Large-scale 3D Data Integration

Challenges and Opportunities

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Part I

Nature of the Problem

1 Bridging the Worlds of CAD and GIS

Peter van Oosterom, Jantien Stoter, and Erik Jansen

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1.1 INTRODUCTION

Computer aided design (CAD) and geographic information systems (GIS) are being used more and more in the development of plans and products (bridges, tunnels, railroads, etc.) as well as for visualization, surveying, and location-based services. As a result, the worlds of CAD and GIS are becoming increasingly intertwined — but not without problems. Several real-world examples point to incompatibility in data formats and levels of abstraction. The need for an integrated CAD and GIS functionality has arisen from the fact that both systems are used throughout the life cycles of the same set of objects. The interoperability problem between CAD and GIS can only be solved by examining it at the right level of abstraction and by studying the different semantics used in both worlds. This chapter presents an outline for an integrated CAD–GIS framework on the basis of two concepts: formal (shared) semantics and integrated data management.

Information systems that involve geometry are used for many different purposes. One could classify CAD as one such family of systems; this, in turn, is often related to another family of systems, "computer aided manufacturing" (CAM). The products that are designed and manufactured consist of moveable objects (tables, cars, airplanes, engines, coffee machines, electronic circuits) and unmoveable objects (plants, buildings, houses, railways, roads, bridges, tunnels, utility networks). CAD systems for unmoveable objects are applied in AEC fields (architecture, engineering, and construction). In this chapter, the term "CAD" is used generically. In other words, it covers all kinds of computer-aided design, manufacturing, engineering, etc., and is not limited to a certain class of objects nor is it limited to a certain aspect (that is, CAD is considered more than geometric modeling).

Unmoveable objects (or fixed objects) are also well known from another family of information systems, GIS. GIS is applied in urban planning, land use, and cadastral data handling, among other fields. CAD and GIS share one major characteristic — both deal with geometry — but they differ in many aspects (size, storage, analysis, semantics, attributes, etc.). The primary aim of this chapter is to explain the need to integrate GIS and CAD. We shall also present the various factors that need to be considered when embarking on this process.

Let us first go back to the fundamental question, why would one like to bridge the gap between the two systems? Though CAD and GIS have been developed and used in different areas and organizations, a growing tendency has emerged in trying to integrate them and use them together in projects. This can be easily explained by the fact that CAD and GIS systems provide information on and deliver representations of the same real-world (man-made) objects in each phase of the life cycle. There are several areas of application (or different phases of the same application) that illustrate the need for an integrated approach (which will be discussed in more detail in the cases in Section 1.2):

- *Plan development:* The design of large infrastructures (roads, railways, bridges, tunnels, etc.) needs both CAD and GIS information — CAD techniques are applied for the design engineering, and construction, while GIS data are essential for the initial planning and layout. In the design phase, the geographic description of the region is often transferred from a GIS to a CAD system. Once the design has been completed in CAD, it is reimported into GIS. So an interesting cycle of information conversions takes place between GIS and CAD. It is not unusual for these conversions to be carried out "by hand," as the differences in the underlying data representations in CAD and GIS cannot be resolved automatically (see Section 1.2.1).

- *Visualization:* Plan presentation and data interaction often require different "views" of the data: a 2D "plan view" for the initial context analysis, a 2.5D "model view" to create and evaluate the different design concepts, and a 3D "world view" to realistically visualize the subsequent design (Verbree et al., 1999). While the 2D plan view is more or less a traditional GIS interface (based on geographic data), and the 3D world view is more or less a traditional CAD interface, the 2.5D model view asks for an interesting combination of the two (see also Section 1.2.2, Figure 1.4).
- *Data collection:* In recent decades, data collection techniques have progressed from manual measurement (resulting in vector-oriented data) to remote sensing (interpretation of 2D raster image data) and photogrammetry (interpretation of 3D data). Some advanced photogrammetric techniques assume knowledge about objects, such as buildings, bridges, and other landmarks, in a CAD-like format (see Figure 1.6). That is, the objects to be reconstructed should be seen as specific instances of classes from a generic library of designs (blueprints). The difficulties of surveying certain types of objects, such as the ever-increasing number of subsurface constructions, in traditional ways (remote sensing, photogrammetry) are fueling an interest in CAD models in 3D GIS modeling (see also Section 1.2.3).
- *Location-based services:* These services also employ a combination of CAD and GIS techniques for positioning, deriving viewing directions, and supplying the user with relevant "sight" information. It will take a lot of GIS and CAD integration before a sentence such as "on your right hand you now see a 12-story building" is generated automatically by the computer (see also Section 1.2.4).

1.1.1 PROBLEMS WHEN BRIDGING THE GAP BETWEEN CAD AND GIS

As indicated above, there are several applications that require input and analysis from both worlds (as will be illustrated in more detail in the following section). So why are these worlds so difficult to bridge? Essentially, because CAD and GIS traditionally focus on different domains and purposes:

- CAD is often used to represent the man-made world, while GIS is also used to capture the natural environment. The underlying mathematical description (and data structure in the subsequent implementation) is therefore quite different. Whereas CAD represents single complex objects in 3D with a high degree of accuracy (including free-form surfaces, etc.), GIS aims to capture large numbers of objects in a common embedding based on an efficient 2D vector (mainly edges and polygons) and raster formats.

- The timescale is quite different. As CAD generally works on a "project" basis, life cycle maintenance is a fairly recent issue. GIS, on the other hand, is geared to a very long period of data collection and maintenance (almost an endless life cycle). Second, whereas CAD often stores data in a file format and performs complex operations on geometric data in "core," GIS analyses data, which is more often maintained consistently and permanently in large databases.
- As a result of all this, CAD systems generally assume a (2D or 3D) orthogonal world, while GIS systems deal with data sources based on many different coordinate systems, which are used to model the spherical (ellipsoid or geoide) world. However, CAD and GIS meet each other during use at larger scales, where local (orthogonal) coordinate systems are dominant.

Appendix A contains a longer list of perceived differences (including those above) and shows how they have evolved over time, as reported in the literature. In general, we can say that, although CAD and GIS information relate to the same real-world objects, the data are quite different and take into account different aspects. To complicate things further, all these different pieces of information are created and maintained by totally different sectors (e.g., industry vs. urban planning) with different tools, optimized for specific tasks. It would, therefore, be no mean feat to merge the two modeling families into one shared representation, which is able to support the entire life cycle.

In the late 1980s and early 1990s many chapters were published on GIS vs. CAD and on how they could be effectively combined (Cowen, 1988; Hobbs and Chan, 1990; Logan and Bryant, 1987; Newell and Sancha, 1990; Shepherd, 1990). However, those chapters tended to focus mainly on how to use CAD systems for certain GIS tasks, ranging from geographic data entry to automated map production (including some cartographic aspects). Using CAD or GIS tasks was motivated by the fact that, two decades ago, CAD systems were more generally available than GIS systems. Moreover, there was no obvious desire for true integration of the different CAD and GIS data models and functionalities. About 10 years ago, inspired by application domains, such as urban and landscape architecture and planning, attention turned to the integration of CAD and GIS functionality (Hoinkes and Lange, 1995; Movafagh, 1995; Schutzberg, 1995; Smith et al., 1998; Sun et al., 2002; Kolbe and Plümer, 2004). But the solutions were often ad hoc (capturing and transferring simple 3D models between the different systems), or they required customized software. Often these chapters ended with the remark that applications would work more effectively if off-the-shelf CAD/GIS functionality could be integrated, but they seldom offered a clue as to how this could be achieved, and they did not specify the fundamental problems behind the integration difficulties.

More recent sources seem to be more of a commercial or development nature (e.g., Maguire, 2003), which emphasize providing data-exchange mechanisms through shared files, translators, or inter-application program interfaces (APIs), but pay very little consideration to fundamental issues, such as integrated geometric data structures (3D and topological support, e.g., see Lee and Lee, 2001, for an overview), harmonized semantics of the concepts, and integrated data management (in contrast to independent and inconsistent information islands with loose data conversions and transfers).

1.1.2 OVERVIEW

In the following sections we will explore ways of addressing the differences between GIS and CAD. We will begin by looking at some examples and cases to illustrate the integration problems (Section 1.2). In Section 1.3 we will describe some well-known conversions *within* GIS and *within* CAD to provide some insight into the conversions that are needed *between* GIS and CAD in order to bridge the gap between the two systems. We will then move on to semantic modeling, a topic that is of interest for both CAD and GIS. Moveable and unmoveable (that is, fixed) objects both have geometry. They also have all kinds of other attributes (e.g., name, function, type of material), explicit relationships (e.g., topology and application-dependent associations), and constraints (within an object and between objects: no overlap, minimum distance between objects, maximum size). Together, the geometrical and thematic aspects provide the semantics for the objects being designed. GIS already has a long history of thematic information related to functional items (houses, roads, etc.), while in CAD, there is a growing interest in product data management, including life cycle and project and process information. A major issue in both CAD and GIS is the maintenance of consistency in geometric and functional data during (complex) modeling or edit operations. Data exchange at a higher semantic level can help to prevent what current data exchange formats do, i.e., destroy most of the topological and semantic meaning and inevitably lead to data loss and re-entry. Section 1.3 concludes with a short discussion of the life cycle concept, which could play a central role in the integration of GIS and CAD.

Section 1.4 presents an outline for an integrated framework along two lines — formal semantics and integrated data management. The development of formalized semantics is crucial to achieving the true integration of CAD and GIS. First, the semantics (of geometry and other information) within a domain need to be formalized, i.e., a domain ontology has to be developed. Next, these domain ontologies have to be matched against each other. This could be realized through an integrated (and refined) ontology covering the CAD and GIS concepts in one framework. Integrated data management is needed to support multiview access and data interrogation while maintaining the overall consistency. In Section 1.5 we draw conclusions and summarize the requirements for the conceptual and technical framework that is needed to bridge the gap between GIS and CAD. Different aspects of this will then be covered in subsequent chapters.

1.2 CASE STUDIES INTEGRATING CAD AND GIS

In this section we present a number of case studies relating to the application areas mentioned in the introduction; these include plan development, (3D) visualization, (3D) data collection, and location-based services. Some of the cases will illustrate open issues (problems) with respect to the integration of CAD and GIS, while other cases may also show initial parts of the solution (often by making agreements and adapting the dataflow for the anticipated integration of CAD and GIS). After studying these cases, we will conclude with an analysis and summary of the problems we encountered when trying to bridge the gap between CAD and GIS.

1.2.1 Plan Development

1.2.1.1 Example 1: Hubertus Tunnel

The first example in the planning process is taken from 3D cadastre research (i.e., actual property registration). Property registration, including the geographic and thematic information, is often implemented with a GIS, usually with an underlying geo-DBMS for data management. Information in 3D on physical objects is required when registering the property of constructions above and below the surface. The question is, how can this 3D description be obtained?

In general, 3D object construction is a complicated process (even with advanced sensors and reconstruction software). It is also relatively time-consuming, as part of it still needs to be performed manually. In addition, underground constructions, such as tunnels and pipelines, cannot be obtained with laser scanning and (nonterrestrial) photogrammetric techniques, since the objects are not visible from above. The next step is, therefore, to take a closer look at the CAD models. Figure 1.1 shows a typical example illustrating the problem that it may not be easy to obtain a 3D description from 2D drawings.

As 3D data on many (new or future) objects are available to designers — mainly as CAD models — they could be used to model 3D physical objects in the DBMS. But how should CAD designs be used? And what selections and generalizations are needed to obtain the required information for a GIS environment, such as the outer boundary of objects? As part of the 3D cadastre research, we visited a municipality (Rotterdam, the Netherlands), two departments of the Dutch Ministry of Transport and Public Works (Projectorganisatie HSL and Bouwdienst Rijkswaterstaat), and an engineering company (Holland Railconsult) in an effort to find usable CAD models. We found that, in the present design process, there are very few, if any, CAD models that are suitable for the GIS (3D cadastral) database and that (automatic) conversion is nearly impossible. This is largely because 3D physical objects are still designed in 2D (in CAD) with the aid of linear profiles and cross sections (see Figure 1.1). Contractors and builders are accustomed to 2D drawings; understanding 3D drawings would require special skills.

1.2.1.2 Example 2: Cycle Tunnel, Houten

In addition to the 2D drawings describing accurate designs of objects to be constructed, there are also plenty of examples of 3D CAD models, which are generated

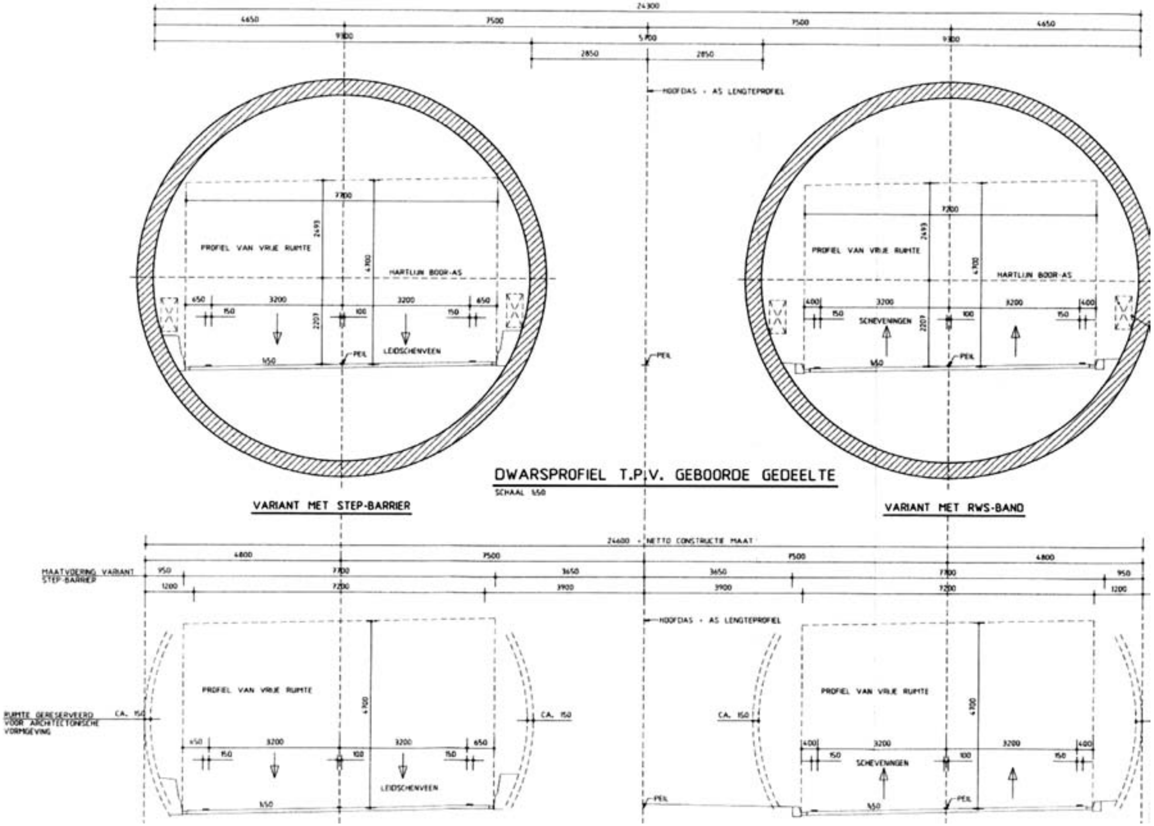

FIGURE 1.1 CAD model designed for the Hubertus Tunnel in The Hague. Courtesy of Bouwdienst, Rijkswaterstaat.

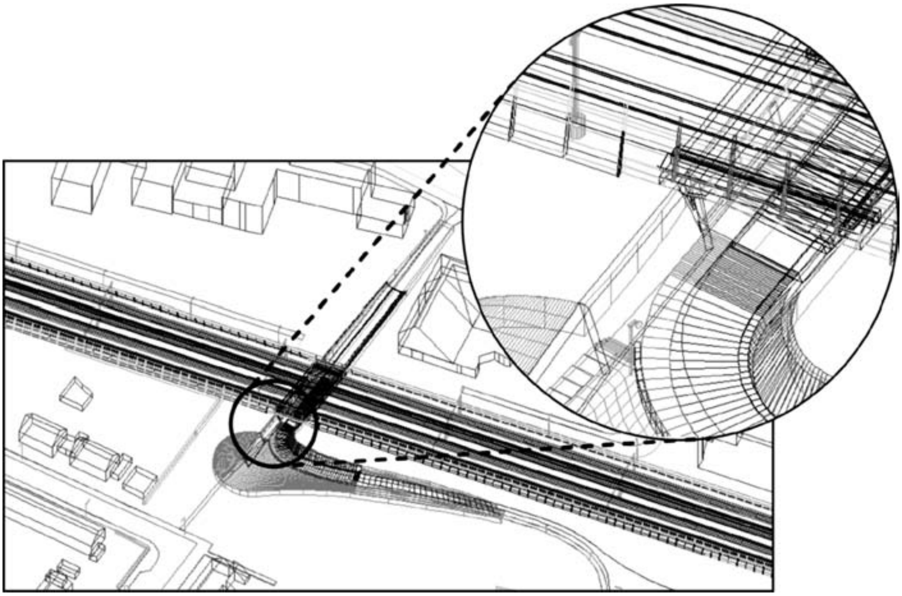

FIGURE 1.2 The CAD model designed for a cycle tunnel in Houten, the Netherlands. Courtesy of Holland Railconsult.

in the design process. However, these are mainly for visualization purposes (see Figure 1.2). Hoefsloot (2003) describes a case study on how 3D CAD models could be converted into a set of 3D geo-objects. This revealed that CAD models, which are designed primarily for visualization, are not (directly) deployable for 3D GIS (cadastre) purposes. Often, the classification and thematic attributes are missing, and the files can easily become unwieldy, as they are not primarily intended for interactive purposes but rather for the generation of animations. Furthermore, they contain too much detail: objects can hardly be recognized in the file-based models, let alone easily selected. Finally, 3D spatial data in CAD models are defined by complex geometries, most of which are described parametrically. At the moment, this data cannot be automatically converted into the primitives that are available in spatial DBMSs (point, lines, polygons, polyhedrons).

1.2.2 VISUALIZATION

1.2.2.1 Example 1: Bridge Amsterdam-Rijnkanaal near Utrecht

Rijkswaterstaat, part of the Dutch Ministry of Transport and Public Works, recently designed (and built) a bridge over the Amsterdam-Rijnkanaal near Utrecht in a 3D CAD system (see Figure 1.3). This new bridge is also included in the 3D topographic base map of Rijkswaterstaat (named “DTB-nat”) via a flat polygon in 3D space. For visualization purposes, it was decided that the bridge would be drawn again in another environment, as this would involve less work (than reusing the existing CAD

FIGURE 1.3 Bridge Amsterdam-Rijnkanaal near Utrecht. Courtesy of RWS/AGI.

model or the topographic base map). The operators were experts in the different software packages (so the problem was “real” and had nothing to do with unfamiliarity with the software). This approach comes across as somewhat unsatisfactory, not only because it introduces redundant data (which may cause inconsistencies), but also because somehow, in the detailed design information is present to be used in a less detailed model, while this information remains unused in current practice.

1.2.2.2 Example 2: Karma System

The Karma system (Verbree et al., 1999) was devised to support plan development for large infrastructural objects (bridges, railway tracks, etc.) and to allow interaction with the model data in 3D virtual reality. Interfaces were written to link the Arcinfo-SDE database to virtual environments that were developed on the basis of the WorldToolKit (WTK) (Sense8, 2004). The WTK allows the same virtual reality program to run on PCs, virtual workbenches, and CAVEs. Three views were developed and introduced to support meaningful interaction on these different platforms: the 2D plan view for overview and orientation, the 2.5D model view for interaction and manipulation (preferably on a workbench), and the 3D world view for visualization (preferably in a CAVE) (see Figure 1.4). The actual integration of CAD and GIS is particularly relevant in the world view, where the abstract 3D representations of GIS objects (extruded 2D objects) from the plan and model view are replaced by CAD models. To implement this idea, CAD models were needed that could be related to the GIS references. However, it proved extremely difficult to relate the complex CAD data structure to the simplified GIS references in such a way that automatic scaling and orientation could be realized. The operation proved just as difficult the other way around (i.e., simplify the complex CAD model to a geometry

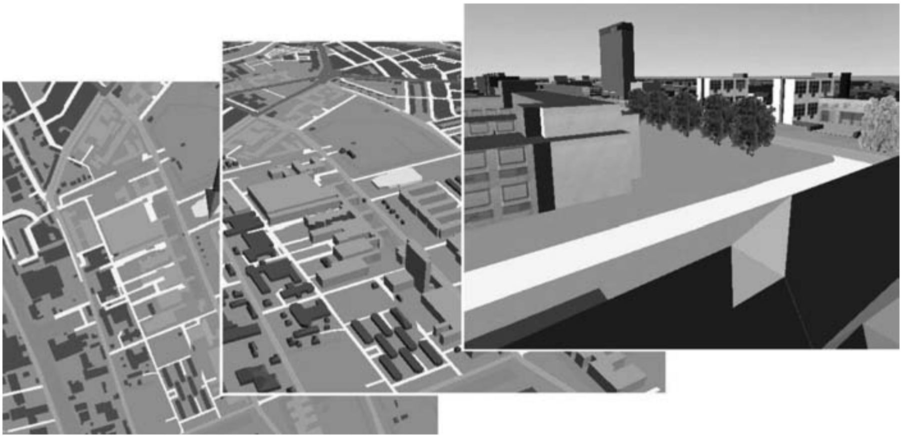

FIGURE 1.4 (See color insert after page 86). 2D plan view, 2.5D model view, and 3D world view in Karma.

that could be linked to the "ground plan" of the object in the GIS database). So, the Karma system did indeed succeed, up to a certain level, to integrate CAD and GIS objects and their functionality. However, as described above, this was not easily achieved, and it involved much nonautomated "hand work," taking too much time.

1.2.3 DATA COLLECTION

1.2.3.1 Example 1: 3D Cadastral Parcel

In some parts of the world (e.g., Queensland, Australia) 3D properties are already commonplace in cadastral registration. These properties can be surveyed (measured), but the geometrical description may also have originated in a CAD environment. This would be the case, for example, if the 3D property did not relate to a construction that can be surveyed (e.g., the outside boundary of a subsurface construction). The models delivered to the cadastral database in Survey Plans (Queensland Government, 2003) are relatively easy to incorporate in a GIS; see Figure 1.5. Here, the gap between CAD and GIS need not be all that great, as long as the model and procedures are correct and clear from the beginning. This also implies that a shared set of concepts (between CAD and GIS) has been used in the communication. The case shows a part of the solution when bridging CAD and GIS: when the concepts are well defined in advance, communication between the different systems is achievable.

1.2.3.2 Example 2: Point Clouds

Other examples, closer to surveying, originate from the use of multibeam sonar or airborne and terrestrial laser-scanned data sets resulting in "point clouds" from which objects can be reconstructed (see Figure 1.6 and Figure 1.7: house, power cable respectively). The task at hand is to derive from the point clouds well-structured CAD models (according to their design) of the surveyed object types to be included

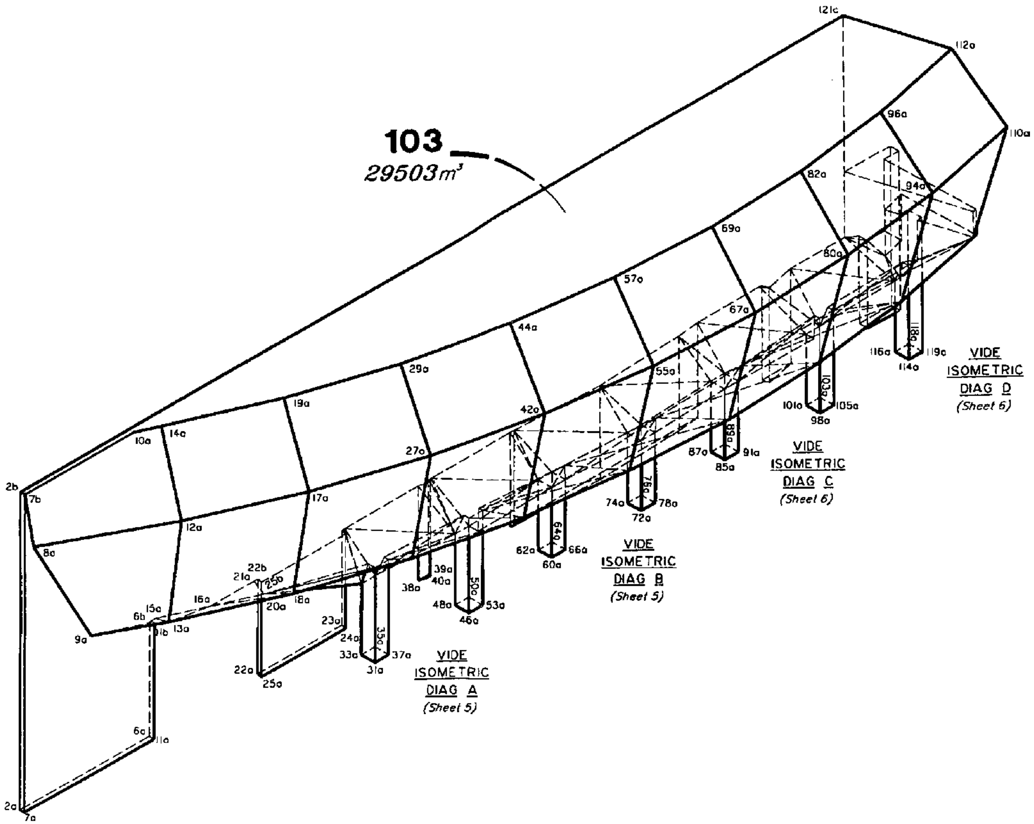

FIGURE 1.5 Survey plan for 3D parcel in Queensland, Australia.

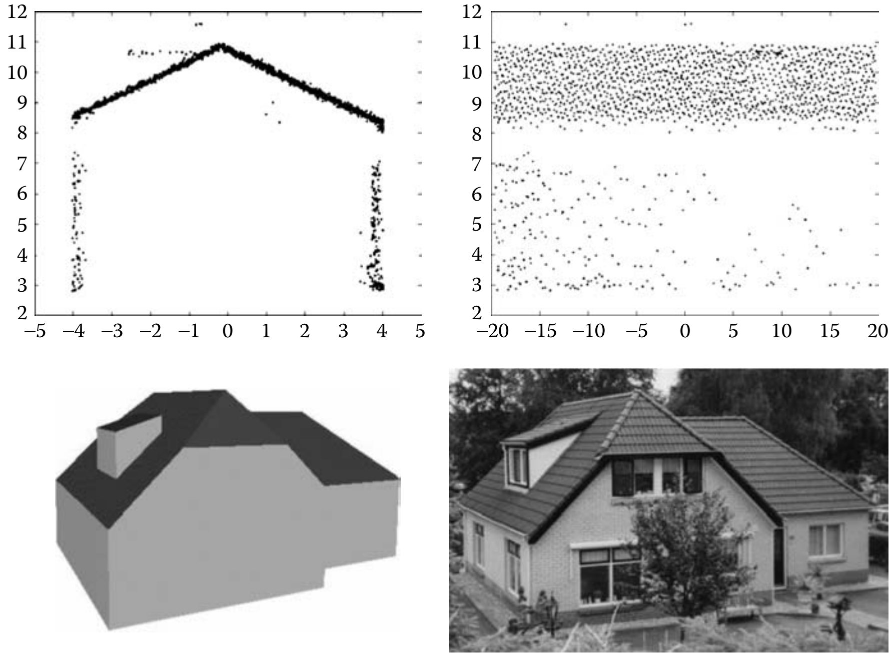

FIGURE 1.6 House object reconstruction from laser scanning 3D point clouds (from Vosselman and Dijkman, 2001).

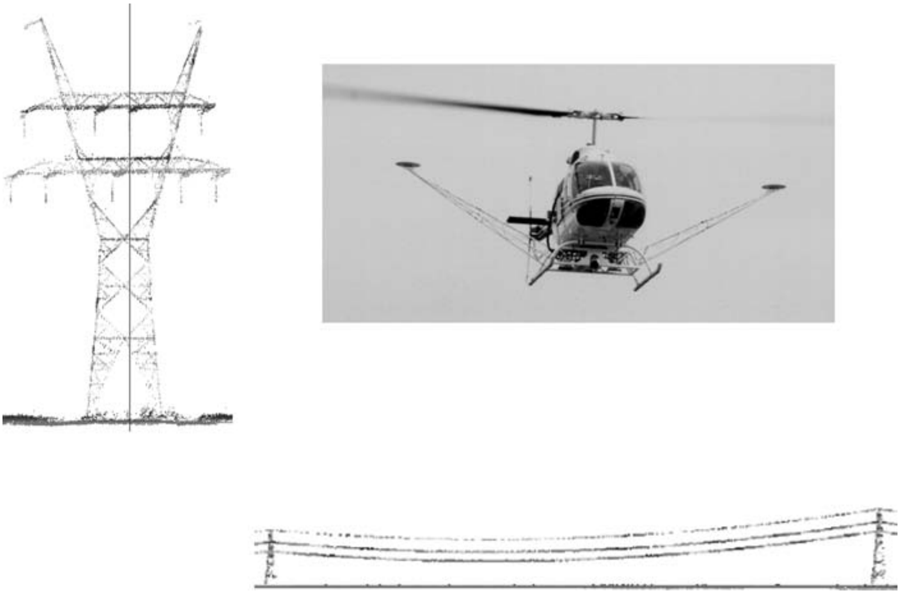

FIGURE 1.7 (See color insert after page 86.) Point clouds of power cables obtained by Fugro's Fli-map (Haasnoot, 2000).

in a 3D GIS environment. This is a nontrivial problem to be solved (automatically). Again, a mix of CAD and GIS functionality occurs (when capturing large scale 3D geo-information).

1.2.4 LOCATION-BASED SERVICES

1.2.4.1 Example 1: Augmented Reality

Location-based services (LBS) have many forms. One of the more advanced forms is Augmented Reality (AR), which requires a mix of GIS and CAD processing to visually insert "virtual" objects (designed in CAD) in good registration (by matching visible objects also available in a GIS database) with the real image of the environment. In the Ubicom system (Zlatanova, 2001), the user wears a see-through mobile augmented-reality display, which is fitted with a camera to record what is seen. A 3D database of the real-world environment is maintained at the server, and lines from the model in the database are matched with the edges in the camera image to derive the exact viewing direction and provide the virtual information at exactly the right spot (see Figure 1.8, top two figures). Different types of "virtual" objects can

FIGURE 1.8 Ubicom example of outdoor augmented reality (top row: matching features from the 3D database with the real world image for correct positioning and orientation; lower left: adding textual information to objects in the real world image; lower right: adding designed objects to the real-world image).

be added to the real-world image: 1. Planned and designed objects not yet realized in the real world, 2. Real, but invisible objects could be displayed in the right perspective (e.g., subsurface objects), and 3. Textual information can be added in "clouds" attached to real-world objects describing certain properties. Again, these cases show the integrated use of CAD and GIS functionality.

1.2.4.2 Example 2: Disaster Management

Another example is the (geo-) ICT support for police, ambulances, and firefighters in emergencies or crisis situations; the emergency services might want to use both outdoor and indoor information in an integrated manner (via the interfaces of their mobile equipment). At present, interior building designs from CAD systems and geographic information (from GIS) have to be combined in one environment. Again, this case shows the need to offer integrated GIS and CAD functionality within one application or user environment.

1.2.5 ANALYZING THE OPEN ISSUES WHEN BRIDGING THE GAP BETWEEN GIS AND CAD

As several of the above examples illustrate, large-scale 3D geo-information is a subject of great interest for CAD and GIS users alike. This is also reflected in the GIS-extended CAD software packages of the market leaders such as Autodesk's AutoCAD/map, and Bentley's MicroStaton Geographics (Bentley, 2004). Recently, CAD designers have been confronted with more and more requests for geo-information (i.e., the geometry of identifiable objects with a fixed location with respect to the earth) to which other information can be linked. This data can serve many purposes, e.g., spatial analysis or the updating of existing geographic data sets with planned (designed) objects. Much progress has been made in 2D in the past few years; after all, cadastral parcels can now be designed in CAD systems (with some kind of geographic extension) and maintained in a DBMS. These local, designed environments are now part of the complete world for which coordinates are needed. As the same information is constantly being reused and updated, a system is needed whereby the integrity and consistency of the spatial, temporal, and thematic data is maintained.

However, data sharing between CAD and GIS appears to be difficult in practice. It is not unusual for two departments (one working with CAD and another with GIS software) in one organization, such as a province or state, to not communicate because they cannot exchange data. Everybody who has tried to import CAD data into GIS software has experienced this in one way or another, e.g., lack of object definitions in the CAD models, different scale representations, transformation of the local (CAD) coordinates into a reference system for both the horizontal and vertical coordinates, parametric shapes that cannot be converted into GIS objects, different levels of detail that require generalization, etc. Often, there is also a conceptual or semantic difference between the concepts in a design (CAD) environment and the concepts in the observed and measured geo-information (as in GIS). These conceptual frameworks (ontologies) have to be made explicit and compared and related to each other before things can improve.

In 3D, spanning a bridge between CAD and GIS is even more of a challenge. CAD software provides all kinds of primitives to create geometric (and their visual attributes) models close to reality; however these primitives are not supported in GIS. How can CAD primitives (e.g., parametric primitives) be used in an Open Geospatial- (or ISO TC211-) compliant environment or the other way round? How can Open Geospatial primitives be used in combination with CAD functionalities (textures, shading, etc.) to represent a model close to reality? In 3D, CAD designers may become major providers (holding the set of tools to edit and update) of large-scale geo-data for use in GIS once a fundamental bridge between CAD and GIS has been established. It should be noted, at this point, that up-to-date, large-scale geo-information is being used more and more as the source of derived medium- and small-scale geo-information after (dynamic or on-the-fly) generalization.

Not surprisingly, if we convert data from GIS to CAD and vice versa, enormous mismatches will arise in the elementary data representations and automatically lead to a loss of (implicitly encoded) semantic meaning or information. Maintaining the integrity and functional meaning of the data is, therefore, a crucial issue in "bridging" the two domains. Much research is needed to examine in detail the interoperability problem between GIS and CAD.

1.3 CONVERSIONS AND MULTIPLE REPRESENTATIONS

To get a "feeling" for conversions between CAD and GIS, it is worthwhile to take a look at some conversions within a domain. Important lessons can be learned up front from these examples, which can later be useful when widening the scope again (and covering both GIS and CAD representations). We will start with some conversions (including geometry and thematic information) from the GIS domain (Section 1.3.1) and then move on to the CAD domain (Section 1.3.2). The important role of semantics during the conversions and several aspects of semantics (attached to the geometric objects) are discussed in Section 1.3.3. Often, the different representations of the same object are due to the specific application environment. Instead of considering the different representations as different objects, it is better to consider them as the same object to which different views are associated (depending on the context). Section 1.3.4 will show that these views are closely related to the phase of its life cycle the object is in (design, construct, survey, maintain, etc.).

1.3.1 CONVERSIONS BETWEEN AND WITHIN GIS

Examples from the GIS domain include the following:

- From large-scale (detailed) to small-scale (overview): This process is called *generalization* (not to be confused with specialization and generalization within the object class hierarchy). It is essential to understand the meaning of the different objects and the purpose or task of the person using the representation or map.

- From digital landscape model (data structure or database) to digital cartographic model (display on screen, paper, etc.): This process is called *visualization*. Again, the semantics are important in order to choose the right graphic primitives or symbols (for the different object classes) and the right graphic parameters (color, width, texture) to represent the value of relevant attributes.
- A thorough understanding of semantics is required to achieve *schema integration* (creating models with "the best of both worlds" in one uniform environment) and *schema mapping* (converting models, objects, or descriptions from one world into the concepts used in the other world) on the basis of geographic data from heterogeneous sources covering the same region.

1.3.2 CONVERSIONS BETWEEN AND WITHIN CAD

Examples from the CAD domain include the following:

- *Levels of detail*: In order to maintain interactivity and real-time display, a complex CAD model often has to be simplified in the polygon count, but not at the expense of visual quality. In a flight simulator, the resolution of the terrain model is adaptively improved and simplified according to the position of the aircraft above the terrain. Here we strive for a continuum between the local detail and the overview. Another technique known as "occlusion culling" reduces the polygon count when rendering large urban environments from street level, where large parts of the town will not be visible anyhow. Using the facades of the street as "clipping planes," and merging these complicated facades into simplified "virtual occluders" will speed up the visualization process with orders of magnitude (Wonka and Schmalsteig, 1999.)
- *Meshing*: Although the same basic geometry is used for several functional analyses (e.g., calculations of strength and stiffness), the exact form can differ from application to application. For instance, finite element stress analysis needs volumetric meshing. Ideally, the mesh resolution should be adapted to the gradient of the local stress in order to avoid unnecessary computations in regions where nothing is happening and to achieve high accuracy in regions with large stress concentrations. A different mesh topology might figure in other finite-element simulations such as "mould flow," because here we want to concentrate on the thin and distant parts that the flow might have difficulty reaching.
- *Feature modeling and conversions* (Bidarra and Bronsvoort, 2000; Bronsvoort and Noort, 2004): The notion of "feature" has been defined to encode thematic information in combination with geometry. A feature is a shape element with some predefined functional meaning. For instance, a cylindrical hole might be defined as a through hole or a blind

hole depending on the topology (open or closed at the bottom) and the manufacturing process. Again, the same part of the geometry might "feature" in different feature representations, depending on whether we want to use a piece of the geometry (e.g., a surface plane) as a reference for the surface smoothness properties, or as a reference plane in an assembly, or as a fixing plane in a machining operation.

1.3.3 FUNCTIONAL AND THEMATIC SEMANTIC ASPECTS

As we can see from these examples, model conversions are seldom based on pure geometric "translations." In most cases, some functional knowledge ("*semantics*") about the geometry is also applied to interpret the functional meaning and to maintain consistency (e.g., the geometry is closed) and validity (it still performs its intended function). The different aspects of "semantics" can be encoded in the following ways:

- Parametrization: Some of the geometry variables are used as defining parameters that discern the product in different classes (discrete parameters) or in continuous shape ranges
- Procedural definition: Algorithmic or computational shape definition to define repetition or a certain randomness
- Topology: Relations between geometric elements to encode "connectiveness" and "uniqueness," i.e., elements do not overlap, and the boundary is complete and closed
- Constraints: As in the case of topology relations but with a general numeric or computational character to define certain geometric or topological properties

A powerful modeler with at least some "solving" capabilities is needed to maintain the functional relations. For instance, if a bridge is lowered, this may inhibit a pass-through function for trucks. Ideally, the system would check and maintain this type of functional constraint. It often takes a complicated process to specify the constraint and determine the degrees of freedom, which are left for adjustment. All of these observations indicate that simple conversions do not exist and, hence, that simple schemata based on "geometry alone" will not work.

1.3.4 MULTIVIEW MODELING

The semantic content of models can also be organized by arranging the data according to aspects of design and manufacturing or life cycle stages. There are several ways of classifying this life cycle. One approach is described below:

- Plan/design
- Engineer/construct/manufacture
- Survey/measure/register
- Maintain/analyze/operate

It should be noted that this life cycle is ongoing, because objects are added, deleted, and redesigned in new cycles (in the spatial context), which again follow the same phases. Different sectors are interested in different aspects of the same real-world objects and use different tools to create and work with the information (models) associated with them. Each sector or organization chooses the tools that are optimized for the task at hand. Also, the (data) model and the data storage (DBMS, files, formats) might be completely different.

The life cycle should be given a central place in the integration, as it comprises the different design, manufacturing, and analysis aspects. To address the life cycle concept in GIS and CAD at a fundamental level, the data should be explicitly stored only once at a basic level, and a "view specific data" structure should support and allow data analysis and manipulation from a variety of perspectives without disturbing the underlying consistency.

Generally speaking, conversion between different representations is not simple — not even within the GIS and CAD packages, let alone between them. The conversions cannot be fully automated within the current state-of-the-art GIS and CAD software and technology, and human intervention is still required to obtain acceptable results. Hence, both versions of a model (original and post-conversion) are often kept and stored explicitly. This could be called a multiple-representation solution. Care must be taken to maintain consistency during updates. However, with technological progress (and the trend toward more formal semantics), it should be possible to have fully automatic conversions (perhaps also by lowering the requirements for the different views). It should be possible in the future to have only one (integrated) source of the model and to compute (updatable) views.

1.4 FRAMEWORK FOR BRIDGING THE GAP BETWEEN GIS AND CAD

The open issues when integrating GIS and CAD representations and functionality (see Section 1.2.5), illustrated in the case studies (see Sections 1.2.1–1.2.4), can be addressed by applying the experience and knowledge gained from the conversions that are already available within GIS and CAD (see Section 1.3). These conversions use both semantics and geometry to arrive at different representations of the same real-world object. What is needed in order to bridge the gap between GIS and CAD is a framework that covers both the geometry and the semantics. This section will begin with a preliminary remark on model class and instance level and then consider the conditions for such a framework, namely: formal semantics (see Section 1.4.1) and integrated data management (see Section 1.4.2).

When we refer to modeling, we can distinguish between two levels:

- Model class level: Define a blueprint (structure) for the objects later on, describe their attributes (spatial and thematic), relationships, etc. Essentially, this is the object class model (derived from object-oriented approaches to modeling and design) with everything at object class level (including the class inheritance hierarchy and aggregation/composite relationships).

- Model instance level: Create an actual abstraction of (some part of) the (planned or designed) real world, i.e., create instances of the object classes defined above: specify actual geometries and thematic attributes, create relationships, and satisfy specified constraints.

Design tools are available to create models at class level. The Unified Modeling Language (OMG, 2002) is used to create models in all kinds of disciplines. Highly appropriate in this context are the class diagrams. These are not only used in the development of information systems, but also to capture (formal) semantics in specific domains (e.g., the semantic web and structured dictionaries).

1.4.1 FORMAL SEMANTICS

It can be concluded from the above discussion that an important key to bridging CAD and GIS is to capture the semantics in the different models. However, implicit knowledge or tidy pieces of natural text and tables are not sufficient for this purpose. A more formal approach is required, as developed in disciplines such as knowledge engineering, ontologies, and object-oriented modeling. On the basis of this formal semantic approach, it becomes possible to decide whether different domain models (or even models within one domain) are or can be harmonized. Meantime, more meaningful handling of spatial information (by machines) will become all the more important and make the formal approach even more necessary. In the last decade, significant technological progress was made in knowledge engineering (via the developments from UML, ontology, semantic web, OWL), which enables knowledge to be further formalized in a practical way.

At present, most spatial (both CAD and GIS) information is used more or less directly by humans; in the future large parts of the information will also be processed (first) by machines (before recommencing communication with humans). Whereas humans are capable of interpreting different concepts by using implicit context information (which domain is involved, who supplied or produced the information, etc.), this knowledge will have to be made explicitly available for a machine. A large part of the formal structural knowledge about the concepts (objects being modeled) is captured in the relationships that one object has with other types of objects (specialization/generalization, part/whole, association), characteristics (attributes), and operations (methods, functions) belonging to the object class. The principles of object-oriented modeling are also discernible in this knowledge-engineering approach.

To make the idea of machine handling of geo-information a little less abstract, one could think of automating the conversions as described in Section 1.3. Other examples are automatic interpretation of sensor information (e.g., aerial photography, remote-sensing, or laser-scanning data sets) or recognizing and classifying objects or executing several (spatial) analyses in the context of a "decision support system." What all these tasks have in common is that, without the "domain knowledge," a machine could never execute them in an adequate manner. Interestingly, the wish for formalization of knowledge also occurs in many other disciplines and domains. Attempts are being made to formalize knowledge within specific domains (e.g., ship construction and medical disciplines) or even to compile complete collections of common and general concepts (dictionaries). Most of the time, these attempts are launched for exactly the same reason (to make a machine do certain tasks in a meaningful manner). For example, efforts are underway in the context of the "semantic web" to provide more meaningful search operation by developing formal frameworks of concepts ("ontologies" and making them operational). The UML class diagrams are frequently used for this purpose (OMG, 2002). Additional methods and tools are also used to, for example, map equivalent concepts in (different) frameworks or "rewrite" information from one set of well-defined concepts to the terminology of another (a geo-information example would be translating from the GBKN (Large Scale Map of the Netherlands) to the TOP10NL (Top10 vector data set of the Netherlands)).

Though UML class diagrams more or less constitute the "default" approach when creating formal knowledge frameworks, the graphic diagram has limited semantic accuracy. A nongraphic language is provided within UML for the further modeling of semantics (knowledge frameworks) with the aid of the Object Constraint Language (OCL, see OMG, 2002; OMG, 2003). This can be used to specify the criteria for a valid model (constraints), such as invariants for classes and pre- and post-conditions for operations. The advantage of using UML is that, as in the case of UML class diagrams, generic tools are available to support OCL (i.e., not CAD- or GIS-specific). The context of an invariant is specified by the relevant class; e.g., "parcel" if the constraint were that "the area of a parcel is at least 5 m^2." It is also possible within a constraint to use the association between two classes (e.g., "parcel" must have at least one owner, which is an association with the class "person"). The following are two examples in UML syntax (keywords in **bold** print):

```
context Parcel inv minimalArea:
 self.area > 5
context Parcel inv hasOwner:
 self.Owner -> notEmpty()
```

Besides UML (and OCL) for the formal description of the semantics (knowledge) of the different object classes in information models, there are specific tools for handling ("reasoning with") formal concepts (semantics, ontology). Cases in point are OWL, the Web Ontology Language (W3C, 2004) or the new ODM (Ontology Definition Metamodel) development from the OMG, which resulted in a proposal submitted in January 2005 (DSTC et al., 2005). The potential use and application of OWL in forming a bridge between CAD and GIS needs to be further explored.

It is already difficult enough to agree on the concepts and their (formal) definitions within a domain, so it will be even harder to do so between quite different domains (as in the case of CAD and GIS integration). A number of domain standards are currently being developed in the Dutch geo-information community (IMRO/spatial planning, IMWA/water, IMKICH/cultural history, GRIM/natural and agricultural environment, topography, cadastral/ownership, soil/subsurface, etc.). These crystallize out after lengthy discussions with many of the parties in a community.

The more recent domain models are described in UML class diagrams, which are a first step toward formal knowledge representation. Needless to say, it is also important to have these domain models in an international context and to harmonize the models from different countries (within one domain). Here, the discussions become even trickier (because laws, regulations, habits, and cultures vary in an international setting). One example of an attempt to create an international domain model is the FIG initiative to specify a "core cadastral model." It should be realized that multiple (natural) languages also feature heavily in the international concepts and that the labels of the concepts need to be translated into different languages (Lemmen et al., 2003).

It is becoming harder to agree on formal concepts, which should be shared between multiple disciplines of domains (already the case in the geo-information world, but even more so in the broader scope of CAD and GIS). Sometimes the same words (labels) are used for concepts with different meanings; other times the same concepts get different labels. This problem can only get worse in our network (information) society, but even so, attempts must still be made to harmonize the different domains. Probably the best approach is to start with a number of formal models in different domains (with a certain amount of "overlap") and to try to reach agreement (or at least try to develop mapping rules for the concepts of one domain to the ones of another domain and vice versa). One country that is relatively advanced in the geo-information domain is Australia, where a harmonized model between different (geo-information) domains has been developed: topography, cadastral, addresses, hydrography (ICSM, 2002).

The time has come to relate the concepts in the geo-information (GIS) world to the world of design, engineering, and construction (CAD/CAE/CAM). As we have seen in the case studies, huge differences (semantic and geometric) can exist even within one single organization (due to the use of different models and different software packages). Obviously, this is deeply disconcerting, given that in the real world, these systems relate to the same objects (roads, bridges, buildings, etc.) but in different "phases" of their life cycles (and from different perspectives).

1.4.1.1 Formal Geometry Semantics in the GIS Domain

In GIS, the geometry (and topology) is standardized by the Open Geospatial Consortium and ISO TC211, that is, also the geometry itself has a well-defined meaning and the different concepts are indicated by the names of the primitives or data types (the semantics). Since 1997, ISO and OGC have worked together on the basis of the large overlap in their area of work. One important concept in the OGC model is a spatial (or geographical) feature, which is an abstraction of a real-world phenomenon associated with a location relative to the earth (OGC, 2001). The conceptual model of the spatial feature is metrically and topologically described in Topic 1 of the OGC Abstract Specifications (called "feature geometry"). The aim of the Abstract Specifications is to create and document a conceptual model that is sufficient to create the Implementation Specifications. The geometry of spatial features is described by the basic class "GM_Object" (see Figure 1.9). At the moment, the implementation of the spatial feature in GIS is usually limited to simple features such as points, lines, and polygons.

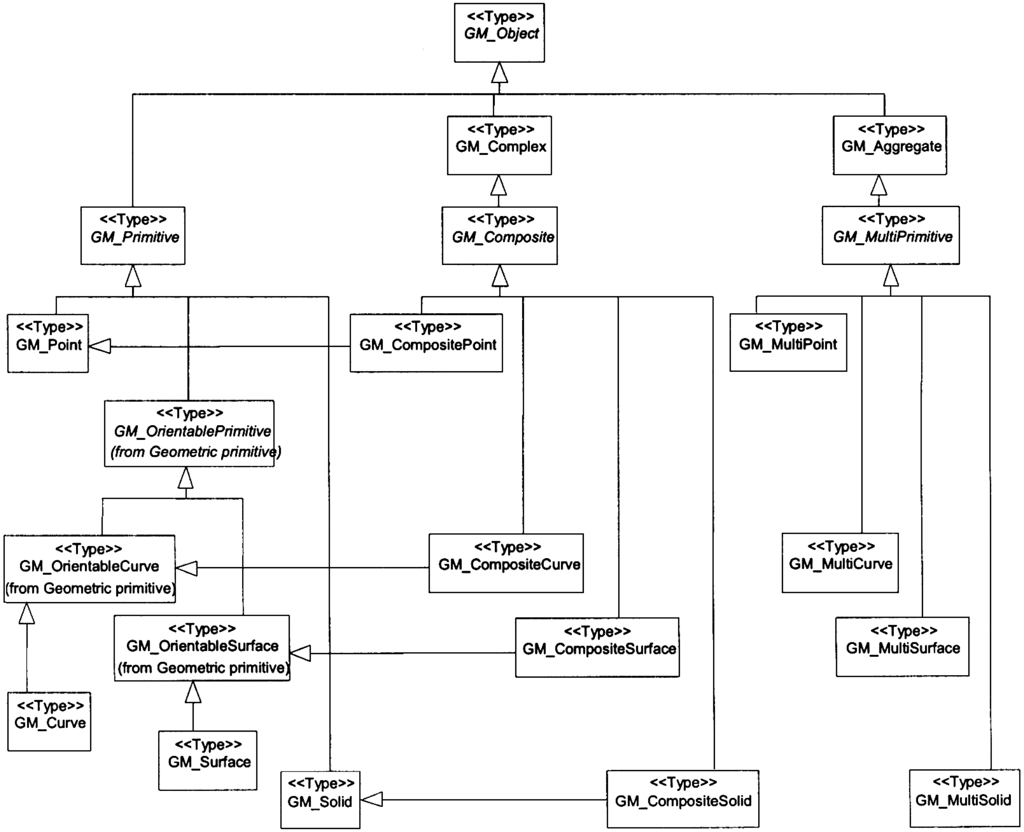

FIGURE 1.9 UML class diagram of geometry basic classes in GIS (from OGC, 2001).

1.4.1.2 Formal Geometry Semantics in the CAD Domain

Several file formats (DGN, DWG, X3D, SVG) have found their way into everyday practice as exchange formats in the CAD and graphics domain, each with their own advantages and disadvantages. The STEP project (STandard for the Exchange of Product model data) was initiated in 1984 by ISO TC184 Industrial Automation Systems and Integration, SC4 Subcommittee Industrial Data, to create a single international standard to describe product model data and provide a basis for sharing life cycle data. The STEP standard was approved as ISO International Standard ISO 10303. Pratt (2001) provides a short overview, and its current status is summarized in STEP (2004). Mason (2002) provides a useful overview of the life cycle aspects.

1.4.2 INTEGRATED DATA MANAGEMENT

After solving the semantic differences, the next step is to create an integrated model that can serve multiple purposes (from both a CAD and GIS background). Different views may be defined on this representation. The integrated model is managed in a way that maintains consistency (during updates or when model data is added to the data management system). So the same model is used as the foundation for planning, design, construction, management, analysis, presentation, etc. The integrated model implies that different applications can be used to perform these specialized tasks and also that different users can be working with the same model at the same time in different environments (or at different locations). As in the GIS world, where a gradual shift has taken place from file-based approaches to database management system (DBMS) approaches in situations where the use of (geo-) information has become more structural and where more than one person updates the data, a tendency toward a DBMS approach has emerged in the CAD world. For example, about two decades ago, when one of the authors was busy with his M.Sc. project (van Oosterom, 1985) at Fokker Aircraft Company, several different departments (predesign, aerodynamics, construction) needed access to the same CAD information on the new aircraft designs. Instead of a file-based approach, a DBMS was used, which served as a common baseline for all applications. Back then, specific interfaces to Oracle had to be developed for the different applications, but today some of these are available in standard products. Be that as it may, to date the CAD systems are still dominated by a file-based use, despite the fact that all modern CAD systems have connections to a DBMS. However, the 3D geometric primitives supported in a DBMS are rather limited, which is of course a serious drawback. A second explanation for the still dominant file-based use, is that the CAD systems are often used in design and construction contexts, which are project (or contract) based; see Appendix A. However, when full life cycle support matures and the information is (re)used throughout and between organizations (and not just by individuals), these needs will change.

Shared data management does away with conversions and all the accompanying problems (as illustrated in Section 1.2). Different applications will operate on (different views of) the same set of objects. So no data conversion is needed and inconsistencies are avoided, because there is only one source for a specific object. Good data management also offers other well-known advantages from DBMSs: multiple user support, transaction support, security and authorization, (spatial) data clustering and indexing, query optimization, distributed architectures, support for the concept of multiple views, maintenance of integrity constraints (especially referential integrity, but also other types), and integration with other relevant information systems within an organization. In a nutshell, "island" automation will be abandoned, as company-wide information management becomes a reality. Though most current DBMSs support spatial data types (Oracle, DB2, Informix, Ingres, PostgreSQL, and MySQL, to name just a few), these are not (yet) capable of supporting the higher geometry demands from CAD systems. That said, it should not be that difficult to extend the DBMS with more spatial data types. The authors of this chapter were involved in extending Oracle with a new spatial data type, the polyhedron (Arens et al., 2003). It should also be possible to implement other required types, but it should be stressed, at the same time, that a DBMS alone is not the answer to bridging the gap between CAD and GIS. The prerequisite is an integrated model, which is rich enough to support the semantics required or implied by the different domains.

The DBMS can be considered as an implementation platform for an integrated CAD–GIS model (with different views). However, when exchanging information (or using services from other sources), the structured exchange of information becomes an important issue. The UML (OCL) models are the foundation for both the storage data models (further described in the data definition languages (DDLs) of the DBMS) and the exchange data models. The latter have not been addressed in this chapter, but they are vitally important in our network society. The eXtensible Markup Language (XML) can be used for the models containing the class descriptions at class level (XML schema document "xsd") and for the data at object instance level ("normal" XML document with data "xml"). XML documents also include the geometric aspect of objects (e.g., LandXML, GML, X3D).

1.5 CONCLUSIONS

This chapter has explained the need to integrate GIS and CAD. Although such integration would offer great potential for the management of representations of real-world objects, it has been very difficult so far to use representations from GIS and CAD in one environment. The life cycle concept takes a central place in the integration: different representations or views of the same real-world object are needed throughout the life cycle of an object (plan, construct, survey, maintain).

It can already be concluded from conversions within one domain (GIS and CAD examples in Section 1.3) that geometric and semantic aspects both need to be taken into account. The same will be true for bridging the gap between GIS and CAD systems. However, as both the semantics and the geometry may be more different than within GIS or within CAD, the task is more challenging. At least two major developments are needed to close the gap between GIS and CAD (which many users want to see). The first is to perform a semantic analysis of the concepts of these "different" worlds and, if possible, develop a two-way translation between the two (or an integrated model with multiple views). Second, both GIS and CAD should base their data management on the same technology, i.e., as proposed in this chapter, a spatial DBMS, which is compliant with Open Geospatial (ISO) and CAD standards.

In this chapter we sketched the framework that is needed to bridge the gap between GIS and CAD. First, a formal description is required of the semantics used in both domains. The preliminary steps were set out in this chapter. The next step is to design one central formal semantic that is compliant with both GIS and CAD semantics. This formal semantic can be used in the factual integration of GIS and CAD, which should be implemented in an integrated data management structure based on the multiview model. This structure should be well defined in a DBMS environment. In effect, this will then close the gap between GIS and CAD in the future, and the user can select his favorite tool for a specific task, operating on a view of the shared model managed by the Spatial DBMS. Of course, this assumes that the GIS and CAD tools will all be adapted to the spatial DBMS with the different (semantic) views. Also, this approach should be used from scratch, which will then make the day-to-day practice of the cases mentioned in Section 1.2 much easier.

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APPENDIX A: DIFFERENCES BETWEEN CAD AND GIS

The "truth" of the following statements on the differences between CAD and GIS (most of them taken from the literature) depends on the perspective of the parties concerned. Note that there is a difference between the most frequent types of use of CAD or GIS versus the system's true capabilities. These statements try to illustrate the general feeling about the differences between CAD and GIS and are hardly ever "absolute truths." Further, it is our opinion that this generally accepted perspective is changing over time, along with the changes in the systems for CAD and GIS (and their definitions). Below, a scale of 1–5 is applied (1 = not true, 2 = sometimes true, 3 = most of the time true, 4 = nearly always true, 5 = always true) to indicate how true the proposition is, or will be generally perceived as such, according to the authors of this chapter at different moments in time.

	Statement Related to CAD and GIS	10 Years Ago	Today	10 Years from Now
1	CAD provides minimal or no thematic attribution; GIS has virtual unlimited attribution (often via a DBMS solution)	5	3	1
2	CAD has 3D geometry with little or no topology (e.g., closed volumes defined by faces in 3D space); GIS has 2D/2.5D geometry with 2D topological structure	5	4	3
3	CAD has no provision for modeling behavior; OO GIS has recently begun to model behavior	4	4	3
4	CAD has data set size limitations (for managing a set of limited objects relevant in the design project); GIS has worldwide size data sets	5	3	2
5	CAD usually deals with man-made objects; GIS deals with both natural and man-made objects	4	4	4

	Statement Related to CAD and GIS	10 Years Ago	Today	10 Years from Now
6	CAD usually deals with one (complex) object or product (possibly consisting of many parts), GIS deals with many (simple) objects embedded in the same space (and some of the objects have explicit relationships)	4	4	4
7	CAD assumes a 2D or 3D orthogonal world; GIS is capable of handling many differing coordinate systems to model a spherical (ellipsoid or even geoide) world	5	5	5
8	CAD may (or may not) be tied to the physical world; GIS must be tied to the physical world	5	5	5
9	CAD supports more complex geometry types (curves, splines, surface patches, etc.); GIS has to do with more simple geometry types (based on straight lines and flat surfaces)	5	4	3
10	GIS and CAD use different concepts and meanings (different semantics based on different, but related, ontologies)	5	4	2
11	CAD is design based (followed by analysis and computation); GIS is based on data collection (survey, remote sensing, photogrammetry, followed by analysis)	5	4	4
12	CAD is project related (design a specific environment followed by adjustments of the environment); GIS is related to constantly changing phenomena (e.g., topography changes); A project-based process leads to a file-based and single-user solution, while an ongoing process leads (registration) to a DBMS and multiuser solution	5	4	3
13	CAD may consider movement of parts of a product in relation to the function of the complete object; GIS considers (change of location and shape over time in) the context of transformations of the real world (both the past and the future) in spatial-temporal models	4	4	4
14	CAD systems have “standard” support for good 3D visualization (on 2D screens); GISs are usually limited to 2D visualizations (and sometimes modest 3D extensions)	5	4	3
15	CAD systems provide 3D coordinate input and digitizing; GISs are (mainly) limited to 2D data entry	5	5	4
16	CAD systems are used to deal with indoor as well as outdoor aspects (of unmoveable objects); GISs only deal with the outdoor (observable from the outside) representation of objects	5	5	4
17	Textures in CAD systems are better supported (for realistic rendering) than in GIS	4	3	2