Chapter 34

Semantic 3D City Modeling and BIM

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Abstract Semantic 3D city modeling and building information modeling (BIM) are methods for modeling, creating, and analyzing three-dimensional representations of physical objects of the environment. Digital modeling of the built environment has been approached from at least four different domains: computer graphics and gaming, planning and construction, urban simulation, and geomatics. This chapter introduces the similarities and differences of 3D models from these disciplines with regard to aspects like scale, level of detail, representation of spatial and semantic characteristics, and appearance. Exemplified by the international standards CityGML and Industry Foundation Classes (IFC), information models from semantic 3D city modeling and BIM and their corresponding modeling approaches are explored, and the relationships between them are discussed. Based on use cases from infrastructure planning, approaches for integrating information from semantic 3D city modeling and BIM, such as semantic transformation between CityGML and IFC, are described. Furthermore, the role of semantic 3D city modeling and BIM for recent developments in urban informatics, such as smart cities and digital twins, is investigated and illustrated by real-world examples.

34.1 Digital Models of the Built Environment

Many applications in the context of urban informatics require detailed information about the physical urban environment. For example, for the planning, design, and construction of buildings, detailed information about the location, the components, their materials and costs, and the construction schedule is required. For all kinds of urban simulations like noise propagation, air quality and pollution assessment, energy demand, and production estimation, but also for driving simulations and autonomous driving, comprehensive data are required on the urban topography.

Digital models of the built environment are computer representations of the objects, their characteristics, and their interrelationships within a specific urban

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terrain. This includes both the natural and man-made features like the digital terrain model (DTM), digital surface model (DSM), vegetation, water bodies, as well as man-made constructions like buildings, bridges, tunnels, and infrastructure. Key properties of the digital representations are spatial, temporal, graphical, and thematic information about the entities in and around cities, providing information on the location, shape, extent, visual appearance, classification, thematic attributes, functional aspects, and their interrelationships.

Different applications and use cases have different requirements regarding the resolution and level of detail of the objects of an urban model and their modeled aspects. For example, for the visual inspection of the urban topography by a human operator, it will be sufficient to represent the geometry and graphical appearance of the urban terrain. If thematic or spatio-thematic queries and analyses are to be carried out, like “list all windows of all buildings which have a line-of-sight to a specific place or route” or “find all buildings having a heating energy demand higher than 100 kWh/m²/year”, then thematic information has also to be represented, because the computer has to know which objects are buildings, their energy demand, which parts of them are windows, and what are their locations and orientations. For simulation applications like blast analysis or the propagation of radio waves, information about the materials of the different objects will also be required.

Urban models that only represent the 3D geometry and appearance information (visual models) will be referred to as virtual reality (VR) models in the following. Typical real-world examples of VR models are the 3D models of major cities in Google Earth or Apple Maps. They are just geometrical representations of the urban surface (3D meshes with graphical textures). A human viewer can easily recognize the different features, but for the computer, these data are not structured into separate meaningful objects. Models of real-world entities that also include the meaning of the objects, their thematic properties, and their logical relationships are generally referred to as semantic models or information models. Thus, urban models containing both the spatial and thematic aspects are called urban information models (UIM).

Now, urban modeling can be carried out in various ways and using different formal modeling techniques and data representations. This diversity results from the fact that 3D urban modeling has been approached from at least four different disciplines: computer graphics and gaming; geomatics (including the disciplines of geoinformatics, geodesy, photogrammetry, and remote sensing); planning and construction (including the disciplines of civil engineering and architecture, urban and landscape planning); and urban and environmental simulation. This is illustrated in Fig. 34.1.

It is important to understand that each discipline has its own scope and thus puts a different focus on the things that are modeled and on the way they are modeled. This has resulted in the development and usage of distinct modeling paradigms, conceptual data models, and data exchange formats, which frequently causes problems in discussions about urban models between people coming from different disciplines. On the other hand, system interoperability issues arise and have to be addressed when data from one discipline are to be brought into another discipline or if data from the different disciplines are to be used in an integrated way.

Fig. 34.1 Different disciplines and their approaches to the definition, generation, and usage of urban 3D/4D models

Data models and methods developed in the field of computer graphics (CG) and gaming aim at the efficient and high-quality 3D visualization of the cityscape and the elements in it. Thus, VR models are in the main focus of CG, containing information on geometry and (graphical) appearance. 3D objects are typically structured in so-called scene graphs, which allow for the definition and multiple instantiation of prototypical shapes and realize a hierarchical aggregation. Scene graphs may also contain light sources, virtual cameras, and information about the environment like fog density, and may provide the means for object animation, describing the dynamic behavior of objects, and user interaction (see, e.g., Foley et al. 1995). In CG, objects are typically modeled in a way that best supports rendering and visualization, which may suggest the aggregation of objects which might not be considered as a unit from a semantic point of view. The representation of semantic information is not a focus of CG and is often neglected.

Models and methods from the field of training simulation and computer games are quite similar to CG with respect to the representation of 3D objects. In addition, these models support the description of object physics (like weight, elasticity, mechanical connections, etc.), kinematic modeling, and complex object behaviors, in order to describe the functions and interactions to be considered by the simulator. Like in CG, object semantics are often not considered, apart from simulator control data.

The planning and construction domain focuses on the representation of man-made objects in fine detail in order to support the design and construction processes. While in the past computer-aided architectural design (CAAD) was mainly used to represent the geometry of the objects, in the past decade a strong transition has

occurred toward building information modeling (BIM). BIM means the classification and decomposition of 3D models according to a semantic data model, where each class has a well-defined meaning. By these means, a comprehensive, centralized information repository will be created that can be used by all stakeholders over the entire life cycle of a building. BIM is focused (and tailored) to building and site models with a very detailed object model, where sites are constructed from components like walls, slabs, stairs, pipes, cables, power plugs, etc. BIM does not address the representation of natural objects like vegetation or water bodies and only recently started to include other object types like bridges, roads, or terrain. Nevertheless, since buildings are one of the most important entities in the urban terrain, and BIM also includes the modeling of their interiors, it is quite relevant to urban modeling. In order to support the design of a building, a generative modeling approach is followed, that is, objects are virtually constructed from a set of volumetric semantic components like walls, slabs, etc. in the same way as the building will be constructed in reality. Typically, the components are geometrically described and combined using constructive solid geometry and sweep geometry. This will be further explained in the section on BIM.

In geomatics, emphasis is given to the representation of the urban topography including natural objects, man-made objects, and the Earth's relief. While in the past 2D maps and 2D digital landscape models (DLM) have been used at different scales to visualize and represent the topographic structure of a region with respect to planimetric (horizontal/flat) shapes and extents, virtual 3D city and landscape models nowadays capture and visualize the 3D geometry, 3D topology, and appearance of the urban entities in different levels of detail (LoD). If the objects are structured according to a semantic model and have thematic attributes and logical interrelationships, these models are referred to as semantic 3D city models. They can be seen as a realization of the concept of urban information modeling. The modeling paradigm in geomatics is oriented toward the representation and mapping of observable features and thus is very close to the results that are obtained from data acquisition methods from photogrammetry, remote sensing, and surveying (see, e.g., Kolbe et al. 2009). Semantic 3D city models are explained in more detail in the next section.

More details about the similarities and differences of models from the planning and construction as well as geomatics domains are given in the fourth section of this chapter and by Kolbe and Plümer (2004) and Nagel et al. (2009).

The models used in the field of urban simulation often are based on regular or irregular decompositions of the urban space into finite elements. Both the air space and the space occupied by physical objects are represented by voxels, meshes of 3D tetrahedra, or 3D volumes bound by triangle meshes. Since all urban features use the same representation, they can be treated by the simulation tools in a similar way. The cells or elements of such a representation are parameterized by properties that are relevant for the respective simulation. For example, in pollution dispersion simulation, all voxels representing the urban air space have a parameter vector for wind direction, wind speed, air temperature, and concentrations of specific pollutants. Other kinds of simulations require the explicit spatio-semantic representation of urban objects. For example, in traffic simulations, the roads have to be represented

together with traffic-related information such as speed limits, traffic lights, turning restrictions, and parking lots. For simulation of building heat-energy demand, 3D building models are required with information about usage type (e.g., residential, office, manufacturing) and about building physics like the wall, roof, and window insulation.

While digital models of the urban environment were often static in the past, that is, they just represented a snapshot of a specific timepoint, nowadays the time dimension plays an increasing role due to new application fields like smart cities and digital twins. In these application fields, sensors and their highly dynamic observations are related to the objects of the digital urban models. In the field of computer gaming, including training simulations, as well as in the field of urban simulations, the representation of dynamic behavior and changes over time has been addressed for long time. However, in the approaches of geomatics as well as of planning and construction to digital urban modeling, the time dimension has not yet been considered to a full extent (see, e.g., Chaturvedi and Kolbe 2019b).

In the remainder of this chapter, we will concentrate on the spatio-semantic modeling of the urban environment, namely semantic 3D city modeling and building information modeling.

34.2 Semantic 3D City Modeling

Semantic 3D city models are virtual models of the urban environment, that is, datasets representing the entities of the physical reality like buildings, streets, trees, bridges, and the terrain. In contrast to virtual reality (VR) models, they are structured (e.g., subdivided and attributed) according to thematic and logical criteria and not according to graphical or rendering considerations. The objects of a semantic 3D city model represent the respective real-world things with their thematic, geometrical, topological, and appearance properties. Furthermore, logical and spatial interrelationships between different objects are expressed. Objects belong to a set of predefined classes like Building, Road, CityFurniture, or WaterBody with spatial and thematic attributes whose semantics—that is, the meaning of the model components and properties—are explicitly defined in a specification. Complex objects are typically further decomposed into meaningful parts, for example, a building can be decomposed into building parts and these again are structured into roof, wall, and ground surfaces. Wall surfaces can further contain windows and doors. Objects can have thematic attributes on all aggregation levels. Their spatial properties are represented using geometric and topologic objects.

34.2.1 Purpose and Key Applications

3D city models are mostly used topographically, to describe the physical environment as it is with respect to the spatial, thematic, and appearance characteristics of the urban entities. They are used to create 3D maps for applications ranging from topographic mapping, cadastres, disaster management, visual exploration, navigation and autonomous driving, and urban simulations. Semantic 3D city models comprise all objects within larger geographical areas, typically starting from city blocks up to entire countries. They can be seen as the 3D successor of traditional 2D digital landscape models as created and maintained by mapping agencies. In fact, most semantic 3D city models today are being created and maintained by mapping departments on municipal, state, or country level. However, 3D city models are also produced by commercial companies as well as by initiatives like the Open Street Map project.

A semantic 3D city model could be seen (and is used) as an inventory of the relevant urban objects. As such, it is useful for applications related to property and asset management, as well as for life cycle management of the man-made and natural urban features. When it comes to urban data integration, semantic 3D city models play a key role, because data from different domains like urban planning, mobility, energy, and ecology are most often related to specific spatial urban objects. Since these objects are represented in a 3D city model, the domain-specific data can be linked with the respective city model objects. Alternatively, the urban objects could be enriched with the domain-specific data. The objects of a 3D city model then play the role of a common denominator, because data from different domains can be linked and interrelated via the urban objects. This is further illustrated below.

In their overview paper, Biljecki et al. (2015) enumerate and describe more than 100 applications of 3D city models. The authors distinguish mainly between use cases that are based on visualization and those where 3D models are being used for computations, queries, and more sophisticated analyses including simulations. While semantic 3D city models can also be used for visualization-based use cases, they are especially relevant for the second category and for many use cases are even required. Willenborg et al. (2018) explain in more detail how semantic 3D city models are being employed in three very different use cases: (1) solar irradiation analysis, (2) detonation simulation, and (3) building energy demand estimation.

34.2.2 Modeling Paradigm

Semantic 3D city models are typically being used to represent the existing physical objects of the urban environment. Hence, a descriptive modeling paradigm is being followed, which best supports the modeling of urban entities by observation methods from surveying, photogrammetry, remote sensing, and laser scanning. Direct results from these methods are typically 2D images and videos from different viewpoints (nadir and oblique views from airborne and space sensing, terrestrial views from

mobile mapping) and 3D point clouds as resulting from laser scanning or stereo-photogrammetric dense image matching. 3D point clouds then can be triangulated, producing 3D meshes that describe the observed surface structures. In order to represent the 3D geometric extent and shape of separated objects, boundary representations (B-Reps) are being used, where volumetric geometries are specified by the accumulation of their bounding surfaces (see, e.g., Foley et al. 1995). In contrast to most other disciplines, geometries in the geomatics domain are always georeferenced with respect to a regional or global coordinate reference system (CRS). The exclusive usage of absolute coordinate values allows GIS and spatial databases to create and maintain spatial index structures, which facilitate efficient processing of spatial queries and analyses on very large datasets. This is not supported in comparable efficiency and completeness by the modeling paradigms which are followed in other disciplines.

Based on the reconstruction of 3D geometry, the semantic objects are then generated. Since only observable parts can be registered from surveying and remote sensing, the object decompositions are typically aligned with the visible surface parts. For example, buildings are decomposed into wall, roof, and ground surfaces as only the surfaces can be reliably detected, whereas in general the entire volumetric wall objects or other constructive elements like beams or slabs are not detectable. As a rule, each (relevant) real-world thing is represented by one classified object. Each object can have multiple representations, such as geometries of different types in multiple levels of detail, as well as multiple visual appearances. It is recommended that all objects should have globally unique identifiers and that these identifiers should also be kept stable over the lifetime of the real-world object. The reason is that this allows keeping track of the object in different applications and for linking information from different sources to it in a sustainable way.

Of course, 3D city models can also be used to represent future development states of cities, but the employed accumulative modeling principle (B-Rep geometries with absolute world coordinates) is not especially supportive regarding manual, interactive changes of object locations, extents, and shapes. This is in contrast to generative and parametric modeling principles that are typically used in building information modeling.

34.2.3 The International Standard CityGML

The City Geography Markup Language (CityGML), issued by the Open Geospatial Consortium (OGC), is the international standard for the representation and exchange of semantic 3D city and landscape models. CityGML defines a common information model and data exchange format for 3D urban and rural objects. It specifies 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. Included are generalization hierarchies between thematic classes and aggregation and thematic relations between objects. CityGML is implemented as an application

schema of the Geography Markup Language 3.1.1 (GML3; see Cox et al. 2004), the extensible international standard for geodata exchange and encoding issued by the OGC and the ISO TC211. It is further based on a number of standards from the ISO 191xx family, the OGC, the W3C Consortium, the Web 3D Consortium, and OASIS (Kolbe 2009; Gröger and Plümer 2012).

The data model consists of class definitions for the most important objects within virtual 3D city and landscape models. CityGML consists of a core module and several extension modules. Whereas the core module comprises the basic concepts and components of a virtual city, each extension module covers a specific thematic field like buildings, bridges, tunnels, digital terrain model, water bodies, vegetation, transportation, city furniture objects, etc. Implementations are not required to support the entire data model but may employ only a subset of modules according to their specific needs. Figure 34.2 shows an excerpt from the top-level class hierarchy of CityGML.

CityGML defines five consecutive levels of detail (LoD), where objects become more detailed with increasing LoD regarding both their spatial and thematic differentiation. Each object may have attached a separate representation for each LoD simultaneously. The five LoDs as defined by CityGML are illustrated in Fig. 34.3.

CityGML comprises class definitions for the representation of complex digital terrain models (DTMs) in various forms from point clouds over raster data or TINs, including break lines. All these DTM data types can be used to build composite or hybrid terrain representations. The LoD concept even allows for the maintenance of

Fig. 34.2 UML diagram of the top-level class hierarchy of CityGML. All thematic objects are considered geographic features (according to ISO 19109), and their classes are derived from the abstract superclass CityObject. Attributes and subclasses are omitted here for the sake of readability

Fig. 34.3 Illustration of the five levels of detail defined by CityGML

several terrain variants in different resolutions. DTMs can be restricted by validity-extent polygons. Holes within these polygons allow for embedding of other DTM components, for example, a fine-resolution TIN embedded into a gridded DTM of a large area.

In CityGML, the coherent modeling of semantic and geometric/topological properties is supported. At the semantic level, real-world entities are represented by features such as buildings, walls, windows, or rooms. The description also includes attributes, relations, and aggregation hierarchies between them. At the geometric level, geometry is assigned to thematic features representing their spatial location and extent. Complex geometry objects are decomposed into geometric primitives. Thus, the model can consist of two aggregation hierarchies in which the corresponding objects are linked by relationships, but also simpler representations are supported (see, e.g., Stadler and Kolbe 2007).

Spatial properties of CityGML features are modeled according to the GML3 geometry model (see ISO 19107:2003; Cox et al. 2004) representing 3D geometry according to the boundary representation (B-Rep, see Foley et al. (1995), typically using a 3D coordinate reference system (CRS) with absolute world coordinates. Spatial database management systems, like Oracle Spatial and PostGIS, as well as many (3D) GIS, provide native support for GML3's geometry model enabling loss-less storage, efficient management, and spatial indexing of CityGML data. Besides geographic and projected coordinates, also compound 3D CRS, that is, different CRS for planimetry and height, are supported.

In order to provide for a simple but yet flexible way of topological modeling, CityGML does not make use of GML's topology classes. Instead, topological neighborhood relations are expressed using GML's capability to establish XLinks from composite geometries to the shared geometry (parts). For example, a surface that is bounding both a house and a garage can be referenced by the two respective solid geometries assigned to each object. If a geometry object should be shared by different composite geometries or different thematic features, it only has to be assigned a unique identifier, which is then referenced by the corresponding GML geometry aggregate objects (see Gröger and Plümer 2012, for examples).

In addition to semantics and spatial properties, CityGML features can be assigned appearance information, that is, observable properties of a feature's surface. In most cases, these surface data are recorded by sensors, for example, a RGB or infrared camera. CityGML appearances are represented by textures, georeferenced textures, and material representations (the latter adopted from the CG standards X3D and COLLADA) of object surfaces, but are not limited to visual data. In contrast, appearance relates to any surface-based theme, such as infrared radiation, noise immision, radio-frequency absorption, and earthquake- or blast-induced structural stress. Consequently, appearance information can serve as input for both visualization and analysis tasks. CityGML supports feature appearances for each LOD and an arbitrary number of themes.

3D objects are often derived from or have relations to objects in external databases or datasets. In order to express these links, each object in the city model may have external references to its corresponding objects in external data sources, given as Uniform Resource Identifiers (URIs). Furthermore, explicit information which facilitates the integration of different 3D datasets/object types can be represented. The concept of the Terrain Intersection Curve (TIC) is introduced to integrate 3D objects with the digital terrain model at their correct height in order to prevent, for example, buildings from floating over or sinking into the terrain.

To allow for the aggregation of arbitrary city objects according to user-defined criteria, CityGML employs a generic grouping concept. Groups may be further classified by additional attributes and may contain other groups as members, allowing for nested grouping of arbitrary depth.

Attributes for classifying objects, such as roof types, often are restricted to a set of discrete values. To facilitate interoperability, in CityGML, these sets are specified as external codelists and implemented as GML simple dictionaries. External codelists can be (re)defined by the user.

Further objects which are not explicitly covered by the specification document can be represented using the concept of generic objects and attributes. In addition, the CityGML data model may be extended for specific applications through so-called Application Domain Extensions (ADEs). All datasets containing ADE can still be interpreted by applications that rely on the basic CityGML data model. By these means, the data model of CityGML balances between strictness and generality. This is realized by the three main parts: (1) the core thematic model with well-defined LoDs, classes, spatial and thematic attributes, and relations; (2) GenericCityObjects and generic attributes allow the extension of CityGML data on the

fly; and (3) ADEs facilitate the systematic extension of the CityGML data model by new classes, attributes, and relations for specific application domains. Many ADEs have already been developed by different communities; for example, the Energy ADE (Nouvel et al. 2015) to support energetic analyses of buildings or the Utility Network ADE (Kutzner et al. 2018) supporting the simultaneous representation and analysis of multiple supply and disposal networks. A comprehensive discussion of existing CityGML ADEs is provided by Biljecki et al. (2018).

34.3 Building Information Modeling

34.3.1 *Purpose and Key Applications*

In the context of digital urban models, the acronym BIM stands for either building information modeling or building information model, two terms that were coined by the architecture, engineering, and construction (AEC) industry. Following Eastman et al. (2011), BIM is used as a verb in this contribution. This is to express that building information modeling (BIM) describes a modeling activity rather than just a collection of static object. According to Borrmann et al. (2015a), BIM is based on the idea of continuous usage of the digital representation of a building from its design, planning, and construction to operation and deconstruction. A basic premise of BIM is collaboration by different stakeholders in the different phases of the life cycle of a facility (National Institute of Building Sciences 2012). Therefore, BIM goes hand in hand with the idea of an improved exchange of data between all stakeholders involved and an increase in efficiency over the whole life cycle of a building. In contrast to computer-aided architectural design (CAAD) which mainly focuses on representing the geometry and appearance of man-made objects, BIM is focused (and tailored) to building and site models with a very detailed information model representing sites, buildings, and their components like walls, slabs, stairs, pipes, cables, power plugs as semantic objects, and the relations between them. The information model also allows representation of aspects like time (e.g., for scheduling tasks in the building project) and costs often referred to as 4D or 5D BIM.

Eastman et al. (2011) group the key applications of building information modeling according to the stakeholders involved in the BIM process as follows:

- Owners: assess design options from cost, time, sustainability and facility operation perspectives (requires quantity takeoff and computation, energy simulation, 3D visualization already in an early design phase); cost and schedule control; commissioning and asset management based on the as-built/as-maintained model
- Architects and engineers: space planning and program compliance, energy analysis, design communication/review (3D visualization), quantity takeoff and cost estimation, design and analysis/simulation of building systems (structure, mechanical and air handling systems, emergency systems, lighting, acoustics, etc.), design coordination (clash detection)

- Contractors: construction planning and scheduling (4D simulation), cost and schedule control, procurement purchasing and tracking, and safety management (4D simulation)
- Subcontractors and fabricators: automated manufacturing, preassembly, and prefabrication.

Common to all applications listed above is that they usually consider a single construction project or facility, not a whole district, a city, or even a larger geographical area.

While BIM in its early days was mainly applied in building construction, it is increasingly getting adopted in infrastructure construction today. An overview of BIM for infrastructure applications like planning, building and maintaining roads and railways, utility networks, etc. was provided by Bradley et al. (2016).

34.3.2 *Modeling Paradigm*

Although BIM can be applied for managing existing buildings (see applications for owners above), the majority of BIM applications is focused around the design and construction phase of a building. BIM models are therefore used as templates to create originals according to the model. This means that BIM adheres to a prescriptive modeling paradigm, as in most cases, the model already exists before the original (Brüggemann and von Both 2015). In addition, BIM follows a generative modeling approach since the model reflects the construction process (Kolbe and Plümer 2004). This requires highly detailed models with representations of all the constructive elements as components. However, the geometric representation of the constructive elements may vary in granularity depending on the state of planning (draft planning, execution planning, etc.). In order to provide the user of a model with information on the geometric granularity, BIM defines so-called levels of development (LoD). To support the dynamic nature of the planning process, the generative modeling approach followed in BIM must also enable changes to models of planned objects to be carried out quickly and efficiently. Therefore, mostly parametric and generative geometry models such as constructive solid geometry (CSG) and sweep representations are applied. Use of parametric representations and local transformations is making the interactive design of BIM models intuitive, as the characteristics of components can be changed easily by adjusting their parameters. For example, the thickness of a wall component can simply be changed by adjusting the width parameter; the change of geometry follows implicitly. Also the placement of a window within a wall could easily be modified by just moving the window object to some other place in the wall, that is, by changing the relative translation of the window object with respect to the wall object. The space taken by the window object then becomes subtracted from the wall in order to generate the hole in the wall. The same is true for the design and construction of a road, where the centerline describes the

road alignment and a cross-section together with some parameters provide information about the width of the lanes and shoulders. If the road needs to be moved by 10 m to the left, for example, just the centerline has to be adjusted accordingly; the rest follows implicitly.

34.3.3 The International Standard IFC

The Industry Foundation Classes (IFC) (International Organization for Standardization 2018) defines a software-vendor-neutral product model and data exchange format for BIM that has been developed by buildingSMART, an international organization from the AEC domain. IFC is widely adopted: According to Borrmann et al. (2015a), IFC is supported by all major software vendors in the AEC domain and serves for realizing Open BIM, that is, for implementing a software-vendor-neutral BIM process which relies on exchanging data between the stakeholders in a standardized format and information model. IFC has been made mandatory for government projects in several countries such as Singapore, Finland, and Great Britain. The US National BIM Standard (National Institute of Building Sciences 2012) is specified based on IFC, and also the German national BIM strategy regards “Open BIM” realized using IFC as an important component for implementing BIM processes in public construction projects.

IFC provides a very detailed and rich information model (see Fig. 34.4) for 3D building representations using constructive elements like beams (class ifcBeam), walls (class ifcWall), etc., and also non-physical spatial objects like stories (class

Fig. 34.4 Excerpt from the IFC information model showing the inheritance hierarchy of the most important top-level entities in EXPRESS-G notation. Source Borrmann et al. (2015a)

ifcBuildingStorey) and spaces (class ifcSpace). Diverse specializations are included for different crafts like steelworks, dry works, plumbing, electrical wirings, and air conditioning (HVAC). The information model includes material properties and costs, allowing, for example, cost calculations, planning of construction phases, and structural analyses to be carried out. Reflecting the scope and key applications of BIM, IFC not only allows buildings and their components to be modeled, but also processes that occur during a construction project and actors and non-physical objects that control other objects like legal directives and building regulations. Since IFC Version 4, the topic of BIM for infrastructure has been taken into account by defining objects for road and rail alignment. IFC data models for bridges and tunnels are in preparation.

The information model of IFC can be customized both by restriction and by extension. Model view definitions (MVD) can be created in order to restrict the data model to a specific purpose, for example, to define data exchange requirements for specific application domains. A range of predefined MVD documents can be found in the MVD database of buildingSMART International. They include an MVD for coordination between architectural, structural, and building services domains, for quantity takeoff, and an MVD for energy analyses. The standardized exchange format for MVD is mvdXML (Chipman et al. 2016). The concepts of property sets and quantity sets allow for a flexible extension of the semantic model by user-defined attributes. This may be done at runtime or can be defined using an MVD. The extension of IFC by new feature classes or the further refinement of existing feature classes by new subclasses is not supported.

IFC has a very comprehensive 2D and 3D geometry model. In line with the modeling paradigm suitable for BIM, IFC offers parametric geometry models like constructive solid geometry (CSG) and sweep, but also B-Rep geometries.

From Version 2.3, simple georeferencing has been included which allows one to specify the real-world coordinates of the origin of an entire site model in geographic coordinates (lat/long according to the WGS84 datum) plus ellipsoidal heights in meters. Along with the increasing importance of BIM for infrastructure and the need to handle objects with larger geographic extents, the current version of IFC 4 supports more complex georeferencing methods, which, however, are not yet sufficient for certain practical cases in large infrastructure projects (see Markič et al. 2018).

34.4 Integration of Semantic 3D City Modeling and BIM

The integration of BIM and GIS is currently the subject of intense research and development efforts in academia as well as in industry, and it has also found its way into university teaching and professional training courses (Hijazi et al. 2018; Noardo et al. 2019).

As a research area, BIM-GIS integration has developed over the past decade and is meanwhile described by several overview articles (e.g., Liu et al. 2017). The following classification of integration approaches builds upon Liu et al. (2017):

- (a) Approaches transforming data between BIM and semantic 3D city modeling based on existing information models from the AEC and geospatial domains with IFC and CityGML being the most prominent information models of the respective domain (Stouffs et al. 2018).
- (b) Approaches defining new information models (e.g., El Mekawy et al. 2012) or extensions of existing information models from the AEC and the geospatial domains (e.g., de Laat and van Berlo 2011). The aim of these approaches is to enable a data transformation between BIM and semantic 3D city modeling that is as lossless as possible. One of the most recent works in this field is described by Stouffs et al. (2018). Based on the use cases they identified with government agencies in Singapore, they extend the CityGML information model using the Application Domain Extension (ADE) mechanism in order to represent semantic information beyond what the CityGML information model provides. The transformation rules between IFC and CityGML are then defined using a triple graph grammar approach (Stouffs et al. 2018).
- (c) Approaches integrating BIM and GIS at process level. According to Liu et al. (2017), this type of integration is characterized by the fact that BIM and GIS data reside in their original data formats and information models. Linking data from both information models can then be achieved, for example, by using semantic Web technologies or by encapsulating the data using Web services. However, it should be noted that although standardized Web-service interfaces exist in the geospatial domain (e.g., OGC WFS), comparable standardized interfaces currently do not exist for accessing BIM models. Researchers have also investigated querying BIM and GIS data residing in their original structures simultaneously. An example of such an approach is given by Daum et al. (2017). They define a spatio-semantic query language for the integrated analysis of 3D city models and building information models.
- (d) Furthermore, application, vendor system, or project-specific approaches for BIM and GIS integration exist. These approaches do not necessarily rely on standardized information models on both sides. For example, GIS software vendors provide functionality to import the native format of a specific BIM authoring tool into their system. In case the geometry in the BIM data is parametric, it is transformed into explicit (mesh) geometry in the GIS software. Semantic transformations are not applied during import but could be applied by the GIS user.

The effort that researchers and software companies put into BIM-GIS integration indicates on the one hand the complexity of the topic, but on the other hand, it is also an indication of the need and benefit of such integration, as described in the following section.

34.4.1 Applications/Use Cases

Figure 34.5 names a selection of use cases for BIM-GIS integration related to the life cycle of a building or an infrastructure object. In the concept phase, an integration of a planned building with the virtual representation of its environment allows variant and feasibility studies and can facilitate stakeholder involvement and participatory planning by 3D visualization. In summary, it can be stated that BIM-GIS integration in the early design phase supports geodesign, according to Flaxman (2010) a “planning method which tightly couples the creation of design proposals with impact simulations informed by geographic contexts”.

Simulations in the geographic context of a building can also be applied during the detailed design phase. This might include energetic simulations involving shadowing effects by adjacent buildings, vegetation, or topography. In infrastructure construction, simulations in the geographic context can also be helpful: When planning motorway junctions, for example, the glare effect is determined using virtual models of the surrounding topography. In the next section, we describe an overall approach to planning integration that enables many more applications based on a consistent virtual representation of existing and planned man-made and natural objects.

Also in the construction phase, a range of applications benefit from an integration. In construction-site logistics, for example, the locations of cranes and storage areas can be planned taking into account the surroundings. The planning and scheduling

Fig. 34.5 BIM-GIS-integration use cases. Modified from Borrmann et al. (2015a)

of (heavy) transports can also be performed using geospatial data from semantic 3D city and landscape models. Environmental regulations must be observed during the construction phase. Schaller et al. (2017) describe, for example, how the construction sequence plan from BIM is compared with regulations for the clearing of woody plants in order to comply with species protection regulations. The species protection mapping is available in the form of geodata. At the end of the construction process, an as-built model of the structure is created. This can be used to update a semantic 3D city model.

Facility management, emergency management, and seamless indoor-outdoor transitions are examples for applications requiring the integration of BIM and semantic 3D city models from the maintenance phase of a building. Hijazi et al. (2011) show, for example, how indoor and outdoor utility networks can jointly be analyzed for building maintenance purposes.

Finally, in the modification phase an integration of BIM models into their geographic context supports feasibility studies for demolition works. Willenborg et al. (2018) show, for example, an approach to couple semantic 3D city models with a blast simulator in order to determine the safety zone around the detonation.

All the applications mentioned above can be classified into one of the following categories:

- Bringing BIM models into 3D city models for joint visualization, analyses, and simulation
- Bringing semantic 3D city models into BIM systems to import the surrounding environment for planned buildings or renovations
- Applications that make simultaneous use of indoor and outdoor representations.

It depends on the use case whether only the geometry, the geometry and the appearance, or whether also the semantics of the objects must be considered with the integration. Furthermore, the application determines whether the main focus is on BIM or semantic 3D city modeling, as the scope of both methods is complementary, with an overlap on the level of managing existing buildings, as explained in the following section.

34.4.2 Relationship of Semantic 3D City Modeling and BIM

Semantic 3D city modeling and BIM have in common that both methods deal with semantic modeling of the built environment. However, as we can see from the description of purpose and key applications of semantic 3D city modeling on the one hand and BIM on the other hand, there are different views on the same real-world objects which are manifested in the scope and scale as well as the different geometry modeling paradigms of the methods.

Figure 34.6 shows the differences in scope and scale. BIM's scale range includes a detailed view of a specific building, from the basic structure to the individual components. The scope is on the construction process (prescriptive modeling approach, see

Fig. 34.6 Relation of semantic 3D city modeling and building information modeling with respect to scope and scale

section on purpose and key applications of BIM above). In contrast, semantic 3D city modeling includes the scale range of an entire region down to an individual room of a building, including further thematic areas like transportation, vegetation, and water bodies. Semantic 3D city modeling primarily describes the current state of the built environment. Semantic 3D city models can thus be seen as an inventory list of the physical objects of the built environment in a specific region and can therefore serve as a hub for linking information from various information systems (descriptive modeling approach, see section on purpose and key applications of semantic 3D city modeling above).

The different scopes and scale ranges of the two methods result in different geometry modeling paradigms, as shown in Fig. 34.7.

In semantic 3D city modeling, diverse sensors like airborne cameras and laser scanners, and terrestrial surveying instruments like tachymeters and terrestrial laser scanners, are applied to observe the surfaces of physical urban objects. Thus, objects are described by their observable surfaces like wall and floor surfaces, which can be accumulated to higher-level objects like rooms or buildings. The resulting geometry modeling paradigm is boundary representation (B-Rep), which means that geometric objects are recursively described by their boundaries (a solid by its bounding surfaces, a surface by its bounding rings, and so on). B-Rep has its strengths, for example, in its ability to be used with spatial indexing, which allows the storage and query of very large datasets. In contrast, BIM models reflect how a 3D object is constructed. Therefore, a generative modeling approach is applied, allowing the representation of constructive elements by volumetric and parametric primitives. The geometry modeling paradigm is often constructive solid geometry (CSG), where complex volumes are created from combinations of volumetric primitives; operators are union, intersection, and difference (set minus). CSG and other parametric geometry paradigms have their strength in the fact that changes can be carried out very efficiently. For example, to change the thickness of a wall in a CSG model means to

Building Information Modeling (e.g. IFC) e.g. Constructive Solid Geometry

Semantic 3D City Modeling (e.g. CityGML) Boundary Representation

Fig. 34.7 Geometry modeling paradigms predominantly applied in BIM and semantic 3D city modeling (Nagel et al. 2009)

just alter one parameter, whereas in a B-Rep model many points would have to be moved individually, whereby inconsistencies could be introduced in the model.

While a CSG model can be uniquely mapped to exactly one B-Rep, the other way around is ambiguous: One B-Rep model can be created by an infinite number of different CSG models (see Kolbe and Plümer 2004; Nagel et al. 2009).

34.5 Recent Developments in Urban Informatics Involving Digital Models of the Built Environment

The following examples from the authors' project environment illustrate recent developments in urban informatics that involve semantic 3D city modeling, BIM, or a combination of the two methods.

34.5.1 Integrated Planning Models

As described in the previous section, the integration of semantic 3D city modeling and BIM can be employed for joint visualization and analysis of planned objects and their geographic environment. The authors of this chapter contributed to several research projects in the field of integrating BIM and semantic 3D city modeling for improving the planning process in infrastructure construction.

The project 3D Tracks (Breunig et al. 2017) developed new methods for collaborative subway track planning. A major research topic was the multi-scale nature of large infrastructure construction projects, with scale ranges from kilometer down to centimeter. Multi-scale representation is well established in the geospatial domain in general and in particular in semantic 3D city modeling (see the LoD concept of CityGML described above). However, as semantic 3D city models are rather static in nature (at least as far as the geometry of buildings is concerned), the LoD concept had to be adapted to the requirements of the highly dynamic planning process. Dependencies between the different levels of detail were introduced in a semantic model for representing shield tunnels (Borrmann et al. 2015b). This allows for the typical top-down planning approach from a coarser level, such as alignment (LoD 1), to a finer level. A key aspect of the model is that a refinement hierarchy between the representations of a tunnel in different LoDs is created with the help of space objects (see LoD 2–LoD 4 in Fig. 34.8), while the constructive elements of the tunnel are only represented in the highest LoD (LoD 5 in Fig. 34.8).

Figure 34.9 gives an example of the construction history of a shield tunnel in several levels of detail. Construction operations provided by parametric 3D CAD systems like sweeping, extrusion, etc. have been performed in a sequence, resulting in a graph structure which allows cross-LoD dependencies to be defined. Therefore, changes in a lower LoD will automatically take effect on objects in higher levels of detail. Although this modeling approach differs significantly from the way objects are represented in semantic 3D city modeling, Borrmann et al. (2015b) demonstrated that a geometric and semantic mapping, and geometric transformation of their tunnel objects to objects according to the CityGML representation of tunnels, is possible in an automated transformation workflow.

Fig. 34.8 A shield tunnel in different, dependent levels of detail (Borrmann et al. 2015b)

Fig. 34.9 Construction history and resulting cross-LoD dependency graph of a shield tunnel (Borrmann et al. 2015b)

Furthermore, in order to integrate parametric BIM authoring tools and analyses based on semantic 3D city models, the project team chose to encapsulate the geoprocessing workflows that had to be carried out for tasks like evaluating the planned rescue shafts of a subway track by standardized Web services provided in a distributed system. This allowed the team to keep the digital representations of the planned objects and the objects representing the geographic context in their own data structures, following integration approach (c) discussed earlier.

Schönhut (2018) describes a different approach of supporting subway planning by the integration of BIM and semantic 3D city modeling. Instead of keeping semantic 3D city models and BIM data in their original structures and bringing them together only encapsulated by processing services for specific analyses, she integrates data from both domains into a common information model (see Fig. 34.10). Her approach uses an integrated planning model and the CityGML schema as common information model. Since CityGML is not representing hydrogeological objects, which is critical for subway track planning, CityGML was extended using the Application Domain Extension (ADE) mechanism by classes of dedicated information models from the geology domain, namely the Geoscience Markup Language and the Groundwater Markup Language. An advantage of such an integration approach—besides a visualization of the BIM models in their environment—is that analysis and simulation methods developed on the basis of the CityGML standard for existing urban objects can now also be applied to the planned objects. Thus, what-if scenarios can be evaluated on different planning alternatives. This is useful not only in infrastructure planning but also in the context of smart cities.

Fig. 34.10 An integrated planning model for subway planning based on a CityGML Underground Environment Application Domain Extension

34.5.2 *Digital Models of the Built Environment, Smart Cities, and Digital Urban Twins*

The notion of the digital twin (DT) was originally defined in product life cycle management for industrial machines (Datta 2017). The DT is a digital representation of the available information on a specific physical thing including its origin, state, history, as well as recorded performance data. It is used for documentation and predictive maintenance. Only very recently colleagues from geospatial information science and urban planning have started to discuss using DTs in the urban context, see Batty (2018). In contrast to industry, where all the information about a specific product is bundled by the manufacturer, the information about real-world objects of cities like buildings, streets, bridges, and so on is distributed across several organizations and stakeholders. Information about one and the same building is, for example, stored and managed by different departments of the city administration, by energy supply companies, and by the owners and users of the building. Creating and maintaining a digital twin therefore first of all means information integration. Due to the distributed and heterogeneous nature of the information about the built environment, creating the digital twin of a city is challenging, both technically and organizationally. In order to link and use such heterogeneous data, spatial data infrastructures

for smart cities can play an important role in establishing interoperability between systems and platforms.

Moshrefzadeh et al. (2017) describe a concept for information integration in this context. Their smart district data infrastructure (SDDI) defines an organizational and technical framework for creating the digital twin of a city district. Their concept consists of actors, applications, sensors, urban analytics tools, a central resource registry of all the distributed information resources, and a 3D virtual district model as a central component (see Fig. 34.11). Based on the SDDI concept, Chaturvedi et al. (2019) present an approach for securing distributed applications and services which facilitates privacy, security, and controlled access to all stakeholders and the respective components and allows single-sign-on (SSO) authentication. Chaturvedi and Kolbe (2019a) describe an approach for interoperable access to sensor observations and time-series data from distributed, heterogeneous IoT and sensor platforms in the SDDI context.

A unique feature of SDDI is the fact that all the information, sensors, and applications coming from different domains are linked with the virtual 3D district model represented in CityGML. As shown in Fig. 34.12, digital representations of physical objects such as buildings and streets in semantic 3D city models can be used as anchor points for linking information from different domains and different stakeholders.

Thus, impacts of changes in the city can be simulated from different perspectives in the digital twin before they are implemented in the real city. Most smart city approaches today do not fully exploit this kind of information integration and therefore limit their view of the city to specific sectors, for example, smart mobility and smart energy, neglecting the interdependencies between those sectors.

A number of applications with real data from cities such as Berlin, London, and New York already show today that the concept of information integration based

Fig. 34.11 Overview of the SDDI components

Fig. 34.12 Digital representations of physical objects in semantic 3D city models as anchor points for integrating information from different domains

on digital models of the built environment, especially semantic 3D city models, can make a valuable contribution to the planning and operation of cities. Examples of application domains are strategic energy planning (Kaden and Kolbe 2014) and solar potential analysis, as well as detonation simulations (Willenborg et al. 2018), traffic simulation (Beil and Kolbe 2017; Ruhdorfer et al. 2018), and flood-inundation simulation (Chaturvedi and Kolbe 2017).

34.6 Summary and Conclusions

Digital models of the built environment provide detailed information on the physical urban reality. Semantic 3D city modeling as well as building information modeling both address not only the representation of spatial and graphical aspects of urban entities, but especially focus on their thematic structuring and decomposition into meaningful objects. However, semantic 3D city modeling and BIM are following different modeling paradigms to achieve that goal. While the former is especially tailored to create descriptive models of the existing urban reality, BIM is tailored to create prescriptive models telling how reality should become. The different approaches are originating from different disciplines, that is, geomatics and AEC, and are supporting the typical applications within their disciplines very well. There is an increasing demand to combine the two representations, though, and a number of different approaches were explained in the chapter. Also, examples for use cases that require combinations of semantic 3D city models and BIM were given. In general, semantic urban models are key for a wide range of urban applications in a multitude of domains, including all kinds of simulations.

It is, however, important that urban models are structured and exchanged according to open standards. Standards play an important role in the acquisition and use of urban models, because data are typically captured, refined, visualized, and used by different parties and systems. Standards specify the exchange of information from the level of object definition and semantics down to the level of the physical file layout. The use of open standards ensures platform- and manufacturer-independent management and processing of data. Platform independence is also important to protect investments on collected datasets against arbitrariness, the risk of failure of a manufacturer, or abandoning of a specific software system.

In conclusion, it is important to point out that the achievable and manageable data quality of urban models is not only limited by the data collection processes (and thus by sensors and the subsequent interpretation of sensed data), but also from the employed standards concerning the data modeling frameworks and data exchange capabilities. Data loss may occur between two parties or systems, if the data exchange standard is not capable of preserving the original content, structure, and logic of a dataset.

CityGML and IFC are the most important open standards for semantic 3D modeling of the built environment.

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