Towards sustainable and clean 3D Geoinformation

Jantien STOTER, Hugo LEDOUX, Sisi ZLATANOVA, Filip BILJECKI
3D GeoInformation, Department of Urbanism, Delft University of Technology
Julianalaan 134, Delft 2628 BL, the Netherlands
E-Mail: {j.e.stoter|h.ledoux|s.zlatanova|f.biljecki}@tudelft.nl

Summary

This paper summarises the on going research activities of the 3D Geoinformation Group at the Delft University of Technology. The main challenge underpinning the research of this group is providing clean and appropriate 3D data about our environment in order to serve a wide variety of applications. The research aims at designing, developing and implementing better systems to model 3D cities, buildings and landscapes. This paper motivates and highlights several topics that are currently being studied by the group: national 3D standard, LoD concept, maintenance of massive 3D data (including validation and automatic reparation), 3D base data, 3D data integration (specifically BIM/GIS) and 3D indoor modelling.

1 Introduction

Technologies for creating and using 3D models have matured impressively over the past ten years. And many people use 3D technologies in their daily lives, ranging from watching TV and movies in 3D, gaming and 3D printing to navigating through 3D maps. Still 3D technologies are not common to solve location-related issues: spatial planning is still mainly done based on 2D maps and databases with geo-information that support location-related policies (like INSPIRE, building registers, land use plans, cadastral maps) are mainly 2D.

This is a problem because important information is lost when the 3D reality is made flat to fit within 2D map based data. A well-known example that illustrates this is the planning of windmills, prominent structures in the landscape. A 3D representation gives significantly more insight than a 2D representation of this planning problem. Besides better visual impact, a 3D representation provides the possibility to calculate the 3D environmental impacts of windmills, like noise and shadow and a 3D approach can easily compare the impacts of different types of windmills and at different locations.

The added value of 3D can be demonstrated by an example of the municipality of Zaanstad, a city north of Amsterdam. The city wanted to redevelop an old industrial area that is surrounded by industry and infrastructure (water, roads and railways). To be able to plan the area in a flexible way, it was important to understand the noise impact of these surroundings at different heights. However, the available workflow did not account for 3D and therefore the output of noise calculation (i.e. noise levels known at x,y, z) had to be divided over several 2D maps, where every map represented a specific floor (see Figure 1). The resulting maps were given to the policymakers, who had the challenging task to combine the 2D maps into a 3D mental map. In addition, if they wanted to propose a different alternative with slightly different noise values, the comprehensive workflow had to be repeated again. A 3D approach would directly give the needed 3D insights (see Figure 2).

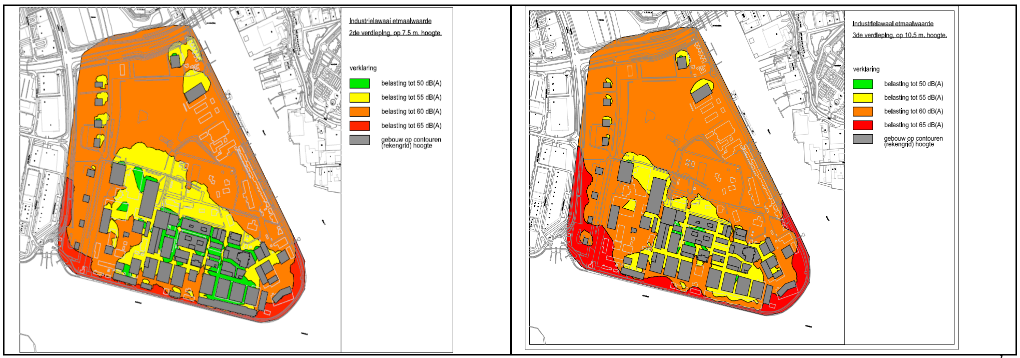

Figure 1: Noise levels varying in height, mapped in 2D with a separate map for every floor (left 2nd floor, right 3rd floor). Source: Municipality of Zaanstad.

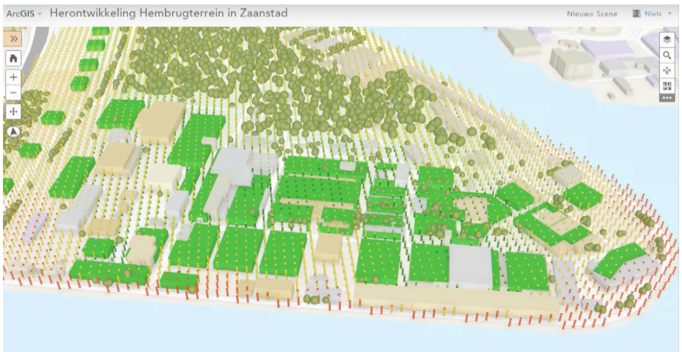

Figure 2: 3D visualisation of points in 3D space. These 3D points were used as source for the 2D contour maps of Figure 1. Source: ESRI

A study in the United States has shown that 3D data would indeed give economic benefits since many 3D based applications can be done better and more efficient (USGS, 2012).

Despite the technological benefits and the potential economic value of applying a 3D approach, 3D solutions are still not common in applications that could significantly benefit from 3D. The main bottleneck is the lack of appropriate 3D data applicable for a wide variety of applications. Often 3D data of an area is not readily available (as is in 2D) and if it is available it is either out-dated or it needs significant pre-processing to make the data suitable for a specific application. A common approach to collect, maintain and disseminate 3D data can improve the efficiency in two main ways. First, the effort to collect the data and keep it updated needs only to be done once. Secondly part of the pre-processing that is required to make the data suitable for a specific application may be useful for another application, for example cleaning the 3D data, collapsing 3D road surfaces into 3D networks or generalising detailed building data into less detailed data to serve as input for simulation software. This is why there is more and more attention to collect 3D base data as common good in Spatial Data Infrastructures, with a predominant focus on buildings. Examples are many cities and states in Germany.

To provide 3D data about cities, buildings and landscape in order to serve a wide variety of applications is the main challenge underpinning the research of the 3D Geoinformation group at the Delft University of Technology (3D Geoinformation, 2015). The research aims at designing, developing and implementing better systems to model 3D cities, buildings and landscapes. This research is carried out in close collaboration with the international community through active involvements in international research and standardisation organisation such as EuroSDR (Commission on data modelling and processing), OGC (SWG CityGML, SWG IndoorGML, DWG 3D Information Management) and ISPRS (WGIV/7: 3D Indoor modelling and navigation).

This paper contains an overview of our research that addresses several problems: national 3D standard (Section 2), specifying the concept of Level of Detail (Section 3), maintenance of 3D data (including validation and automatic reparation) (Section 4), 3D base data (Section 5), 3D data integration focusing on BIM/GIS integration (Section 6) and 3D indoor modelling (Section 7). The paper ends with conclusions.

2 National 3D standard

A national standard for 3D data provides a solid and uniform base for 3D applications. The 3D data structured according to a national standard may not be ready-to-use for applications. However, a 3D standard allows other applications to build interfaces on top of the 3D base data and therefore the pre-processing required to make the 3D data suitable for a given application can be automated. For the same reason, a 3D standard provides a solid ground for the market for 3D software developments.

In the Netherlands the importance of such a national 3D standard was recognized in 2012 and a national 3D standard has been developed that aligns to the OGC standard CityGML (see Van en Brink et al (2013a; 2013b) for details). The national standard is called "Information model Geography" (IMGeo) and contains agreements how to model objects in the physical world such as roads, water and buildings. Representing these objects in 2D according to IMGeo is mandatory for two sides: First for the organisations who are responsible for the objects (mainly municipalities, provinces and water boards). They are obliged to collect the data for reuse by other organisations. Secondly, other governmental organisations are obliged to reuse the data, i.e. they cannot invest in their own data collection process.

To be able to both cover 2D and 3D in IMGeo, IMGeo has been modelled as application domain extension of CityGML. Consequently, IMGeo is CityGML with extensions for Dutch specific classes and attributes and, more importantly, an extension for every class with a 2D geometry type to support the full range of levels of detail (LoD): from 2D, LoD0 and LoD1 to LoD2 and LoD3. An earlier version of IMGeo was remodelled such that a direct mapping between IMGeo classes and CityGML classes became possible. The 3D modelling is currently optional and reuses the semantics that is modelled for the mandatory 2D data set.

To support municipalities in implementing the national standard a "3D IMGeo toolkit" was developed. An important part of this toolkit is the "implementation specifications for

CityGML" (Geonovum, 2013). The commonly agreed specifications ensure that the generic CityGML standard is interpreted in a uniform way in the acquisition process so that 3D data will be uniform at the national level. In addition, the specifications define more precise specifications in situations where CityGML allows freedom (see also Benner et al., 2013).

3 Specifying the Levels of Detail of 3D data

A related research on standardisation is the one on the concept of the level of detail (LoD), an important aspect of the specifications of 3D geoinformation. LoD indicates the amount of detail in a geo-dataset and its adherence to the real-world. A number of topics related to the LoD concept have been investigated in Delft. Biljecki et al. (2014) study several standards that provide LoD categorisations and rules ranging from the ones of national mapping agencies to those of data producers. The work formalises the concept, and it provides an approach to specify and translate LoDs of a 3D city model between different standards.

The most prominent LoD categorisation in 3D city modelling is the one of CityGML 2.0, which describes five LoDs that increase in their geometric and semantic detail (Figure 3).

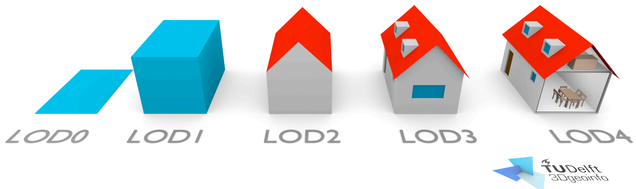

Figure 3. The five LoDs of CityGML 2.0. (Figure adapted from Biljecki et al. (2016a))

In a subsequent research of the group, the LoD concept of CityGML has been analysed, and the different choices that are possible within one specific CityGML LoD have been exposed (Biljecki et al., 2016a). For instance, CityGML does not specify whether 3D building models modelled according to LoD2 need to contain roof superstructures such as dormers. Such ambiguity may cause misunderstandings among stakeholders (e.g. discrepancy between contracted and delivered data), and may introduce errors in the utilisation of the data.

To address this issue, the research proposes a refined specification of 16 LoDs that are described in a more precise manner to diminish modelling ambiguity, and are designed after a comprehensive survey of publicly available data. The recommendations of the research have been adopted by the national mapping agencies comprising the EuroSDR Special Interest Group 3D, as a base for common guidelines for 3D mapping. Members of the 3D Geoinformation Group have also taken part in the revision of the LoD concept for the forthcoming version 3.0 of CityGML.

In a next step, the impact of 3D city models at different LoDs in spatial analysis has been investigated. This topic is important because 3D city models are used for a number of purposes, while data requirements for each use case have not been investigated from the quality point of view. For instance, 3D city models are routinely used to estimate the shadow cast by a building on its surroundings for urban planning and energy estimation. In such analyses, coarse LoD1 block models are most commonly used (Strzalka et al., 2011). However, the accuracy of using a model of a particular LoD has not been investigated. Therefore, we are currently benchmarking the performance of different LoDs in spatial analyses, and already concluded that obtaining 3D data at a fine LoD may not always be beneficial (Biljecki et al, 2015; Biljecki et al, 2016b).

4 Data maintenance & quality

Collecting geographical data about existing physical objects is prone to errors. This is not different from the 2D case for which tools to validate and correct unwanted geometrical artifacts have been developed (Ledoux et al., 2014; Arroyo Ohori et al., 2012). In 2D, examples of these are overlaps, self-intersections and dangling geometries. Because in 3D the objects to be surveyed are far more complex than those in 2D, and because the modelling tools (data structures and software implementation) to represent these in a computer are not as developed, the quality of 3D city models that are found in practice is usually poor.

Geometries (in 2D or 3D) containing errors is a real problem in practice because practitioners might not be able to convert the data to other formats and/or use spatial analysis operations in their downstream applications. The validity of geometries is indeed a prerequisite for many GIS operations. Invalid solids will either yield wrong results or, even worse, could make the software crash. The simple calculation of volumes of a building is for instance impossible with datasets containing errors (Steuer et al., 2015).

To tackle that issue, we have worked on two aspects: (1) the validation of 3D geometries, and (2) the automatic repair of 3D geometries. We have developed a methodology to validate solids against the definition of the ISO/OGC (ISO, 2003) that is used in CityGML. The details are available in Ledoux (2013). Our methodology goes one step further than other known methodologies and implementations, e.g. Gröger and Plümer (2011), Kazar et al. (2008), Bogdahn and Coors (2010) and Wagner et al. (2012), because holes in primitives of dimensions 2 and 3 are handled. The methodology is hierarchical, i.e. the primitives of different dimensionalities are validated separately. This ensures that the user does not get cascading errors (errors caused by errors in lower dimensionality primitives). More importantly, the methodology has been implemented (the source code is available under a permissive licence at https://github.com/tudelft3d/val3dity) and tested with several real-world datasets. We are currently working on extending this to all 3D primitives (e.g. CityGML *MultiSolid*) and to the validation of the topological relationships between different primitives. For instance, are two buildings adjacent or are they overlapping? Is a building touching the terrain or simply floating a few millimetres above it?

When a 3D geometry is invalid, then one has to repair it. While the manual repair of geometries is possible, it is in practice a very tedious and time-consuming task. We are currently working on two different approaches to automatically repairing 3D buildings (stored as CityGML LOD2 solids). Both methods are *volumetric*, that is we first fill the solid with 3D primitives, then we select the primitives that are inside it, and then we reconstruct the boundary of the building by unioning these. We have successfully used voxels (Mulder, 2015) to repair geometries, for instance with a real-world 3D city models in which 90% of LOD2 were invalid we improved this to only 4%. It must be noted however that during this process sharp features were rounded off and jagged surfaces appeared. The boundaries of the buildings were thus automatically repaired (so that the volume or the union of buildings were possible) but their shape was sometimes modified (symmetries in buildings were often lost for instance). A more promising approach we have explored is using constrained Delaunay tetrahedralisation to fill the buildings (Zhao et al., 2013). The jagged surfaces are avoided, but the methodology is more prone to errors. In addition, large errors, such as walls missing, often cannot be recovered.

5 3D base data

The need for 3D base data serving a wide variety of applications is met by countrywide, up-to-date 3D data, generically available. The extension of IMGeo towards 3D is the responsibility of individual organisations and therefore not ready yet to provide a countrywide 3D data set. Therefore, in 2014 a countrywide 3D dataset has been generated from the object-oriented data at scale 1:10k (the largest scale as maintained by the Netherlands' Cadastre, Land Registry and Mapping Agency, i.e. Kadaster) in combination with high-resolution airborne LiDAR data (10+ points/m^2, available as open data). The 3D model was reconstructed in a consortium composed of Kadaster, the Delft University of Technology, the Twente University and the Free University of Amsterdam. For the 3D reconstruction the open-source tool was used developed by (Oude Elberink and Vosselman, 2009a; 2009b; Oude Elberink et al, 2013). The tools reconstruct a LOD0 representation for each class in the 2D map by the integration of the 2D data and high resolution LiDAR data. For the volumetric objects (buildings and plant cover) the 3D reconstruction is limited to LOD1 (block models). This is because the scale of the source data (1:10K) does not allow reconstructing 3D geometries at higher levels of detail. The reconstruction is driven by rules that prescribe how to process the LiDAR data, how to model specific object types, and how to connect neighbouring objects in 3D (Oude Elberink and Vosselman, 2009a; 2009b; Oude Elberink et al, 2013). For this purpose, LiDAR data needs to be filtered into ground points, which are assigned to the map polygons of class ‘terrain’, ‘water’ and ‘roads’, and non-ground points, which are used for volumetric objects (i.e. ‘buildings’ and ‘vegetation’).

To apply this 3D reconstruction method to the whole country, a parallel processing workflow has been implemented also taking into accounting specific issues such as objects that cross one or several tile-boundaries and extremely large objects that contain millions of height points. The result is a 1:10k 3D dataset of the Netherlands, which we believe to be at this moment the only country-wide 3D dataset in the world. The countrywide 3D data set is the starting point of a research projects funded by the Dutch Science Foundation that studies how to improve the 3D data set, how to maintain and disseminate the large 3D data set (including terrain objects) and how to apply the 3D data as input data for environmental modelling (noise, water, energy, air quality). The project is a collaboration of three universities (Delft, Twente and Amsterdam) and eleven partners form the field, see www.3D4em.nl.

We are currently working on creating the 3D BGT of the Netherlands, that is the large scale (~1:1k) 3D map. Since the BGT contain significantly more 2D features at higher detail, and since the original process was rather computationally expensive (several fitting of planes with least-square adjustment), we are currently investigating simpler alternatives to assigning elevations to the features. Each feature, or part of a feature, would be “lifted” to 3D by using rules such as lowest within a given area (e.g. for water) or by using a certain percentile of all elevations points within an area. We believe this will allow us to scale the process to the whole country easily, and we will plan to compare the results to those obtained with the original method. For the buildings, we plan to decompose each footprint into parts whose elevation is similar. For this we will use the methodology of Commandeur (2012).

6 3D data integration

With the observation that a 3D approach can model our world closer to reality, 3D data integration becomes a fundamental issue in 3D modelling, i.e. integrating data across domain boundaries so that all information about a specific location can be taken into account in the decision making process of both professionals and citizens. 3D data integration may be one of the biggest challenges for the 3D domain: how to integrate 3D data with different semantics; how to integrate data above and below surface; how to integrate vector and voxel data; how to integrate bathymetry data with digital terrain data; how to integrate sensor data (temperature, wind air quality) with a 3D city model and how to integrate these with simulation software etc.

A data integration issue that we would like to highlight here is the integration between BIM (Building Information Modelling) and GIS. Although BIM is not equivalent to "3D" in the construction and building domain and GIS is not similar to 3D modelling in the geo-domain, there is a common understanding that it would be useful to be able to reuse 3D GIS data (for instance stored in CityGML) in BIM software, and vice versa.

However, one view of the world that both covers the geo-information scale (i.e. a database covering a city, country or state) and the BIM scale (i.e. a database per building site) is not feasible. Therefore, attempts are being made to convert BIM data (standardised in IFC) into CityGML data. A straightforward conversion (as implemented in many software systems) where every geometrical element in an IFC model is converted into a CityGML LoD3 equivalent is not sufficient because there are several unwanted geometries. An example is for LOD2 models: only the exterior envelope of a building is required (forming a 2-manifold), while a conversion with most software yields a model having walls with thickness and several features inside the building (see Figure 4).

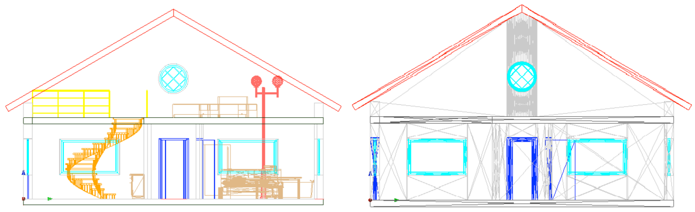

Figure 4. Cross-section of an IFC model (left) for which all the relevant geometries are converted to CityGML geometries (right model). Observe that the result is not a single envelope because several volumes are constructed (e.g. each slab of the roof is a volume) while other objects (such as the stairs) are not remained because they are not CityGML object types. (Figure from Donkers (2013)).

We have developed an alternative solution in which geometrical and topological operations are performed on the 3D model, after a semantic mapping of the necessary features. All geometries are unioned, the appropriate semantics are assigned to each bounding surfaces (by reusing those in the IFC or extracting them from the geometry), and we ensure that a single envelope (2-manifold) is constructed. The methodology has been documented (Donkers, 2013; Donkers et al., 2015), implemented, tested with real-world datasets, and released under an open-source licence.

The differences between GIS and BIM models are well to be observed for large fast developing industrial establishments or large civil engineering projects. To be able to follow the progress in the development of such a building project, design and as-built information have to be integrated in one environment, checked and if needed, clashes have to be corrected. An example of such a fast developing industrial establishment is the Port of Rotterdam.

The Port of Rotterdam accommodates large number of public and private stakeholders (companies, environmental authorities, municipalities, various institutions, and citizens), which are constantly involved in the processes of the harbour. The information is spatially distributed above ground (topography, cadastral parcels, buildings, streets, parking areas), underground (cables and pipes, geological and geotechnical data, tunnels), in the air (sensors for measurement of air quality, radar coverage, camera coverage), and in the water (depth of the harbour). Additionally, the designs of quays, buildings, cargo areas, factories are provided as BIM models. The management of the harbour has experienced an urgent need to integrate all these different data sets in a 3D Spatial Data Infrastructure (3DSDI). To facilitate the management of this information, we have proposed an approach for 3D data integration and developed a demonstrator to illustrate the ideas (Zlatanova et al 2013, Beetz et al, 2015). Some major principles were followed:

1. We recommended and implemented a semantic-driven 3D model. It is based on international and national standards in BIM and GIS domain and re-uses existing feature descriptions when possible. New concepts and descriptions were devised only when compatible ones could not be found in national standards (such as IMGEO or other national standards like the one on cables and pipelines, water and the geological underground). A new extension to the IFC model capturing the semantics of quay walls has been developed.
2. Geometries of all objects are stored as 3D GIS simple features in the database for analysis purposes. Detailed IFC representations of design objects are stored per object as IFC files for maintenance purposes. The granularity of semantics to be used for GIS simplified representation is still under study.
3. The system architecture follows distributed data management, i.e. data are maintained by the individual stakeholders. Integration of 3D information is then provided 'as a service' to be combined in real time. This approach is possible because of use of standards for the exchange of information. Data for which the Port of Rotterdam is responsible are organised according to the same 3D model in a DBMS.
4. The interfaces for visualisation of 3D information can be performed in different environments, i.e. desktop and web. The developed mock-ups (Figure 5, left) and final demo (Figure 5, right) illustrate two visualisation and interactions within WebGL and game engine (Flare3D). The 3D data can also be analysed and appropriate reports can be derived.

A similar approach can be applied for integrating sub- and above surface data. A typical application that needs such integration is management of rainfall. Rainfall pattern has changed drastically in the last years causing heavy rainfall in relatively short periods of time. This often results in fast flooding especially in dense urban areas. In order to cope with this issue, multiple municipalities in the Netherlands have invested in upgrading the sewage systems to enlarge their discharge capacity.

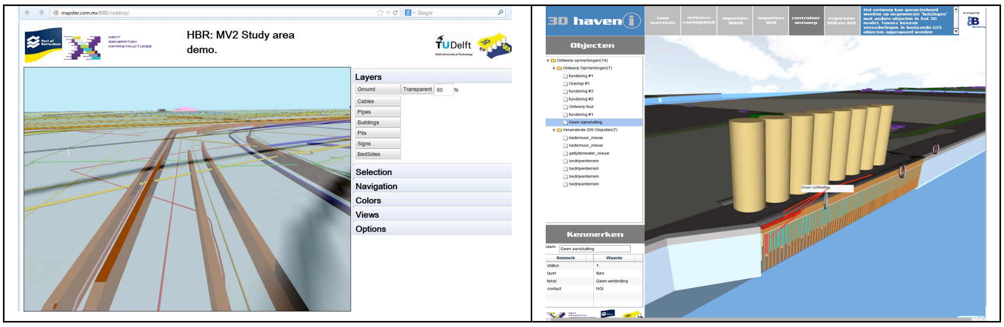

Figure 5: Left: Visualisation of underground utilities (geometry created on the fly) in WebGL. Utilities are represented as lines, 3D geometry is created on the fly (Guerrero et al 2013). Right: Visualisation of a clash between IFC design object (i.e. a new quay wall) and GIS existing situation (e.g. silos). The IFC geometry is compared with the GIS geometry in the application. Both IFC and a simplified GIS representation are stored in the database.

The sewage capacity is estimated by dedicated models taking into consideration soil infiltration, evaporation and run off as surface water. To make estimations of these parameters, we have integrated subsurface geological data GeoTOP (represented as large voxels), TOP10NL (2D topographic data set of the Netherlands) and sewage network in one 3D model using the 3D multipatch data type of Esri (see Figure 6).

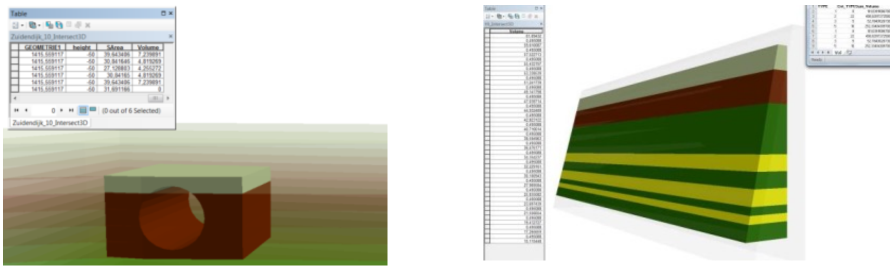

Figure 6: Intersection between volumetric objects: complex sewage valve (left) and inclined section of GeoTOP(right) all represented as mutipatch (Janssen, 2015)

A number of tests were performed to investigate the possibilities for 3D analysis in ArcGIS on the integrated 3D model (Janssen, 2015). Experiments were conducted with three Boolean operations *Intersect3D*, *Union3D* and *Difference3D* between objects of different dimension (volume and volume, surface and volume, surface and surface). The results have shown that only Intersect3D can cope with objects of different dimensions. Union3D and Difference3D work on volumetric objects only. Generally, the results are stable, but some warnings are released in some specific cases. For example, in case of touching volumetric objects (at face, edge or point), Intersect3D does not provide the common geometry. The semantic of the objects is properly assigned in all cases. In case of intersecting objects, the new object inherits the semantics of the two intersecting objects.

7 Indoor modelling

3D indoor modelling is another trend that has rapidly gained the interest of researches and developers and belongs to the challenges described in this paper for building clean and smart 3D information for the future. Humans perform many activities indoors related to work, shopping, leisure, dining, sport, etc. The buildings and the large variety of associated spaces such as underground passages, sky bridges, metro lines, garages, stations, yards, gardens, and roof terraces are becoming elaborated conglomerates of enclosed spaces. This complexity poses many challenges for building managers, occupants and visitors.

To facilitate human activities, to provide comfort, safety and security, to ensure the necessary infrastructure is available, the enclosed spaces have to be represented by semantically and geometrically rich models to be able to reflect the personal profile of an individual or a group of individuals. Indoor space differs from outdoor space in many aspects: the space is smaller and closed; there are many constraints such as walls, doors, stairs and furniture, the structure is multi-layered frequently containing intermediate and irregular spaces, the lighting is largely artificial and so forth. To be able to represent indoor spaces in a proper manner, many data acquisition concepts, data models, and ISO/OGC standards have to be adapted to meet the requirements of indoor spatial applications.

The issues related to 3D indoor modelling are very compatible to those outdoor, but also exhibit a slightly different problematic. Broadly, the creation of such virtual representations involves (i) digital acquisitions of the spaces, (ii) structuring of acquired data, (iii) formalisation of the structured data to establish the relationships between spaces and sub-spaces, and (iv) imprinting of application or user requirements onto the formalised structured data. However there are many differences. Zlatanova et al, 2013 attempted to create an overview of existing and emerging problems (Figure 7).

Most of the challenges in creating 3D indoor models are not new and are inherited from current 3D outdoor modeling and applications. However there are many new challenges specific for indoor. Examples are real-time data acquisition, data structures for indoor applications (indoor navigation, facility management) or advanced 3D graphic user interfaces to overcome ‘tunnel’ effects. The area of indoor applications will boost, if cognitive approaches for 3D modelling are developed. Indoor 3D modelling is much more ‚human’ dependent indoors compare to outdoors. In this respect, semantic annotation of 3D indoor models plays a critical role.

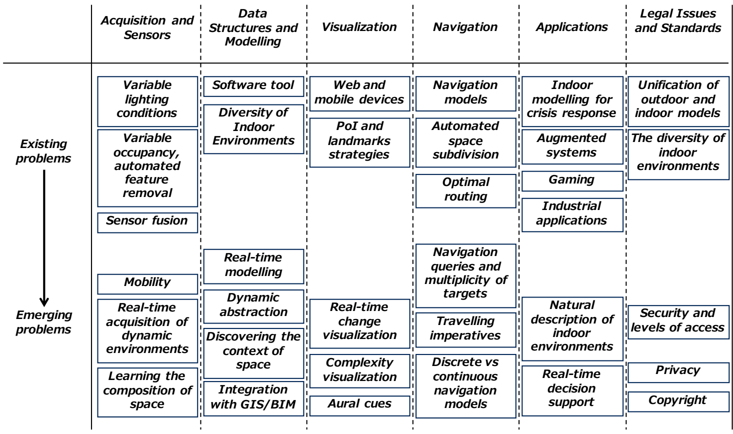

Figure 7: Challenges in indoor mapping and modelling

8 Concluding remarks

This paper summarises the on going research activities of the 3D Geoinformation Group in Delft. The objectives of the research of this research group are to design, develop and implement better systems to model 3D cities, buildings and landscapes. The research is carried out in close collaboration with national and international partners from research institutes, governmental organisations and industry, such as the national and the EuroSDR 3D Special Interest Group. This ensures an environment where theoretical concepts on how to develop and implement a sustainable 3D data infrastructure are tested in practice and where topics for further research are identified.

Acknowledgements

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