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3D Geoinformation – Then and Now

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Abstract

This paper discusses the trends of 3D geoinformation from past (1990s) to present. It highlights the initial 3D GIS research frameworks in the aspect of 3D spatial data acquisition, processing, databases, visualization, standards, and exchange formats. Several important R&D stages are described as well as CityGML, CityJSON, INTERLIS, and LADM standards. The paper also discusses some challenges faced by the 3D GIS users and community. Finally, the paper concludes the 3D GIS ability for supporting various applications.

1. Introduction

1.1 Initial 3D GIS Research Framework

This paper describes the development of 3D geoinformation from the 1990s to today. It highlights tremendous scientific discoveries in data acquisition, processing, databases, visualization, standards, and exchange formats. Initially, data structure was the focus of early 3D GIS research in academia, with significant contributions from institutions such as Graz University (Austria), ITC (the Netherlands), Wageningen University (the Netherlands), and the University of Glasgow (UK). Later, more work emerged from TU Berlin, TU Munich, TU Delft, Stuttgart University, the University of Seoul, and University College London (UCL) in the UK. Other groups, such as the University of Melbourne (Australia) and, more recently, the National University of Singapore, have also contributed to the 3D GIS body of knowledge. The development of data exchange formats, such as CityGML, CityJSON, LADM, and Interlis, has paved the way for a greater understanding of the domain. All these developments are part of the bigger picture of the 3D system, where topology is still in its early stages. Several works related to the Land Administration Domain Model (LADM) and 3D Land Administration (LA), recently concluded, will also be discussed, especially concerning 3D geometry from BIM for LADM. This paper will conclude with several key points on the development of 3D geoinformation, including research and commercial systems, and provide insights into new trends. Discussions will primarily focus on data structures and spatial data modelling, followed by database and visualization aspects. The remaining of the paper describes data acquisition, spatial data modelling, spatial data structure and indexing. Section 2 describes standard and exchange format. 3D spatial database will be discussed in section 3. Meanwhile, section 4 for the discussion and finally section 5 for conclusions of the paper.

1.2 Data Acquisition

It was one of the major tasks in any mapping and land related agencies world-wide where traditional land surveying techniques were employed – from photogrammetry, remote sensing, laser scanning, LiDAR, and recently by using UAV systems. Almost all major National Mapping Agencies (NMAs) products were generated from those technologies, i.e., from maps to 3D generated buildings (mainly). The maps were utilized as base data whereas 3D data then parts of component to enhance the generated information with 3D city model and digital twins. We have seen that data acquisition aspect is now focus on fast and quick techniques like LiDAR and drones where more and more authorities able to generate various required datasets in relatively short time. The efforts from data acquisition vendors generate 3D GIS software development ecosystem in place as we have seen within major vendors like ESRI, and others. Reports and papers from (Esri.com, Bentley.com, Hexagon.com, Topcon, Trimble.com, Pix4D, Riegl, Leica, and Vexcel) clearly show the data acquisition and techniques advancement to the community, especially to the photogrammetry community. Several leading research institutes such as including Wuhan University from China, Polytechnic University of Hong Kong, Technical University of Berlin, Germany, Technical University of Denmark, Ohio State University, Columbus, USA, and TU Graz, Austria. Other leading research institutes such as University of Stuttgart produced a number of significant tools for handling and managing 3D spatial data connected to photogrammetric data acquisition (DTM software, 3D data fusion, and also 3D data adjustment). The trends of data acquisition and the related software tend to heavily involve with artificial intelligence (AI) as recently announced by the Photogrammetric Week 2025 conference in Stuttgart, Germany.

1.3 Spatial Data Modelling

This aspect of data processing and modelling is considered one of the most important in geoinformation, thus, 3D GIS. It is the aim of modelling task that all captured data to be recognized as useful data with proper shapes, geometry, etc. without which would be unrecognized by the software or systems. Thus, it is crucial to develop proper tools or computing modules.

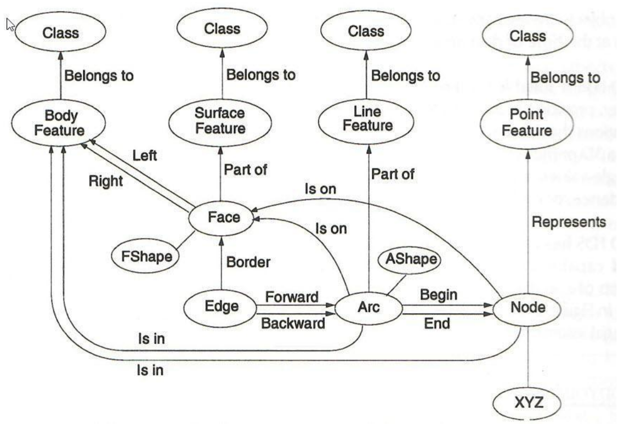

Figure 1. The fundamental data model for geospatial objects (after Molenaar, 1989).

1.4 Spatial Data Structure and Indexing

It has been instrumental research works by GIS "engine" software developers years ago until today for storing and indexing data for fast and quick database retrieval. Works particularly by Oracle Spatial group and other database vendors have generated tremendous interests in the 3D GIS community since then. In this paper, data structures especially for 3D objects are described (see papers by Molenaar (1990), Pilouk (1996), Zlatanova (1998), Ledoux (1999), Ellul (2010), and others. These papers focussed on ways of connecting nodes, lines, surfaces, and solid (volume) into structures where their relationships could be established and known – geometrical and topological. These relationships are crucial in generating spatial information out of the objects. Although geometrical connections of these objects' primitives were solved for 2D objects, however the 3D counterpart is still unresolved completely for the topological relationships. Works on this 3D topological part is still ongoing until today as reported by Boguslawski (2023). Figure 1 illustrates the most fundamental 3D data structure and modelling by Molenaar (1989) and has been researched on since then by others including AbdulRahman (2000). The structure began with point class, line class, and area class where the relationships between these classes were clearly linked, thus, the information was established. In terms of representational methods, 3D data can be stored as volumetric data (e.g., voxels), boundary representations (B-rep), triangulated surface (TIN) or surface models. Each model type serves different purposes; voxel-based methods are often used in environmental modelling due to their ability to represent solid volumes, while B-rep is more suitable for structural details in architecture (Breunig & Zlatanova, 2011). The choice of model can impact database performance and storage requirements, influencing its applicability in specific use cases. Figure 2 illustrates the triangulated surface features data type, representing both natural and urban elements.

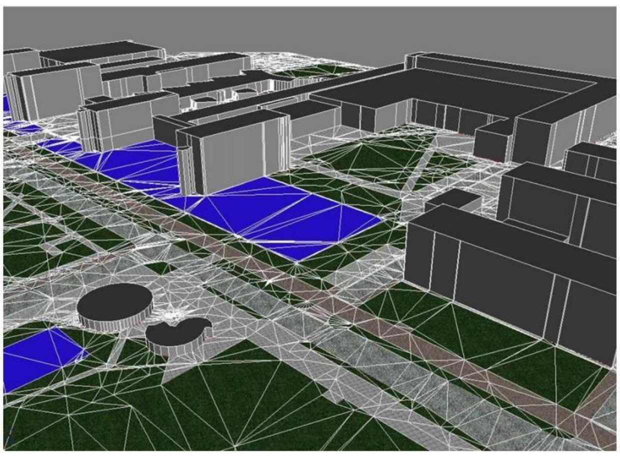

Figure 2. Integration of natural and urban objects in the TU Delft campus model as represented through triangulated surface features (adapted from Breunig & Zlatanova, 2011).

The basic data structure framework then improved for a more practical structure as of Pilouk (1996) where more classes were incorporated into for accommodating advanced situations as in Figure 3. Here, classes associated with 3D spatial objects such as body class was introduced where body feature as part of tetrahedron-based objects or in other words objects were constructed from 3D triangulation irregular network (TIN) – tetrahedron-based data model, then established the relational data structure and consequently the database. Furthermore, the relevant query out of the created database. Example of query – show some 3D features (together) with visualization. This was one of the earliest methods of generating 3D spatial information from the scratch. More advanced approaches were researched into as reported by including Bruenig (2015), Coors (2015), Zlatanova (2000), Kolbe (2010), Boguslawski (2016).

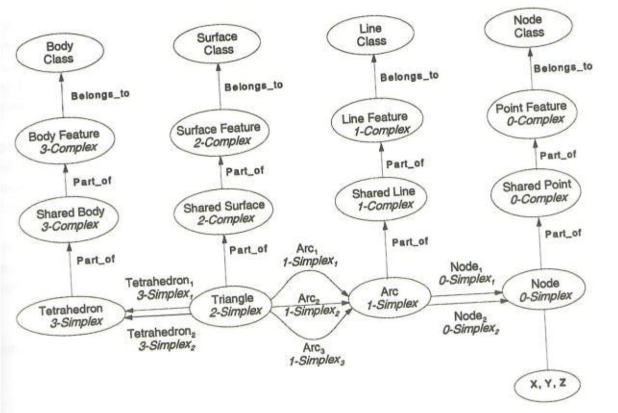

Figure 3: An extended data model adapted by several 3D GIS researchers (Pilouk, 1996).

Database research is highly related to indexing mechanism especially for fast records searching. In general, database indexing is like R-Tree, B-tree, hash indexing, clustered indexing, etc. Oracle uses B-tree. The following section briefly describes database indexing via 3D geo-clustering technique for 3D R-Tree data structure as reported by (Azri, et al. 2018). The approach produced a faster (significant level) searching method (crisp clustering algorithm) for 3D data like buildings stored in a database. Indexing is essential for retrieving spatial data quickly and accurately. Spatial indexing techniques like R-trees and k-d trees have been adapted to handle three-dimensional queries, allowing databases to perform operations such as volume intersection, spatial proximity, and adjacency checks efficiently (Biljecki et al., 2015). Specialized query languages, including SQL extensions for 3D data, have been developed to support complex spatial queries in applications such as real-time simulations and navigation systems (Breunig & Zlatanova, 2011).

2. Standard and Exchange Formats

The standardization and exchange of data play a vital role in 3D geoinformatics, ensuring interoperability, data integrity, and efficient workflows. Over time, several data formats have emerged as industry standards, each catering to specific requirements and applications (Praschl & Krauss, 2023). Among these, CityGML, CityJSON, INTERLIS, and LADM have significantly contributed to advancing the understanding and capabilities of 3D GIS. These standards provide a structured approach to managing and exchanging geospatial data, enabling more accurate and comprehensive representations, particularly in urban environments and land administration systems.

2.1 CityGML

CityGML is a widely used open data model and XML-based format for storing and exchanging virtual 3D city models. It facilitates the representation of complex 3D geometries, semantic information, and topology, promoting interoperability across diverse systems and applications.

Research into integrating CityGML with Industry Foundation Classes (IFC) has highlighted promising opportunities for enhanced interoperability. For example, El-Mekawy et al. (2011) proposed a Unified Building Model (UBM) that harmonizes IFC

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and CityGML by aligning relevant classes, attributes, and relationships. IFC, developed by buildingSMART, is a standard for representing building and construction data, commonly used in Building Information Modeling (BIM) (Zamzuri et al., 2024). The UBM framework addresses the limitations of standalone models like IFC and CityGML by offering a comprehensive solution for 3D cadastral information. This unified approach benefits applications such as urban planning, land administration, and disaster management, where managing complex 3D data is crucial.

CityGML has evolved over time, with its latest version, CityGML 3.0, introducing features like a revised Level of Detail (LoD) concept, support for time-dependent properties, and multi-version management of city models (Kutzner et al., 2020). These enhancements expand its usability and application scope. CityGML is increasingly integrated with BIM and Geographic Information Systems (GIS), enabling better representations of urban environments, and supporting initiatives such as digital twins and smart cities (Tan et al., 2023).

However, challenges persist. For instance, the integration of CityGML with BIM can be complex due to differences in modeling languages, geometric representations, and semantic structures (Rashidan, H., et al. 2024). The conversion process requires accurate mapping across varying levels of detail, necessitating careful attention to component definitions during integration (Tan et al., 2023). While CityGML offers a robust framework, its lightweight counterpart, CityJSON, provides an alternative suited for specific applications (Apeh & AbdulRahman, 2022).

2.2 CityJSON

CityJSON complements CityGML by offering a more compact, developer-friendly format while maintaining full compatibility. This bidirectional interoperability allows users to choose the format best suited to their needs, ensuring seamless integration. CityJSON was designed to address the need for efficient 3D city modeling, particularly in real-time applications like smart cities and digital twins (Ledoux, 2019).

As of November 2023, CityJSON v2.0 has been recognized as an Open Geospatial Consortium (OGC) community standard (Ledoux & Dukai, 2023), underscoring its reliability and acceptance. Recent innovations, such as CityJSONSeq, enable the efficient handling of large datasets by managing sequences of CityJSON objects, making it ideal for extensive 3D city models. Tools like cjio simplify file manipulation, and CityJSON's extensibility allows customization for various use cases (Ledoux et al., 2019).

CityJSON has found applications in urban planning, disaster management, and web-based 3D visualization. Its compact format makes it particularly well-suited for web and mobile platforms (Vitalis et al., 2020). While CityJSON and CityGML are powerful frameworks for 3D city modeling, precise conceptual modeling languages like INTERLIS address broader challenges in geoinformatics.

2.3 INTERLIS

INTERLIS is a conceptual modeling language designed to precisely describe and exchange geospatial data. Its systemneutral approach and robust quality control mechanisms have driven its adoption, particularly in cadastral surveying and national spatial data infrastructures (NSDI). Switzerland, for instance, has standardized over 160 data models within its NSDI using INTERLIS, enabling seamless data integration and exchange across government agencies.

Research highlights INTERLIS's effectiveness in overcoming challenges in land administration. In Switzerland, it was integrated with LADM profiles to improve geospatial data exchange and ensure quality. Greece applied INTERLIS to create a multipurpose land administration system that supports diverse spatial units, including 3D representations and archaeological sites. Meanwhile, Colombia leveraged INTERLIS to develop a multipurpose cadastre tailored to its complex institutional framework. These efforts introduced structured semantic code lists and precise constraints, showcasing INTERLIS's capability to automate data validation, generate schemas, and ensure compatibility across geospatial systems (Kalogianni, 2017).

2.4 LADM

LADM complements standards like INTERLIS by offering a standardized framework for managing legal, administrative, and spatial relationships in land administration. It has been standardized as ISO 19152, serves as a comprehensive framework for managing the complex relationships between legal, administrative, and spatial data in land administration. It provides a formalized structure to address Rights, Restrictions, and Responsibilities (RRRs), legal boundaries, and the parties involved in land transactions. One of the key strengths of LADM is its flexibility, enabling customization to align with the unique requirements of individual countries through the creation of LADM-based country profiles.

Since its approval as a standard in 2012, LADM has been widely adopted and extended. Countries like Switzerland, Greece, and Colombia have effectively implemented LADM in combination with INTERLIS to address their specific land administration needs. In Switzerland, LADM was integrated with INTERLIS to improve the consistency and exchange of cadastral data across multiple government institutions. Greece leveraged LADM to design a multipurpose land administration model that supports a diverse range of spatial units, including 3D representations and unique cultural heritage sites. Meanwhile, Colombia used LADM as the backbone for its multipurpose cadastre, addressing the country's complex institutional and legal framework (Kalogianni, 2017).

The importance of LADM is also evident in its ability to support modern land administration challenges, such as urban densification and the increasing need for 3D cadastres. By linking legal information with physical data, LADM facilitates integrated representations of aboveground and underground property rights. This is especially critical in dense urban environments, where traditional 2D representations fail to capture the spatial complexity of overlapping ownership and utility rights (van Oosterom et al., 2018).

Recent advancements have further extended LADM's functionality, including its integration with emerging technologies such as digital twins and 3D geospatial databases. For instance, the integration of LADM with 3D models developed using formats like CityGML and IFC has shown promising results in creating comprehensive, interoperable systems for urban planning, land valuation, and disaster management. This integration aims to combine the legal and physical aspects of land and property management, providing a more comprehensive and accurate representation of property rights, restrictions, and responsibilities (RRRs). Several studies have explored this integration, focusing on using BIM's rich 3D data to enhance LADM's legal framework (Zamzuri et al., 2024a). For instance, researchers have proposed using Industry Foundation Classes (IFC) to bridge the gap between BIM and LADM, allowing for better interoperability and data exchange2. This approach helps in accurately representing legal spaces within buildings, such as individual units and common areas, and managing complex ownership arrangements (Zamzuri et al., 2024b).

Countries like the Netherlands, Australia, and Turkey have considered adopting this integrated approach to improve their land administration systems. The integration of LADM and BIM not only enhances the precision and utility of land administration but also promotes sustainable development, conflict prevention, and digital transformation (Atazadeh, 2021; Alattas et al., 2021; Broekhuizen, 2021). These integrations ensure that legal and spatial data are harmonized, facilitating seamless queries, analyses, and visualizations in 3D environments (Ying et al., 2022).

Looking forward, the fusion of LADM with 3D geospatial databases represents a significant leap in geoinformatics. By coupling LADM's structured legal and administrative data with the spatial precision of 3D geospatial databases, land administration systems can achieve unparalleled accuracy and interoperability. This synergy not only supports current needs but also paves the way for advancements in areas like smart cities, infrastructure management, and spatial data infrastructures.

3. 3D Geospatial Database

The development of 3D geospatial databases has been instrumental in advancing the field of geoinformation, particularly in supporting complex spatial analyses and applications in urban planning, environmental monitoring, and disaster management. Unlike traditional 2D databases, which primarily handle two-dimensional information, 3D databases are designed to manage volumetric data, capturing height and depth dimensions essential for accurate representations of realworld spaces (Goodchild, 2020). Early efforts in 3D geoinformation were constrained by storage and computational limitations, but recent advancements have enabled more efficient storage, retrieval, and manipulation of large 3D datasets, creating new opportunities across various industries (Breunig & Zlatanova, 2011). Effective data modelling is central to the functionality of 3D geospatial databases. One prominent approach is the object-relational data model, which uses standardized schemas like CityGML and Industry Foundation Classes (IFC) to represent complex urban landscapes and infrastructure elements (Zlatanova et al., 2021). CityGML, for instance, provides a hierarchical structure that enables detailed modelling of buildings, terrains, and urban features, making it a preferred standard in city planning and smart city applications (Biljecki et al., 2015).

3.1 Data Storage and Compression

Storing 3D geospatial data requires significant computational resources, especially as data resolution increases. Hierarchical structures such as octrees and k-d trees have been widely adopted to organize 3D data efficiently, reducing the need for storage by structuring data in a multi-level format (Zlatanova et al., 2021). Compression techniques, including wavelet compression and predictive coding, have also been explored to handle large 3D datasets without sacrificing data quality (Goodchild, 2020). By optimizing data storage, these techniques facilitate the practical application of 3D databases in resourceconstrained environments.

3.2 Integration with 3D Standards and Multi-source Data Fusion

To ensure interoperability across platforms and applications, 3D databases often rely on standardized data formats, such as CityGML and LandXML. These standards facilitate data exchange and integration across different domains, from urban planning to infrastructure development (van Oosterom, 2020). Additionally, multi-resolution data fusion techniques allow databases to combine data from various sources, including satellite imagery, LiDAR, and CAD models, enabling richer and more detailed 3D models (Goodchild, 2020).

3.3 Tools and Software for 3D Geospatial Databases

As 3D geospatial data has become increasingly integral to various fields, specialized tools have emerged to support the unique requirements of 3D geoinformation systems. These tools facilitate not only the storage and management of 3D spatial data but also advanced visualization and analysis. Here, we explore some of the most significant software solutions that have evolved over time to meet the demands of 3D geospatial database applications.

The development of tools like PostGIS, Oracle Spatial, 3D City Database (3DCityDB), ArcGIS, and CesiumJS has transformed the capabilities of 3D geospatial databases. These tools are designed to handle the complexity of 3D spatial data, from database management and spatial indexing to real-time visualization.

PostGIS originally an extension of PostgreSQL designed to handle 2D spatial data, PostGIS has progressively incorporated 3D and 4D (spatiotemporal) functionalities, enabling users to manage and query 3D data. Over time, PostGIS has integrated additional data types and indexing methods to support complex 3D geometries. The evolution of PostGIS is closely linked to the rising demand for affordable and flexible geospatial database solutions (Goodchild, 2020).

Meanwhile, Oracle Spatial provides extensive 3D data handling capabilities, supporting advanced geospatial queries, 3D indexing, and volumetric analysis. Developed for enterpriselevel applications, it is widely used in large-scale urban management projects and government databases. For the meantime, 3D City Database (3DCityDB) is a specialized opensource tool developed by the Technical University of Munich. It is tailored to store, manage, and visualize 3D city models in compliance with the CityGML standard (Groger & Plumer, 2012; Yao et al., 2018).

Esri's ArcGIS suite, one of the most widely adopted GIS platforms, has expanded significantly to include robust 3D capabilities. It allows users to create and analyze 3D data models, perform volumetric analyses, and utilize cloud-based resources for large-scale projects. The integration of ArcGIS with cloud services, including ArcGIS Online, demonstrates Esri's response to the increased demand for accessible, scalable, and real-time 3D geospatial solutions (Esri, 2021).

3.4 Applications and Case Studies

One of the most notable applications of 3D geospatial databases is in smart cities and urban planning. Cities like Singapore and New York have developed comprehensive 3D city models to support infrastructure management, disaster preparedness, and public services (Zlatanova et al., 2021). In disaster management, 3D databases provide essential information for planning evacuations, assessing damage, and coordinating response efforts during natural disasters, demonstrating their value in real-time scenarios (Biljecki et al., 2015). Figure 4 shows an example of the potential applications and their use cases.

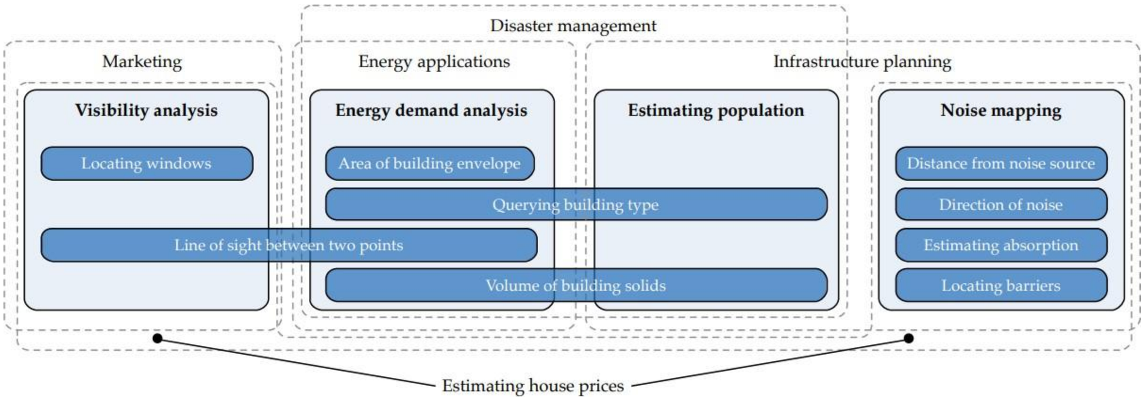

Figure 4. The relations between spatial operations (dark blue), use cases (light blue) and applications (outlined with a dashed stroke) (from Biljecki et al., 2015).

3.5 Visualization for 3D GIS

The visualization aspect could be considered as last component for any geoinformation systems. Many years ago, most of visualizations were based on simple 2D and 3D representation via wireframes, as it was utilized during Arc/Info ESRI era. The visualization capabilities upgraded into solid together with web based functions and queries as reported by Zlatanova, (2000). The thesis was one of the earliest outputs in 3D GIS research domain. Today, we have seen several interesting visualization technologies such as Cesium, OpenGL, Direct3D, Unity3D, including Unreal Engine. All these visualization engines able to render large and complex geometries objects by leveraging Graphic Processing Unit (GPUs). Recently, Bentley applied Cesium 3DTiles technology for visualization task. Several open sources GIS software utilizes OpenGL as well as Direct3D for hardware accelerated 3D rendering. Geoinformation systems related to gaming and Virtual Reality (VR) / Augmented Reality (AR) normally utilize Unity3D / Unreal Engine, e.g., within Bentley Microstation software. Figure 5 illustrates the most recent 3D visualization within geoinformation domain based on Cesium for Unreal Engine.

Figure 5. Example of 3D visualization based on Cesium for Unreal Engine

The visualization aspects of GIS provide more interesting R&D innovations for future development.

4. Discussion

4.1 Challenges

The recent trends in 3D GIS domain seem lacking complete solutions for modelling 3D spatial data in such a way user of the systems hardly gained the correct output (as we perceived in the real-world). We strongly believed that the existing techniques and algorithms, processing, etc. still not be able to solve the complex situations. Here are the possible challenges.

4.1.1 3D Spatial Data Recognition-Ready: It is quite hard for the time being to have 3D spatial data completely ready for users to apply directly for specific tasks. Some of the data were restricted due to the privacy and agreement concern between the data stakeholders. The experiences show that minimizing data preparation, handling including formatting leads to fast jobs completion.

4.1.2 3D Objects Generalization: Different users have different goals when it comes to data resolutions, traditionally it is quite simple to minimize (extract) data from high resolution data. Here, generalization plays an important role representing certain object Level of Details (LoDs). Many research have been conducted in this issue, however the generalization of objects still requires research efforts in some aspects such as aggregation and simplification. Research in 3D objects generalization helps / useful for map making authorities.

4.1.3 3D Data Usability and Adaptability (Interoperability): It seems now GIS has transformed to a larger dimension where the available datasets should be available to various users at every level, however, in many places, the situation remained restricted and hardly applicable in some cases (e.g., typical Spatial Data Infrastructure (SDI) in various countries). Data providers need to ensure that data are readily accessible and interoperable (e.g., data formats, etc.) between users.

4.1.4 3D Data Updating: It is one of the expensive "exercises" in mapping agencies around the globe. Efficient data updating still a problem – ability to update automatically for a certain part of the data / area which introduces better data management. Several European national mapping agencies are engaging in these exercises from time to time (e.g., UK Ordnance Survey, Dutch Kadastre, IGN France, IGN Belgium, and German NMA).

4.1.5 3D Data Accuracy: It is an important aspect of 3D spatial data especially for generating accurate models and related products. It has been a routine task in mapping and modelling development within small and large mapping agencies. Many data collection techniques now able to produce data with acceptable accuracy – useful for many applications for instance, accurate 3D city models, etc.

4.1.6 3D Data Transformation and Fusion: 2D and 3D spatial data normally come from various sources with different datums and formats. Transformations for a common platform or format are crucial as we encounter in various GIS and mapping operations especially in integrating data from multiple standards and exchange formats (e.g., LADM, CityGML, BIM/IFC, etc.). The issue remains unsolved (at certain degrees).

4.1.7 3D visualization system: The visualization of 3D objects normally based on advanced 3D tools such as Cesium, OpenGL, Direct3D, Unity3D, including Unreal Engine. These tools provide different level of quality and functionality – different applications such as gaming and standard visualization. At the moment, the visualization aspect of 3D geoinformation able to fulfil various requirements. It is very much related to the advancement of computer science.

5. Conclusion

The domain has been investigated and explored by various research groups in several parts of the world since middle 1990s. The 3D GIS seems able to offer incomplete solutions to the problems. The existing and available tools warrant for more advanced techniques and algorithms. The domain shows that data modelling and standards aspects transformed tremendously in supporting challenges and complexities of 3D real-world models. On the other hand, the data usability and adaptability still require lot of research efforts as being discussed by various stakeholders (researchers, vendors, institutes, and government agencies) in seminars and conferences. Based on our experiences, it looks like the 3D GIS able to offer better solutions and services provided all the challenges that we put forward (section 4.1) to be addressed.

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