeoBIM Project in The Netherlands". In: *ISPRS International Journal of Geo-Information* 7.8, p. 311. DOI: 10.3390/ijgi7080311.

Ozturk, Gozde Basak (May 2020). "Interoperability in building information modeling for AECO/FM industry". In: *Automation in Construction* 113, p. 103122. DOI: 10.1016/j.autcon.2020.103122.

Rafiee, Azarakhsh et al. (2014). "From BIM to Geo-analysis: View Coverage and Shadow Analysis by BIM/GIS Integration". In: *Procedia Environmental Sciences* 22, pp. 397–402. DOI: 10.1016/j.proenv.2014.11.037.

Vaart, Jasper van der (2022). "Automatic building feature detection and reconstruction in IFC models". MA thesis. Delft University of Technology. URL: http://resolver.tudelft.nl/uuid:db6edbfc-5310-47db-b2c7-3d8e2b62de0f.

Volk, Rebekka, Julian Stengel, and Frank Schultmann (Mar. 2014). "Building Information Modeling (BIM) for existing buildings — Literature review and future needs". In: *Automation in Construction* 38, pp. 109–127. DOI: 10.1016/j.autcon.2013.10.023.

Yao, Zhihang (2018). "3DCityDB-a 3D geodatabase solution for the management, analysis, and visualization of semantic 3D city models based on CityGML". In: *Open Geospatial Data, Software and Standards* 3.1, pp. 1–26.

Zadeh, Puyan A and Wei, Lan and Dee, Arianne and Pottinger, Rachel and Staub-French, Sheryl (2019). "BIM-CITYGML data integration for modern urban challenges". In: *J. Inf. Technol. Constr.* 24, pp. 318–340.

Zhou, Xiaoping et al. (Feb. 2019). "OutDet: an algorithm for extracting the outer surfaces of building information models for integration with geographic information systems". In: *International Journal of Geographical Information Science* 33.7, pp. 1444–1470. DOI: 10.1080/13658816.2019.1572894.

Zhu, Junxiang, Peng Wu, and Chimay Anumba (Nov. 2021). "A Semantics-Based Approach for Simplifying IFC Building Models to Facilitate the Use of BIM Models in GIS". In: *Remote Sensing* 13.22, p. 4727. DOI: 10.3390/rs13224727.

Zhu, Junxiang, Peng Wu, Mengcheng Chen, et al. (Mar. 2020). "Automatically Processing IFC Clipping Representation for BIM and GIS Integration at the Process Level". In: *Applied Sciences* 10.6, p. 2009. DOI: 10.3390/app10062009.