3D City GIS – A Major Step Towards Sustainable Infrastructure

A Bentley White Paper

Benoit Fredericque, Product Manager 3D City GIS Products

Alain Lapierre, Senior Director, Civil and Geospatial Frameworks

Bentley®
Sustaining Infrastructure

Introduction

Our mission at Bentley has always focused on helping our users improve the world's infrastructure. We do this by providing software solutions, products, and services that improve the productivity and quality of the work performed by architects, engineers, constructors, and geospatial professionals through the design-build-operate lifecycle of infrastructure.

Infrastructure – everything from roads, bridges, buildings, and factories to water, electric, gas and communications networks – provides the basic facilities, services, and installations for a society to function. Creating a sustainable world has become a clear priority for the world's communities as well as for Bentley. Bentley shares its view on how infrastructure sustains our society, the environment, and the professions in the white paper "Sustaining Infrastructure," available **here**. This paper shows examples of the creativity and innovative work of Bentley users that resulted in the successful completion of infrastructure projects that have contributed to this objective. Given that urbanization is accelerating worldwide, the battleground for sustaining infrastructure will be at the local government level. In response to this trend, this paper focuses on how the use of 3D city geospatial information systems can assist in sustaining infrastructure at the local level.

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The Case for a 3D City Geospatial Information System

Local governments are challenged by growing city populations, leading to increasing demands on local infrastructure. As existing infrastructure deteriorates in these dense urban areas, new infrastructure must be built, even though most areas of the world currently face decreasing financial and environmental resources.

Because infrastructure is the interface between people and the world, better design and management of our infrastructure leads to an improvement in the quality of life for all of us and the increased sustainability of the planet. An important aspect of quality of life is public safety, which is particularly relevant for local governments. Disaster prevention, response, and recovery are of critical interest to all local governments. This paper argues that a 3D city geospatial information system can significantly improve the ability of local governments to fulfill these responsibilities.

The role of a geospatial department within a municipality or a local government has long been important to infrastructure sustainability. A geospatial department's mission is to provide geospatial information for an entire municipality to support a wide range of applications related to infrastructure. These include urban planning, civil engineering, and utility projects. This geospatial information must meet the requirements of many stakeholders and must be accurate, up to date, exhaustive, and rich from a semantic point of view (i.e., it must be well classified with several descriptive attributes).

In the past, geospatial data[1] was mostly 2D, but interest in 3D maps has increased dramatically. Today, it's widely recognized that 3D city models for visual simulation help support urban planning, and the promotion of tourism on the web.

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1 In this paper we consider data and information as synonyms.

For example, for professionals involved in urban planning or urban renewal, simulations make it easier to make effective decisions leading to improvements in the long-term ecological and social health of the community.

Additional benefits of using 3D models for simulations include helping police officers learn how to safely drive their vehicles through city traffic in an emergency, and providing a better platform for generating realistic renderings of new infrastructure, especially if a temporal context, such as solar or seasonal studies, is required. 3D city models are also used for security applications such as landslide prevention or flood simulation. Consequently, it's clear that geospatial departments will rely more and more on the creation, management, and distribution of a 3D city model.

In applying 3D city models, geospatial departments within a municipality or local government have to determine how best to:

- Persist a 3D city model,

- Produce it or subcontract the production to service providers,

- Perform quality control and manage the updates,

- Warrant the accuracy of the managed and produced data (i.e., provide consistency between pretty illustrations and the built results),

- Deal with the growth of the 3D city model,

- Reuse existing data,

- Define 3D model specifications.

For infrastructure projects involving limited geographic coverage but requiring high accuracy 3D data, frequently the information provided by a geospatial department can't fill the need. In fact, the majority of needs answered by geospatial department maps don't involve detailed geospatial data or detailed 3D geometry. In cases where a high level of detail is required, a detailed survey of the terrain is conducted to generate an accurate Digital Terrain Model[2] and facilitate the creation of a 3D city model within the area of interest. Projects requiring this level of detail typically are managed independently, resulting in the loss of valuable information (i.e., detailed information that is discarded after the project is complete) and the potential for duplicating surveying/design efforts – since overlapping areas across multiple projects are surveyed several times. Consequently, improving the management of 3D modeling efforts is an important issue to optimize existing information use, as well as to maximize its return on investment.

Geocoordination provides an interesting avenue and its benefits are more and more obvious today. This fact is particularly well illustrated by web search engines that use maps and geocoordinated content. At the local government level, geocoordination reinforces the relationship between information technology (IT) and geospatial

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2 We consider digital elevation model (DEM) as a generic term referring to elevation data combined with interpolation technique allowing computing Z value for a given XY location. Digital terrain model (DTM) refers to a specific type of DEM describing bare earth topography void of vegetation and manmade features. A digital surface model is a specific type of DEM describing the surfaces of terrain, building, etc.

departments (providing geo-coordination skills). As part of their mission, IT departments are required to provide other departments, such as the civil engineering or water engineering departments, with technologies dedicated to information creation and management.

This is a particularly complex assignment, and these projects typically involve many challenges. Among them is a lack of interoperability among systems and information, the requirement to deal with large volumes of heterogeneous data (geospatial and non-geospatial information, 2D and 3D data, CAD files, Word files, PDFs, etc.), long project time spans (often several years or decades) and numerous stakeholders with different levels of responsibilities, skills and concerns.

This means that, in addition to making the determinations noted earlier, the geospatial/IT departments must also decide how to:

- Manage huge volumes of heterogeneous datasets (GIS files, CAD files, BIM files, Word files, etc.,) delivered by different sources,

- Deal with data describing existing city objects as well as on-going and future projects, often for the same areas,

- Deal with different project propositions for a similar area,

- Warrant and improve the effectiveness of data access and exploitation even with terabytes of data and several stakeholders,

- Do all of the above in a secure framework.

Hence, 3D city model production and improving large-scale infrastructure project management are significant challenges that geo/IT departments must address as they strive to improve infrastructure sustainability. Bentley's vision is to move toward an information management system suitable for geospatial as well as nongeospatial information – what it calls the 3D city geospatial information system.

3D City Geospatial Information System Defined

Bentley defines a "3D city geospatial information system" as information technology that provides the functionality required enabling the management of data, user workflows, and processes related to a city's infrastructure. It includes a reference 3D city model suitable for the management and geocoordination of detailed infrastructure information. This can provide information ranging from a geographic scale overview of the 3D urban assets to a detailed engineering view of specific infrastructure assets. It also provides a framework supporting the information lifecycle from its creation to its exploitation by different stakeholders.

Here's what each of the words in the phrase "3D city geospatial information system" means:

- 3D – acknowledges that we live in a three-dimensional world in which objects are not flat. Consequently information managed in a 3D city geospatial information system has to be geolocalized in a 3D space and geometries of the objects can be defined in 3D.

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- City – includes urban areas ranging from campuses, such as universities, to metropolitan areas large and small.

- Geospatial – emphasizes that a significant part of the managed information is localized on the Earth.

- Information – refers to the fact that 3D models should be semantically rich, beyond simple graphics for visualization, allowing a user to query city objects, their relation with other infrastructure assets, and the detailed engineering information used to build them.

- System – refers to the management of information. Workflows have to be managed in a secured and distributed environment, allowing all stakeholders to work as efficiently as possible.

For conciseness, the abbreviation "3D City GIS" will be used from here on in this white paper in reference to "3D city geospatial information system." "3D city information model" will be used only when referring to data and metadata and excludes the technology and management functionality for creating and exploiting the data.
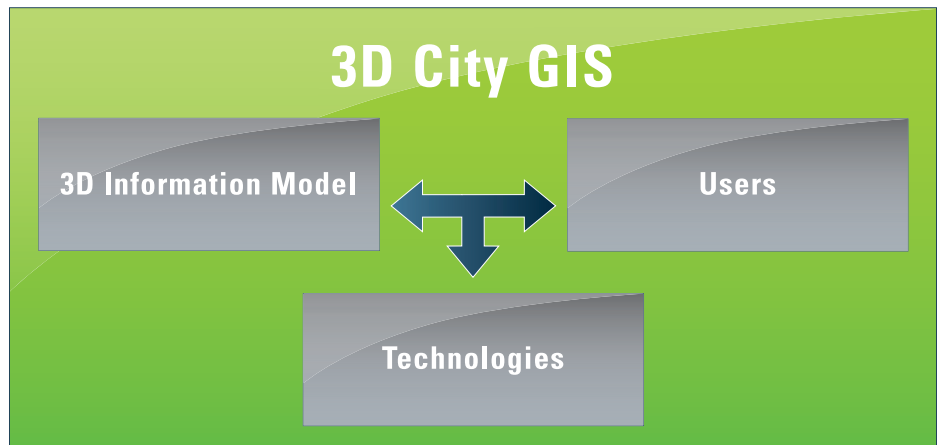

Figure 1: Relationship between 3D city information model and 3D City GIS concepts

The path to building a 3D City GIS will vary depending on priorities, budgets, resource constraints, responsibility of the municipality, its size and more. It is likely that the 3D City GIS will continually grow through the execution of specific projects, in parallel with the current system already in place. Creating relationships between 2D GIS data, 3D GIS data, and 3D engineering is not simple a task. Therefore, a 3D City GIS implementation should be viewed as an evolutionary process in which flexibility and scalability are fundamental characteristics of each of the 3D City GIS components. The following sections provide a description of 3D City GIS architecture and include guidelines for addressing geospatial/IT department questions and issues.

3D City GIS Components

Although each organization will take a different approach and adapt their system architecture diagram to their priorities, the primary functional components of a 3D City GIS are presented in Figure 2.
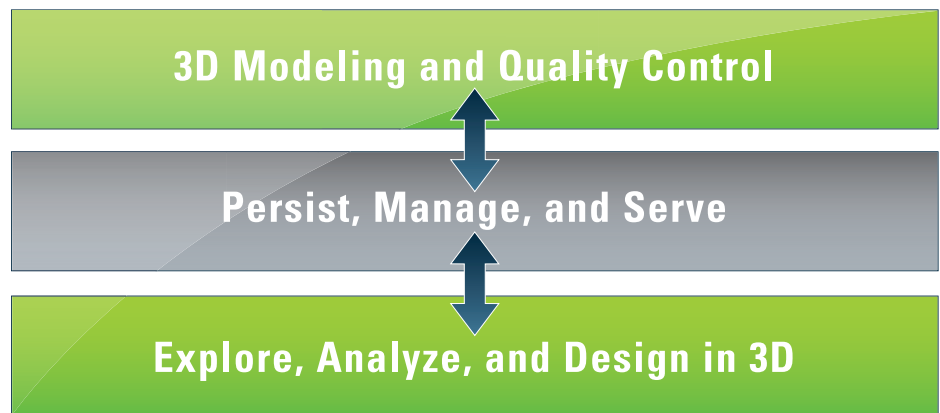
3D Modeling and Quality Control

Persist, Manage, and Serve

Explore, Analyze, and Design in 3D

Figure 2: Main functional components of a 3D city geospatial information system

These primary components are:

- 3D Modeling and Quality Control – Creating 3D models requires data, techniques, tools, and effort. Also, whether a municipality subcontracts the execution of the 3D models or creates them in-house, some quality control steps must be conducted before it can commit to the 3D City GIS.

- Persist, Manage and Serve – A scalable software platform is required in order to manage all the infrastructure related data, resources, and workflows, and to maximize control and productivity. The data can be persisted in various forms such as spatial databases, files, or even paper. Sharing information with the stakeholders, especially through the tremendous potential of the web, makes interoperability a key component.

- 3D Analysis and Design – The ultimate goal of the system is to enable consumers to make appropriate decisions for sustaining society and the environment. Those decisions can take shape in the establishment of a new design. This is made possible by visualizing and analyzing all of the available information.

In the following sections we will elaborate on the content of these logical components.

Persist, Manage and Serve

Persist, manage, and serve – the essential functions of the platform of the 3D city GIS platform – should provide a secure, collaborative, interoperable, and scalable environment:

- Secure because the 3D City GIS includes "sensitive" information, which can only be accessed and modified by authorized people;

- Collaborative because multiple distributed teams will need to interact to use and update the system;

- Interoperable because each stakeholder, either inside or outside the immediate organization, requires the use of the appropriate tools for his or her work and should not be forced to use a "lowest common denominator" environment;

• Scalable for cost-effectively satisfying a small municipality or project, as well as fully serving a large city with multiple projects, departments, and external actors.

With these characteristics in mind, let's review each functional component in more detail in Figure 3.
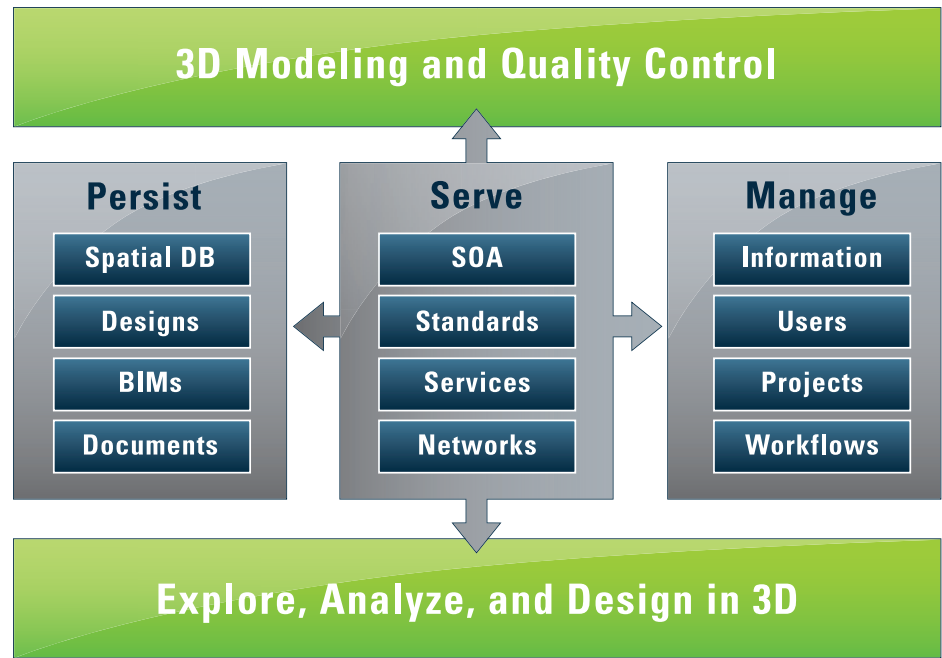

Figure 3: Main components of a 3D City GIS with emphasis on persisting, managing, and serving

Persist

Typically, city information related to infrastructure exists in a wide variety of data formats. This information, which is accumulated and maintained from the time the infrastructure was created to its ongoing use, includes:

• Landbase data such as aerial photos, digital terrain models, and street networks,

• Architectural and engineering designs, either in 3D or distributed as plans and profiles,

• As-built information captured after construction or renovation projects,

• Scores of documents such as bid packages, contracts, schedules, and right-of-ways.

The nature of this data varies from structured to unstructured. Structured refers to data that is associated with the data model describing the objects, their properties, and their relationships. The use of a data model facilitates searching and manipulation because the application knows exactly what kind of object is under consideration and its intelligence. Traditionally, GIS systems have used relational databases, which impose the use of a data model and, therefore, have been often referred to as intelligent applications manipulating intelligent data. Recently, most architectural and engineering applications have evolved around structured data like building information models (BIM)

or bridge information models. Although most users choose files stored in a file system as a repository, these applications also work with unstructured data.

Although these applications use files to store this data, these applications definitely work with structured data. Unstructured data refers to data without a formal data model describing the objects related to the infrastructure. This includes office documents, CAD files, calculations, scanned drawings, and even paper. One might think that this data is transient and nonessential, but it is well known in the infrastructure community that a very large percentage of decisions are made based on the content within unstructured data. Therefore, it is important that both structured and unstructured data be supported in the data repositories.

Two types of data stores can be used to persist information in a 3D City GIS:

• Spatial databases have the advantage of storing and indexing large amounts of data that can span a huge territory such as a city or region. For many years, spatial databases have been the preferred choice for GIS data and have enabled the storage of geometry such as 2D points, lines and polygons, along with traditional database properties. Examples of spatial databases are Oracle Spatial, ESRI geodatabase, PostgreSQL, MySQL, and the recent addition of spatial capabilities in Microsoft SQL Server. In the last few years, some software vendors have significantly expanded the range of data types. For example, Oracle Spatial 11G includes raster support for aerial and satellite images, 3D TIN for digital terrain models, 3D point clouds for Light Detection and Ranging (LIDAR) data, and 3D simple and composite solids, which can be used to represent infrastructure such as buildings. Although databases are evolving, they do not support all the geometry types required for AEC[3]. Spatial databases are not adapted to the management of unstructured data like office documents (e.g., Word, Excel, PowerPoint), digital paper (e.g., PDF) and multimedia e.g., video, voice, and animation), all of which are widely used.

• File systems present the advantage of being supported in all operating systems, and, therefore, do not require additional software investment and IT administration. File systems can deal with structured data as well as with unstructured data without requiring any conversion. They are a convenient way to store small to large quantities of data and exchange that data at detailed levels. File systems can also involve innovation and backward compatibility since application software vendors control the file format they use. As an example, for architects and engineers, a file format such as DGN, used in MicroStation, has been supporting 3D data for decades, and has support for specialized geometries such as spiral curves (clothoids, bloss, etc.) used in road design and innovations such as generative components for building designs. The drawback of files for geospatial data is that their access and query capabilities are less advanced than geospatial databases.

Considering that spatial databases and file systems each have an important role to play, a 3D City GIS should support both approaches for persisting a 3D city information model. For example, a large organization could use a spatial database for

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3 AEC: refer to lexilogos for a detailed definition

covering large areas with low granularity information and use file systems for detailed engineering information and unstructured information. Moreover, to support many advanced workflows, a 3D City GIS should also allow the managing and indexing of both to provide seamless navigation from spatial databases to files and back, which brings us to the management aspect of the 3D City GIS.

Manage

Modeling and maintaining a 3D city information model will likely require many internal and external resources working on multiple projects over significant periods of time. The city information for visualization and analysis purposes will also be used in multiple projects from different departments or organizations. In order to have a sustainable 3D City GIS with control over data quality, the management aspect becomes critical for everything involved in the system, such as the data/information, users, workflows, and projects. The primary management aspects to consider are described below.

Information: Multiple representation and levels of detail

Digital data stored in GIS, CAD, building information models (BIMs), and office repositories are used to describe real-world objects. The same object can have drastically different representations depending on the application that is manipulating it. For example, the representation of a building can range from a 2D point associated with a postal address to a rich 3D BIM including accurate geometry and rich semantic information. These representations of the geospatial objects can be structured according to their scales and referred as "level of detail" (LOD).

In some cases, multiple representations are available for the same scale – for example, a 2D building footprint for cadastre purposes vs. a 3D volumetric shape for noise propagation. Levels of detail and multiple representations require that several representations be available for the same real-world object. In addition to well-defined representations (defined with an explicit data model), many aspects of that same building will be represented and defined in a large number of unstructured files. Maintaining a link with these representations in different data models and related documents is also required for seamless searches. A 3D City GIS should support explicit relationships between multiple representations and levels of detail of the same real-world object.

Federated searching

A 3D City GIS should easily track available information from each data repository and easily support searches across multiple disparate repositories, also known as federated searches. For example, searching with a building address could result in a 2D and 3D simple representation from a spatial database, a detailed BIM from a managed file, a set of digital plans and profiles from a construction project, electrical schemas from scanned as-built drawings, contracts and construction schedules from office documents, and so on.

> A 3D City GIS should easily track available information from each data repository and easily support searches across multiple disparate repositories, also known as federated searches.

Because multiple persistency mediums such as databases and files are used, it is important to not only consider the metadata about the container (e.g., file name, date, and geographical coverage) but also the content of the unstructured information (i.e., indices to objects within the files, such as buildings, pipes, circuits, etc.). In order to maximize the benefits of the available information, a 3D City GIS should support federated searching.

Users and authorizations

Users from the back office (those modeling and maintaining the models), the mid office (IT administrators and project administrators maintaining the system) and front office (various levels of users accessing the system for visualization and analysis purposes) would require different levels of authorization depending on their position and role. Therefore, a 3D City GIS should provide a secured and controlled environment where user accesses are totally controlled.

Projects and workflows

A 3D City GIS will likely grow through multiple projects taking place over multiple years and involving internal and external resources. To manage the progress of the projects, allow collaboration, and ensure the quality of the data, the definition of workflows must be allowed where each state gives appropriate access to authorized users and a state change triggers automatic tasks such as messages, e-mails or archiving. A 3D City GIS should include project management capabilities.

Serve

Implementing a 3D City GIS suitable for the specific needs of each local government requires scalability and flexibility. Moreover, sustaining infrastructure typically involves users from multiple organizations with different needs and constraints. Practitioners typically use specialized desktop applications to interact with the 3D city information model, front office users might prefer web applications or collaboration portals, and field workers need mobile devices.

To satisfy such a broad set of heterogeneous users, a 3D City GIS should combine flexible solutions to bring information as well as editing, analysis, or design capabilities to different users on different platforms. A 3D City GIS should provide desktop and web applications with visualization and navigation capabilities across a 3D city information model including advanced web GIS capabilities.

In recent years, commonly characterized as the Web 2.0 generation, many organizations have evolved their web applications from a web-publishing -only paradigm to a web GIS environment, defined as dynamic interaction with data and a basis for collaboration. Software, such as Bentley Geo Web Publisher, has proven suitable for aggregating data from multiple sources to perform analysis as well as redlining.

Team collaboration on projects that involve visualizing and proposing modification improves the project quality and facilitates user adoption. While the benefits of web GIS applications are recognized today, most systems have offered this functionality with 2D data only. Even if the advent of virtual globes, such as Google Earth and Microsoft Bing Maps, has proved the viability and democratized 3D visualization on the web, those innovations do not meet many of a local government's 3D web GIS needs such as:

- Controlling the quality of the data, the frequency of updates, and the level of detail,
- Navigating and querying infrastructure inside buildings and underground,
- Bringing their sophisticated web GIS collaborative applications to the 3D world.

Although a 3D City GIS should have a lot of information about the city's infrastructure, many applications, whether they are desktop based, web based, or mobile, would require business processes that integrate the information of the 3D City GIS with information from other enterprise systems, such as SAP, ERP systems, work management systems, and inventory systems. Therefore a 3D City GIS should offer integration capabilities with other enterprise systems.

Achieving such scalability and flexibility in serving data and processes among different technologies (and different software providers not necessarily in the same domains) on different platforms (desktop, web, mobile) requires interoperability capabilities. Bentley is totally committed to the interoperability challenge and describes this vision in the "**Interoperability Platform White Paper**". A summary adapted to 3D City GIS is provided below and includes the role of a service-oriented architecture (SOA), the role of standards and proprietary file formats, and application programming interfaces (APIs).

Service-oriented architecture

A service-oriented architecture can be defined as a group of services that communicate with one another. The process of communication involves either the passing of simple data or could involve two or more services coordinating some activity.

A 3D City GIS would ideally be implemented with a series of specific and well-defined services that can be combined and reused in the production of applications. In fact, in the context of the 3D City GIS, one can imagine a series of "city infrastructure" services that can be combined into the required applications. Some services would be more data-centric, such as one for each city object type (terrains, buildings, and transportation networks) or for the information system objects (documents, projects, workflows, and authentication).

These services can be combined into more complex services such as 3D scenes, 2D maps, plans and profiles, 3D thematic, and plotting. Other more business-centric services would provide analysis capabilities such as solar studies, noise propagation, line of sight analysis, network tracing, and so forth.

In recent years, commonly characterized as the Web 2.0 era, many organizations have evolved their web applications from a web-publishing only paradigm to a web GIS environment, defined as dynamic interaction with data and a basis for collaboration.

Role of standards

In order to maximize interoperability among the multiple software applications required by the stakeholders, the 3D City GIS should support public and proprietary standards used for file import/export, as well as for communication between services.

The use of web services, discovered and used through standard protocols, appears to be a productive environment for rapid development of server-side processes. Probably the most widely used service protocol is the combination of XML over HTTP, sometimes referred as Plain Old XML (POX). This is the protocol currently used by the Open Geospatial Consortium standards, such as WMS (Web Map Service) and WFS (Web Feature Service). However, in business-to-business system integration, a series of standards (i.e., SOAP, WSDL, and UDDI) has been adopted by major enterprise systems vendors.

Compliant web services can be discovered with UDDI (Universal Description, Discovery and Integration), understood with Web Services Description Language (WSDL) and consumed with Simple Object Access Protocol (SOAP). In order to create a business process that combines and executes a sequence of web services, the Business Process Execution Language (BPEL) standard is also supported by major software vendors. Lastly, another protocol gaining popularity for large commercial sites is Representational State Transfer (REST). Its growth is primarily due to its simplicity and scalability.

The data exchange standards lists below are of particular interest and required for the city information system:

- CityGML from OGC (www.opengeospatial.org) is a new XML-based standard adopted in 2008 specifically designed to exchange 3D urban objects (i.e., terrain, buildings, bodies of water, transportation objects, vegetation objects, city furniture, and land use). As described in the **www.citygml.org** site, CityGML defines the classes and relations for the most relevant topographic objects in cities and regional models with respect to their geometrical, topological, semantic, and appearance properties. These include generalization hierarchies between thematic classes, aggregations, object relationships, and spatial properties. This thematic information goes beyond graphic exchange formats and allows the use of virtual 3D city models for sophisticated analysis tasks in various application domains like simulations, urban data mining, facility management, and thematic inquiries.

- PDF initially from Adobe has now been adopted as an ISO standard (**www.iso.org**). Although PDF originally targeted a 2D space, support for embedded interactive 3D scenes was added in Adobe Reader 1.6. Adobe Reader offers many tools for manipulating the 3D scene like interactive navigation, animations, and control over lightning effects and render modes. Objects can have attributes that can be reviewed and queried. In 2008, georeferencing capabilities were added with the release of PDF 1.7.

- IFC from IAI (**www.iai-international.org**) is an object-oriented file format with a data model that was developed to facilitate interoperability in the building industry. It is a commonly used format for BIM and can include all the details required for

construction projects and lifecycle management. It also includes tangible items (e.g., doors, windows, fans, ceilings, and abstract concepts (e.g., schedule, activity, and space organization).

- LandXML from (**www.LANDxml.org**) is a specialized XML data file format containing civil engineering and survey measurement data commonly used in the land development and transportation industries. It is meant to be used for:

  » Transferring engineering design data among producers and consumers,

  » Providing a data format suitable for long-term data archival,

  » Providing a standard format for electronic design submission.

- KML initially from Google Earth has now been adopted as an OGC standard (www.opengeospatial.org). KML is also an XML-based language schema for expressing geographic annotation and visualization. Its best known implementation has been for web visualization in Google Earth, which has seen tremendous adoption in recent years.

The use of standard web services will bring the benefits of a SOA into multiple applications. In the context of a 3D city, the following standards are gaining in adoption:

- Catalog Service for the Web (CS/W) from OGC (**www.opengeospatial.org**) proposes a set of services to publish and access digital catalogs of metadata for geospatial data, services, and related resource information.

- Web Feature Service (WFS) from OGC (**www.opengeospatial.org**) allows queries and web editing of 3D simple features.

- Web Map Service (WMS) from OGC (**www.opengeospatial.org**) is the most widely adopted web service from OGC and, although it is limited to 2D renderings, a WMS layer can often be used as a backdrop in a 3D scene.

Role of proprietary file formats and application programming interfaces

As mentioned earlier, proprietary file formats offer some advantages regarding innovation and can be synonyms of backward compatibility. It also frequently happens that such proprietary file formats are considered de facto standards due to their effective use by the industry. This is the case, for example, with DGN, DWG, and SHP file formats. Consequently, a 3D City GIS should support proprietary file formats required by its applications and the main industry file formats.

For broader adoption, some proprietary formats, like DGN and DWG, have been made available through the Open Design Alliance (**www.opendwg.org**). Some software vendors are also signing specific agreements to allow even more integration, such as the **recent announcement between Bentley and Autodesk**. For similar reasons, communicating through standard services doesn't allow users to reap the benefits of all data and processing capabilities offered by a technology. Sometimes a standard simply does not exist. In such cases, technology integration can be accomplished through application programming interfaces (API). One approach is to use API's to develop a point-to-point solution for a specific mission-critical application.

Bentley has defined a more comprehensive and scalable approach to support loosely coupled workflows involving multiple proprietary systems and applications. These workflows are referred to as "federated information workflows." In this context, the APIs are used to publish and consume "i-models," which are managed, transformed, and delivered through Bentley's ProjectWise servers.

Persist, Manage, and Serve with Bentley: All These Capabilities in One System

Bentley developed the Bentley Geospatial Server, based on ProjectWise, to take benefits from both file repositories and geodatabases. It provides a unique flexibility that allows Bentley users to choose the best persistency strategy. Bentley is committed to supporting standards such as WMS, WFS, GML, LandXML, and LAS. In addition, the Bentley Geospatial Server supports major file formats such as DWG, DXF, SHP, DOC, and PDF.

The Bentley Geospatial Server allows access to spatial databases such as Oracle Spatial and ArcSDE, and responds to all the requirements relative to users, projects, and workflows. By indexing the spatial location and the content of engineering files, office documents and spatial databases, federated searches can be performed without data conversion to find the required information.

Bentley technology also makes information sharing possible for end users and other technologies. In fact, many Bentley products bring valuable information to different kind of end users. The architecture of Bentley products, as well as their adoption of standards and advanced APIs, allows communication with third-party technology for enterprise integration (e.g., SAP and SharePoint).

3D Modeling of Existing City Objects

Several techniques can be used and combined to produce a 3D city information model of existing city objects. Depending on the municipality's strategy, data production can be performed externally by service providers or internally by a geospatial team. In either case, quality control is generally the domain of the city geospatial department.

The integration of the data production tools with the management platform is an important aspect when considering 3D City GIS. Indeed, the ability of data production tools to directly populate the destination file or databases reduces import/export tasks and consequently reduces translation issues (e.g., time spent for such conversion and possible lost of information). It also helps with quality control since each transaction is recorded and managed by the persistence platform with references to the source of information without intermediate export/import stages. A data manager who needs to assess the quality of a geometric component can, for example, audit that this geometry has been extracted with a LIDAR tool by a given technician. The data manager can also reuse the same LIDAR tool to directly compare the geometry with the reference point cloud.

The following section describes available data production techniques, and summarizes their benefits for the main object classes.

Modeling Techniques

The techniques used to model existing city objects can be grouped into three categories: terrestrial surveying techniques, aerial surveying techniques, and integration processes that transform and deliver content in the appropriate format to multiple stakeholders and systems. Aerial and terrestrial surveying techniques share the same underpinnings of photogrammetry and LIDAR sensing. Each of these techniques has pros and cons and its interest depends on the context. Consequently, a 3D City GIS should offer an extensive range of 3D modeling capabilities. Choosing a modeling technique should be based on the best compromise between cost and fidelity. The criteria to be considered are "level of detail" (i.e., scales, accuracy, and data model), object classes, and available data.
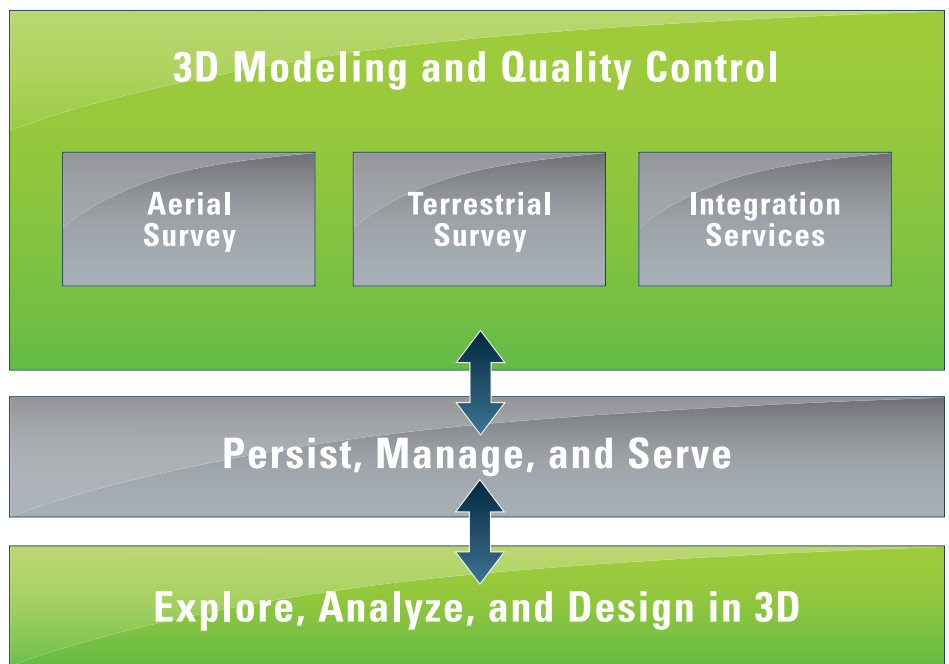

Figure 4: Techniques for modeling existing city objects

Photogrammetry and LIDAR

Photogrammetry is perhaps the oldest remote sensing technique and is defined in the fourth edition of the Manual of Photogrammetry as "the art, science and technology of obtaining reliable information about physical features through the process of recording, measuring and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena."Photogrammetry is generally used by combining pairs of images, stereo images, to extract 3D information (e.g., location and shapes) of the object observed on the images.

Stereo photogrammetry is the primary technique used to extract 3D geometries from photographs. Mono-plotting based on Digital surfaces models (DSM)[4] can also be used to extract 3D geometries. The user, without any stereo-viewing capabilities, is then able to measure in 3D, but the accuracy depends on the accuracy of the DSM. Photogrammetry is particularly mature and has been used for several decades by mapping agencies.

LIDAR is an optical remote sensing technology that, for a given direction, is able to determine distance between the sensor and an object or a surface. When such a sensor is static or combined with positioning systems (i.e., GPS and inertial measurement units) it allows for remote generation of a 3D point cloud describing the observed scene (e.g., a city scanned from an airplane or a building facade scanned from the ground).

LIDAR sensors can also be combined with digital cameras acquiring RGB, multi-spectral, or hyperspectral information. Such sensor combinations allow the association of spectral data (i.e., RGB) to each acquired point. This facilitates the visual point cloud interpretation and can be used to improve automatic classification. These images, combined with a 3D point cloud, can be used for accurate 3D mono-plotting. LIDAR sensing is a widely adopted mature technology. But the growing amount of data being generated creates new challenges that the processing software needs to address. Interesting software solutions are already available, but we can expect important progress in the coming years regarding the management of huge point cloud datasets, automatic classification, and semiautomatic feature extraction.

Both photogrammetry and LIDAR can be used independently either for aerial or terrestrial surveys. However, terrestrial photogrammetry is only used marginally. In a 3D city modeling context, for example, terrestrial LIDAR is usually combined with images.

Aerial survey using photogrammetry

Aerial photogrammetry has been used for several decades as the main mapping technique for extracting the geometry of the ground, buildings, roads and other features. Most of these feature extraction processes are still performed manually, even if automatic digital surfaces models and digital terrain models[5] extraction can provide better results in good conditions. Automatic DTM extraction algorithms are often suitable for projects in urban areas or in areas without dense vegetation. Such automatically generated DSM are generally not accurate enough for true-ortho production, but can be used as support for feature extraction.

Aerial images provide extraordinary support to end users in understanding geospatial context quickly. The success of Google Earth and Bing Maps illustrates that. The geometry of the acquired aerial images can be rectified to generate ortho-images (with DTM) or true orthophoto (with DSM) to be part of a 3D city model.

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4 Refer to glossary section for a definition of DSM
5 Refer to lexical for a complete definition

Aerial survey using LIDAR

Point cloud data acquired with LIDAR on an airborne platform is a new type of data that offers value in tackling mapping issues, including 3D city model creation. LIDAR provides accurate ground points suitable for DTM creation almost directly, and allows automatic feature extraction if the point density is detailed enough. An added advantage when compared to photogrammetry is its capacity to extract DTM even with vegetation. Indeed, the penetration capacity of the LIDAR pulses is such that, for an area with dense vegetation, returns describe not only the top of the trees but also the ground. This phenomenon allows for an automatic discrimination of the vegetation and the ground.

Aerial LIDAR data allows for almost automatic extraction of 3D building, vegetation, and ground data for medium accuracy levels of detail. The main planes of the building roofs are extracted, but without details like windows or chimneys.

> Aerial LIDAR data allows for almost automatic extraction of 3D building, vegetation, and ground data for medium accuracy levels of detail.

Aerial survey combining LIDAR and photogrammetry

As mentioned, combining LIDAR and digital cameras enriches the acquired data. However, combining these sensors is not widespread in the aerial context. Indeed, it can result in an increase in flight cost since adding a digital camera increases the flight's constraints. Operating a LIDAR sensor alone is done without concern for either light conditions or cloudy skies.

LIDAR sensors can be operated at night. Consequently, adding a digital camera requires that flight planning also consider the weather and the season. But operating a LIDAR sensor also involves specific constraints: the LIDAR sensor's field of view is smaller than that of large photogrammetric cameras and thus requires more stripes. The sum of the constraints for the two techniques can sometimes dictate performing two independent flights, rather than a single one. Consequently, combining aerial LIDAR and aerial photogrammetry involves an increase in flight costs, which must be balanced with the effective benefits during the following processing steps.

Terrestrial survey by land surveying

Land surveying is based on optical measurement systems and allows the surveyor to compute the three-dimensional coordinates of the objects he or she identifies. It's a time-consuming process because it requires the field operator to identify explicitly each point and line to be surveyed. On the other hand, office post processing is relatively quick since only relevant information is collected and drawing steps can be automated. Indeed, geocoding (i.e., introducing codes during the survey, which defines the object classes, and beginning and ending point) can reduce office drawing time. This technique is particularly suitable for large-scale surveying aimed at producing topographic maps.

Terrestrial survey by static LIDAR and photogrammetry

The use of LIDAR sensors for terrestrial application has also grown significantly in the past decade. Sensors are improving each year by increasing their speed, portability, and accuracy. Most sensors combine digital cameras, which are mounted co-axially. In the terrestrial context, using a combination of LIDAR and digital cameras is more generalized. Images acquired by the digital cameras are directly georeferenced (i.e., position and orientation) with the scan registration since their relative location on the scanner is a known parameter (obtained through a calibration process).

Terrestrial LIDAR sensors have many advantages. They allow fast remote 3D measurements, which reduce in-field time and improve security, since operator doesn't have to touch the objects to be surveyed. They are suitable for a wide range of applications including 3D city modeling: building facades, indoor building, bridges, and streets.

Terrestrial survey by mobile LIDAR and photogrammetry

Different sensors can be combined and mounted on the same vehicle (i.e., a car or a train) to reduce weight and overcrowding. Today, several hardware providers, or integrators, offer terrestrial mobile platforms combining GPS, IMU, several LIDAR sensors, and digital cameras. These solutions are particularly relevant for detailed 3D city modeling since they can provide quick detailed datasets describing road networks and building facades. Indeed, tens of linear kilometers can be acquired per hour with oblique-oriented images and point clouds.

These kinds of platforms are relatively new and are still progressing rapidly, so their operational costs are not yet well known. Such costs are mostly defined by the sensing hardware since, as opposed to flying an airplane, driving a car or a small truck doesn't involve specialized skills, nor does it involve any legal issues. As a reference, operating such platforms seems to be two or three times less expensive than operating aerial platforms. The processing challenges are similar to those of static terrestrial platforms, but with an additional challenge: a dramatic increase in data.

Integration processes

Since most municipalities in the developed world already have plenty of data, the reuse of this data is an avenue to reduce production costs and can be part of the 3D City GIS strategy.

In the context of 3D city information model creation, this reuse can take shape in different ways requiring data integration. For example, it can be using existing 2D digital data describing building footprints and performing extrusion using height values stored in a database. It can require a wide variety of formats as well as automatic analysis capabilities such as doing optical character recognition on raster document or doing automatic text matching in a Word document to find a postal code. Quality management is particularly important when such integration processes are used. Indeed, combining different data sources can result in uneven quality through the data set. Efficient persistence and management of metadata is particularly crucial in this context.

Modeling Existing City Objects

In the context of a 3D city model, the main objects that can be modeled are the following: ground, buildings, transportation network, bodies of water, city furniture, electric/power lines, and vegetation objects. For each of these object classes, a description of the suitable capture techniques is proposed hereafter. Since the choice of the technique is related to the LOD (level of detail), we frequently refer to the CityGML taxonomy to define the modeling specification. CityGML defines five levels of detail numerated from zero to four. These are defined such that:

- The coarsest level LOD0 is essentially a two-and-a-half dimensional digital terrain model, over which an aerial image or a map may be draped.

- LOD1 is the well-known block model comprising prismatic buildings with flat roofs.

- In contrast, a building in LOD2 has differentiated roof structures and thematically differentiated surfaces. Vegetation objects may also be represented.

- LOD3 denotes architectural models with detailed wall and roof structures, balconies, bays, and projections. High-resolution textures can be mapped onto these structures. In addition, detailed vegetation and transportation objects are components of a LOD3 model.

- LOD4 completes a LOD3 model by adding interior structures for 3D objects. For example, buildings are composed of rooms, interior doors, stairs, and furniture.
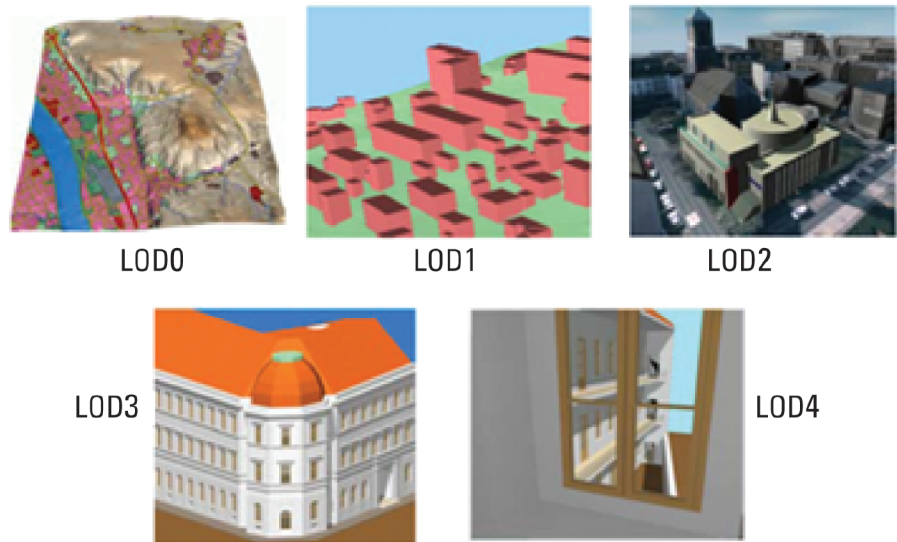

LOD0   LOD1   LOD2

LOD3   LOD4

Figure 5: The five levels of detail (LOD) defined by CityGML (source: IGG Uni Bonn)

Readers may find detailed information related to CityGML on the **CityGML website**.

Digital Terrain Model Creation

DTMs are composed of 3D points and break lines. All of the techniques mentioned before can be used to generate 3D points. Aerial photogrammetry and aerial LIDAR are suitable for wide coverage, while terrestrial techniques are more appropriate for localized or detailed surveys. 3D point measurements by aerial photogrammetry are accurate, but done manually most of the time. With dense vegetation, aerial photogrammetry doesn't allow fixing the ground point, since the ground cannot be discriminated. Aerial LIDAR is definitely faster since the automatic classification of the ground points requires only a few manual corrections. It also allows discriminating vegetation and ground even with dense vegetation conditions.

Break lines are of high importance in the DTM definition, particularly near infrastructure like roads or ditches. In opposition to the point extraction case, aerial LIDAR is not adapted for break line extraction. Indeed, defining break lines requires a planimetric accuracy, which is attainable with aerial LIDAR only by increasing the point density. Additionally, the process of extracting break lines from LIDAR data is not automated today. Photogrammetry allows accessing the required planimetric accuracy, and stereoviewing allows the operator to get 3D relief perception required to extract the break lines.

The choice between aerial LIDAR and aerial photogrammetry depends on the importance and availability of break lines in the project, and of the necessity of acquiring ground points. For example, if road networks are already defined in 3D, but important vegetation areas have to be surveyed, then aerial LIDAR may be more suitable. On the other hand, if there are very few vegetation areas while most of the road network must be acquired in 3D, photogrammetry may be a better choice.

Land surveying and terrestrial platforms mounted on mobile platforms are suitable for both break lines and point extraction at a large scale. But, they are restricted to areas easily accessible, and are more adapted to reduced coverage.

Accessing existing data is also a useful way to integrate points as break lines in the DTM. In these cases, the integration challenges are mainly related to interoperability, in that external sources must be handled carefully to avoid inconsistency from a quality standpoint.

Buildings

Buildings play a major role in 3D city models. If we refer to the CityGML taxonomy, the survey of LOD0, LOD1, and LOD2 is generally addressed either by aerial based techniques or by the integration of existing data for cost considerations. LOD2 textures, LOD3, and LOD4 generally require terrestrial approaches in order to get the expected accuracy.

Block models (e.g., CityGML LOD1) can easily be generated through several mechanisms. If existing 2D data describing the building footprints is available with height as an attribute then transformation processes can be used. Another possibility is to

compute the building height either from LIDAR data or by stereo-photogrammetry. Without existing building footprints, good automation levels can be achieved with aerial LIDAR data if the point density is detailed enough (six points per square meters) and if the building shapes are not too complex. Manual capture of complex cases (i.e., many planes defining the roof, footprint not only composed of rectilinear elements) is still needed and can be performed with photogrammetric tools or LIDAR tools.

As for block models, buildings with a simple roof structure (e.g., CityGML LOD2 without details defining chimneys or windows) can be generated by combining existing foot-print 2D data with a LIDAR high-density point cloud. Since the feature extraction task is more complex than LOD1, more manual corrections have to be performed. Key factors are the complexity of the architecture, the vegetation, and the point density.
The textures of the walls can be acquired by terrestrial survey or using aerial oblique images. Street width and building height are limiting factors.

As soon as details like chimneys or windows are required (i.e., LOD2 and higher), LIDAR techniques are no longer suitable. Today, such highly detailed roofs have to be acquired by a manual photogrammetric process. The building façade and inner structure are usually acquired by land surveying or using terrestrial platforms. Mobile platforms offer a straightforward way to effectively collect the façade data of a city.

When architectural plans are available, transformation techniques can also be used to convert the existing architectural data to a 3D model at a level of detail suitable for the 3D city information model. This can involve the vectorization of raster plans or the simplification of existing IFC files. The suitability of such techniques depends on the quality of the available data and on the expected quality of the 3D city information model. Indeed, even if a 3D architectural model defining the project is integrated in a straightforward way, its consistency with the as-built reality will usually still need to be established.

Transportation network

Transportation networks can be surveyed using the techniques already introduced. Again, the LODs determine if an aerial or terrestrial approach is more appropriate. Both aerial photogrammetry and aerial LIDAR require human intervention for the capture of the networks. The geometry of the area to be covered is a key element in choosing between these two techniques.

For corridor surveys like highways, LIDAR techniques can be chosen since the reduced field of view of the LIDAR is not a problem, and the LIDAR allows for automatically generating a model of the ground surface corresponding to the roads. On the other hand, if wide, nonlinear coverage is required, photogrammetry can be more suitable. Indeed, the large field of view of the photogrammetric cameras reduces the number of needed stripes, and thus the flying cost.

For large scale survey with a limited extent, land surveying and static terrestrial LIDAR are both relevant techniques. The terrestrial LIDAR offers many benefits since it reduces the field time for road areas that may be particularly dangerous. Large-scale

> Multiple techniques can be used to model and render 3D buildings at various levels of detail to create a realistic 3D City model.

surveying of a wide coverage is the use case targeted by mobile terrestrial platforms. Large volumes of information can be quickly collected less dangerously. Similar platforms also exist for railways.

Transformation tools can also be used if existing data is available. In addition to the file format and data model issues, transportation networks can also require that several spatial referencing systems be used (i.e., geographic vs. linear referencing along the network). Such additional difficulties have to be considered when integrating network data.

Water

Water is an important object class due to its role in sustaining life but also for safety issues, since flooding is a source of major disasters. A distinctive aspect of water features is their dynamic character. Indeed, water levels depend on tidal variation and precipitation levels, making them particularly difficult to model.

The representations of water features can be highly generalized (as in LOD0 and LOD1 in CityGML) and focus on the water surfaces (visible from the sky). Such description can be surveyed using aerial LIDAR and aerial photogrammetry. The use of aerial LIDAR simplifies the post processing since the water surfaces can be extracted with a high level of automation. However, the accuracy impacts of (1) the LIDAR pulse penetration in the water surfaces and of (2) the water surface's discontinuity are not well known today. Such accuracy considerations are more important when higher levels of detail are required (i.e., LOD2 in CityGML and higher).

Additionally, for those detailed levels, the underwater topography can be modeled (i.e., LOD2 and higher in CityGML refers to water ground surfaces) and water bodies are defined as volumetric objects. The bathymetric surveys of the bottom of water bodies are generally done using sonar sensors and positioning systems mounted on boats. Aerial LIDAR techniques using a specific wavelength capable of penetrating water (SHAUL) have emerged in recent years, but are not widely adopted today. When existing data is integrated (transformation process), the management of geodesic systems requires specific attention, since marine maps frequently use different coordinate systems.

City furniture

City furniture generally corresponds to high levels of detail and requires large scale surveying techniques. It covers a wide range of object types (i.e., public benches, bus stops, and street lights) that can be represented by common prototypical geometries. For example, several trees will be represented by a single 3D shape referred several times in the 3D model. From a survey standpoint, this dictates that modeling components are less important and that surveying such objects mainly involves their identification and the measurement of specific parameters (i.e., insertion point and orientation). Land surveying and mobile terrestrial platforms can be particularly efficient for such purposes.

Electric/power lines

Aerial-based techniques are preferred for surveying high tension power lines. These surveys are considered as "corridor" surveying because they involve linear elements. Photogrammetry requires manual measurement since automatic correlation techniques are handicapped by the complexity of the objects and the surrounding vegetation. LIDAR is particularly suitable for such applications. It offers a higher level of automation, allowing a classification of points corresponding to ground, vegetation, and power lines. Additionally, the power line geometries can also be semi-automatically extracted.

Vegetation objects

Vegetation objects can be acquired using terrestrial and aerial techniques. The use of aerial photogrammetry allows human-based photo-interpretation, which can be relevant if species are required. The drawback of photogrammetry is the low level of automation for the trees extraction. Therefore, this technique is more interesting to extract plant cover area than to extract individual trees. Vegetation extraction is well suited to LIDAR automation possibilities. Solitary trees and height of plant cover can be extracted during the automatic classification of the point clouds. Such automatic processes may also progress with hardware improvement involving multiple return analysis or full waveform analysis.

	Aerial		Terrestrial			Integration Services
	Photogrammetry	LIDAR	Mobile LIDAR & Photogrammetry	Static LIDAR & Photogrammetry	Land Surveying	
0–DTM	■	■				■
1–Blocks	■	■				■
2–Textures, Roof	■	■	■		■	■
3–Detailed	■	■	■	■	■	■
4–Interior			■	■	■	■

Figure 6: Matrix of 3D City Modeling techniques

3D Modeling of Existing City Objects with Bentley

The users of Bentley software users have the unique opportunity to employ all of the 3D modeling techniques on the same 3D platform, which improves workflow management and quality control. In fact, TerraSolid products (i.e.,TerraModeler, TerraMatch, etc.), are powerful software applications for aerial LIDAR processing based on MicroStation®. Most of the stereoplotters on the market have direct connection to MicroStation, including Leica LPS-PRO600; Intergraph ISFE for MicroStation; DVP; DATEM; ESPA; KLT atlas/DSP; Photomod Racurs; Usmart; VirtuoZo; MSMapper; and BOIENG IDS/Softplotter.

These links allow for real-time modification of the geometric object managed by MicroStation, and provide a direct integration between data production and management because it doesn't require any import/export. This is particularly useful in an update or a quality control context in which the stereo-plotter can directly be used to control the geometry stored in the persistency platform (e.g., DGN and Oracle).

Bentley offers a wide range of applications to support land surveying processes, both in the field and at the office (e.g., PowerSurvey, InRoads® Survey, and GEOPAK® Survey). Users have the opportunity to process terrestrial LIDAR directly in MicroStation with Bentley CloudWorx and PHIDIAS. PHIDIAS offers additional photogrammetric capabilities including point-cloud-based monoplotting. Efficient management tools are required to deal with the datasets as they are processed. Bentley® Geospatial Server provides a powerful management platform for geospatially indexing these datasets and allows supervision of each step of the processing workflow.

The users of Bentley software have access to tens of file formats and databases, which can be relevant in a 3D city modeling context. These include many GIS file formats (e.g., shp, geodatabase, and MapInfo), as well as architecture file formats like IFC used for building information models, or civil file formats such as LandXML. Additionally, these users can benefit from standards like LAS for LIDAR data or GML for features. A wide range of image file formats are natively supported in MicroStation and can be combined with OCR algorithms and when using Bentley Descartes text information can be extracted.

Explore, Analyze and Design in 3D

The reason for establishing a 3D city information model is to support decision processes for a wide range of applications including road design, urban planning, and land planning. Such decision processes require not only data, but also dedicated decision-making tools.

Exploration of 3D city information models corresponds to the process of finding and discovering information in the sum total of available data. Finding refers to the case in which a user is looking for specific information and discovering refers to the case in which a user finds something accidentally. Analysis aims to enrich the available information by computing specific measurements (e.g., area of a parcel) or solving specific

problems (e.g., compute the optimal shortest itinerary). Lastly, the design process of new infrastructure generally starts from an exploration and analysis process.
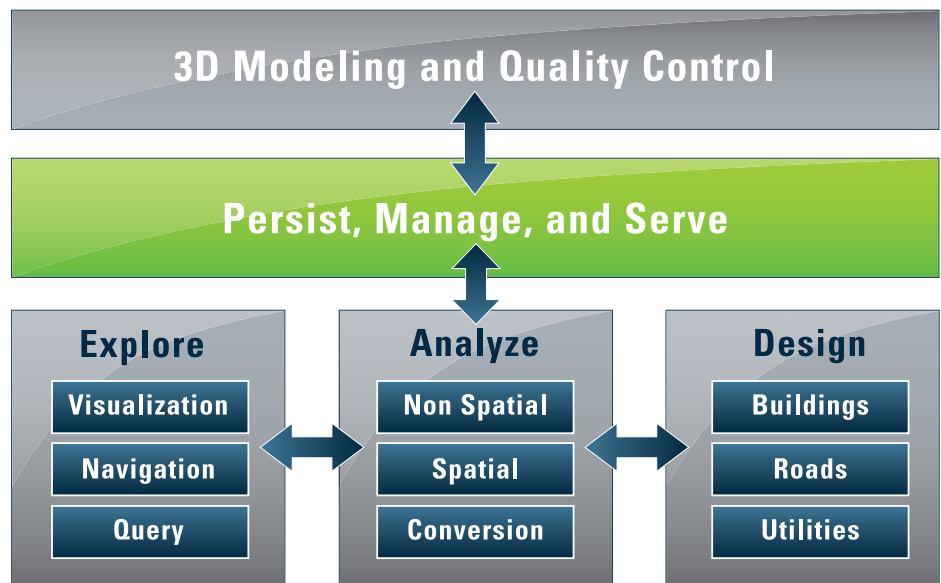
3D Modeling and Quality Control

Persist, Manage, and Serve

Explore
- Visualization
- Navigation
- Query

Analyze
- Non Spatial
- Spatial
- Conversion

Design
- Buildings
- Roads
- Utilities

Figure 7: Using the 3D City GIS through exploration, analysis and design

Explore: 3D Navigation and Querying

3D city information modeling exploration through 3D navigating and querying is particularly crucial since its purpose is to extract the relevant information in the available data. In a 3D world, high-density infrastructure and data volume make this challenging.

3D visualization[6] and navigation of 3D maps provide a powerful way to explore a 3D city information model by visualizing the data through different points of view and by supporting simple querying capabilities. 3D visualization allows users to easily understand large amounts of information. There are two factors that make this possible:

1. Humans have an extraordinary capacity to understand 3D scenes. In fact, everyday 3D scenes are always full of information but easily understood.

2. Advanced rendering techniques allow the generation of virtual images of 3D scenes by modeling complex physical phenomenon like light propagation, shadows, material roughness, and more.

Navigating in 3D is, of course, important since it allows the user to define his or her viewpoint (i.e., zoom level and area displayed in the view) from which to observe the 3D model. 3D navigation requires users to express movements by mouse "clicks and drags" or by key-ins. Consequently, the ergonomics of the interface are particularly important when addressing 3D navigation.

Navigation can also be simplified by reducing degrees of freedom used to navigate in

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6 Process of representing a 3D scene on a 2D support such as a computer screen

a 3D city information model. For example, navigation can be constrained to keep the observer on the ground (and/or along a specific path and/or without crossing objects). Allowing such navigation constraints, as opposed to free fly-through navigation, is particularly relevant when users who are not 3D experts, such as like politicians or members of the public, are accessing the system.

System requirements and simple access are two other important aspects to consider when providing 3D visualization or navigation to nonexpert users. Consequently, a 3D City GIS should also include simple 3D visualization and navigation capabilities without requiring sophisticated technology or applications.

Even if well structured, the information is not always expressed geometrically. The 3D visualization and 3D navigation of a 3D city information model has to be completed by other tools to visualize and access the semantic or nongeometric data. For example, tables with sort and filter capabilities or graphic charts are particularly useful to visualize nongeometric information.

Queries are another way to extract and find information in a 3D city information model. Different querying techniques (e.g., dedicated graphical user interface and dedicated application programming interface) can be considered depending on the query complexity and on the user's skills. Displaying and querying tools are major features of a 3D City GIS.

3D city information models can also include unstructured data. But, with unstructured data, the classical DB/GIS querying approaches are not suitable. Therefore, providing search engine capabilities is a key issue in deriving benefits from the available unstructured information. The querying tools in that context must be as flexible as possible by supporting free text search on data as well as metadata. Query capability for unstructured data plays a major role in the construction of a 3D city information model so as to avoid conversion and integration within the centralized data model.

Due to the richness and complexity of the data managed in a 3D city information model, there are multiple requirements to support data exploration (e.g., 3D visualization, navigation, and structured data based querying as unstructured search). A 3D City GIS needs to offer such capabilities and then provide users with the flexibility to take advantage of the 3D city information model. Bentley offers several 3D visualization and 3D navigation capabilities, including MicroStation, ProjectWise® Navigator, export to 3D PDF, and export to KML/Google Earth. These products feature strong querying and searching capabilities for structured and unstructured data stored in databases or files repositories, including ProjectWise Explorer with a Geospatial viewer and Bentley Map® and Oracle connectors.)

Analyze

The information directly managed in a 3D City GIS is not always enough to support decision processes, but it can be enriched or transformed by semi-automatic computing. Analysis aims at enriching the available information by computing specific measurements (e.g., overlapped area between two shapes) or solving specific problems (e.g.,

compute the optimal shortest itinerary). These analysis processes can involve all the information managed in the 3D city information model: geometric, semantic, geospatial, structured and unstructured data. Depending on the application, it can take forms such as:

- Noise propagation simulation: This combines a 3D city model (i.e., geometry and description of object surfaces) and a mathematical model of 3D wave (i.e., audible domain) propagation in the air to establish a map of noise.

- Flood simulation: This combines a 3D city model (i.e., geometry and description of object surfaces) and computational fluid dynamics. It should include mechanical properties of dikes, dams, and other infrastructure.

- Lines and zones of sight studies: This combines a 3D city model and a light propagation model to establish what points and areas are viewable.

- Geo-statistical analysis: This form extracts statistical measurements (i.e., average age, median revenue, etc.) related to the population living in different areas of the city.

Non-geospatial analysis

Analysis requirements in the context of a 3D city information model include non-geospatial analysis tools that leverage all available information. Requirements for non-geospatial analysis tools depend on the amount and nature of the managed non-geospatial information. It can include statistical functions, capacity to establish joins between tables, and more advanced database analysis techniques such as dashboards or data mining. Some of these techniques are also useful to extract geo-information that is not yet explicitly geo-localized. For example, string matching techniques enable users to find postal codes to produce automatic geo-coding.

Spatial analysis

3D spatial analysis tools constitute an extension of 2D spatial analysis. Consequently, a 3D City GIS should offer the typical geospatial analysis components suitable to deal with 3D shapes in 3D space. It includes 3D spatial operators and data type conversion capabilities. 3D spatial operators should include:

- 3D spatial overlay with volumetric shapes: intersection, difference, union, buffer; convex hull, filter, and buffer;

- 3D spatial intersection between volumetric and non-volumetric shapes: volumes, surface, lines and points in 3D space;

- 3D geometric descriptors and measurement: shortest distance between primitives e.g., 3D segments), surfaces (e.g., surface of the 3D triangle of a TIN), volumes, point density, automatic detection of point groups, detection of spatial correlations, extraction of minimum bounding box, and convex hulls;

- Network analysis;

- Analysis such as watershed or gas propagation.

Data conversion

Conversions between data types are also particularly important to describe reality in a way suitable for analysis. Let's consider the example of a 3D BIM and the problem of finding the optimal evacuation path. Even if the BIM model is composed of richly detailed geometric and semantic information, this information has to be converted to a network topological structure to support the analysis (e.g., identification of the circulation areas and of their connection and computation of their length and risk factors). A lot of data type conversion can be relevant, for example:

- Conversion between raster DTM and TINs. TINs are easier to edit and render in 3D. In addition, TINs reduce the amount of data that needs to be processed. Raster is suitable for grid-based operation and map algebra.

- Conversion between a mesh description of a road and a description based on alignments and sections. A mesh description is useful for rendering and for volume computation, but profiles are more suitable for the human interpretation of road slopes.

The importance of analysis functions, geospatial or not, and of the data type conversions that are needed in a 3D City GIS depends on the analysis to be performed. Because supporting all the data types, data conversions, and all the application dedicated analysis is a nice goal but a bit utopian, a 3D City GIS should have an open architecture. Consequently, interoperability and an API with access to object intelligence and analysis operators are important considerations before conducting analysis in a 3D City GIS.

Design

Design of new infrastructure usually follows exploration and analysis of the context, which can also be reiterated during the design to evaluate its feasibility and its potential impact. For example, a 3D model of an urban area can be used to evaluate the opportunity associated with the destruction of an old factory. By deleting the existing factory in the 3D city model and simulating the new project, it's possible to anticipate the visual impacts of new buildings. It's also possible to estimate new project impact regarding noise propagation. Additionally, managing network information in a 3D city GIS is useful to evaluate interaction with existing transportation networks or other utilities.

Therefore, when considering design tools, there are two challenges:

1. Those tools have to handle the complexity of the infrastructure to be designed.

2. The design tools have to be well integrated in the 3D city information model in order to access and benefit from all of the available information.

The design of new infrastructure is one activity that can greatly benefit from a 3D city information model. To make this possible, effective integration of design tools with the 3D City GIS is crucial.

Explore, Analyze and Design in 3D with Bentley

Bentley offers a wide range of data exploitation tools to meet all user requirements from back office to front office. MicroStation offers advanced 3D visualization and rendering capabilities to deal with huge datasets. Bentley Geospatial Server gives users the ability to search through 3D/2D files and databases, structured and unstructured datasets, and provide a 2D geospatial view of all the geospatial information.

Bentley also offers Bentley Navigator, a lighter solution dedicated to 3D navigation through 3D models. The software provides the user with the capacity to perform tasks such as collision detection or access to object attributes. It's also possible to publish information not requiring specific software by using, for example, the 3D capabilities of PDF or advanced 2D GIS capabilities on the web with Bentley Geo Web Publisher. Thanks to server plotting capabilities and other automatic publishing processes, it's possible to create applications that combine 2D GIS view with on-click access to 3D PDFs.

A comprehensive set of analysis capabilities is also available across Bentley products. For example, MicroStation offers numerous conversion capabilities between 3D volumetric shapes like "mesh to solid" or "solid to surfaces," and Bentley Map offers most of the 2D GIS spatial analysis like buffers and overlay or network analysis. In addition to the available analysis capabilities, the users of Bentley software also have the opportunity to access the richness of their data through the MDL API. It allows the development of personalized analysis functions.

Bentley offers a wide range of design tools as extensions to MicroStation. These tools address the entire object classes covered in a 3D City GIS:

- Buildings (Bentley® Architecture; Bentley® Structural; Bentley® Building Mechanical Systems; Bentley® Building Electrical Systems; STAAD.Pro®; Bentley® Facilities; Speedikon® Architectural; and GenerativeComponents®);

- Roads and rail and transit (Bentley civil products: GEOPAK® Civil Engineering Suite; InRoads® Suite; Bentley® Rail; and Bentley® MXROAD® Suite);

- Bridges (Bentley and BrIM);

- Electric (Bentley® Electric);

- Gas (Bentley® Gas);

- Water (Bentley® Water);

- Wastewater (Bentley® Wastewater);

- Communications networks (Bentley® Coax, Bentley® Fiber, Bentley® Copper, and Bentley® Inside Plant).

> Bentley offers a wide range of data exploitation tools to meet all user requirements from back office to front office.

Customer Examples: 3D City GIS is Already on its Way

Bentley provides a unique opportunity to cover all the aspects of a 3D City GIS. Several Bentley users have already done impressive sustainable projects dealing with infrastructure. Here are some examples:

City of Melbourne – AAMHatch

Combining modeling tools on a same customizable platform – BE Awards Winner 2007

AAMHatch produced a high resolution 3D city model and a true orthophoto of the City of Melbourne by combining aerial LIDAR and aerial photogrammetry.

"The orthophotography and 3D wire-frame is of a commensurate order of accuracy to match their Property Mapbase, …The City of Melbourne (CoM) had established a Digital Property Mapbase, which is accurately positioned by survey to 0.1 meter. The orthophotography was required to have a commensurate horizontal spatial accuracy at ground and roof level. Generally, all features in the imagery should be within 0.1 meter of their true position with a nominal ground feature resolution of 0.06 meter" (John Blackburn, project manager, AAMHatch).

> "Using Bentley software, 2,500 buildings were modeled for the City of Melbourne in just two minutes compared to about 400 hours using manual plotting." (AAM Hatch)

To achieve this goal, AAMHatch successfully combined the benefits of aerial LIDAR (TerraModeler – extension of MicroStation) and aerial photogrammetry (BAE's SocetSet interface with MicroStation). The 3D objects required for the 3D city model and for the true-orthophoto production have been produced on the same MicroStation platform. Removing unnecessary import/export steps and performing 3D editing on the same powerful 3D platform allowed AAMHatch to optimize its workflow. AAMHatch also increased workflow productivity by implementing VBA macros supported in Bentley API.

"Over 600 frames of low-level aerial photography were acquired under specific environmental conditions to minimize the effects of shadows and reflections from buildings. More than 200 million data points were acquired by airborne laser scanning and 2,500 buildings were measured to support the creation of the true orthophoto and the generation of a 3D model of the city.

Together with the resultant orthophotography and 3D model, the data sources totaled more than 500 gigabytes of data. Softcopy photogrammetry techniques were employed, using BAE's Socet Set, to capture the roofline data. This software allows data to be captured directly into MicroStation using standard MicroStation functions and commands. The macro to generate the model takes approximately two minutes to run after 15 hours of MDL programming. A conventional manual alternative, on the other hand, would take approximately 10 minutes per building. Using Bentley software, 2,500 buildings were modeled in just two minutes compared to about 400 hours using manual plotting."

More Customer Examples

Jurong International realized a master planning and design infrastructure project for the City of Abu Dhabi by combining Bentley product's design efficiency and advanced visualization capabilities. This project addressed both road and water network infrastructure.

The City of Hamburg is using MicroStation technology as platform for the management and growth of its 3D city model at different LODs. 3D PDF file formats are used to bring complex spatial data sets to customers and citizens.

The City of Helsinki is using MicroStation platform for 3D surveying with aerial LIDAR tools to simulate urban planning projects. Bentley Geospatial Server is used for the workflow management.

The City of Toronto developed an innovative approach using MicroStation GeoGraphics, Oracle Connectors, Bentley Geospatial Server, and building permit information to manage photogrammetric updates directly from stereoplotters to Oracle.

The City of Warsova uses MicroStation to produce 3D city model required for noise simluation.

For more examples of projects that have implemented 3D City GIS, visit **www.bentley.com/yearininfrastructure**.

Conclusion

The use of a 3D City GIS offers numerous potential benefits in sustaining city infrastructure, including handling the full complexity of our infrastructure, reducing duplication of effort, facilitating access to relevant information, simplifying the communication between the stakeholders, and more. But implementing a 3D City GIS within an organization is not a simple process. Numerous and organizational aspects must be considered.

Establishing a 3D City GIS must be regarded as an evolutionary process based on existing data and technologic infrastructure. This paper presented a hierarchy of the main components of a 3D City GIS and explored the key points to consider when implementing one.

Flexibility, scalability and interoperability are the most important elements needed to support the growth of 3D City GIS, and all of these are part of Bentley's basic culture. Moreover, Bentley has unparalleled expertise and experience in 3D CAD/CAE, BIM and GIS, enabling it to fully support users in implementing a highly successful 3D City GIS.