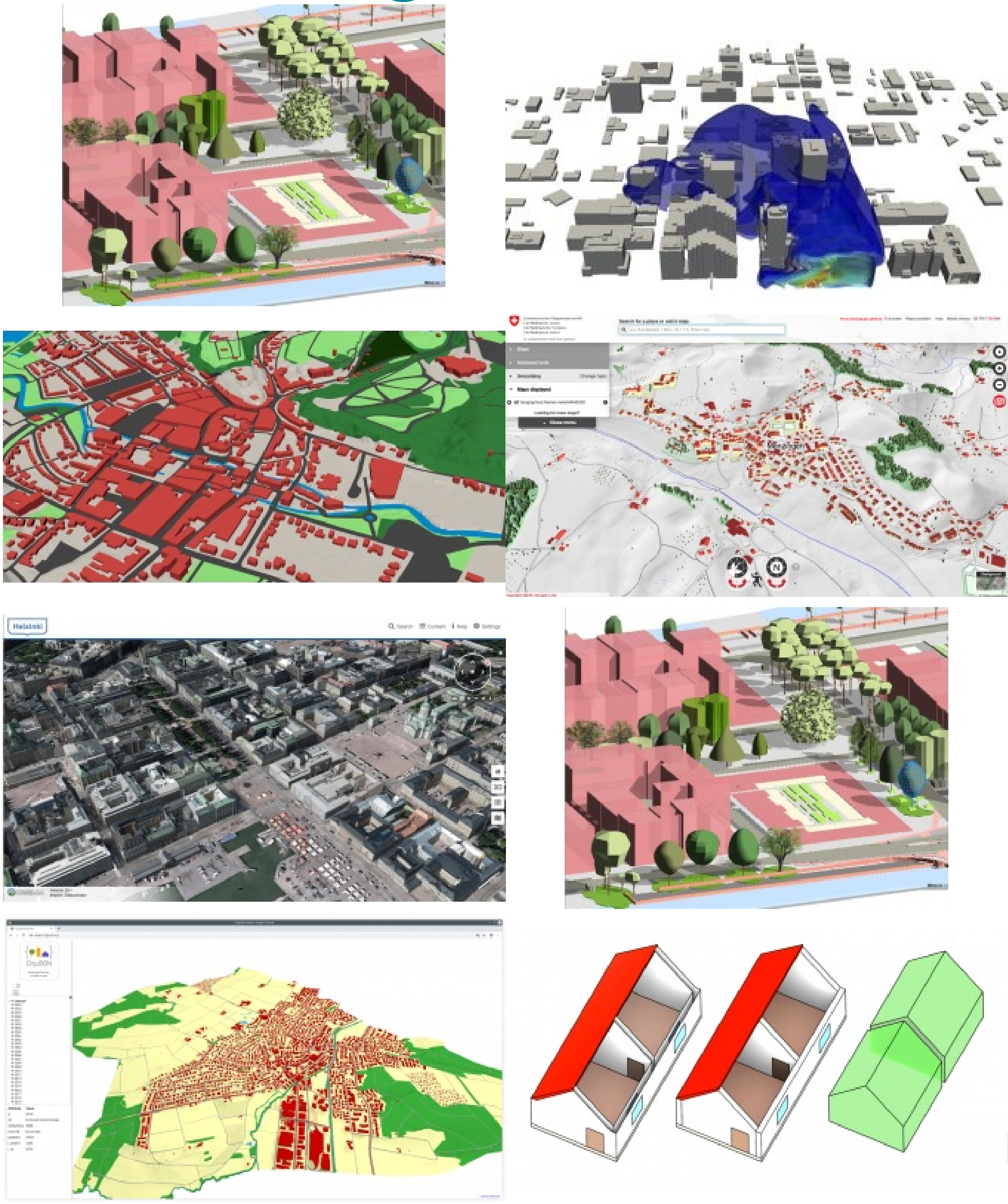
SIX CHALLENGES FACING 3D DATA AS A PLATFORM

State of the art in 3D city modelling



How does 3D city modelling fit within the context of broader developments such as smart cities and digital twins? And which six challenges must be overcome before 3D data as a platform becomes a reality?

Semantically enriched 3D city models have the potential to be powerful hubs of integrated information for computer-based urban spatial analysis. This article presents the state of the art in 3D city modelling in the context of broader developments such as smart cities and digital twins, and outlines six challenges that must be overcome before 3D data as a platform becomes a reality.

(This article is a co-production of seven authors, all of whom are mentioned at the end of the text.)

3D city models, as digital representations of urban areas, can be used to facilitate many applications, such as urban wind and dispersion simulations, energy studies, noise studies and various types of analysis that require a planned architectural design to be placed in its context (e.g. line of sight and shadow analysis, clash detection with cables and pipelines in the underground, impact of wind circulation, see Figure 1). These 3D models, which also contain semantics, are different from 3D meshes (as found in computer graphics and the gaming world) and from raw point clouds. These can be used for visualization and visual analysis, but they are not suitable for most other spatial analysis purposes.

Figure 1: Determining the impact of wind circulation with 3D city models, taken from Sanchez (2017).

In order to allow for the development of advanced applications, a 3D city model should describe the geometry and attributes of all the individual elements that are typically present in a city, e.g. the terrain, roads, water bodies and buildings (Figure 2). In addition, relevant semantic information can be included with the geometries, such as the year a building was constructed, the number of people living in it and the construction materials it is made of – all important information to optimize circular economy flows or energy consumption. Such semantically enriched 3D city models potentially represent powerful hubs of integrated information to be used for computer-based urban analysis purposes, including in the context of broader developments such as smart cities and digital twins.

Advances in technologies for the collection of 3D elevation information through Lidar and photogrammetry have made it relatively easy for practitioners in different fields to automatically reconstruct 3D city models (see Figure 3 for a couple of examples). These models typically contain mainly buildings, but other object types are increasingly being included too, such as roads, bridges, trees (see Figure 4) and water. The availability and applications of 3D models are still increasing in the fields of city planning and environmental simulations, as listed above. Furthermore, since elevation data can be acquired at relatively low cost, this data can be frequently updated. It is also possible to reconstruct 3D city models covering the same region at different periods in time.

Figure 2: Part of the 3D city model of Valkenburg, the Netherlands. Elements that can be represented in a 3D city model include: buildings, vegetation, water bodies, built-up areas, green areas, roads, etc. (Courtesy: Dutch Kadaster)

3D city models have the potential to play a crucial role in shaping the future. This holy grail of 3D city models that goes beyond 3D visualization requires an integrated approach to 3D city modelling based on the implementation of 3D data as a platform. In this approach, the same up-to-date, 3D virtual representation of reality serves different urban applications and at the same time offers an environment for integrating the findings of different applications. However, before 3D data as a platform becomes a reality, the following challenges must be overcome:

Challenge 1: consistency between models

The first challenge is the lack of consistency between 3D city models covering the same area. Currently, 3D city models are generated independently, often using different base (sensor) data, reconstruction methods and software. Therefore, the resulting models often significantly differ in their geometry (e.g. a collection of surfaces versus a volumetric representation), appearance and semantics. Moreover, as these models are stored using different formats (XML, graphics or binary formats), their underlying data models often also differ. Substantial differences can even occur when models that were originally identical are processed independently, either through mismatched updates or through conversions between different formats (e.g. in an attempt to deal with software incompatibilities). All these differences have profound consequences in practice, such as affecting the applications for which a 3D model can be used, the processing that is necessary to use it and the likely errors that will be present in the end result. It is thus important to be aware of the way 3D city models are modelled and to provide this information explicitly in the metadata of the model.

Figure 3a: Example of a 3D city model from Swisstopo. (Courtesy: https://map.geo.admin.ch)

Challenge 2: standardization

To ensure consistency, both for geometry and semantics, standardization is essential. The OGC standard CityGML is the main standard for storing and exchanging 3D semantic city models. Its aim is to define the basic classes that can be used to describe the most common types of objects present in a 3D city model, their components, their attributes and the relationships between different objects. Although most CityGML examples and datasets focus on buildings, CityGML also represents other feature classes, such as land use, relief, roads and railways, vegetation, bridges and city furniture. While CityGML prescribes a standard data model for a 'generic' city, it is possible to extend it for specific domains by defining application domain extensions (ADEs), such as for the energy demand of buildings or for a country-specific data model. The main issue with ADEs is that software packages and libraries often cannot automatically read and process the application-specific information from them because extensions do not need to follow many prescribed rules.

Figure 3b: 3D city model of Helsinki. (Courtesy: https://kartta.hel.fi/3d/#/)

CityGML is used both as an information model (in the form of UML models of its classes) and an encoding model, which is an XML-based representation using geometric definitions from the Geography Markup Language (GML). One challenge when working with CityGML-encoded data is that software support for CityGML is still limited. This is partly due to the huge number of possible ways in which objects can be defined in CityGML, which makes full implementation difficult (i.e. the software needs to support all possible situations). In addition, XML (and thus GML) can be verbose and complex, which makes it impractical for many applications.

There are other solutions that implement the CityGML data model to overcome these problems. One is 3DCityDB, which is an open-source database, built upon Oracle Spatial or PostGIS, to store the CityGML data model in a relational database. Another alternative to CityGML encoding is CityJSON, which is a format that encodes a subset of the CityGML data model using JavaScript Object Notation (JSON). CityJSON was designed with programmers in mind, so that tools and APIs supporting it can be quickly built. It is also designed to be compact, with a compression factor of around six when compared to XML-based CityGML files, and is friendly for web and mobile development (i.e. it supports the use of 3D data beyond exchanging data). CityJSON v1.0 was released in 2019 and is supported in several software packages including viewers, 3D modellers, 3D city model generators and GIS software (Figure 5).

Challenge 3: data quality

Quality – or lack of it – is another issue that limits the sharing of 3D city models between different software systems and applications. As highlighted by Biljecki et al. (2016), most openly available 3D city models contain many geometric and topological errors, e.g. duplicate vertices, missing surfaces, self-intersecting volumes, etc. Often, these errors are not visible at the scale on which the datasets are visualized or they are not a problem for the specific software in which they are modelled. As a consequence, practitioners are unaware of the issue. However, these errors prevent the datasets from being used in other software and for advanced applications, and that is essential to facilitate 3D data as a platform. All these geometric errors could be prevented if modelling software forced the 3D geometries to comply with ISO 19107, i.e. connecting surfaces, planar surfaces, correct orientation of the surfaces, watertight volumes, etc. Another solution to this problem could be to use automatic repair algorithms. However, these are still often semi-manual, plus it is possible that fixing one error could introduce a new one elsewhere.

Figure 4: Modelling of trees at different levels of detail from, taken from Ortega-CÃ³rdova (2018).

Challenge 4: data interoperability

The conversion of semantic 3D city models from one format to another is challenging, both from a geometric point of view and because of incompatible semantics. In the case of the IFC standard used in building information modelling (BIM), it is desirable to integrate into a 3D city model the highly detailed models that have already been generated for the design and construction of a building. However, the automatic conversion between IFC models and CityGML models is not straightforward. For a building which is modelled according to both standards, for instance, the mappings between the semantic classes are complex because different semantic information is attached to the geometrical primitives in the two models. Moreover, IFC has many more classes, whereas CityGML contains a limited number of classes structured in a hierarchy. In addition, a simple house can easily be made up of a thousand volumetric elements in IFC, whereas in CityGML it contains just the outer shell and a few other elements such as doors, windows and chimneys. As a consequence of these differences in semantics, coupled with the fact that different software and geometric modelling paradigms are used, it is rather difficult to reuse data from other domains. OGC (2016) and Arroyo Ohori et al. (2018), among others, explain in more detail the issues preventing automation of the process and provide recommendations for better alignment of both standards. This requires a better understanding of how detailed BIM models are needed in GIS-based applications and how GIS-contextual data can be better accessed from BIM software. Deriving the GIS-relevant concepts from a detailed BIM model that can act as an interface between both domains is considered as a crucial step forwards (see Figure 6). In addition, georeferencing of BIM models is needed to be able to locate them in their geographical context.

Figure 5: The 3D city model of Oberwil (Switzerland) in CityJSON. (Courtesy: The Amt fÃ¼r Geoinformation Basel-Landschaft.)

Challenge 5: data maintenance/governance

Many governmental organizations have invested in their own 3D city models. However, despite growing awareness of the importance of up-to-date 3D city models, they often fail to put strategies in place for updating the models and maintaining different versions of the data. One potential method to do so would be to use data about new designs structured in IFC/BIM models. However, this requires good agreements regarding the design data to be submitted and the preprocessing of the IFC/BIM data (e.g. deriving georelevant concepts such as the footprint and outer envelope in a georeferenced context), as well as organizational/institutional agreements (i.e. Who is responsible for the data? How can it be ensured that the IP of the architect/designer is respected?).

Figure 6: Deriving GIS-relevant concepts (spaces) from a collection of volumetric elements in a BIM model.

Challenge 6: from utopian pilots to real-world use cases

Technical innovations regarding 3D data usage that look promising in prototypes and pilots may encounter problems in practice. A real-world production setup usually covers larger areas and requires more automation, which can make it more difficult to monitor and control the data quality. In addition, solutions that work well for small test areas are pushed beyond their limits (both in terms of performance and situations they have to cover) when applied to large areas like complete cities or even countries. Further attention is therefore needed to obtain higher-quality 3D city models and building models so that they can indeed form the basis for a 3D data platform serving a wide variety of urban applications. This requires more precise definitions of specifications, as well as validation mechanisms to check whether the 3D data acquired meets those specifications. ‘Higher quality’ does not necessarily mean ‘greater precision’; it means up-to-date 3D data without errors and aligned with the specific needs of urban applications rather than serving visualization purposes only.

Not all challenges facing 3D data as a platform are technical ones. Organizations that want to implement 3D as a platform often lack the latest knowledge and skills to do so. This can range from gaps in their knowledge of issues regarding the acquisition, maintenance and dissemination of 3D data, to a lack of understanding of urban data quality, how to express it in metadata and how data quality impacts on the outcome of urban applications. There are also institutional and organizational issues facing 3D data, e.g. what 3D data should be available, where and how it should be available, who is responsible for updates and maintenance, and how to integrate larger-scale public-sector 3D city models with detailed private-sector architectural models of individual buildings.

Conclusions and future outlook

More and more 3D city models are becoming available at different levels of detail, for different periods in time and for different applications. It is therefore important to have adequate ways to store such historical collections of 3D city models in a manner that is both standardized and structured with semantics. The ability to translate the physical world into a virtual reality has become a valuable asset in the design, planning, visualization and management of a wide range of urban applications such as noise, heat stress, pollution, etc. However, an increase in complexity (i.e. 3D city modelling beyond visualization) often comes at the expense of usability, interoperability and maintenance. Current practices still show a lack of specific and user-friendly software to deal with 3D city models, as well as several disconnected and inefficient software options, while data integration is an inherent component in 3D city modelling. This integration needs further attention in order for 3D city models to serve as ‘digital twins’ of reality and provide information for a wide variety of applications. The integration of sensor data in a 3D city model is another area that needs further development to turn 3D city models into dynamic representations of reality. Lastly, the integration of highly detailed and differently structured IFC/BIM models remains an area for further study as well as for further agreements to support integration.

This article has listed the current challenges standing in the way of 3D city models being used for sustainable urban environments. Based on this list, it may seem as though a lot still needs to be done. While that is true, over the past decades there has of course been a huge increase in the number of 3D city models available and many developments in terms of acquiring, modelling, maintaining, using and visualizing them. All of this has laid a foundation for realizing the potential of 3D city models. By tackling the challenges described in this article, another major step can be taken so that the 3D city model indeed will become a powerful information hub that can be used for computer-based urban analysis.

Acknowledgements

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 677312 UMnD).

Further reading

- Arroyo (2018) Ohori, K, Abdoulaye Diakité, Thomas Krijnen, Hugo Ledoux and Jantien Stoter. 2018. Processing BIM and GIS models in practice: experiences and recommendations from a GeoBIM project in the Netherlands. *ISPRS International Journal of Geo-Information* 7(8), August 2018.
- Biljecki et al. (2016). The most common geometric and semantic errors in CityGML datasets. F. Biljecki, H. Ledoux, X. Du, J. Stoter, K. H. Soon and V. H. S. Khoo. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, 2016, pp. 13–22.
- OGC (2016) Open Geospatial Consortium inc., 2016. OGC. Future City Pilot-1: Using IFC/CityGML in urban planning engineering report. http://docs.opengeospatial.org/per/16-097.html
- Ortega-Córdova (2018), Lessie M., Framework for Urban Vegetation 3D Modelling. MSc thesis,, https://repository.tudelft.nl/islandora/object/uuid:8b8967a8-0a0f-498f-9d37-71c6c3e532af?collection=education
- Sanchez (2017), Quantifying inflow uncertainties for CFD simulations of dispersion in the atmospheric boundary layer, García-Sánchez, Clara, PhD thesis, Antwerp University, Sciences Faculty, https://hdl.handle.net/10067/1460450151162165141

About the authors

Prof Dr Jantien Stoter chairs the 3D Geoinformation research group. She also works as innovations researcher at both Kadaster and Geonovum. Jantien did her PhD on 3D Cadastre (2004), received a personal grant from the Dutch Science Foundation on 5D modelling (2011) and was awarded a grant from the European Research Council for her current research on urban modelling in higher dimensions.

Dr Ken Arroyo Ohori is a postdoc researcher in the 3D Geoinformation research group. His research interests include higher-dimensional (4D+) GIS representations and algorithms, geometric modelling and processing, GeoBIM integration and automatic data repair.

Balázs Dukai, MSc, is a research software engineer in the 3D Geoinformation research group. His focus is on methods for generating datasets, and writing software.

Anna Labetski, MSc, is a PhD candidate in the 3D Geoinformation research group, focusing on the generalization of 3D city models. Her research interests include generalization, levels of detail, transportation networks, active transportation and metadata.

Kavisha Kumar, MSc, is a PhD candidate in the 3D Geoinformation group. Her research includes compact representation of massive 3D city models for efficient storage and management.

Stelios Vitalis, MSc, is a PhD candidate in the 3D Geoinformation group. His research interests are versioning of 3D city models, multi-dimensional GIS data, topological data structures and GIS software development.

Dr Hugo Ledoux is an associate professor in the 3D Geoinformation research group. His work is mostly focused on semantic city modelling and computational geometry.