

GeoBIM benchmark

ISPRS Scientific initiative 2019 - Final report

Noardo, F.; Arroyo Ohori, G.A.K.; Krijnen, T.F.; Stoter, J.E.; Ellul, C; Harrie, L; Biljecki, Filip; Agugiaro, G.; Kokla, M.

Publication date

2020

Document Version

Final published version

Citation (APA)

Noardo, F., Arroyo Ohori, G. A. K., Krijnen, T. F., Stoter, J. E., Ellul, C., Harrie, L., Biljecki, F., Agugiaro, G., & Kokla, M. (2020). *GeoBIM benchmark: ISPRS Scientific initiative 2019 - Final report*. ISPRS.

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

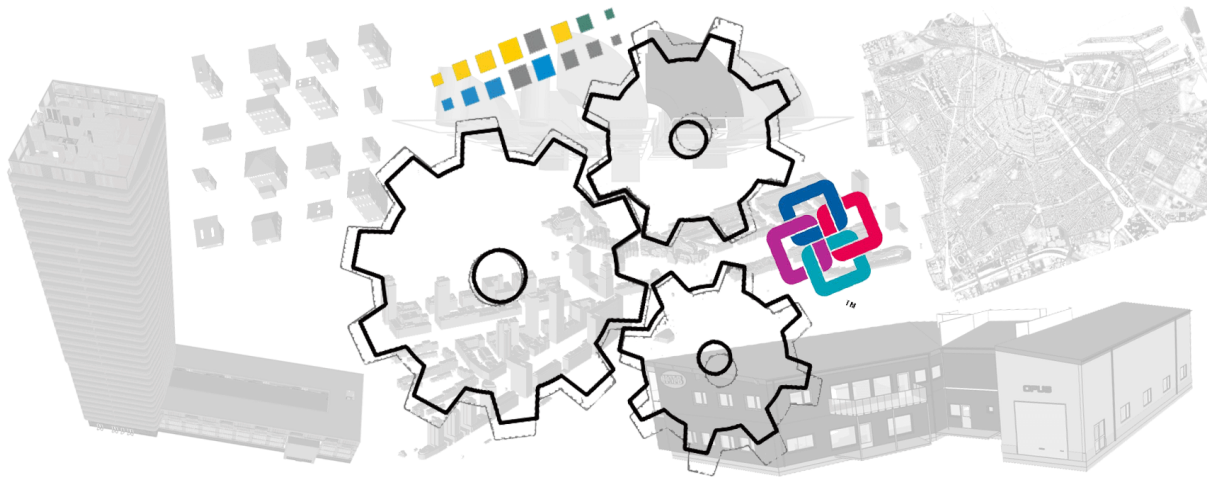
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.



GeoBIM benchmark



ISPRS Scientific initiative 2019

Final report

Team:

Francesca Noardo, TUDelft, 3Dgeoinfo (NL), ISPRS WG IV/2

Ken Arroyo Ochori, TUDelft, 3Dgeoinfo (NL), ISPRS WG IV/1

Thomas Krijnen, TUDelft, 3Dgeoinfo (NL)

Jantien Stoter, TUDelft, 3Dgeoinfo (NL), EuroSDR

Claire Ellul, University College London (UK), EuroSDR

Lars Harrie, Lund university (Sweden), EuroSDR

Filip Biljecki, National University of Singapore, ISPRS WG IV/10

Giorgio Agugiaro, TUDelft, 3Dgeoinfo (NL), ISPRS WG IV/10

Margarita Kokla, National Technical University of Athens (Greece), ISPRS WG IV/2





1. Abstract

In both research and practice, data interoperability is considered essential to support a rising number of applications that need data from different domains. Therefore, standard data formats and models are developed by standardization organizations such as Open Geospatial Consortium (for the Geo domain) and buildingSMART (for the BIM domain). However, from practical experiences, problems were noticed (standards implementation and use of standardized data). Nevertheless, it was hard to discover what the most serious issues were and what was their reason.

For GeoBIM (integration of geoinformation with building information models), the CityGML standard, by Open Geospatial Consortium, and Industry Foundation Classes (IFC) by buildingSMART, were considered and tested in this initiative. A sample of datasets in the two formats were provided. External volunteers were asked to import the datasets in tools supposed to support the standards, check relevant aspects for the use of data (geometry, semantics, georeferencing, functionalities), report on them, and re-export the datasets in the standard format. Other tasks were intended to describe and test georeferencing procedures for IFC models and conversion tools between CityGML and IFC.

This benchmark was useful to gather best practices and data about the functioning of useful tools to manage standardized data. Common behaviors and potential problems were pointed out and the discussion about the use of standards was further pushed.

2. Introduction

3D information systems about cities and constructions became more and more powerful and critical to assist users in a number of use cases (city and building representation, documentation and design, environmental analysis, asset and facility management support, emergency management planning and so on).

The two kinds of such 3D information systems are:

- 3D city models, which are used to represent city objects and substitute previous maps and other cartographic products, in order to support city analysis and management, city planning, navigation, and so on;
- Building information models (BIM), which are used in architecture, engineering and construction (AEC) field to design and manage buildings, infrastructure and other constructions, and which also have features useful to project management and asset management.

Due to the overlapping interests in both fields, increasing attention is being paid to 3D city model-BIM integration (GeoBIM), where the exchange of information between geospatial (3D city models) and BIM sources enables the reciprocal enrichment of the two kinds of information with advantages for both fields (e.g. automatic updates of 3D city models with high-level-of-detail features, automatic representation of BIM in their context, automated tests of the design, and so on). To achieve this, two major technical issues have to be overcome, one is the georeferencing of BIM and the other are the conversion procedures from one format to the other one.

Since interoperability is a key factor to use and exchange data (including 3D city models and BIMs) effectively, open standards in both fields are further studied in this benchmark: CityGML for storing 3D city models and the Industry Foundation Classes (IFC) for Building Information Models.

2.1. Open Geospatial Consortium CityGML

CityGML¹ (by Open Geospatial Consortium, 2012) is the most prominent standard to store and exchange 3D city models with semantics in the GIS domain. It presents a structured way to describe the geometry and semantics of city objects. CityGML as a data format is implemented as an application

¹ citygmlwiki.org



schema for the Geography Markup Language (GML) (CityGML uses version 3.1.1 of GML) (OGC, 2004).

CityGML 2.0 (current version) contains classes structured into 12 modules, each of them extending the core module, containing the most general classes in the data model, with city object-specific classifications (e.g. Building, Bridge, WaterBody, CityFurniture, LandUse, Relief, Transportation, Tunnel, Vegetation).

CityGML geometries are essentially the same for all classes: objects are represented as boundary surfaces embedded in 3D and consist of triangular and polygonal faces.

2.2. *buildingSMART Industry Foundation Classes*

The buildingSMART Industry Foundation Classes (IFC)² standard (ISO16739:2013) is an open standard data model for Building Information Modelling (BIM) to be shared and exchanged through software applications, domains and use cases, within the Architecture Engineering and Construction (AEC) and Facility Management (FM) fields. It includes classes for describing both physical and abstract concepts (e.g. cost, schedule, etc.) concerning AEC-FM for buildings, mainly (recent versions are extending it for including infrastructures and other kinds of constructions³). It has also been adapted as the ISO 16739 international standard (ISO, 2013).

It can be seen as an inclusive model covering the description and representation of all the possible information and concepts related to buildings' components and processes for AEC- FM, for all related use cases.

The **geometries** in them can use several different representation paradigms which can be combined freely. In practice, most IFC objects are built using sweep volumes, explicit faceted surface models and CSG.

Its geometric aspects are mostly defined or derived from a different standard, the ISO 10303 (ISO, 2014), which also specifies the STEP Physical File (SPF) encoding that is most commonly used in IFC files (.ifc).

3. Objectives

The researchers of this project (both as users of data and developers of tools adopting such standards) could notice, over their research activities, how the use of those standards in data and their implementation in software was not always straightforward and completely consistent with the prescriptions. Many tools, when managing standardized data, do not always effectively support features or functionalities as they do when the data is held in the native formats of the software. In addition, software tools have limitations in the representation (geometry, semantics, georeferencing) of data structured in these standards, or can generate errors and wrong representations.

This was confirmed by the informal exchanges within the scientific community and especially with the world of practitioners, supposed to work with those standardized data and formats. The web also reported related issues (e.g. blog post "GML madness"⁴, from 2014, posts on Twitter⁵ and other social networks). However, evidence on the state of implementation of these open standards and what problems could be connected to the standard themselves was never built.

The GeoBIM benchmark was intended to link the expertise of many people with different skills, coming from different fields and with different interests, in order to provide a framework as complete as possible to describe the present ability of existing software tools to use (i.e. read, visualize, import, manage, analyse, export) CityGML and IFC models and to understand their performance while doing so, both in

² <https://technical.buildingsmart.org/standards/ifc/>

³ <https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/>.

⁴ <http://erouault.blogspot.com/2014/04/gml-madness.html>

⁵ E.g. <https://twitter.com/jamesmfee/status/748270105319006208>



terms of information management functionalities, and, eventually, information loss, and in terms of ability to handle large datasets.

Therefore, the aim of the benchmark was to get a better picture of the state of software support for the two open standards IFC and CityGML and their integration, in order to formulate recommendations for further development of the standards and the software that implements them.

For this purpose, a set of representative IFC and CityGML datasets were provided (Noardo et al., 2019a) and used by external participants in the software they would like to test in order to check the support of it for open standards, following common instructions and providing results in a common template.

In particular, the four topics investigated in the benchmark are:

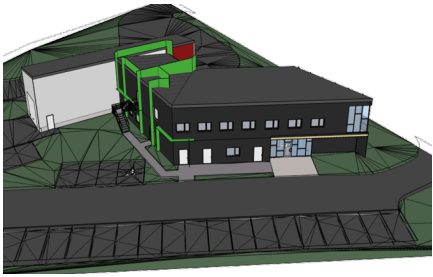
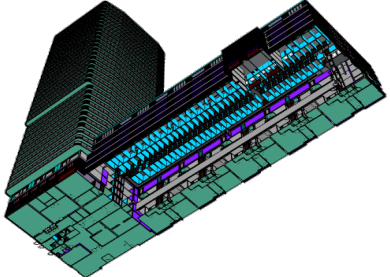
- Task 1. What is the support for IFC within BIM (and other) software?
- Task 2. What options for geo-referencing BIM data are available?
- Task 3. What is the support for CityGML within GIS (and other) tools?
- Task 4. What options for conversion (software and procedural) (both IFC to CityGML and CityGML to IFC) are available?

A parallel but not less important goal of the benchmark was to offer a common ground where people coming from various fields and having different interests can meet to tackle a common challenge, namely, the use of open standards for exchanging cross-discipline information and models.

4. Provided data

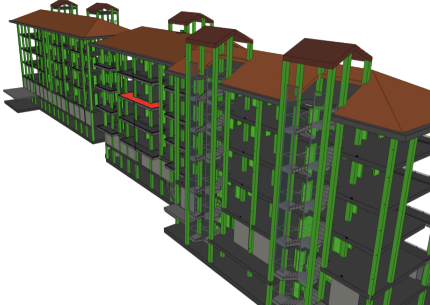
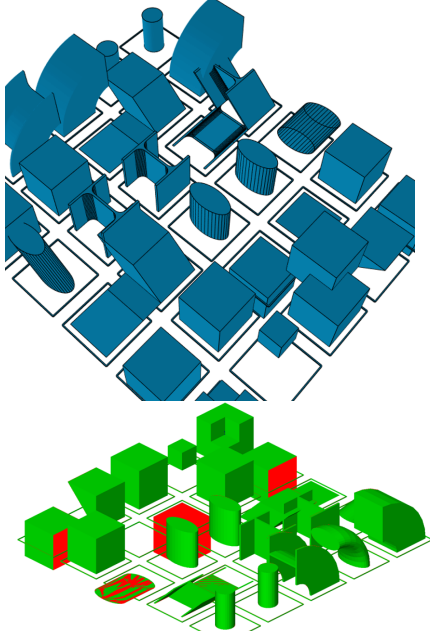
A number of datasets from different sources were identified and pre-prepared (and pre-processed) for this benchmark activity (see Noardo et al., 2019 for details) (Table 1).


Table 1 summary of the descriptions, features and aims of the provided datasets⁶.

IFC datasets			
Name	Description	Aim	Image
Myran.ifc	Model of a small 2-floor building in Sweden, by Swedish architects. Georeferenced. IFC v.2x3	Test of the main functionalities of software and common-requirements procedures.	
UpTown.ifc	Model of a big complex tower in Rotterdam, by Dutch architects. IFC v.2x3	Test of the hardware-and-software connected performances.	

⁶ <https://3d.bk.tudelft.nl/projects/geobim-benchmark/data.html>

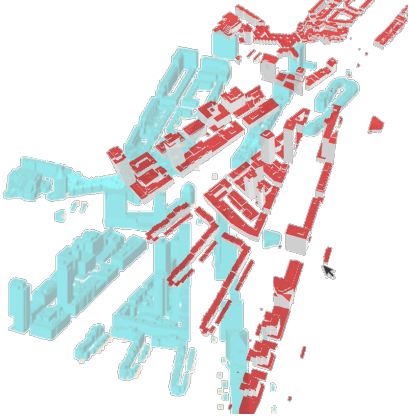
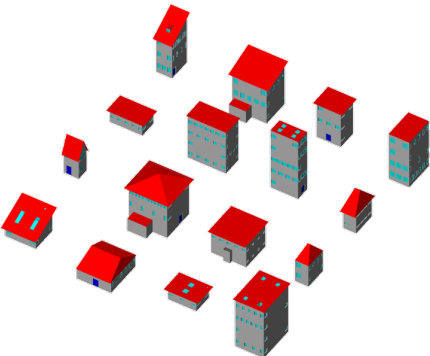


<p>Savigliano.ifc</p>	<p>Model of a building in Italy, by Italian architect within research environment. IFC v.4</p>	<p>Test of the support for IFC v.4 and to enable the tests of procedures and tools working with IFC v.4</p>	
<p>Specific IFC geometries</p>	<p>Set of geometries modelled using a range of the modelling alternatives allowed in IFC, which are usually little supported or incorrectly interpreted by software. Two versions of the file are provided, in IFC v.2x3 and IFC v.4.</p>	<p>Test of the support and behaviour of software with respect to these specific geometries.</p>	

<p>CityGML datasets</p>			
<p><i>Name</i></p>	<p><i>Description</i></p>	<p><i>Aim</i></p>	<p><i>Image</i></p>
<p>Amsterdam.gml</p>	<p>Seamless city model covering the whole city of Amsterdam, including several CityGML city entities (vegetation, roads, water, buildings, and so on). Level of Detail (LoD)1. Generated through 3Dfier by TUDelft⁷</p>	<p>Test of the hardware-and-software connected performances (it is a very heavy model), and support for the included city classes.</p>	

⁷ <https://github.com/tudelft3d/3dfier>



<p>RotterdamLoD12.gml</p>	<p>Texturised CityGML model of one district in Rotterdam, including only Buildings in LoDs 1 and 2.</p>	<p>Test of the support for multiple LoDs and texturised files.</p>	
<p>BuildingsLoD3.gml</p>	<p>Procedurally modelled buildings in LoD 3 through <i>Random3Dcity</i>⁸ (Biljecki et al., 2016).</p>	<p>Test of the support for LoD 3 files and related classes.</p>	

5. The voluntary external participation

To eliminate any bias in the results as much as possible, it was tried to recruit participants from a wide variety of backgrounds, with different expertise (e.g. BIM, GIS and more) and with access to different software packages that can be tested.

In order to make the delivered results uniform, a results template was provided as online forms both giving detailed instructions to perform the tests and guiding the answering through specific questions. The aim of this approach is to ensure that the results can be systematically compared, and to allow users to detail their experiences for each task, issues encountered and specific functionality offered (or not offered) by the tested software. Importantly, they could include screenshots to highlight specific results or challenges.

To better assess the results, a question in the results template asks explicitly for the level of expertise with the software they are testing, allowing values:

- 1 - Novice user (nearly the first time using the software);
- 2 – Regular user;
- 3 - Expert user (knows very well technical details and less documented tricks);
- 4 - Developer of the tested software.

We could check a good balance in the delivered results, since people having all the levels of expertise were involved in all the tasks: from the very beginners to the very expert users, being developers themselves or working for software companies. Interestingly, similar results were often provided by both categories.

41 people participated in the tests, delivering relevant results about the tested tools, divided as follows:

⁸ <https://github.com/tudelft3d/Random3Dcity>



Task 1 – 35 tests, 28 software

Task 2 – 8 tests, 8 software

Task 3 – 22 tests, 16 software

Task 4 – 7 tests, 7 software

Full details about the tested software can be found in the web page (<https://3d.bk.tudelft.nl/projects/geobim-benchmark/software.html>). And full list of participants at <https://3d.bk.tudelft.nl/projects/geobim-benchmark/participants.html>. The balance in skills, working field, interests and geographical provenance (Figure 1) offered the possibility to minimize bias in the results.

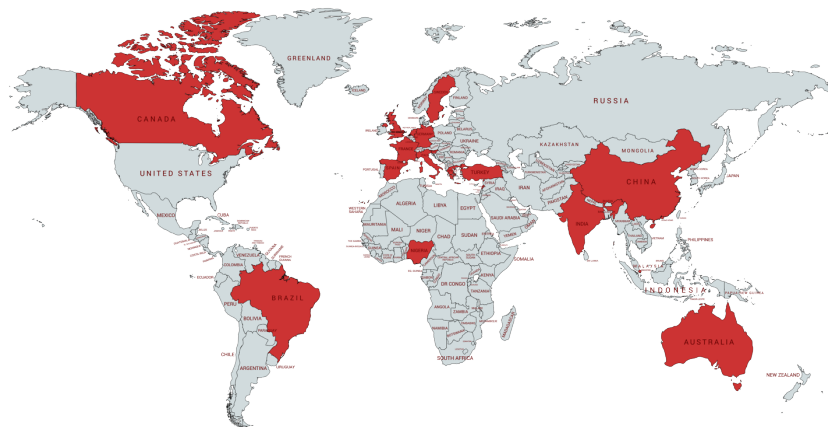


Figure 1. *Provenance of the registered participants.*

The initiative had a good response in terms of interest: 77 people registered with the intention to participate and follow the related activities, and even more subscribed to the newsletter. Raising more the discussion about the tackled topics (open standards quality and use in implementation) could be considered one additional (minor) outcome.

6. Results

In the following subsections 6.1-6.4 the initial analysis of the test results oft delivered by the participants is presented. The full issues outlined by them were more complex than expected and it will require a few more weeks of analysis and insight, that will be though published in the first few months of 2020 and published in the website.

6.1. Task 1: Support for IFC

A wide variety of software tools is assessed during the benchmark: Autodesk Civil 3D, eveBim, Solibri, Bentley Map Enterprise, ACCA usBIM.viewer, ACCA PriMus-IFC, Simplebim, ArchiCAD, Bentley MicroStation TerraSolid, Allplan, AutoCAD Architecture, ACCA Edificius, FreeCAD, FreeCAD, eveBim, Autodesk Revit, Autodesk Revit, Autodesk Revit, Other, BIM Vision, Other, FreeCAD, Autodesk, SketchUp, FZK Viewer, Autodesk Revit, Autodesk Revit, Vectorworks, Vectorworks, ArchiCAD, Archicad, eveBim, Solibri, Bentley Map Enterprise, ACCA usBIM.viewer, ACCA PriMus-IFC, Simplebim, ArchiCAD, Allplan, AutoCAD Architecture, ACCA Edificius, FreeCAD, eveBim, Autodesk Revit, Autodesk Revit, Autodesk Revit, BIM Vision, Other, Other, FreeCAD, Autodesk, SketchUp, FZK Viewer. Both the general behavior of software (e.g. number and kind of errors given when importing and exporting data) and specific geometries were tested.



A preliminary conclusion is about the differences in interpretation by the software of handling valid input and reporting on invalid input. Moreover, we can observe that those differences are due to: importer errors, exporter errors and schema unclarity.

Listing 1 - Excerpts of task 1 results

Errors communicated to used	

No	24
Yes	22
Other	7
Curved surfaces displayed	

Smooth	31
Other	15
Faceted	7
Shape with negative extrusion depth visible	

Yes	30
No	12
Other	11
Shape with perpendicular extrusion direction visible	

Yes	32
Other	11
No	10
Fillet radii visible on I profile	

A (with)	23
Other	16
B (without)	14

6.2. Task 3: Support for CityGML

For Task 3 the majority of software which are declared able to manage CityGML format were tested (a subset of the tested ones in Figure 2).



Figure 2. Logos of the tested software. Find the full list in the software page of the website

The initial considerations about the tests include the fact that none of the tested software was able to export the same CityGML file they imported without any changes. Usually, the semantic schema is generally valid, besides occasional losses, but geometries always have issues. See more remarks in Table 2 and 3.



Table 2 - Remarks reported by the delivered tests by participants.

Best and worse	<ul style="list-style-type: none"> • FME and 3DCityDB show best support • GIS software is lacking
Import performance	<ul style="list-style-type: none"> • GIS have trouble handling semantics (at best parent-child relationships through IDs) • Low support for Multi-LoD
Import of the Amsterdam.gml dataset⁹	<ul style="list-style-type: none"> • Few submissions • ArcGIS, ArcGIS Pro, tridicon, eveBIM and 1Spatial Elyx crashed
Analysis	<ul style="list-style-type: none"> • Only FME offers wide range of 3D analysis • 1Spatial Elyx 3D: visibility analysis and buffers • novaFACTORY: visibility analysis, shadows analysis, sun analysis and extract height profiles.
Editing	<ul style="list-style-type: none"> • Only QGIS and ArcGIS offer extensive editing (semantics and geometry) • Some 3D viewers (e.g. eveBIM, novaFACTORY) support semantics editing • FME supports geometry editing, but in batch form (through transformations)

Table 3 - Remarks about specific software for Task 3

3DCityDB	<ul style="list-style-type: none"> • Alters the input the least • Only one file was broken (bad xlink) • Slight reduction in objects in Amsterdam dataset
FME	<ul style="list-style-type: none"> • FME makes more changes but results are generally okay • Some methodologies can result in splitting of objects using the same IDs or in the loss of some object classes (i.e. bridges)
QGIS	<ul style="list-style-type: none"> • Only one file submitted with QGIS • Total loss of data • Output doesn't even have valid schema
ArcGIS	<ul style="list-style-type: none"> • Surfaces are converted into independent CityObjects • Big increase in objects and the loss of some semantics. • Minor schema issues (e.g. empty dates)
NovaFactory	<ul style="list-style-type: none"> • Perfect output with Rotterdam dataset (100% valid) • Amsterdam can't even be read

General conclusions from the initial analysis of the results were that GIS software generally does not fit with CityGML, while ETL and specially tailored software is required when working with CityGML. Moreover, the software tools report less errors regarding the semantic schema than the geometry.

6.3. Task 2: IFC georeferencing

For this task, it was more difficult than in the other cases to compare the performances of the different procedures, since each tool is a specific case. Some of the most interesting remarks are reported in Table 4.

⁹ heavy dataset, to stress computational performances



Table 4 - Remarks about specific software for Task 2

<p>ArcGIS Pro</p>	<ul style="list-style-type: none"> • Georeferencing tools are available in the standard version • It is not allowed to use the georeferencing tools on the IFC file • It is not possible to rotate the model towards cartographic North or to move the model to the correct 'world' coordinates <p><i>Comment:</i> Even if the project was uploaded with the correct CRS, ArcGIS pro did not position it in the right place. So all the coordinates, even if are shown for each feature, are not correct.</p>
<p>eveBIM</p>	<ul style="list-style-type: none"> • Georeferencing tools are available in the standard version • It is possible to rotate the model to a correct orientation towards cartographic North and to move the model to the correct 'world' coordinates • The supported coordinate reference systems can be used in the 'move' operation
<p>FME Desktop</p>	<ul style="list-style-type: none"> • Georeferencing tools are available in the standard version • Height reference systems are not explicitly supported • It is possible to rotate the model towards cartographic North and to move the model to the correct 'world' coordinates • The supported coordinate reference systems can be used in the 'move' operation
<p>FKZViewer</p>	<ul style="list-style-type: none"> • Georeferencing tools are available in the standard version • Height reference systems are not supported • It is not possible to rotate the model towards cartographic North • It is possible to move the model to the correct 'world' coordinates, but there are no options to change the CRS during this operation <p><i>Comments:</i> FKZViewer reports error on import and export of the IFC files. Moreover, after transforming Savigliano the model cannot be displayed, zoomed, panned or rotated</p>
<p>IfcGeorefChecker</p>	<ul style="list-style-type: none"> • It is a specific tool to georeference IFC files • It is possible to rotate the model to a correct orientation towards cartographic North and to move the model to the correct 'world' coordinates • The supported coordinate reference systems can be used in the 'move' operation
<p>Revit 2020</p>	<ul style="list-style-type: none"> • Georeferencing tools are available in the standard version • It is possible to rotate the model towards cartographic North and to move the model to the correct 'world' coordinates

6.4. Task 4: Conversion procedures CityGML to IFC and IFC to CityGML

The conversions were mainly tested in the direction from IFC to CityGML (36 answers), which is apparently more popular than the conversions from CityGML to IFC (7 answers). Few software were used, mainly customized workflows in Safe Software FME, FZK viewer and ESRI ArcGIS Pro. Some bespoke pieces of software were also tested: IFC2CityGML and CityGML2IFC¹⁰.

We could notice from the initial inspection of the converted models that their semantics are all different one from the other, and, since there is no ground truth, a more complex analysis will be necessary to

¹⁰ <https://github.com/nsalheb/CityGML2IFC>



assess the quality of conversions from the semantic point of view. In some cases, the semantics is lost and the element is converted to a generic element.

It was possible to notice some errors in the geometry of the converted models, e.g. elements missing, inverted surfaces, non-transformed geometries, solids transformed in invalid closed surfaces, invalid geometries.

The resulting Level of Development (for BIM) and Level of Detail are also something to be discussed in more detailed and on which the two fields should agree, starting from their meaning.

7. Outreach

7.1. Website

The website <https://3d.bk.tudelft.nl/projects/geobim-benchmark/> was built and updated regularly during the whole extent of the project with the aims of:

- Explaining premises, motivation, aim of the project and illustrate background information;
- Inviting and explaining how to take part to the project;
- Communicate the progress in the tests and in the participation and in the project in general (e.g. page for participants and page for tested software);
- Disseminate intermediate results, organised events and produced materials (page 'presentations&publications' and 'event' page).

The final results and the coming presentations and publications will be added to the website and rest available.

7.2. GeoBIM benchmark (web)meeting

To further strengthen this multi-sectoral collaboration, some open events were organised¹¹, the first of which, the GeoBIM benchmark (web)meeting, was held on 8th July 2019.

In the meeting, 14 people from different countries and affiliations participated, including Universities and research institutes, National Mapping and Cadastral Agencies, software companies and developers. All of them work or have an interest in the integration of 3D city models with BIMs.

After discussing some improvements to the provided materials to help the testers, the participants presented their experiences in performing the different tasks. The initial results discussed in Noardo et al. (2019a) were confirmed: all participants found common issues such as error messages when importing IFC files (even if the software was able to open them), the difficulty for tools to manage large datasets (specifically, amsterdam.gml and UpTown.ifc), among others. Additional tests on the benchmark datasets were carried out by some participants, in order to have an external confirmation that the datasets can be used and will not affect the software test results.

7.3. GeoBIM benchmark Workshop

On December 2nd and 3rd the GeoBIM benchmark workshop was held at the Amsterdam Institute for Advanced Metropolitan Solutions¹² and streamed via youtube the two days.

The workshop focused on insight into the GeoBIM benchmark results and explored in detail the related topics:

- 3D city models

¹¹<https://3d.bk.tudelft.nl/projects/geobim-benchmark/events.html>

¹² <https://www.ams-institute.org>



- Building Information Models
- Respective open standards (CityGML, CityJSON, IFC, and more)
- GeoBIM use cases (automatic building permission issuing, asset management, energy simulations, etc.)

It was a good opportunity for experts and stakeholders from a diverse amount of backgrounds to meet, achieve new overview on the two joined fields of 3D city models and BIM and discuss major challenges of the treated topics (Figure 3).

Presentation slides, workshop materials and the recordings of the two days can be found in the event webpage¹³.

With over 60 participants and a lot of online visualizations (207 and 150 for the two days, respectively), it was a positively-perceived educational and collaborative event (Figure 4).

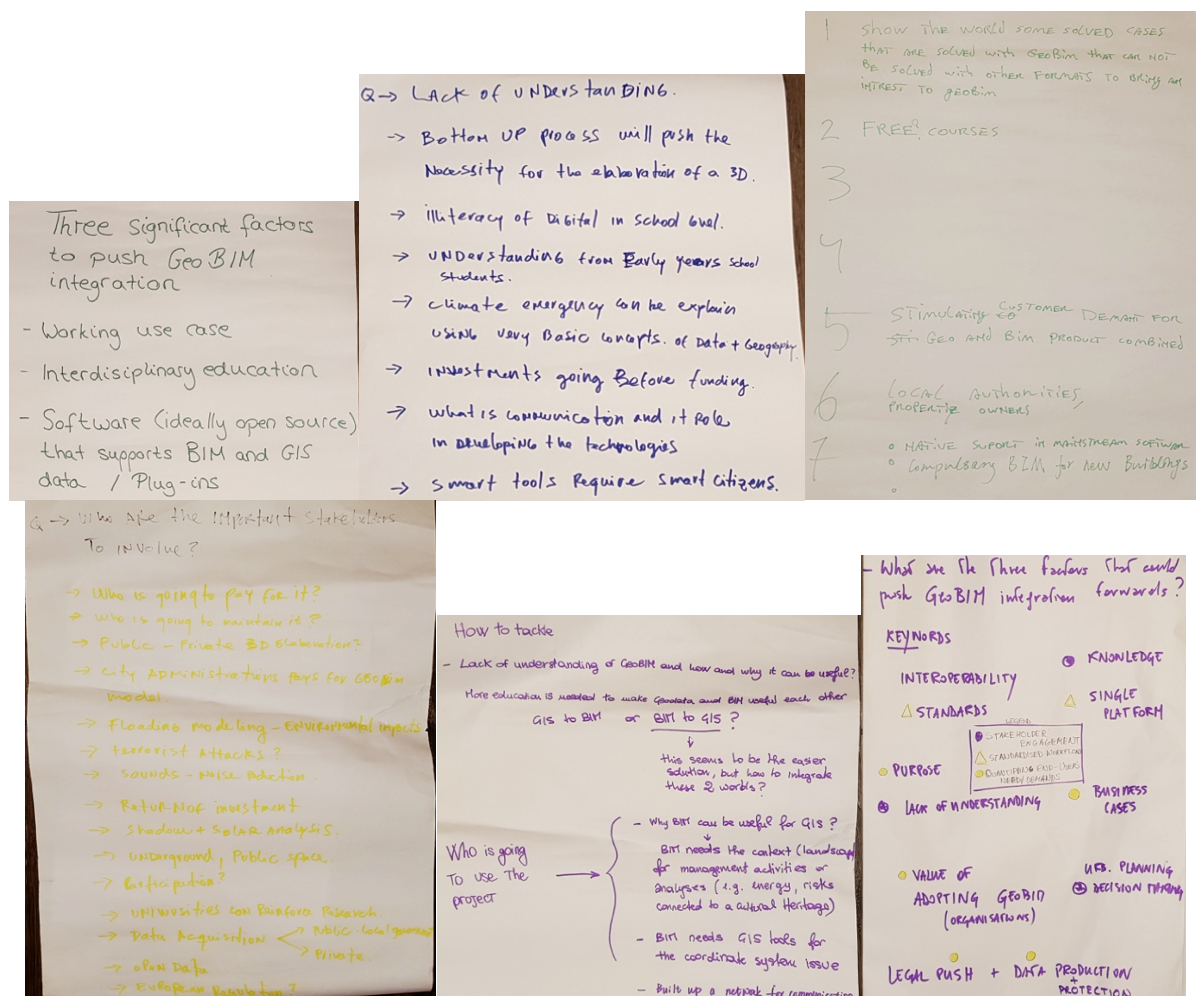


Figure 3. Outcomes of the ‘interactive session’ of the workshop, where participants were asked to discuss in (most likely heterogeneous) groups some of the main issues related to GeoBIM: How to tackle the lack of understanding of GeoBIM and how and why it can be useful; how to tackle the lack of GIS/BIM skills and especially combined skills across both; how to tackle the high costs of implementation (changes to workflows, new staff skills...); what are the best standards to use in GeoBIM (and how to use them); How to make Geo- & BIM worlds talk to each other; who are the most important stakeholders to involve; what are the three factors that could significantly push GeoBIM integration forward?

¹³ <https://3d.bk.tudelft.nl/projects/geobim-benchmark/events.html>



Figure 4. Pictures of the GeoBIM benchmark workshop.



7.4. Papers & presentations

Some papers about the initial steps of the project and the intermediate results were presented to conferences, also as a mean to disseminate the scientific challenge and invite people to participate.

Paper presented to the GeoSpatialWeek 2019 conference, Enschede, 13rd June 2019¹⁴: Noardo, F., Arroyo Ohori, K., Biljecki, F., Krijnen, T., Ellul, C., Harrie, L., Stoter, J. (2019). GeoBIM benchmark 2019: design and initial results. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, XLII-2/W13, 1339-1346, 2019.

Paper (invited as a Keynote, F. Biljecki presented) at the 3D Geoinfo 2019 conference - 2nd International IAG Workshop on BIM and GIS integration, 25th September 2019¹⁵: Noardo, F., Biljecki, F., Agugiaro, G., Arroyo Ohori, K., Ellul, C., Harrie, L., Stoter, J. (2019). GeoBIM Benchmark 2019: Intermediate Results. *14th 3D Geoinfo Conference 2019, ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences IV-4(W8)*. 2019.

More papers and presentations about the achieved final results will be published in the coming months, and will be added to the specific page of the website¹⁶.

7.5. Conclusions

This activity was useful to gather best practices and data about the functioning of most part of useful pieces of software which are supposed to manage standardized data. Initial common behaviors and potential problems were pointed out and will be further investigated from the point of view of the standard schema, the implementation, or the use of the schema and standards in the datasets.

8. References

Biljecki, F., Ledoux, H., & Stoter, J. (2016). Generation of multi-LOD 3D city models in CityGML with the procedural modelling engine Random3Dcity. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, IV-4/W1, 51-59.

ISO 2013. ISO 16739:2013. *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*. International Organization for Standardization, March 2013.

ISO, 2014. *Industrial automation systems and integration - Product data representation and exchange*. International Organization for Standardization, August 2014.

Noardo, F., Arroyo Ohori, K., Biljecki, F., Krijnen, T., Ellul, C., Harrie, L., Stoter, J. (2019a). GeoBIM benchmark 2019: design and initial results. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, XLII-2/W13, 1339-1346, 2019.

Noardo, F., Biljecki, F., Agugiaro, G., Arroyo Ohori, K., Ellul, C., Harrie, L., Stoter, J. (2019b). GeoBIM Benchmark 2019: Intermediate Results. *14th 3D Geoinfo Conference 2019, ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences IV-4(W8)*. 2019.

OGC, 2004. *Geography markup language (GML) encoding specification*. Open Geospatial Consortium inc., 2004. Document 03-105r1, version 3.1.1.

OGC, 2012. *OGC City Geography Markup Language (CityGML) Encoding Standard 2.0.0*. Technical report, April 2012.

¹⁴ <https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2-W13/1339/2019/>

¹⁵ <https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-4-W15/47/2019/>

¹⁶ <https://3d.bk.tudelft.nl/projects/geobim-benchmark/presentations-publications.html>