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BUILDING INFORMATION MODELING (BIM) IN GEOTECHNICAL ENGINEERING

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Supervisor
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MASTER THESIS

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ABSTRACT

The rapid and continuous urbanization during the 20th century has led to an increase in man-made geohazards. Insufficient geological information and uncertainties in geological and geotechnical models have contributed to this problem. As a result, it is essential to assess geohazards in specific areas before undertaking civil engineering projects. Geospatial data plays a crucial role in the planning and management of civil facilities. Traditional Geographic Information Systems (GIS) have been used as tools for storing, manipulating, and analyzing spatial and geographic data. However, recent advancements in methods and technologies have transformed the methodologies and processes of the Architecture, Engineering, and Construction industry. Building Information Modelling (BIM) has gained popularity as an integrated digital model that complements the traditional planning approach. This study focuses on the integration of BIM and GIS with geotechnical/geological modeling (GeoBIM), which presents several challenges. The goal is to explore different integration strategies and establish a preferred workflow based on specific requirements and preference parameters. The foundation of GeoBIM is a versatile and comprehensive database that can handle digital geotechnical data seamlessly throughout the entire design process of underground infrastructure projects, eliminating the need for manual transformations. It is important to note that the accuracy of the database is crucial, as any inaccuracies may impact the study's outcomes. To address this, 3-D geological models are increasingly used to characterize ground engineering. Examining soil, rocks, and geological structures through a 3-D view proves highly effective in geotechnical design and construction to optimize costs and minimize damage and risks caused by unforeseen ground conditions. Technological advances continually reshape modeling and integration workflows. However, the proposed evaluation framework in this study is universal and adaptable for any new integration approach. Further research is needed to minimize attribute data losses and enhance interoperability between systems and professionals.

Keywords: BIM, GIS, database, geotechnics, geospatial interoperability.

HASAN KALYONCU ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ
İNŞAAT MÜHENDİSLİĞİ BÖLÜMÜ

GEOTEKNİK MÜHENDİSLİĞİNDE YAPI BİLGİ MODELLEMESİ (BIM)

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YÜKSEK LİSANS TEZİ

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ÖZET

Yüzyıllar boyunca sürekli olarak hizli bir sekilde artan şehirleşme, farkli jeolojik tehlikelere neden olmuştur. Yetersiz jeolojik bilgi ve geoteknik modellerdeki belirsizlikler bu soruna katkıda bulunmuştur. Bu nedenle, inşaat mühendisliği projelerine başlamadan önce belirli alanlardaki tehlikelerin değerlendirilmesi önem arz etmektedir. Cografi mekansal veriler, sivil yapilarin planlanması ve yönetiminde kilit bir rol oynamaktadır. Geleneksel Coğrafi Bilgi Sistemlerinde (CBS), mekânsal ve coğrafi verileri depolamak, manipüle etmek ve analiz etmek için kullanılmıştır. Ancak, Mimarlık, Mühendislik ve İnşaat endüstrisinin metodolojilerini ve süreçlerini dönüştüren yöntem ve teknolojilerdeki son gelişmeler, Yapi Bilgi Modellemesi (BIM) gibi entegre bir dijital modelin geleneksel planlama yaklaşımının tamamlanmasına neden olmuştur. Bu çalışma, BIM ve CBS'nin geoteknik/jeolojik modelleme ile entegrasyonu üzerine odaklanmaktadir. Amaç, farklı entegrasyon stratejilerini keşfetmek ve belirli gereksinimlere ve tercih parametrelerine dayalı tercih edilen bir iş akışı oluşturmaktır. GeoBIM'in temeli, dijital geoteknik verileri tasarım sürecinin tamamında sorunsuz bir şekilde işleyebilen çok yönlü ve kapsamlı bir veritabanı olusturmaktir. Veritabanı bilgisinin doğruluğu kritik olduğundan, herhangi bir yanlışlığın çalışmanın sonuçlarını etkileyebileceğini belirtmek gereklidir. Bu sorunu çözmek için, üc boyutlu jeolojik modeller, zemin mühendisliğini karakterize etmek için giderek daha fazla kullanılmaktadır. Zemin, kaya ve jeolojik yapıları uc boyutlu olarak incelemek, geoteknik tasarım ve inşaatta maliyetleri optimize etmek ve beklenmeyen zemin koşullarından kaynaklanan hasarı ve riskleri en aza indirmek için oldukça önemlidir. Teknolojik gelismeler iş akışlarını sürekli olarak şekillendirmektedir. Bu çalışmada önerilen değerlendirmeler evrensel ve yeni bir entegrasyon yaklaşımı için uyarlanabilir niteliktedir.Ayrica sistemler arasındaki veri kaybını en aza indirmek ve etkileşimi artırmak için daha fazla araştırma yapılması gerekmektedir.

Anahtar Kelimeler: BIM, CBS, veribankası, geoteknik, coğrafi mekan, birlikte çalışabilirlik.

My precious family ....

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I hope this thesis will serve as a valuable resource for engineers, geotechnical experts and project stakeholders involved in similar projects and help them make informed decisions about soil improvement strategies.

I offer my endless respect, love and gratitude.

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ABBREVIATIONS OR SYMBOLS LIST

AEC	Architecture, Engineering, and Construction
AIA	American Institute of Architects
AIM	Asset Information Model
API	Application Programming interface
BIM	Building Information Modeling
CAD	Computer-Aided Design
CDE	Common Data Environment
COBIE	Construction Operations Building Information Exchange
CSG	Constructive Solid Geometry
DSI	Discrete Smooth Interpolation
ICT	Information Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IFC	Industry Foundation Class
ISO	International Organization for Standardization
GIS	Geographical Information System
LCS	Local Coordinate System
LOD	Level of Definition/Development
LPS	Local Placement System
MEA	Model Element Author
NBS	National Bureau of Standards
NURBS	Nonuniform rational B-splines
ODBC	Open Database Connectivity
TIN	Triangulated Irregular Network
WCS	World Coordinate System
XSD	XML schema definition file
ifcXML	XML-based IFC standard
2D-GIS	two-dimensional Geographical Information System
3D-GIS	three-dimensional Geographical Information System

1. INTRODUCTION

1.1. General

When planning and evaluating a geotechnical site, mineral deposit, hydrocarbon reservoir, or aquifer, it is critical for project engineers and technical managers to have a comprehensive understanding of subsurface conditions. However, the available samples only provide a limited understanding of a small section of the total volume, resulting in uncertainty in the remaining parts. Despite this challenge, it is essential for experts to assess and estimate the characteristics of the unknown elements to develop an appropriate engineering arrangement. For instance, when planning a major structure like a dam or power plant, the foundation's underlying layers and materials should be accurately characterized to create proper engineering arrangements. Precision is also vital in predicting fluid flows in rocks or sediments in fields such as petroleum engineering, hydrogeology, geotechnical applications, or mining activities, and in planning mining projects. In all these cases, geological boundaries define the required characteristics, and their precise characterization is the first vital step. However, the practice is significantly challenging owing to economic constraints, geological complexity, and difficult subsurface access.

In most cases, subsurface samples can only be obtained through drilling or diggings. Occasionally, geophysical measurements are used to map underground physical characteristics and correlate them with geological features. However, these measurements can have a considerable level of uncertainty and do not directly provide information on geological characteristics. Nevertheless, they still offer valuable data. Geostatistical methods help streamline the incorporation of various information sources, estimate unknowns, and assess the uncertainties in generated models. The main challenge is determining the essential parameters and uncertainties of the subsurface when dealing with limited data and information sets. (Caers 2005).

Traditional mapping methods relied on manually drawing facies and parameter boundaries in two-dimensional slices and connecting them to create three-dimensional images.

However, these manual techniques did not take into account the detailed and analytical structure of three-dimensional data. Furthermore, conventional modeling approaches lacked a clear and consistent modeling criterion.

Recent advancements in technology, such as three-dimensional data acquisition tools, powerful computers, computational techniques, software, and modeling techniques, have become available. This has allowed the use of interactive and criteria-based modeling tools for three-dimensional modeling, which enables better integration of available data, expert knowledge, and mathematical rules. This approach leads to more accurate and realistic representations of the subsurface. The availability of three-dimensional data sources, such as well-bore data and three-dimensional seismic measurements, along with improved modeling methods, has further expanded the use of three-dimensional models. These models facilitate enhanced data integration and accuracy.

To summarize, the significance of three-dimensional models in geotechnical and other applications can be emphasized in the following points:

a. Geotechnical modeling and foundations:

The primary function of the foundation for structures like dams, bridges, buildings, and railroads is to distribute the loads from the structures to the ground. In order to ensure the safety and stability of these structures, a geotechnical engineer must develop a thorough plan to investigate the subsurface soil and bedrock characteristics, as well as the geological features of the area. This mapping process is important in determining the earth's capacity to bear the loads and identifying any associated hazards and risks.

The first essential step is to locate and determine the extent, shape, and properties of the weak and load-bearing layers. It should be noted that the mechanical, geotechnical, and hydrogeological characteristics of the underlying materials in a given geological and geotechnical category are generally consistent and similar. For instance, a layer primarily composed of coarse sediments may exhibit higher permeability and fall into a specific geotechnical or geological category. Similarly, layers with similar conditions within the same geotechnical category also share similar properties. Therefore, the delineation of these geological bodies and the categorization of their geotechnical or geological classes are crucial steps in order to model their continuous characteristics effectively (Geotechnical Engineering, Wikipedia, 2012).

b. Hydrogeology and groundwater aspects in geo-engineering problems:

Layers beneath a structure's foundation that possess high hydraulic conductivity and sufficient thickness can allow greater water flow below and around the foundation, which can pose a risk to its stability. On the contrary, layers with comparatively low hydraulic conductivity can serve as barriers to prevent foundation failures. The behavior of underground flows is significantly influenced by the hydrogeological characteristics of these layers, including their extent, thickness, geometry, and distribution (Marinoni, 2003).

There are other potential risks associated with the hydrogeological and geological characteristics of a site, such as swelling, shrinking, liquefaction phenomena, and seepage zones under dams. Furthermore, for hydrogeological applications, it is important to determine the specific characteristics of these layers.

Hence, the initial crucial step in conducting hydrogeological, hydrological, and geotechnical surveys is to thoroughly and comprehensively characterize the types and textures of the layers in detail. This comprehensive determination of the three-dimensional hydrogeological, geological, and geotechnical characteristics of engineering sites is of utmost importance (Hamilton, 2005; Lam et al., 1987).

Geostatistical methods provide a range of quantitative tools that facilitate the three-dimensional delineation of geotechnical category zones, estimation of the required parameters, and evaluation of the associated risks and uncertainties involved in these problems.

c. Plasticity and deformable materials and layers:

Some materials can be dangerous to foundations, especially when they are thick, and particularly materials that undergo plastic deformation or are too loose. Some examples of such hazardous materials include organic or evaporative sediments (Das, 2011).

d. Hazardous soils and quaternary sediments:

When dealing with foundations, it is crucial to pay attention to specific characteristics of hazardous soils. One significant concern is soil liquefaction, which can lead to landslides and create issues during seismic events. Several factors play a role in the vulnerability of soil to liquefaction, such as its grain-size distribution, composition, geological origin and condition, hydrogeological condition, and density (Johansson, 2017).

Granular soils that are loose to moderately saturated and have weak drainage are more susceptible to liquefaction. Soils such as silty sands or sands and gravels with impermeable seams or caps fall into this category. Under loading conditions, especially cyclic undrained loading like earthquakes, loose sands tend to shrink, increasing porewater pressure and reducing shear strength, ultimately resulting in liquefaction.

The most at-risk deposits for liquefaction are young sands and silts composed of particles of similar size (Holocene-age, well-sorted deposited sediments within the last 10,000 years). These deposits, several meters thick and saturated with water, are commonly found in areas like riverbeds, beaches, dunes, and accumulation zones for windblown silt (loess) and sand. Glacial sediments may also contain substantial quantities of sediments like quick clay (in the Pleistocene epoch), which can trigger landslides. Therefore, it is crucial to thoroughly investigate and analyze the texture, structure, composition, and shape of young granular soils like silty sands, sand and gravel, and clay bodies. (Wikipedia, 2012).

The Leine river valley and the sediments beneath it require careful attention and investigation due to potential risks in engineering. This study primarily focuses on the Pleistocene sedimentary zone, which exhibits varying geotechnical and geological soil classes.

Some sediments found beneath project sites may contain specific minerals that have deformation characteristics such as swelling or shrinking when in contact with water, including certain types of clay minerals. These minerals can cause deformations in the underlying foundation layers and pose significant hazards. It is crucial to consider all these characteristics, as indicated by the geotechnical and geological categorization of the sediments, as well as their interactions with the surrounding environment, in engineering applications. Considering these factors and other considerations, having an accurate and comprehensive three-dimensional subsurface model with assessments of uncertainty becomes an invaluable and necessary tool for decision-making in the location, design, and construction of structures.

e. Urban development plans:

A precise and comprehensive three-dimensional model of the subsurface, which includes information on geology, geotechnical characteristics, and hydrogeology, can be a valuable tool for making well-informed decisions in urban development planning. This model can assist in evaluating ground stability, identifying potential risks, and designing suitable foundation systems. It can also offer insights into groundwater flow patterns and their potential impact on construction projects. Scholars like Stoter and Oosterom (2006) and De-fu (2009) have underscored the significance of utilizing such subsurface models in urban planning, highlighting the necessity of accurate and up-to-date data to support decision-making processes.

f. The distribution and geometry of the weak and bearing layers:

During the planning phase of constructing structures, it is essential to not just identify weak and hazardous areas but also to ascertain the arrangement and shape of the bearing layers and their capability to withstand the anticipated loads and importance of the structure (Gedeon 1992).

The bearing capacity of a layer refers to its capacity to endure the applied loads from the ground. Essentially, it is the highest average contact pressure between the foundation and the soil that should not cause the soil to fail in shear (Wikipedia, 2012).

g. Further foreseen applications:

The three-dimensional subsurface model, in conjunction with the classification system, can serve various purposes. Possible uses of this model include managing groundwater, planning agricultural activities, exploring geothermal energy, and more.

It is worth mentioning that there are multiple definitions and discussions surrounding geotechnical concepts that have not been covered here. The main purpose of the previous section was to highlight the importance of three-dimensional modeling in geotechnical and hydrogeological investigations.

Nonetheless, the main goal of this study is to develop a three-dimensional geotechnical model of the subsurface using geostatistical estimation and simulation techniques.

1.2. Aim of the Study

The main objectives of this thesis is:

- to evaluate the literature about GIS and BIM interoperability;
- to make a comparison between the softwares and their interoperability

1.3. Outline of the Thesis

Chapter 1 – this chapter introduces the research questions and hypotheses along with an explanation of the research goals and the significance of contributing to the topic.

Chapter 2 - provides background information about GIS.

Chapter 3 –provides background information about BIM.

Chapter 4 – this chapter provides the evaluation and discussion of the interoperability of BIM and GIS.

Chapter 5 – in this chapter conclusions and recommendations are presented.

2. GEOGRAPHICAL INFORMATION SYSTEM (GIS)

2.1. General

In this chapter, an overview of GIS is given, along with the components of GIS. The literature review includes an overview of GIS, and specific and how it makes modelling.

2.2. Introduction to GIS

This section provides an overview of the current techniques utilized in representing, generating, and visualizing subsurface models in computerized characterization processes. In the previous chapter, we established that geotechnical characterization involves determining the shape of the subsurface and estimating the spatial variation of properties within it. The outcome of this characterization is a geotechnical model of the subsurface. This model is necessary to conduct engineering analyses and evaluate the performance of complex systems where an engineering structure interacts with the subsurface.

When carrying out subsurface characterization using computer-based methods, an integrated set of software tools is required. These tools should collectively serve the common objective of constructing a subsurface model that aligns with the study's purpose. A suitable tool for this task is a three-dimensional geo-information system (3D-GIS). To accomplish this, a 3D-GIS should incorporate the following essential components: tools for generating the subsurface shape, tools for estimating the spatial variation of properties within the subsurface, and advanced visualization tools for effectively communicating results.

Conceptually, the process of characterization for geotechnical purposes is fundamentally similar to characterization conducted in various other fields. Examples include hydrogeology, where characterization is performed for fluid flow or contaminant transport purposes, mining for reserve calculations, or the oil industry for the characterization of oil and gas reservoirs. However, it is important to note that the specific objectives of each application may differ, and the methods employed to carry out the characterization can also vary.

The aim of this chapter is to examine the various methods and techniques that are applicable in the representation and modeling of 3D spatial objects in the geosciences. The discussion focuses on three key aspects of geo-objects: their shape, the range of internal properties, and the level of uncertainty involved in generating the model. We will also review common visualization techniques, as well as the importance of scientific visualization in 3D modeling

2.3. Representing and Modeling Geo-Objects

Objects can exhibit varying levels of dimensionality and can be portrayed in different forms, including points, lines, surfaces, and volumes (refer to Figure 2.1). The modeling of 3D objects, which is the main focus here, is a common requirement in various fields like engineering, architecture, and medicine. Various modeling techniques, such as solid modeling techniques, play a crucial role in the overall process of 3D modeling, and they are discussed as a primary topic.

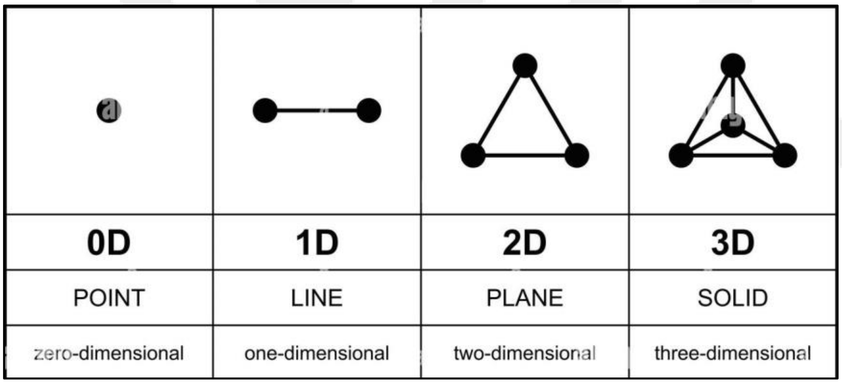


Figure 2.1 Dimensionality of spatial objects.

When discussing 3D geo-objects, it is important to differentiate between how a geo-object is digitally portrayed (known as representation) and the actual techniques utilized to create such a portrayal (known as modeling). Computer-based representations of geo-objects have been divided into two categories: surface representations and volume representations (as described by Fried and Leonard, 1990). Surface techniques are suitable for representing the outer boundaries of objects, while volume techniques are used to represent properties that exhibit continuous variation throughout an object. Both of these representations are explored in this text, along with the modeling techniques needed to generate them.

2.3.1. Methods and representations for solids

Solids are objects that possess a defined geometrical shape. The need to represent and model solids arose in various industries involved in the manufacturing of mechanical parts. Extensive research in solid modeling has led to widely accepted representation schemes for solids, which are now commonly used in computer-aided design (CAD) systems. More detailed explanations of these representation schemes can be found in the works of Requicha (1980), Foley et al. (1990), and Voelcker and Requicha (1993).

In contrast to man-made mechanical parts, which have predefined shapes, geo-objects are naturally occurring, irregular, and non-homogeneous. However, some of the methods and representation schemes developed for solids can be applied to model complex geometries in the field of geosciences, as discussed by Jones (1989).

- boundary representations, and
- spatial partitioning representations.

On the other hand, there are other schemes such as primitive instancing, sweep representation, and constructive solid geometry (CSG) that are designed for constructing models with predefined shapes or parts. As a result, they are not particularly well-suited for applications in geosciences.

However, these representations are valuable in engineering design, such as for creating excavations or tunnels.

2.3.1.1. Boundary representations

Boundary representations (b-reps) are used to describe an object based on its bounding surfaces. These surfaces are defined by polygonal facets, edges, and vertices. The facets can be either linear (planar) or curved and can be represented using various types of surface representations. The advantage of b-reps in geosciences is that they can accurately capture the irregular geometries of objects, preserve the input data, and facilitate efficient visualization.

However, there are also disadvantages to using b-reps. One challenge is that they can be difficult to validate, as pointed out by Foley et al. (1990). Additionally, b-reps are not suitable for representing the spatial variability of internal properties within the objects being modeled.

2.3.1.2. Spatial partitioning representations

These representations break down an object into a collection of adjacent, non-intersecting simpler solids, known as volume primitives. These primitives can vary in type, size, position, and orientation. The primary advantage of spatial partitioning is that it allows for the representation of the variation of internal properties within the modeled objects. Spatial partitioning combines two schemes originally developed by Requicha (1980): spatial occupancy enumeration and cell decomposition.

In spatial occupancy enumeration, the object is decomposed into volume primitives, typically cubic but sometimes tetrahedral. Two types of representation schemes are distinguished: linear and hierarchical. In a linear scheme, the volume primitives are equal in size and arranged on a regular grid. There is a direct analogy between the 2D-GIS raster data structure represented by pixels and the 3D-GIS volumetric data structure represented by voxels when using cubic cells. This scheme offers simplicity, ease of spatial querying, and spatial analysis. However, it may face challenges in accurately representing irregular geometries and requires large storage space. In a hierarchical scheme, volume primitives are obtained by recursively subdividing the space into octants until the desired resolution is achieved. This leads to the creation of an octree representation, which is similar to quadtrees in 2D-GIS.

Octrees partially overcome the limitations of regular volume discretization. However, converting from a boundary representation to spatial occupancy enumeration involves approximation and cannot be reversed.

The technique of cell decomposition involves dividing an object into volume primitives of various shapes and sizes. It is an extension of spatial occupancy enumeration. The significant advantage of cell decomposition in geoscientific applications is that it allows for adaptive tessellation, which is necessary when interpolating properties from irregularly distributed points or when tessellation needs to follow an irregular pattern of discontinuity. Another benefit of this representation is that it naturally supports finite-element analysis. Converting from a boundary representation to a cell decomposition representation can be exact and reversible, such as converting between a triangulated surface and a tetrahedral mesh.

2.3.2. Surface representations

There are two commonly employed methods for representing surfaces: polygonal and parametric. Polygonal representation involves using a collection of polygonal planar surface patches to represent a surface. This method is more commonly utilized in practical applications compared to parametric representation. In polygonal representation, the subdivision of a surface can be irregular, with triangular patches forming a Triangulated Irregular Network (TIN), or regular, with quadrilateral patches forming a grid. On the other hand, parametric representation uses parametric functions to define surface patches.

2.3.2.1. Triangulated irregular network

Triangulated irregular networks (TINs) are a method of representing a surface using a collection of triangular facets. This representation relies on explicitly defining both the geometry and the topology (i.e., the connectivity of the triangle vertices) of the surface.

TINs are well-suited for capturing the spatially varying complexity of surfaces. They offer flexibility in terms of node density and placement, allowing for local adaptations to the surface complexity. They also require fewer points compared to rectangular grids to represent surfaces of the same level of complexity.

However, TINs generally involve more computations to perform various operations on surfaces compared to rectangular grids. Additionally, surfaces represented as TINs are non-smooth, showing abrupt changes in slope along the edges of adjacent triangles.

2.3.2.2. Grids

Typically, grids involve dividing a surface into regularly shaped square or rectangular cells. However, grids can also be considered unstructured when both the geometry and connectivity among the grid nodes are irregular and explicitly defined. Structured grids can be further divided into different subdivisions.

- uniform or regular grids, with square grid-cells;
- rectangular, with rectangular cells;
- rectilinear, with a nonuniform spacing between grid nodes in the directions of co-ordinate axes;
- irregular, with quadrilateral cells of various shape.

Uniform and rectangular grids are the prevailing methods used to represent surfaces. Rectilinear grids are primarily used for finite-difference calculations, while irregular grids are occasionally utilized in finite-element computations.

Uniform and rectangular grids maintain the same level of detail across a surface, making them suitable for surfaces that exhibit smooth variations across the area of interest. The advantages of using grids include their simplicity in structure, availability in most computational environments, and ease of implementation for computations, including at the hardware level (Tipper, 1992).

However, rectangular grids have drawbacks in their inability to adapt well to complex and rapidly changing surface geometries. To compensate for this limitation, a finer grid size is required, leading to higher computational loads and increased storage space demands. Additionally, rectangular grids impose a global directionality on a surface, aligned with the two main axes of the grid. These limitations can be overcome by employing TINs and parametric surfaces, but at the expense of increased complexity.

2.3.2.3. Parametric surfaces

Parametric surfaces refer to higher-degree approximations of surfaces that are based on parametric functions. These surfaces are composed of polynomial surface patches mathematically defined by given input points. Typically, parametric surfaces employ cubic polynomials to generate smooth surfaces that can exhibit changes in slope between interpolated points.

The main categories of parametric surfaces include Hermite surfaces, Bezier surfaces, and splines, each of which can be further divided into various types (Foley et al., 1990). Non-Uniform Rational B-Splines (NURBS) are considered the most suitable parametric representation for geological surface modeling (Fisher and Wales, 1992; Fisher, 1993). NURBS are defined as ratios of polynomials with unevenly spaced control points. The primary advantages of NURBS over other parametric representations are their ability to accurately represent complex and smooth surfaces while adhering to input data and allowing local control over patch position.

Parametric representations require fewer polynomial surface patches compared to polygon meshes to achieve a desired level of accuracy in approximating curved surfaces. However, working with polynomials involves more complex algorithms compared to polygons. Despite the usefulness of splines in engineering applications like automobile design and their suitability for representing geological surfaces, they have not been extensively utilized in 3D-GIS.

2.3.3. Surface modelling

Geological applications of surface modeling can be categorized as either surface-fitting or equation-solving, according to Tipper (1992). When fitting input data, the resulting surfaces usually do not adhere to any specific mathematical model and are only constrained by the available information. On the other hand, equation-solving yields surfaces with a known mathematical form, obtained through numerical modeling of physical processes, such as simulating groundwater flow to determine a required piezometric surface for landslide stability analysis.

Surfaces can be further classified into two categories: single-valued surfaces, where each coordinate pair (x, y) corresponds to only one value of z, and multi-valued surfaces, where an (x, y) location may have multiple z values.

The techniques used for modeling surfaces are presented in increasing complexity:

- Modeling single-valued surfaces from randomly distributed input points.
- Modeling multi-valued surfaces from random points.
- Modeling surfaces from polygonal outlines obtained through sectional interpretations.
- Modeling discontinuous surfaces.

2.3.3.1. Modelling single-valued surfaces

In the geosciences, computerized techniques for surface mapping and modeling have traditionally been employed to map single-valued surfaces. These techniques rely on various interpolation algorithms, often referred to as contouring algorithms, as surface elevations are typically represented by contours. The input data should be available at random and discrete locations where the surface has been sampled. The commonly used algorithms are summarized in Table 3.1 and can be categorized as global or local, deterministic or stochastic, exact or approximate, depending on whether all data points or only neighboring points are considered in the interpolation and whether the weights of samples are determined deterministically or statistically from the input data. Another important distinction is whether the algorithms are direct or indirect, such as triangulation or gridding.

Triangulation, a direct technique, is typically performed by placing the triangle vertices at the given data points. The triangulation method most commonly used is the Delaunay triangulation, which ensures that the circumscribed circle of any triangle includes the three points of the triangle and no others. To learn more about triangulation and various algorithms used for it, refer to sources such as De Floriani et al. (1985), Schumaker (1993), Lattuada and Raper (1996), and others. Triangulation algorithms can also be implemented using hierarchical concepts to generate multiresolution representations of surfaces, as explained by De Floriani and Marzano (1994).

Gridding, on the other hand, is the most frequently used method for interpolating single-valued surfaces. It involves estimating the elevation (or other measured property) at each node of a grid using an interpolation method. Gridding is an indirect method because it uses the original data points to calculate a set of secondary points on a regular grid. There are several gridding algorithms available.

Calculated grids refer to surfaces defined by regularly distributed points. To create a continuous surface, it is essential to fit the surface patches between adjacent grid points. If a traditional contour-based representation is required in a two-dimensional space, smooth contour lines can be constructed using spline functions that accurately fit the local data points.

2.3.3.2. Modelling Multi-valued surfaces

When surfaces contain multiple values, surface modeling becomes more complex. Although surfaces can still be represented by TINs (triangulated irregular networks) and grids, the algorithms used to construct them vary from those used for single-valued surfaces. Mailet (1992) provides a Discrete Smooth Interpolation (DSI) algorithm for constructing TINs that are suitable for complex geological surfaces such as domes and overturned folds. These TINs are created from both input data points and interpolated points and can be manipulated interactively – however, manipulating one point could potentially affect the entire surface which is a disadvantage of this method.

Another system that uses TINs to model complex surfaces is the Discontinuity Modeling System (Sides, 1992a, 1992b). Additionally, establishing hierarchy is crucial as the surfaces do not define a closed volume, meaning the problem of interrelationships among irregular surfaces in complex geological conditions has to be considered. Splines are another way to model complex and continuous surfaces.

2.3.3.3. Modelling surfaces from sections

In many cases, the data sets used for reconstructing a 3D surface are not randomly distributed. This could be due to the sampling pattern or the nature of the interpreted information that needs to be considered during surface construction. In geological applications, it is common to have input data available on a set of sections, where the spatial location of the surface under study is either measured or interpreted. To reconstruct a 3D surface that accurately represents the input data, it is necessary to employ a "surface from sections" modeling approach.

The challenge of modeling 3D surfaces from sections also arises in medical imaging and CAD engineering, such as the "Tofting technique." However, algorithms developed for medicine and engineering cannot be directly applied to geological applications due to the lower density of sections typically found in geological data. For further information on modeling surfaces from sections, refer to Meyers et al. (1992) and Müller and Klingert (1993).

2.3.3.4. Modelling discontinuous surfaces

One important aspect of surface modeling involves addressing the modeling of discontinuous and faulted surfaces. Some 3D mapping and modeling systems offer functionalities for directly and automatically handling faults. For instance, the GOCAD package, which utilizes TINs to represent surfaces, employs vectorial constraints to manage the shape of surfaces (Mailet, 1992). Additionally, the CPS-3 mapping package includes a fault handling option in the majority of its gridding algorithms (CPS-3, 1995).

2.3.4. Volume representations

Volume representations are utilized to represent geo-objects using volumetric elements of varying complexity. This type of representation allows for the characterization of an object based on its internal properties, which may differ from one element to another or from one node to the next. Volume representations can be classified into different categories based on the volumetric primitive used to tessellate a geo-object, including tetrahedral, hexahedral, prismatic, and polyhedral representations.

Tetrahedral volume elements are employed in 3D irregular networks, and they offer similar advantages to those provided by triangulated irregular networks in 2D space. Tetrahedra are flexible in adapting to the level of detail in a local area, effectively honoring bounding surfaces and preserving the topology of input data.

Hexahedral cells, with non-planar bases and tops and varying heights, are used in geocellular representations. These cells offer greater flexibility in honoring irregular external boundaries and in internally tessellating a geo-object compared to representations based on cubes and rectangular blocks. Deformed hexahedral cells represent the most complex form of hexahedra that may be required in engineering analysis.

Prismatic volume elements can take various shapes, ranging from simple triangular prisms to complex polygonal prisms. Truncated triangular prisms, with non-parallel base and top, are suitable for modeling thin, continuous layers between two triangulated surfaces. Conversely, complex polygonal prisms, with parallel base and top, are typically obtained in geological applications.

In geological modeling, models composed of cubes or rectangular blocks are often referred to as block models.

Polyhedral volume elements are the most intricate type of volume primitives, and they include polytrees, a type of vector octree representation. Polytrees can store additional nodes within the cells and accurately capture the geometry of the surfaces that bound a geo-object. They are well-suited for geological applications but are not commonly utilized in practice.

2.3.5. Volume modelling

Volume modeling refers to the use of algorithms and procedures to represent geo-objects through a volume representation. The generation of a volume representation involves two main methods: converting from one representation to another, and directly constructing volume components.

2.3.5.1. Conversion between representations

The volume representation of a geo-object is typically achieved by converting a surface representation. It is crucial that the surface representation accurately describes the object. The conversion process has been extensively studied in computer graphics and computer-aided design. While it is generally relatively straightforward to convert between volume and surface representations, the conversions are often only approximate.

The simplest conversion is from surface representations to voxel models. In this case, the main consideration is selecting the voxel size, which may be predetermined in certain cases such as mineral reserve estimation. However, the interpreter must choose appropriate voxel dimensions that balance geological complexity, available information, required accuracy, and computing resources.

Converting from surface representations to octrees can be done using different algorithms, which have been presented by Bak and Mill. Octree tessellation schemes generally improve upon voxel models in terms of accuracy and storage requirements but only provide approximate boundary representations. Prissang developed a practical application of an octree structure for modeling mineral deposits.

Conversion from grids to geocellular representations requires the grids to be stacked in a way that the projection of their grid nodes on a reference plane aligns. Conversion from one volume representation to another may be necessary when properties estimated using one tessellation scheme require a different tessellation for computational reasons. For example, a geocellular representation based on hexahedral elements may be suitable for modeling internal properties, while a tetrahedral tessellation is needed for finite-element analysis using the same model.

Conversion involving hexahedral components can be generated by constraining them between two input grids representing the upper and lower surfaces of the unit being modeled. In more complex cases, multiple layers of hexahedral cells can be created within the bounding surfaces. The generation of internal grids required to create the hexahedral cells can be done in various ways, such as replicating one of the bounding surfaces at specified intervals.

Conversion from triangulated surfaces to tetrahedral networks follows the principles of Delaunay triangulation extended to higher dimensions. The tetrahedra form an irregular network in 3D and are generated with vertices at the sampling points, preserving topology and enabling efficient interpolation. Conversion between surface representation in the form of a TIN and volume representation in the form of a tetrahedral irregular network is accurate in both directions.

2.3.5.2. Direct volume modelling

Some techniques for geological modeling of orebodies include the direct construction of volume components. This approach involves manual interpretation of geological features on sections or plans, typically in the form of polygonal outlines. These outlines are then transformed into volumetric components.

For instance, in a serial slice model, polygonal outlines are extruded on both sides of each interpreted section, halfway to adjacent sections, and converted into prismatic components. In a linked slice model, the components are more complex, but they must still adhere to parallel polygonal outlines on the interpreted sections.

Direct construction methods for volume components are primarily used to represent the geometry of the targeted geo-object, such as an orebody, rather than capturing the spatial variation of internal properties within the volume, such as ore-grade. Consequently, the solid components created through direct construction still need to be converted into simpler volume primitives that can be associated with the internal properties.

2.4. Modelling Properties of Geo-Objects

Property estimation involves determining the spatial variation of a specific attribute, parameter, or variable within a geo-object. It is assumed that these properties change continuously throughout the object. The properties of interest can be scalar quantities representing physical and mechanical characteristics (e.g. unit weight, compressive strength), vector quantities (e.g. orientation of bedding planes), or tensors (e.g. hydraulic conductivity in rock masses).

To estimate properties, a set of points known as nodes within the geo-object are defined. These nodes typically represent the centroids or vertices of the volume primitives that make up the object. Estimating a value at the centroid of a volume element implies that the element is homogeneous, and the estimated value is considered representative of the entire element.

Different methods exist for property estimation, and the choice of method depends on factors such as the quantity and quality of available data, the spatial variability of the property, and the objectives of the estimation. If the geo-object exhibits heterogeneity in terms of the property in question, the estimation approach relies on the characteristics of the input data. Interpolation techniques are commonly used when there is a large number of observations in the dataset. However, some datasets may be more challenging to interpolate, and additional information may be required to achieve satisfactory interpolation. This additional information, known as "soft" data, can take the form of uncertain, imprecise, or qualitative information. In summary, three different approaches can be distinguished when estimating the spatial variability of a property: interpolation using commonly applied techniques, interpolation with the aid of additional information, and considering uncertainties associated with the estimation.

- the data set is numerous and Interpolation can be performed using various techniques;
- the data set is sparse and Interpolation is only possible if additional Information is provided; and
- the data set is sparse and Interpolation is not possible, the property can only be directly attributed using the expert judgement of an interpreter.

For the definition of sparse data set, presented in the following subsection, it is necessary to first review the principles of Interpolation.

2.4.1. Interpolation methods

Most Interpolation methods used for estimating single-valued surfaces can be extended to three dimensions (3D) to estimate the spatial variability of a property. However, the extension to 3D introduces additional complexities in the Interpolation algorithms and increases the computational load. The most commonly used algorithms for 3D property estimation are kriging and other weighted moving average methods, which are described in various textbooks.

When interpolating properties, it is common practice to use a uniform or rectangular grid, although other sets of nodes can also be used. The goal is to estimate the value of the property in each cell of the grid. For kriging and other weighted average Interpolation methods, it is necessary to define a search neighborhood around each estimation point. The search neighborhood represents a volume or area (in 2D) within which samples are searched for. To define the search neighborhood, the shape, size, and orientation of the volume need to be determined. Commonly used search volumes include search spheres defined by a search radius and search ellipsoids defined by three axes. In cases where a tetrahedral network is used instead of a grid, the search neighborhood is determined by the four closest sample points located at the vertices of the tetrahedron that contains the estimation point. Tetrahedral networks generated using Delaunay triangulation help define the natural neighborhoods of estimation points.

Using tetrahedral networks may provide advantages over grids for property estimation when input data in 3D space is relatively dense and randomly distributed. However, this is rarely the case in site investigations, where samples are typically clustered along boreholes.

Currently, grids with search ellipsoids are widely used for interpolation. To estimate the property in a specific estimation cell, at least some samples need to be found within the search neighborhood (i.e., ellipsoid). The selection of the minimum number of samples is subjective, but a rule-of-thumb is to have at least three samples; otherwise, the estimated value remains undefined. If a significant portion of grid cells are left undefined after interpolation due to not meeting the minimum number of samples criterion, the input data set is considered sparse.

2.5. Geostatistical modelling of uncertainty

In geosciences, the interpretation and characterization of subsurface conditions are always uncertain because the volume that is observed and sampled is considerably smaller than the volume that needs to be characterized. It is important to quantify this uncertainty and assess its potential impact. The issues of uncertainty and errors in 3D modeling in geosciences have been discussed recently by Sides (1992a) in relation to errors in mineral reserve estimation, and by Houlding (1994) in a more general context of geological modeling.

One way to quantify the uncertainty associated with geological models is by using geostatistical techniques. These techniques can provide an estimate accompanied by a standard error, or the conditional probability of a property meeting a specified criterion at a location that has not been sampled. Additionally, geostatistical techniques can generate a multitude of possible realistic representations of geological conditions, which depict both the subsurface geometry and continuously varying properties. This offers significant advantages in many applications where kriging estimates, which are essentially local averages, are too smooth to capture the impact of uncertainty.

2.5.1. Kriging

Kriging is an interpolation method that not only gives an estimate but also provides an indication of the uncertainty associated with that estimate. This uncertainty is described by either the kriging variance or the standard error. As traditional statistical methods assume that errors follow a normal distribution, it is common to associate the uncertainty with probabilities.

2.6. Visualization

Visualization plays a significant role in the interpretation of geological data and the creation of geological models. It allows for the visualization of input data, geological and geotechnical models, engineering analysis results, and proposed engineering structures or designs. Various visualization techniques have been developed in the field of computer graphics, with some primarily used for 2D graphics and widely applied in presenting geological data. However, more advanced techniques like 3D graphics are currently underutilized in geological applications.

Recent advancements in computer graphics include computer animation and virtual reality. Animation is useful for visualizing time-dependent phenomena, such as mass movement, while virtual reality enables users to interact with three-dimensional computer models in real-time. Although virtual reality applications in the geosciences are still relatively rare, it is expected that these techniques will see increased usage in the future.

This section mainly focuses on visualization techniques related to 3D graphics. The benefits of visualization in 3D geological modeling are as follows:

- Efficient utilization of available data during the interpretation stage, where geological data is retrieved from the database and visually displayed to create 3D geological models and verify them against input data.
- Qualitative consistency checks of the created models, resulting in improved model reliability.
- Possibility for interaction with the models.
- Effective means of communicating interpretation results.

The first part of this section provides a comparative analysis of 2D and 3D graphics in geological applications. The subsequent subsections describe the principles of common 3D visualization techniques used for surfaces and volumetric data visualization.

2.6.1 Two-dimensional versus three-dimensional graphics

There are several visualization techniques that use 2D computer graphics for displaying geological data in 2D Geographic Information Systems (GIS). These techniques include graphical symbols of different types, sizes, and colors to represent point data, lines of different styles and attributes to represent line data, and contour lines, polygons, and pixels to represent surface data. Borehole data, which is a type of data not commonly found in 2D-GIS, can be visualized as curved lines with different attributes to represent recorded parameters.

However, 2D visualization techniques have limitations and are insufficient for representing complex, multi-valued surfaces and volumetric data. Surfaces can only be represented by contour lines or color-coded raster maps when they are single-valued. For multi-valued surfaces, these techniques produce ambiguous results or are not possible. Volumetric data sets can only be viewed partly on sections, and techniques capable of visually representing complex surfaces and volumetric data require 3D computer graphics developed in fields like medicine, computational science, and engineering.

Volumetric data sets can be either measured or computed, depending on whether they were obtained through direct measurement or numerical modeling. Measured data examples include those obtained through computer tomography in medical applications and 3D seismic imaging in geophysics, while computed data can be obtained through interpolation of a property on a 3D grid.

2.6.2. Visualizing surfaces

Surface rendering, which is a highly advanced technique in 3D graphics, involves representing complex surfaces using geometric primitives of different dimensions such as points, lines, and surface patches. When the bounding edges of a surface are represented using lines, it is called a wireframe model. While wireframe representation can be improved by removing hidden lines, it is considered a basic way of representing surfaces. More realistic images can be generated when surface patches are rendered as well.

Surface rendering algorithms calculate the color intensity of each surface patch by simulating the effect of light. These algorithms, known as shading algorithms, include the Phong or the Gourand shading algorithms. The input for calculating the color intensity requires parameters describing the location and intensity of the light source, as well as the reflectance properties and normal of the surface patch being rendered. The calculation of a surface normal is straightforward only in the case of planar surface patches, making Triangulated Irregular Networks (TINs) the preferred representation for surfaces in terms of visualization. In addition to coloring and shading, surface rendering can also incorporate transparency and texture mapping, both of which are useful in geological applications. Transparency can reveal the internal structure of the model being visualized, while texture mapping enables the mapping of digital images onto surfaces, such as aerial photographs or satellite images onto a digital terrain model. By combining different surface rendering methods, levels of transparency, and image draping, visually pleasing effects can be achieved. The availability of surface cutting tools and interactivity further enhances the visualization process.

2.6.3. Visualizing Volumetric data

The large size of Volumetric data sets, which can reach millions of grid cells, makes it nearly impossible to analyze the internal structure of the data without the use of scientific visualization. The dense nature of Volumetric data sets allows for the automatic extraction and visualization of features of interest. Most of the visualization algorithms for Volumetric data are designed for medical applications and require the data to be available on a uniform or rectangular grid.

The visualization of 3D data sets can be done through surface or volume-based rendering. While it is still possible to use lower-dimensional geometric primitives such as points and contour lines, they may produce ambiguous results.

Surface-based rendering involves creating isosurfaces, which are the 3D equivalents of contour lines. Isosurfaces are used to define specific geo-objects. To extract surfaces of interest from volume data on a regular grid, an automatic algorithm like the marching cubes method can be used. This algorithm classifies each element in a grid using a set threshold, constructing an isosurface represented by triangles. However, this can generate large Triangulated Irregular Networks (TINs), which are well supported by graphics workstations. The drawbacks of surface rendering include its inability to represent properties of the volume data set that can't be depicted by a surface, and the discarding of a significant amount of input data during rendering.

Volume-based rendering, on the other hand, directly generates images from the volume data without the need for an intermediate step of generating geometric features like in surface rendering. This approach is becoming an alternative to surface rendering. Volume rendering can be seen as a 3D extension of continuous color-coded raster maps. Various algorithms, such as image-ordering or ray casting, and volume-ordering algorithms, can be used for volume rendering. Currently, volume-based rendering is mainly used in the field of medicine, while its potential for visualizing geological data has not been extensively explored.

2.7. Conclusions to GIS

There are various methods and techniques for representing and modeling 3D geo-objects in computer systems. These representations can be divided into two categories: surface representations, which effectively represent the object's geometry, and volume representations, which are suitable for representing the spatial variability of properties within the objects. In subsurface characterization, it is necessary to model both the geometry and properties of the subsurface, so both types of representations are needed.

For relatively simple and data-rich geometries, there are algorithms available that can automatically define the geometry in an appropriate manner. However, geo-objects often have irregular and complex geometries, while the available input data for characterization is limited. In order to define the geometry, additional information provided by the interpreter is necessary. Therefore, methods and techniques that offer interpretational control in modeling are beneficial.

Representing the spatial variability of properties within geo-objects requires dividing the objects into simple volume elements, known as tessellation, and estimating property values for each volume element. There are different tessellation techniques available for converting between different representations of a geo-object automatically. The choice of technique depends on the requirements of the interpolation method or the numerical method used in engineering analysis.

When there is sufficient data, the use of geostatistical methods is preferred over other interpolation methods in subsurface characterization. Interpolating properties using kriging provides estimates with a measure of uncertainty. Geostatistical simulations can generate alternative and realistic models of the subsurface, which are necessary for assessing the impact of spatial uncertainty in certain engineering applications.

The process of 3D modeling heavily relies on visual display of both data and interpretation. Complex subsurface conditions and multidimensional data can only be effectively understood when visualized. Both traditional 2D graphics and more recent 3D graphics techniques are necessary for this purpose.

3. BUILDING INFORMATION MODELING (BIM)

3.1. Introduction

Building Information Modelling (BIM) has been a crucial part of the Architecture, Engineering, and Construction (AEC) industry for over four decades. According to Aryani, Brahim, and Fathi (2014), there are six perspectives in BIM development, which include design, estimation, construction process, building life cycle, performance, and technology. The growing complexity of modern projects, such as the competition to build the tallest skyscraper, and the need for collaboration among multiple disciplines in designing, constructing, and managing these structures have rendered traditional CAD software inadequate. Miscommunication and mishandling of thousands of documents, ranging from 2D drawings to operation manuals, often lead to costly errors. Therefore, the industry needs BIM to computerize and efficiently organize information. In the following chapter, the text will delve into the components of BIM and how it enhances the AEC industry..

3.2. Building Information Modeling

Projects in the AEC industry involve intricate collaboration among participants from various specialized backgrounds in order to achieve a common goal with multiple facets. The complexity of these projects arises from the large number of complex drawings and documents that are manually created and updated using 2D information. This manual process can often result in miscommunication and misinformation among the parties involved. In the AEC industry, any misinformation can lead to significant mistakes and errors, resulting in additional costs and wasted time to rectify the issues. To improve information exchange, Information Communication Technology (ICT) is introduced to manage the vast amount of information and data, while also ensuring a reasonable level of reliability and consistency in the shared information (Aryani et al., 2014).Building Information Modeling (BIM) is a concept created in

1970 by Professor Charles Eastman. He argued that the state of the drawings at that time were not enough as they did not provide their reader with the capacity to visualize the project.

BIM has a significant impact on various aspects of the AEC industry, including design, life-cycle management, performance, and construction processes. Its utilization varies depending on the phase of construction (pre-construction, construction, and post-construction). Computerized information management systems have effectively implemented BIM in construction projects

Starting from the mid-2000s, the AEC industry has actively employed BIM in its projects, utilizing computer software and ICT. BIM functions as a facilitator of interoperability among the different parties involved in the AEC industry (Sani & Rahman, 2018).

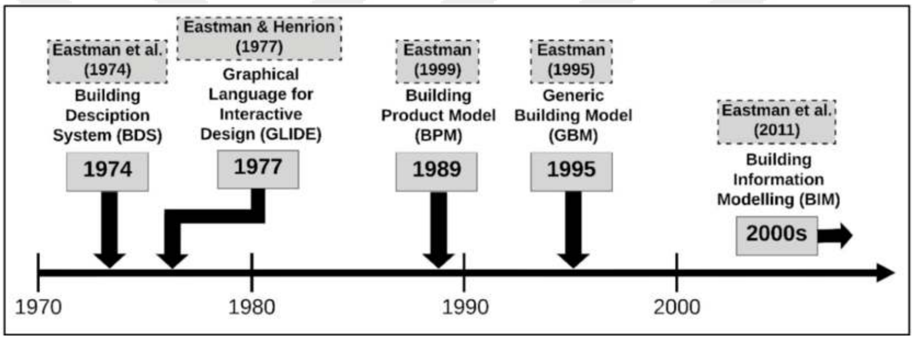


Figure 3.1. illustrates the evolution of BIM from the 1974s to the 2000s.

BIM, which involves 2D and 3D geometry modelled through the use of Industry Foundation Class (IFC), is commonly used by engineers in the AEC community to handle design geometry and visualize the model from 2D and 3D views while evaluating different design options, with consideration to client needs. Elements in BIM are represented as intelligent 3D objects that embed data such as energy use information, geometry, cost, scheduling data, etc, and mainly concern internal environments. The success of BIM models relies heavily on two essential concepts: object decomposition and specialization in each model. A critical factor is the semantic relationship between objects which refers to the addition of significant information to a digital model of a structure in software capable of comprehending new information, depending on pre-defined processing rules and relationships. The information included in BIM can be obtained from either personal or online databases. Information, which can change the standards of living, is a vital resource and must include syntactic information, semantic information, and pragmatic information to be useful. Semantic technologies, which are integral to current IoT research, enhance interoperability and data integration. The authors describe the concept of "ontology" as a compilation of conditions and relationships that link them. They provide a hierarchical structure as an example representing the indoor location ontology in figure 3.2.

3.3. The meaning of “M” in BIM

As per British Precast, BIM refers to the process of generating information models or datasets comprised of graphical and non-graphical data. These models are then shared among project stakeholders in a digital environment known as a common data environment (British Precast Concrete Federation Ltd, 2020).

The acronym BIM is somewhat misleading as it does not solely pertain to buildings. Additionally, it encompasses more than just the design and construction phases, extending to include information and details about the entire lifecycle of the project. The letter "M" in BIM can refer to Model, Modeling, or Management.

To begin with, we will delve into the concept of "Modeling" represented by the letter "M" in BIM. This term is widely utilized as it encompasses the entire building process. It involves a range of interconnected tools and processes that extend beyond basic 2D drawings and include additional dimensions of data throughout all construction phases (refer to figure 3.2). BIM enables active information input into the model, allowing for quick analysis and visualization of the effects of any applied changes on the project and its goals. This process, known as parametric modeling technique, maintains the established relationships between elements even when modifications are made. Such an approach enhances coordination among various disciplines within a single virtual model, leading to a reduction in errors. All stakeholders involved can assess the costs and benefits of each option, including factors such as quality, time, scheduling, etc., and subsequently make informed decisions. BIM serves as a supportive tool for innovative work techniques within a unified workspace, thanks to its high interoperability. Building information modeling within the AEC industry now offers different firms the ability to customize existing components and families, and even create new ones that align with their specific requirements. Customization is among the significant advantages offered by BIM software. Its foundation lies in object-oriented parametric modeling technique (Del Giudice, Osello, & Patti, 2015).

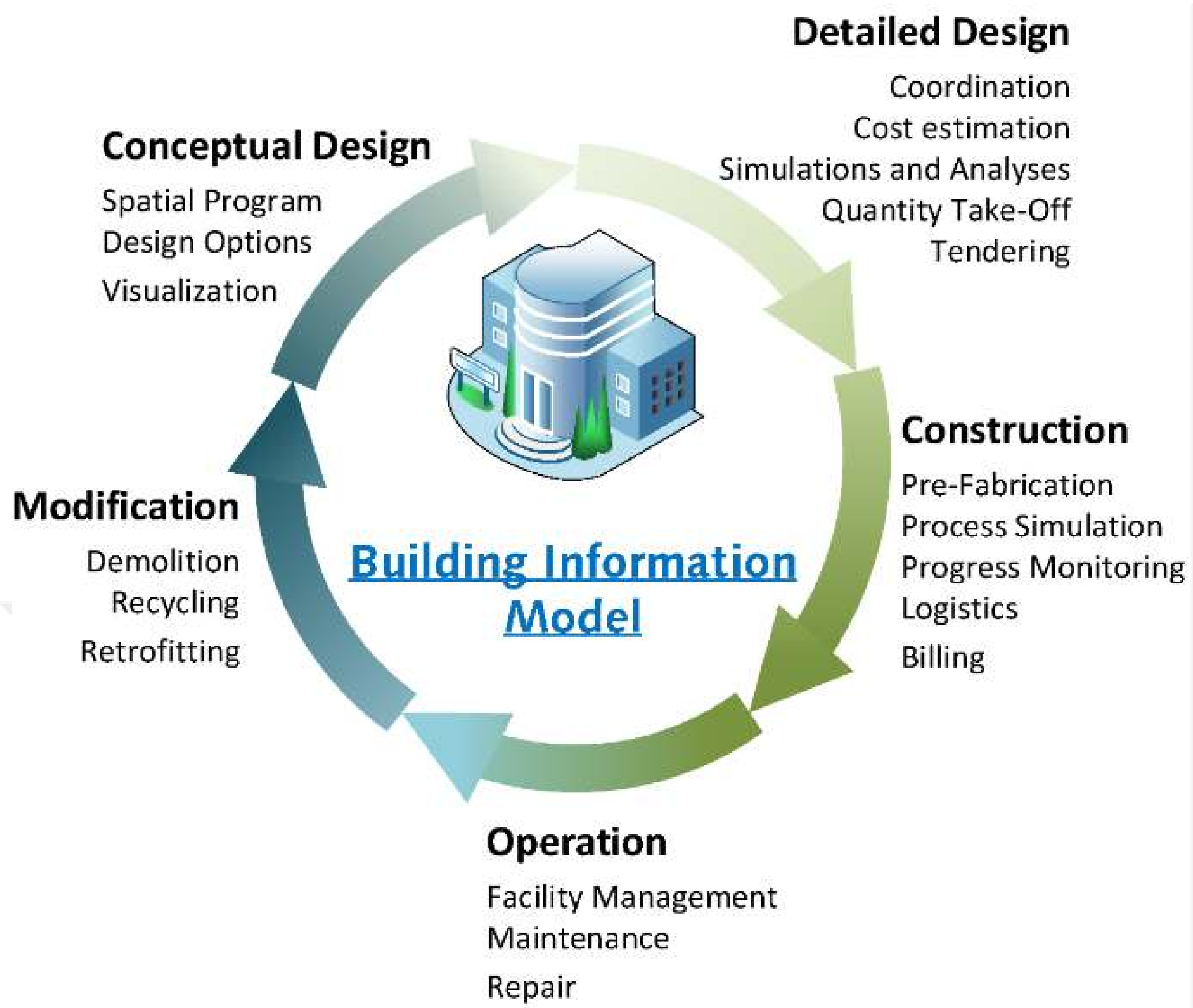


Figure 3.2. The concept of Building Information Modeling (Borrmann, König, Koch, & Beetz, 2018).

Next, let's explore the "M" in BIM as the technology used to create a "Model". BIM is a 3D object-oriented parametric modeling technique. According to the American Institute of Architects (AIA), BIM is a model-based technology that is connected to a database of project information. From a technological standpoint, BIM involves reproducing a project in the form of 3D models that include all the components and their links to relevant information. It represents both the physical and functional characteristics of the project, whether it's a building or a facility (NBIMS-US, 2015).

Lastly, we examine BIM in the context of "Management". The concept of BIM as a management tool has gained prominence in recent years. As mentioned earlier, BIM encompasses all the components and links that make up the structure. With access to this comprehensive information, the management of the building, from its conception to its demolition, can be significantly streamlined. In addition to enhancing information exchange and collaboration among different stakeholders, BIM also creates a knowledge database specific to the building or project.

3.4 The Concept of LOD in BIM

When discussing the Level of Definition/Development (LOD), we are referring to a framework used to determine the clarity and reliability of information within a Building Information Model (BIM) at different stages of the process (BIMForum, 2018). "Content" refers to the geometric and linked information in the model, while "reliability" pertains to the trustworthiness and understanding of the usability and limitations of the information within the model by downstream users. Accurate definitions of LOD specifications are crucial for each phase of the project's lifecycle in order for it to fulfill its purpose.

The level of detail in a model increases as the project progresses, starting from a simple concept and evolving into a detailed computer-generated model and, ultimately, an as-built Asset Information Model (AIM). It's important to note that different features of the model may develop at different rates, depending on which aspects of the project are handled by various team members (employer, contractor, supplier, etc.). Thus, clear LOD definitions are essential at different stages of the project. This enables the employer or client to have a sufficient level of detail and confidence in the design's evolution, allowing for better decision-making regarding project progress and the functioning of the as-built asset. LOD extends beyond graphical data and encompasses the integration of information from different disciplines and non-graphical data such as materials, quantities, costs, and operation manuals (Acampa, Parisi, & Grasso, 2018)

LOD definitions may vary by country, but the overall principles remain the same across guidelines. The U.S. LOD definitions are the most well-known and commonly referenced. In the U.S. system, LOD stands for Level of Development, and it follows a format of LODXXX, such as LOD100, LOD200, or LOD300. The system is organized based on the CSI Uniformat 2010, which organizes construction information according to functional elements or parts of a project with similar functions, regardless of the materials and methods employed. This system has been standardized by the American Institute of Architects (AIA). BIMForum, the current U.S. chapter of BuildingSMART, expanded upon the AIA's Level of Detail specifications and issued new Level of Development Specifications. Given the widespread use of BIM in various fields, BIMForum's definitions primarily focus on model element geometry. It's important to note that LOD does not indicate the progress of a project at each stage but rather serves as a field verification tool (BIMForum, 2018)

According to BIMForum, the primary objectives of LOD specifications are to assist stakeholders in specifying BIM deliverables, provide a clear understanding of what will be included, simplify the process of providing information and details during different points of the design phase, and offer clear guidelines that can be referenced in contracts and execution plans. These specifications are adopted by the U.S. National BIM Standard. Table 1 illustrates the LOD according to the U.S. system.

Figure 3.3. Level of Development according to the US System

The purpose of these spreadsheets is to gather and correlate LOD information for different types of elements within a specific project. The first spreadsheet is called the Model Element Table, where the rows represent building elements and the columns define the LODs at different project milestones. Each column is divided into three sub-columns: Level of Development (LOD), Model Element Author (MEA), and Notes.

The other spreadsheets are Attribute Tables that focus on specific building systems, such as structural steel, concrete, and precast concrete. The columns in these tables are divided into two main parts: Attribute Description, which lists the attributes relevant to that particular building system, and Project Specific Milestones, which indicates the attributes required for a specific milestone.

In the UK, LOD standards are defined in the PAS 1192-2 (Publicly Available Specifications) published by the British Standard Institution. In the UK system, LOD stands for Level of Definition. According to the National Bureau of Standards (NBS), the PAS 1192 framework outlines the requirements for model detail (graphical content), model information (non-graphical content), model definition (meaning), and model information exchanges. These documents establish the requirements to achieve BIM level 2, which is the minimum legal requirement in the UK. They are developed to meet market demands and comply with regulations set by the British Standards Institution (BSI). Since 2007, the PAS 1192 documents have provided guidelines for all aspects of BIM specifications as shown in table 2 (McPartland, 2017b).

Table 3.1. List of the Publicly Available Standards in the UK regarding BIM

Specification	Details
PAS 1192-1: 2007	Definition of the Common Data Environment
PAS 1192-2: 2013	Definition of the requirements for BIM Level 2. Mainly concerns the Construction Phase. Includes more detailed information about the
PAS 1192-3: 2014	Mainly concerns the Operational Phase. Deals with the use management and
BS 1192-4: 2014	Code of practice documenting the best practice for the implementation of
PAS 1192-5: 2015	Specification for security-minded building information modelling (smart asset

Over time, the standards for BIM have become more detailed, covering various phases of a construction project. The 2015 edition even includes guidelines for managing the completed facility. These standards focus on both the graphical and non-graphical data of the models, with the amount of each type varying across different stages. The Level of Development (LOD) component represents the graphical data, while the Level of Model Information (LOI) component represents the non-graphical data.

The LOD and LOI components develop together, progressing from LOD1 to higher levels such as LOD2, with increasing detail in both visual and structured data. The required LOD and LOI for specific project milestones are defined in the Employer's Information Requirements, which are incorporated into the contract. At each key point of the project, the information is assessed and compared to the specified level, allowing stakeholders to make informed decisions.

The Common Data Environment (CDE) acts as a central repository for all project information, including BIM resources, documentation, and both graphical and non-graphical data. The use of CDE enhances collaboration among project stakeholders, reducing errors, time, and cost. The CDE can take different forms depending on the project team's choice, following conventions from BS 1192:2007 or other custom environments. It allows team members to access the latest information and ensures synchronization and coherence through monitoring by a senior member. Each team member retains ownership of their provided information, often granting a license to the client for specific purposes.

The Asset Information Model (AIM) is a compilation of approved information, including models, data, and documents, related to the as-built asset. It supports the ongoing management of the asset during the operational phase. The AIM is built upon the requirements specified by the client in the Employer's Information Requirements (EIR). The Project Information Model (PIM) is developed during the design and construction phases and is transformed into the AIM at the end of construction.

COBie (Construction Operations Building Information Exchange) is an international standard for information exchange in construction projects. It involves the delivery of asset data to facility managers from the construction phase. COBie is versatile and can be viewed in different software and representations, with spreadsheets being the most common. It is based on the BuildingSMART data model and aims to improve the efficiency of exchanging information between the construction team and facility managers. COBie has foundational principles including a data model associated with the open IFC format, multiple delivery format options, and the need for a classification system.

COBie is part of the OpenBIM movement, which promotes collaboration in all project phases, and is also included in the UK BIM task group level 2 initiative.

3.5. The “Dimensions” in BIM Data

Every dimension in BIM adds additional information or detail to the data. A model with more dimensions is considered richer and provides a better understanding of the project. While BIM is commonly recognized for its graphical representation in 2D and 3D, it goes beyond that by offering numerous complex and significant non-graphical data dimensions. These dimensions enhance the provided information and increase the advantages of the model. The dimensions specified in BIM are as follows (Richard McPartland, 2017).

❖ **3D – The Shared Information Model or Three-dimensional rendering of the element**

- This dimension is the typical and widely used dimension in BIM. It encompasses the graphical data of the design and includes certain non-graphical information related to the elements. This information is typically shared in the Common Data Environment (CDE) and continually updated until the project is completed. Some tasks and outputs associated with this dimension include clash detection, project visualization, and model walkthroughs.

- At this level of dimension, the integration of models from various disciplines involved in the project forms what is referred to as the federated model. To meet the minimum requirement of Level 2 BIM maturity, this model is crucial. The federated model enhances project visualization and facilitates communication and collaboration between disciplines, thereby preventing clashes and errors in later stages.

❖ **4D – Construction sequence or Duration analysis**

- Time management is a crucial dimension in any construction process, encompassing non-graphical attributes assigned to elements that define the construction sequence as the project progresses. Various attributes can be included, such as lead time, installation time, installation sequence, dependencies on other elements, and more. Integrating 4D capabilities into the federated model offers significant advantages to planners. It enables them to plan material and equipment deliveries more effectively, following a "just in time" approach, and provides a visual understanding of the construction progress. Efficient work planning ensures safety and eliminates costs associated with errors. Within a digital workflow, planners continue to be essential team members, but in this case, they contribute to shaping proposals during the early stages of a project.
- Replacing traditional methods like Gantt charts with a digital workflow prevents the loss of data between designers and companies and improves communication between parties involved. Discussions around whether a contract duration should be "static" or "dynamic" highlight the necessity of reducing, managing, and reorganizing construction timelines through a more dynamic approach. This can be achieved by adopting new methodologies:

❖ **5D – Cost Estimation**

- The financial aspect of any project plays a crucial role in its conception and construction. BIM simplifies the process of budget tracking and cost analysis. Quantity takeoff is a significant feature of 5D BIM that saves a substantial amount of time compared to traditional methods. Previously, data extraction for material quantities required manual updates from 2D drawings, and prices were assigned in a separate file to determine the total cost. However, with a BIM model, all objects are parametric, enabling any changes or updates to be automatically reflected throughout the model, including the required amount of materials or elements.
- Additionally, BIM simplifies the role of cost managers. Vital cost information, such as capital cost, running cost, and replacement cost, is associated with each element. BIM facilitates quantity takeoff, allowing cost managers to apply cost rates to the quantities and determine the final cost. The inclusion of costing within the model brings several benefits, including 3D visualization of the cost and the ability to rapidly calculate the cost of any changes or updates.
- Various techniques can be employed to link the BIM model with the cost estimating system, including the Application Programming Interface (API), Open Database Connectivity (ODBC) to estimation programs, and exporting data to Microsoft Excel. The inclusion of precise 4D information simplifies the tracking of projected and actual project costs. Regular cost reports ensure that the project remains within budget. However, the effectiveness of these processes relies on the accurate sharing of information within the Common Data Environment.
- The information model encompasses three types of quantities: those directly derived from the visible model components, those indirectly derived from the model components (not always visible), and quantities that are not part of the model (such as temporary works). A cost manager must be capable of identifying quantities from sources beyond just the model components.

- ❖ **6D – Project Lifecycle Information or Energy Analysis**

- The notion of sustainability encompasses three core principles: environmental sustainability, which prioritizes the conservation of natural resources; economic sustainability, which emphasizes income generation and job creation; and social sustainability, which is centered around promoting the well-being of humanity.
- In recent decades, sustainability has emerged as an important subject, with efforts aimed at enhancing current processes and securing improved living conditions for future generations. Historically, the AEC industry prioritized evaluating the initial capital costs associated with a project. However, with the integration of 6D BIM, the focus has shifted towards determining the long-term costs associated with the entire lifespan of the project (including the prediction of CO_2 emissions and energy consumption). This enables stakeholders to make sustainable decisions at an earlier stage of the project:

  6D BIM, also known as Integrated BIM (iBIM), involves incorporating data related to the operation and management of the facility. This includes information on the manufacturer, installation date, energy performance, and cost of replacement. This comprehensive data enables better decision-making, particularly in choosing more sustainable and durable equipment for long-term use. With 6D BIM, designers have the ability to evaluate multiple options throughout the lifecycle of the project and understand the potential impacts of each choice. Facility managers can take a proactive approach by pre-planning maintenance schedules well in advance, sometimes even years ahead. However, for this approach to be fully effective, it is crucial to continuously update the information during the in-use phase and include all relevant diagnostics.

- ❖ **7D – Facility management**

- In this dimension, the model presented is known as the as-built model. It includes details about the initial design model as well as any modifications made during the process, resulting in the final model. The information gathered at the 7D stage pertains to the operations and management of the facility.

- During the handover process, the facility manager is provided with the information extracted through the use of 7D. This data encompasses details such as the status of components, maintenance schedules, warranties, specifications, and more. It is important to continuously update and maintain this information throughout the in-use phase.

3.6. The IFC Data (Industry Foundation Class)

The AEC industry has traditionally relied on basic computerized processes and information technologies for many years. However, the effective utilization of modern computer and information exchange methods offers numerous possibilities for the industry. Despite the vast amount of information generated in a single project, a significant portion is often lost or misplaced and not fully utilized.

In 1993, major AEC companies in the United States initiated discussions about using advanced information technology in the building industry. This led to the formation of the Industry Alliance for Interoperability (IAI) in 1994, which demonstrated interoperability between different CAD and simulation tools. The organization later expanded globally and was renamed the International Alliance for Interoperability, also known as buildingSMART International. The mission of buildingSMART International is to define and distribute specifications for Industry Foundation Classes (IFC) as a means of sharing information across disciplines throughout the lifecycle of a project. IFC, currently in its fourth release, is registered as ISO 16739.

IFC is a standardized digital description of the built environment, encompassing buildings and civil infrastructure. It is an open and international standard that is vendor-neutral and compatible with various hardware devices, software platforms, and interfaces. IFC goes beyond traditional sharing methods and allows for the description, sharing, and exchange of project information from conception to demolition across all disciplines and applications. It employs an object-based file format with a hierarchical structure and is designed to facilitate interoperability in the AEC industry. While IFC is primarily an EXPRESS-based entity-relationship model, there is also an XML-based IFC standard (ifcXML) developed by buildingSMART, although it is not widely used due to larger file sizes.

Globally Unique Identifiers (GUIDs), STEP physical files, and EXPRESS (an object-oriented data definition language) are the technologies used to describe IFC within the ISO 10303 Standard for the Exchange of Product Data (STEP). IFC enables interoperability between software applications, allowing for the exchange of data with simulation software. Numerous software applications, around 150, support IFC, facilitating collaboration across different domains. One key feature of IFC is its ability to formalize the representation of building elements, their attributes, relationships, and associated schedules and costs.

Interoperability is critical in BIM, prompting the development of IFC as a robust process for exchanging digital information regardless of the software used. The use of non-proprietary open formats, such as IFC, is necessary to ensure interoperability between platforms from different manufacturers. This compatibility enables direct communication and information exchange of common interest or reference, resulting in various benefits for the industry. Some benefits of using IFC in the AEC industry include

- Cost-free access to both graphical and non-graphical facility data.
- Improved collaboration among different disciplines.
- Reduced planning effort due to the automated acquisition of data from models and external IFC compliant libraries.
- Interoperability is achievable as long as software vendors support and comply with the IFC format.

According to Xu et al. (2014), the IFC schema can be divided into four layers, each consisting of several modules with numerous classes:

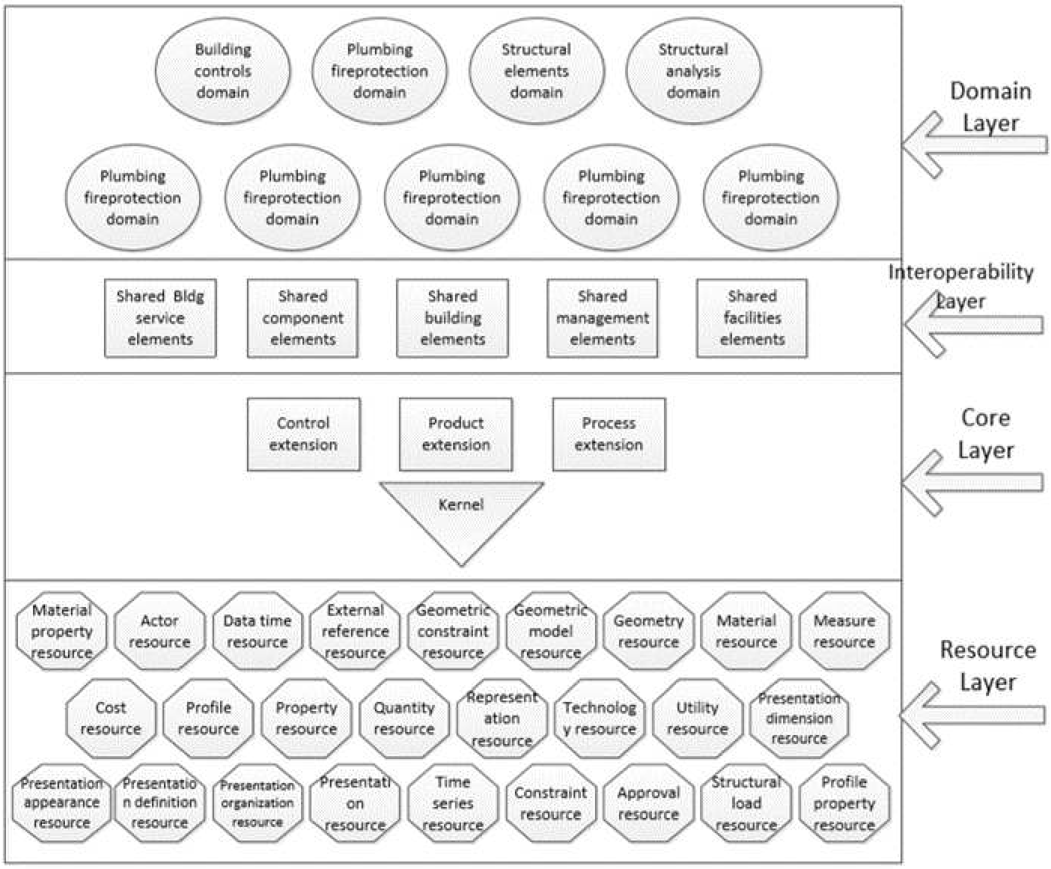


Figure 3.4. IFC Schema (Xu et al., 2014)

The key concepts in IFC consist of three distinctive methods for representing objects in three-dimensional space, as outlined by Zhu et al. (2019).

- Boundary-representation (B-rep) is a method utilized to depict shapes by determining their external surface. This technique represents a solid object as a collection of interconnected surface elements. The B-rep model incorporates two primary elements: geometry, which describes the shape and location of the surfaces, and topology, which establishes the connectivity among these surfaces. This approach is especially valuable for representing intricate objects, as stated by Deng, Cheng, and Anumba (2016a).

- Constructive Solid Geometry (CSG) is a methodology that employs Boolean operations, including difference, union, and intersection, on primitive objects to depict three-dimensional objects. This technique is less flexible compared to B-rep and primarily relies on utilizing simple shapes such as cones, spheres, or pyramids. Within a CSG tree, all the essential data is present to construct a model.
- The sweep method utilizes a 2D profile to determine the form of a 3D geometry. This profile is then extended along a designated path to achieve the desired length and orientation for the object, as discussed by Deng et al. (2016a). The concept of Level of Development, previously discussed in the preceding section, has already been explained.

Forms of the IFC Standard.

The organization of IFC data is based on a hierarchical structure at the class level. Objects are categorized into meaningful classes that have distinct properties like name, relationships, and constraints (Ellul et al., 2018). The entire data structure is controlled and governed by classes. All classes are subtypes of a single root class called ifcRoot. In practice, there are only three main abstract class groups, as depicted in figure 10 (Zhu et al., 2019).

IfcObject: It encompasses all possible aspects concerning construction activities. This can include physical objects (IfcProduct), construction processes (IfcProcess), or individuals/organizations involved in the construction (IfcActor).

IfcPropertyDefinition: It outlines all the possible characteristics that an object can possess, such as its name, size, color, and so on.

IfcRelationship: It establishes a connection between objects and other classes, whether it be through properties or linking to other objects:

Figure 3.5. Hierarchy of IFC data (Zhu et al., 2019)

IFC's spatial structure follows an inverted tree format where each element serves as a node. These nodes can have a parent node from which they derive or a child node that derives from them. A node without any children is referred to as a leaf node, while a node without any parents is considered a root node. The project node always serves as the root node, providing access to all elements within the IFC model.

Position plays a significant role in defining an IFC element, as it pertains to its local coordinate system (LCS). Each IFC model consists of at least four levels of LCS: element level, storey level, building level, and site level. In the research presented by Zhu et al., the term "LPS" (local placement system) refers to the relationship between a child LPS and its parent LPS. Accurate understanding of an element's LCS, determined by its origin and axis direction, facilitates the transformation of the LCS at the element level to other levels, including the LCS of the site and even the World Coordinate System (WCS) if the site is properly linked (Zhu et al., 2019). Figure 3.5 shows the IFC spatial structure.

To acquire the geometric details of an element within the model, two types of data are required: the position of the element (IfcLocalPlacement) and its form (IfcProductDefinitionShape).

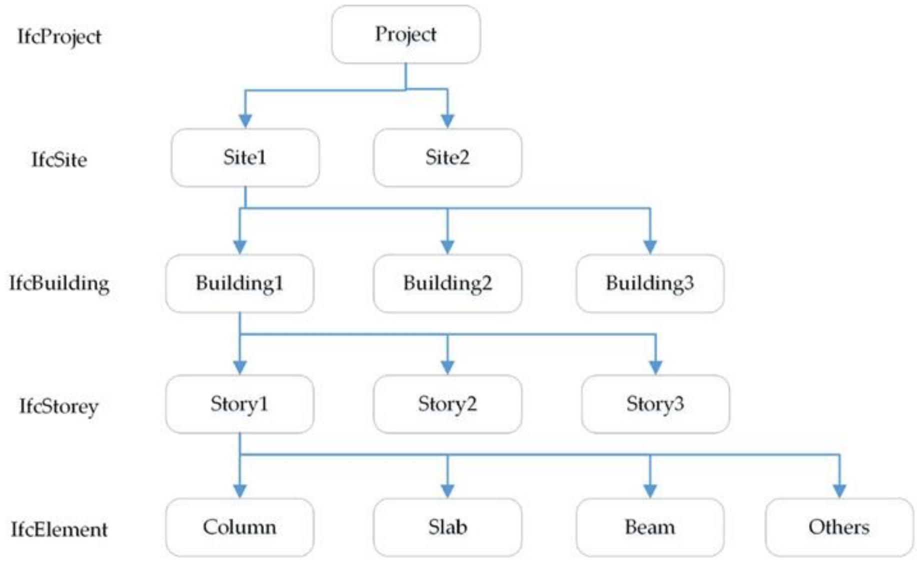


Figure 3.6. IFC spatial structure as shown in (Zhu et al., 2019)

To fully harness the potential of BIM, it is essential for objects within the model to possess a distinct hierarchical relationship assembly. This means that each object should be connected to at least one other object in the model. The nature of this relationship can fall into one of the following five categories (U.S. General Services Administration, "BIM Technical Standards: Grouping & Relationship", n.d.):

- **Composition:** This pertains to a type of relationship where there exists an exclusive containment of the parts within the whole. An example of this relationship could involve dividing a building into floors and subsequently subdividing these floors into rooms.
- **Assignment:** This is referring to a situation where one object includes or incorporates the functionalities or services of another object. For instance, it could involve assigning a specific task to a building element.
- **Connectivity:** This expresses the linking between specific objects, such as a beam being connected to a slab.

- **Association:** designates external links to an object for example an external IFC library file which includes the definition of the object.
- **Definition:** designates an instance of a particular family type for example a column being circular.

Furthermore, BIM objects are automatically organized into logical groups within a model. For instance, objects belonging to a particular level are logically assigned to that specific level. However, not all classifications are done automatically as some may need to be arranged manually by the creator.

4. INTEROPERABILITY OF GIS AND BIM

4.1. Introduction

In different domains, the term "interoperability" is defined in various ways. Therefore, in order to have a clear understanding of the topic, we decided to adopt a well-established definition for interoperability. In particular, when discussing interoperability between software tools, it is considered an IT-based concept. To establish a strong definition for this term, we explored IT-based definitions from recognized sources such as the IEEE Standard Glossary of Software Engineering Terminology published by the Institute of Electrical and Electronics Engineers (IEEE), as well as the Information Technology - Vocabulary jointly published by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). ISO/IEC provides various types or features of interoperability, including syntactic interoperability, semantic data interoperability, and behavioral interoperability. For the purpose of this paper, we will use the general definition of interoperability provided in ISO/IEC 2382:2015 to simplify the discussion. Additionally, we have identified the definitions of "integration" and "conversion" as these concepts are sometimes mistakenly used interchangeably with interoperability in the literature (IEEE, 1990; ISO, 2011; 2015; 2017).

Table 4.1. Definitions of important terms based on international standards

Terms	IEEE [13]	ISO/IEC [14]
Interoperability	"The ability of two or more systems or components to exchange information and to use the information that has been exchanged".	The capability to communicate, or exchange data between different functional units in a manner that demands the user to have little or no knowledge regarding each unit
Integration	"The process of combining software components, hardware components, or both into an overall system".	"progressive assembling of system components into the whole system"
Conversion	"Modification of existing software to enable it to operate with similar functional capability in a different environment".	Changing "the representation of data from one form to another, without changing the information conveyed".

The definitions related to IT in Table 1 clearly explain the concept of interoperability, as well as what it is not. It is important to note that interoperability should not be mistaken for data conversion or modification of data representation. It is also not about combining or assembling different data models into one. Instead, we define interoperability as the capability to communicate and exchange information between various software tools, and to effectively utilize the exchanged information. In the context of this paper, the software tools pertain to applications used in the BIM and GIS domains. This defined concept of interoperability will serve as a requirement for evaluating different approaches in achieving interoperability in this study.

4.2. Semantic Interoperability Problems and Solutions

In his work, Kuhn (2005) introduces three problem categories related to data interoperability. These categories address specific challenges encountered when making systems and services compatible with one another. Before delving into these problem categories, it is crucial to understand the concept of matchmaking, which forms the basis of semantic interoperability. Matchmaking involves a reasoning process aimed at determining whether an information offer matches a query. This can be done by humans, software, or a combination of both. The outcome can be binary (match or not) or a calculation of the degree of similarity.

Semantic heterogeneities between requests and offers are the main obstacles in matchmaking. Heterogeneities can be in the form of different terminologies for the same concept or different concepts represented by the same symbols. Naming heterogeneities can further be subdivided into syntactic heterogeneities (different symbols) and structural heterogeneities (different expressions). For example, a heterogeneity of syntactic naming could be the representation of a distance value as a floating-point number or a distance form. On the other hand, a heterogeneity of structural naming could involve representing a position with two separate coordinates or a form of point data. Another example is a conceptual heterogeneity, such as a measured distance on a sphere or in a plane.

It is generally easier to link data to specifications and resolve resulting heterogeneities than it is to link services to requirements. These two cases represent the first two problem classes in achieving interoperability. The third problem class pertains to the complexity of matchmaking when it comes to constructing programs that generate the desired behavior. Matches are sought between services, formulated services, and search requests. Each problem class builds upon the previous one.

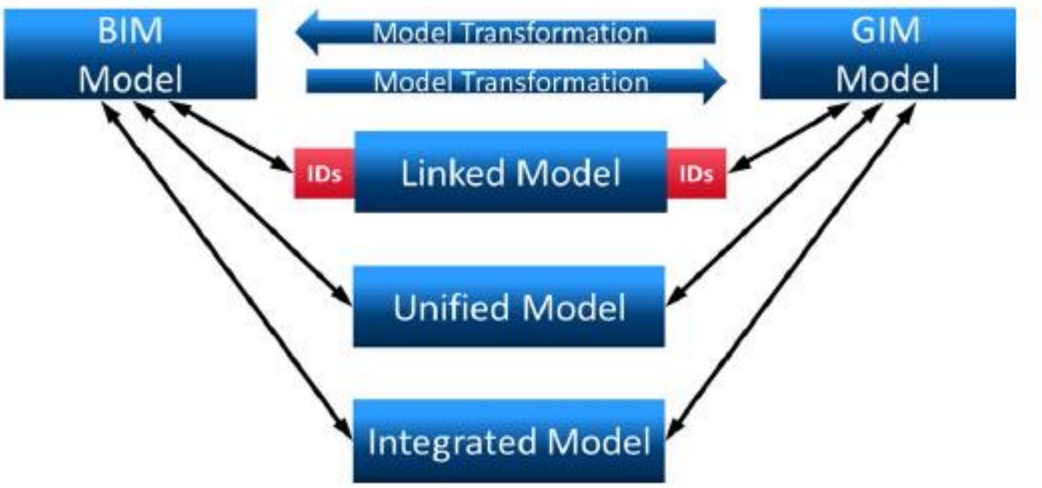
The first problem class focuses on the search for data sources and evaluating their contents in achieving semantic interoperability. Nowadays, a significant amount of digital geospatial knowledge is stored in databases and files. Users of this data need a clear understanding of what it represents. Accessing data through various means, such as database queries or web services, results in receiving values, attribute names, and complex objects. Ambiguities in interpreting this data can be resolved through matchmaking. However, current metadata specifications and catalogue services often fall short in adequately addressing naming and conceptual heterogeneities. Keyword-based search and lack of formalized vocabulary contribute to these limitations. Efforts have been made to utilize the semantic web to improve these shortcomings in geospatial applications.

The second problem class involves the discovery and evaluation of geospatial data sources. While the amount of available geospatial information services is increasing, their matchmaking process is hindered by similar limitations as the first problem class. In addition, the functionality of the services becomes a more significant consideration, leading to further semantic complexities. For example, defining the meaning of a distance operation can vary depending on the context, such as track lengths in a graph, Euclidean or Manhattan distances in a plane, or geodesic distances on the Earth.

The third problem class of semantic interoperability arises when attempting to create more complex services or applications through automated or manual software compositions. This problem class requires not only the identification and utilization of specific resources but also the coordination of multiple services. Both the service providers and consumers need to have a shared understanding of the services and their interfaces. Matchmaking in this context becomes more intricate, as service requests rely on previously identified service offers. This problem class also involves mediating between the outputs provided by one or more services and the inputs required by another service.

4.3. Interoperability approaches

The integration of Building Information Modeling (BIM) and Geographic Information System (GIS) can occur at different levels: the data level, the process level, and the application level. At the data level, structures are modified to be compatible with the other system, either by extending existing data standards or using tools like ESRI's ArcSADE and Safe's FME for data transfer and translation. This level can be further divided into the semantic and geometry levels. The process level involves implementing BIM and GIS in a workflow, allowing them to cooperate. It is more flexible than the data level. Lastly, at the application level, new applications can be developed that utilize the functionalities of both BIM and GIS, or existing applications can be extended. This level is considered the most challenging and time-consuming as it requires full data interoperability. Different classifications have been provided to categorize integration methods, focusing on either fundamental standards for data exchange or the development of new applications and methods. Some integration methods are unidirectional, transforming one data type to another, while others aim for bidirectional interoperability. Meta-models, such as the IFC to GIS project and the Unified Building Model, have been developed as mediators between GIS and BIM. However, the loss of semantics can be significant on the GIS side, requiring harmonization and modification of both systems. Integration methods are reviewed based on effort, flexibility, extensibility, and effectiveness. Herle et al. provide an extension of the interoperability approaches proposed by Hijazi, as shown in Figure 4.1.



The first approach, known as Model Transformation, is a unidirectional method that involves Application Domain Extension and Feature Manipulation Engine. In this approach, both models remain separate, and the results are generally satisfactory. However, there may be challenges in geometric transformations, and certain connections between elements or attributes of the models may not be mappable.

The second approach is called Linked Model, where an intermediate model is introduced to establish connections between subject-specific models using Identifiers. Similar to the first approach, both models remain independent. An example of this approach is Semantic Web Technology, which can be further enhanced by using Web Ontology Language. This method provides technical and syntactic interoperability, as shown in Figure 4.2 by Wang et al. in 2009. However, it requires intelligent implementation and may require maintenance if the original models are modified.

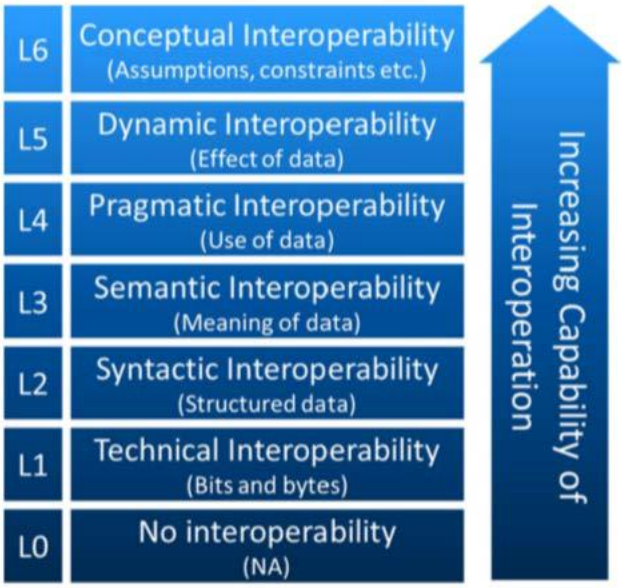


Figure 4.2. Level of Conceptual Interoperability model.

The third approach is known as the Unified Model, where a single model is created to incorporate the common details of both domains. This approach requires significant efforts to coordinate and harmonize the new model. An example of a Unified Model is the Unified Building Model developed by El-Mekawy et al. This model utilized BIMServer to enable bidirectional information exchange between the two systems, covering LOD1 to LOD4. While this model facilitates mapping between the domains, it primarily focuses on relationships between building components and does not address geometric or semantic information.

The last approach is the Integrated Model, which encompasses all the details and aspects of both domains. If successfully achieved, it could establish a new standard that replaces the separate standards of IFC and CityGML. The LandInfra standard, if properly developed, holds potential as a solution.

In this chapter, we will explore the existing research and integration methods, including Application Domain Extension, Feature Manipulation Engine, the collaboration between Esri and Autodesk, unidirectional and bidirectional approaches, the open-source approach, and the ontology-based approach.

4.4. Application Domain Extension

Methods of integration at the application level, such as Application Domain Extensions, are considered in this context.

CityGML serves as the primary open data format for exchanging semantic 3D models of cities. It is widely used in various geographic contexts and software applications. One of its key features is its flexible object modeling at multiple levels of detail, allowing for the creation of virtual city models that can adapt to various application requirements and offer accessibility to building parameters (Nouvel et al., 2015). However, it is important to note that certain types of information may not be readily available in a CityGML model. While CityGML ensures that a minimal set of common properties is stored in a compact core data model, it also allows for the extension of these properties for specific applications.

According to Biljecki et al. (2018), there are two main approaches to enhance the data support in CityGML.

- Through generic objects and attributes
- Through the use of Application Domain Extension (ADE) mechanisms

ADE is a tool that enhances the data model of CityGML by introducing new classes and attributes while preserving the semantic structure. CityGML was not designed to cater to specific applications, thus it permits the utilization of extensions. The two primary approaches for Application Domain Extensions to expand the CityGML standard are:

- Enrichment of existing standard classes of CityGML by adding new properties. The current classes can be enriched with new attributes and relationships.
- Addition of completely new object types or classes, known as ADE classes, to support particular applications. These new additions can be derived from already existing classes in the CityGML standard.

In general, an Application Domain Extension (ADE) can be implemented in two ways: by using an XML schema definition file (XSD) or by extending the Unified Modeling Language (UML) model of CityGML with application-specific information, and then generating the XSD from the UML model. However, when it comes to CityGML, the primary approach considered is using an XML-schema that contains a specific namespace and interfaces with the CityGML base schema (Nouvel et al., 2015). When an ADE is well-documented and proven to be beneficial, it can be directly integrated into the CityGML standard. For example, as mentioned by Biljecki et al. (2018), the Tunnel ADE and Bridge ADE were integrated as standard modules in CityGML 2.0.

When dealing with ADEs, there are certain aspects to consider. An ADE must have its own namespace to avoid any conflicts with CityGML modules. Additionally, an ADE can have an impact on multiple CityGML modules simultaneously, and multiple ADEs can be applied simultaneously in the same dataset. It is important to note that the use of ADEs does not require authorization from the OGC or any standardization organization. Any user can develop and implement an ADE. However, the CityGML 2.0 standard offers guidelines regarding the creation of ADEs within the XML schema.

In their research, (van den Brink, Stoter, & Zlatanova, 2012) provide information about six different methods to create a CityGML Application Domain Extension using UML. One of the ways to add new attributes to a CityGML feature class through Application Domain Extensions (ADEs) is by using the GML "hook" in the form "_GenericApplicationPropertyOf<Featuretypename>". Another method is to use sub-classes, which involve extending the CityGML model with new sub-classes that provide additional properties and features to existing classes. Tools like ShapeChange can be used to create XML schema for ADEs created using UML, specifically for the affected ADE classes and attributes, rather than the entire model.

In a research review, the author examined over a hundred papers on Application Domain Extension in the 3D GIS field and identified 44 relevant papers. These 44 papers categorized the ADEs into two categories: those developed for specific applications, such as the Energy ADE for energy simulation and the Noise ADE for road partitioning based on noise requirements, and those that can be used for multiple applications.

The Energy ADE, for example, focuses on storing and managing data required for building energy calculations, specifically related to buildings and their systems. It is designed to be flexible and compatible with different levels of detail and information qualities, while avoiding duplicate data by integrating with CityGML classes. The Energy ADE includes attributes for energy analysis and can be used for simulations, as well as socioeconomics and demographic data.

ADEs can be adjusted or developed from different ADE schemas. For example, an independent Noise ADE for road traffic was created, enriching the model with data for noise propagation calculations. Other examples of ADEs for specific applications include the ADE for Ubiquitous Network Robots Services, Computer Aided Facility Management ADE, and indoor application ADEs.

Some ADEs are developed to integrate CityGML with national standards, such as the INSPIRE building specification. ADEs are also used to facilitate the integration of IFC and CityGML standards, addressing the differences between the two. Semantic City Model ADE and PANTURA ADE are examples of ADEs that store semantic information from IFC into CityGML and capture specific IFC data types and hierarchy, respectively.

The GeoBIM extension is a widely known ADE that focuses on the conversion between IFC and CityGML. It combines IFC semantics and attributes with CityGML by extending existing CityGML classes and types. The authors used the BIMserver as a central model server to export IFC information into CityGML.

Prior to the GeoBIM extension, most research focused on the geometrical integration between IFC and CityGML.

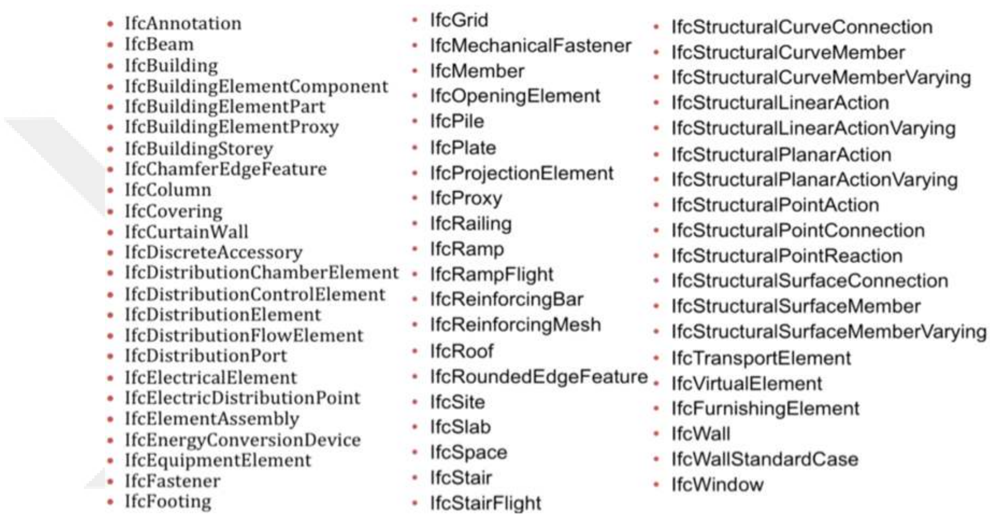


Figure 4.3. List of IFC classes that can be used in GIS

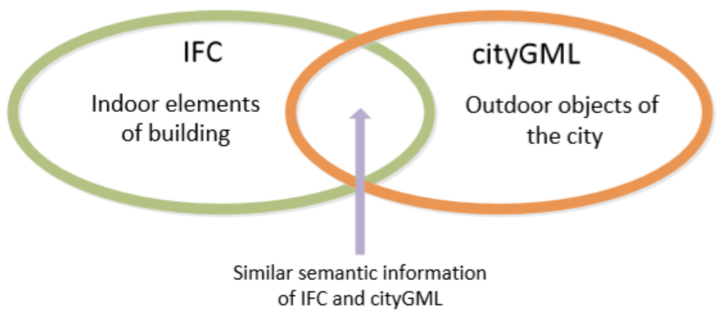


Figure 4.4. Relationship between IFC and CityGML

After examining the list of classes offered by the authors, it was found that a significant number of these IFC classes are not useful in a GIS setting. Based on their analysis, it was determined that approximately 17 of these classes and their attributes can be effectively utilized in the GeoBIM extension of CityGML.

As explained by De Laat and Van Berlo, the conversion process is done on an object level and it takes 6 steps (de Laat & van Berlo, 2011):

- Obtain an object from BIMServer (IFC Object)
- Process the object through the IFC Engine DLL library
- Obtain the triangles from the object. The IFC Engine DLL Library is connected to the EMF interface in order to transform geometries from IFC to CityGML.
- Obtain the IFC properties related to the object
- Obtain the next object
- Transform data from memory to CityGML file. The objects which are similar to existing objects in CityGML will directly be converted as the correct CityGML objects with the extra properties added from IFC.

The authors observed a significant increase in the file size of CityGML compared to the original IFC, often by a factor of 10 or more. To address this issue, they utilized the "download as ZIP" option from the BIMserver.

Upon testing the new CityGML files in software, the authors found that certain programs, such as FZKViewer, did not fully convert the geometry. However, Autodesk LandExplorer successfully opened the CityGML file and accurately read the geometry. Therefore, the GeoBIM extension does not completely resolve the known geometric issues and still relies on basic triangles to model the geometry in CityGML.

The availability of expanding the capabilities of GIS through ADEs has provided the industry with numerous solutions and a wider range of possibilities for utilizing this standard. However, an excessive use of ADEs in a file could impede the information flow, suggesting that a plateau has been reached. A more progressive and advantageous long-term solution would be to enhance CityGML itself by adding more classes and broadening its scope.

4.5. Collaborations Occurring to Encourage the Integration

The undeniable connection between CAD and GIS in the development and management of the built environment has long been recognized. Over the years, there have been numerous attempts to integrate these two concepts into a single software solution.

In 2017, Autodesk and Esri announced a collaboration to enable BIM and GIS workflows in their respective products. The initial phase of this collaboration resulted in the release of the Autodesk Connector for ArcGIS, which facilitates a more seamless connection between GIS data and BIM design models created in Autodesk InfraWorks.

While Revit is primarily used by BIM designers for building projects, there are landscape architects who have also utilized it. Revit models offer spatial details and contextual information about non-spatial data. Engineers can import data from Revit into ArcGIS Online, allowing for direct integration of infrastructure elements like highways, pipelines, and electrical transformers. ArcGIS Pro provides the ability to directly open Revit BIM models, along with tools for accurate georeferencing. The Revit data applied in ArcGIS is compatible with other 3D GIS data, allowing for querying, calculation, and analysis.

However, data interoperability issues have arisen in the integration process, prompting Esri and Autodesk to collaborate and create a fusion between their software solutions in order to address these challenges.

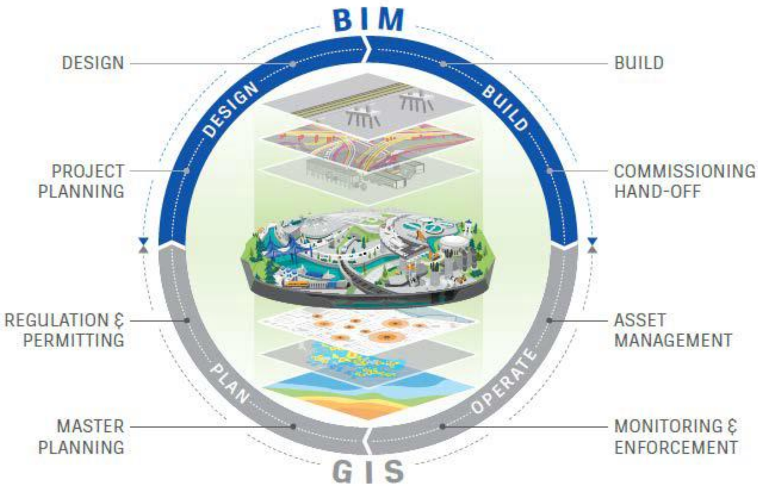


Figure 4.5. BIM and GIS collaboration.

This new software will have the power of both location intelligence and design process combined (Autodesk, 2018).

There are many benefits achieved by this software (see also figure 4.6):

- Transforming the project lifecycle
- Building site is incorporated with the environment
- Detecting site changes
- Designing and visualizing the project in 3D in the specific environment □ Optimizing infrastructure operation intelligence
- Open and extensible systems

Figure 4.6. Benefits of integrating BIM and GIS according to Autodesk

By utilizing GIS, it is possible to develop a comprehensive data model that incorporates various geographic, built, and social layers. This includes layers related to soil, geology, vegetation, land use, structures, highways, infrastructure, social data, and code requirements. Integrating BIM and GIS allows designers to incorporate site-specific geographic information into their designs. It is expected that GIS data will gradually become more accessible within designers' existing workflows. For instance, applications like Autodesk's Revit would enable designers to directly access GIS information layers, including real-time spatial data from the Internet of Things.

This software solution offers a fresh approach to the project handover process. Traditional manual data input is prone to human error and leads to the loss of critical information. Exporting data manually often results in outdated data, as it becomes disconnected from the original BIM or CAD system. However, by using this integrated software, all GIS and BIM data can be managed in one centralized location, avoiding such problems. It is common for project teams to use GIS data that is not linked to an authoritative reporting system, resulting in designs based on unreliable and outdated information. Linking all data to an authoritative system ensures the credibility of information throughout the project and in the future. Failure to address these issues can result in critical data loss and inefficiencies, especially in large-scale construction projects.

According to the Autodesk website, the integration of GIS and BIM follows a symbiotic relationship, where GIS informs BIM and BIM fuels GIS. This optimized utilization of assets within the project system leads to more sustainable projects. This approach can bring several benefits, such as:

- Enable well informed Decision-Making
- Improve stakeholder engagement

- Accelerated project timelines due to advanced planning Massive cost reductions
- More robust infrastructure and smart cities

The introduction of BIM and GIS has opened up new workflows that allow for the faster delivery of complex projects, improved communication with stakeholders, and reduced risk. It is predicted that by 2040, architects and design companies will need to create 10,000 new Smart Cities to accommodate the projected urban growth. BIM and GIS integration form the foundation of the mechanism known as CIM (City Information Modelling), which enables the planning, construction, evaluation, and development of entire cities beyond individual projects. City information models serve as the technical basis for Smart Cities and aid in urban planning activities.

While BIM technology has revolutionized construction projects by promoting collaboration through a shared model, CIM has the potential to revolutionize urban planning, governance, and infrastructure. It inspires designers and builders to create solutions that are tailored to the unique geographic and social context of a city.

To improve interoperability and data integration between BIM and GIS domains, BuildingSMART and the Open Geospatial Consortium have initiated a collaboration. This partnership aims to synchronize the development of data standards and is known as the Integrated Digital Built Environment (IDBE) task force. Additionally, the OCG and BuildingSMART have announced a new open standard called LandInfra, which adopts an integrated model approach based on UML conceptual model and InfraGML encoding. However, LandInfra relies more on GIS modeling standards, limiting its interoperability with BIM formats.

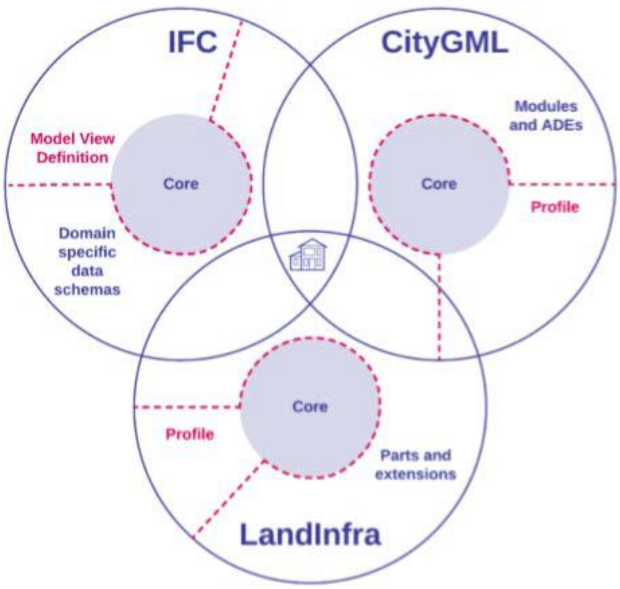


Figure 4.7. Comparison between the three standards IFC, CityGML and LandInfra (buildingSMART International, 2020a)

4.6. Benefits

The optimal integration of BIM and GIS involves combining the strengths of both and establishing a harmonious collaboration between them. BIM and GIS have complementary features: BIM excels in 3D geometry modeling, while GIS is beginning to explore 3D capabilities. BIM traditionally utilizes a file-based approach for data sharing, but there is a shift towards a more server-focused approach already seen in GIS.

BIM has become a crucial tool in the AEC industry due to its ability to depict 3D geometry and capture complex relationships between objects. This facilitates better resource utilization, such as human and material resources, through high levels of interoperability between platforms. BIM provides designers and managers with detailed information to answer questions like the quantity of building components, budget feasibility of a design, and the impact of design changes on project scope and timeline.

GIS adds geographic information to the decision-making process, enabling spatial awareness and a more comprehensive visualization of the project within its geospatial context. When combined with time information, stakeholders can visually understand the consequences of decisions even before construction begins. Additionally, integrating GIS allows for a better understanding of the real-world context surrounding the project, including environmental and demographic factors. For instance, GIS can provide data on flood zones to help designers determine the optimal location, orientation, and materials for a structure. As BIM lacks spatial analysis capabilities, incorporating building data into a GIS supports the complex spatial relationships between topographic and transient objects. The integration of BIM and GIS also enables the creation of structures at an object level.

Integrating geophysical information into the BIM model yields valuable insights and information.

Optimal locations for the temporary facilities in the site. Example: the locations of toilet facilities or the optimal position of tower cranes.

- The storage of construction material in the site and how they can be monitored through the supply chain
- Dangerous and hazardous areas in the construction site.

The GIS has been widely used to address the problems of pre-construction planning and to support the broad spectrum of spatial analysis used in the construction activities. In fact, the integration of BIM and GIS can be useful in different phases for different scenarios. Table 4.1 indicates some of the uses throughout a project.

Table 4.1. BIM-GIS Applications in Different Stages of a Construction Project (Karan et al., 2015)

Project stage	BIM/GIS application
Design	Digital modeling of building and landscape-level components (Karan et al. 2014) Site selection and fire response management (Isikdag et al. 2008)
Preconstruction	Identifying optimal number and location of tower cranes (Irizarry and Karan 2012)
Construction	Evaluation and visualization of construction performance (Elbeltagi and Dawood 2011) Construction supply chain management (Irizarry et al. 2013)
Operation	Detecting and mapping utility network information (Liu and Issa 2012) Facility management supply chain (Karan and Irizarry 2014)

The integration of BIM and GIS has benefits beyond the construction phase. Geospatial tools, BIM modeling, and geographic information systems are valuable for facility management post-construction. The combination of robust GIS/BIM models ensures that operations have access to any necessary information. Clients can also utilize integrated GIS/BIM solutions to retrieve and reuse essential data throughout the lifecycle of a structure.

GIS data is crucial for planning operations related to infrastructure such as airports, rail networks, bridges, highways, etc. It helps situate this infrastructure in its environmental context.

The integration of BIM and GIS involves incorporating the BIM model into geospatial layers. This allows designers to gather precise details about specific building areas. For instance, when the environment is prone to erosion, planners can use GIS to inform decisions regarding building materials, orientation, position, etc.

A study by Ohori et al. (2017) from Delft University of Technology identified three use cases for the integration of GIS and BIM at a data level. These include analyzing the relationship between the 3D model of a building and its physical environment represented by a 3D city model, using urban area information in BIM during the early design stage (particularly for infrastructure projects), and integrating sub-surface data in the early design phase of BIM.

According to Autodesk, the main benefits of integrating BIM and GIS include:

- High level of understanding of the geographic location and natural environment of the
- project.
- Even higher communication between team members and better workflows leading to lower data loss and inefficiency levels.
- Better decision making leading to faster construction and improved operations and maintenance.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Results

This chapter will provide a summary of the case study results, draw conclusions, and offer suggestions for future work. The thesis focused on the introduction of BIM and GIS, as well as the evaluation of interoperability based on existing studies in the literature. Various approaches in the past have been explored to connect open data standards between BIM and GIS, which were summarized and classified into data standard conversion, data standard integration, and linked data approach.

Among these approaches, the use of linked data methods emerged as a promising approach to enhancing interoperability, as it allows information exchange without modifying the original data. However, there are challenges in achieving harmonization between knowledge bases created by different domains when using linked data methods. Further studies implementing linked data methods in real-world use cases are necessary to better understand their role in the interoperability discussion between BIM and GIS tools.

The collaboration between BIM and GIS domains is essential to address the relationship between buildings and their surrounding environment. BIM facilitates the design, construction, and operation of buildings, while GIS provides spatial data on the surroundings and interior space of these buildings. Interoperability between software tools in both domains enables the combination of their functionality for effective management of the built environment. To facilitate the discussion on interoperability, this paper adopted a well-developed definition of interoperability from IEEE and ISO/IEC standards.

- **a.** The literature indicates that verifying the IFC hierarchy in Revit is more challenging compared to other software such as eveBIM and FME Data Inspector. However, Revit offers the advantage of being able to modify attributes and data to a greater degree than other software.
- **b.** Revit 2019, being a BIM software, has its own coordinate system. However, it offers the functionality to accurately geo-locate a project by specifying real-

world coordinates. Additionally, Revit allows for the import of CAD files that incorporate the topography of the location, enabling the acquisition of accurate elevations.In contrast, the literature highlights that eveBIM is distinguished by its capability to import multiple models (IFC and CityGML) simultaneously. If these models are within the same neighborhood or city and have been properly geo-referenced, the building models can be visualized in their accurate contextual environment.

c. QGIS and ArcGIS Pro are considered the leading software options in the field of GIS. While ArcGIS Pro is typically the preferred choice for this task, the literature primarily relies on QGIS due to its availability as a free software and its extensive analysis capabilities. However, it should be noted that QGIS encountered difficulties in opening two of the provided models.Both ArcGIS and QGIS are predominantly utilized for cartography purposes, and most online tutorials assume users possess a certain level of expertise in cartography and mapping. Consequently, for users who are new to GIS or beginners in the field, FZKViewer is a more user-friendly option. It allows for the opening of files and simple queries in smaller-sized models, albeit with limited functionality.

d. In eveBIM, there is an option to convert IFC models to CityGML models using Safe Software FME workbench and the plugin called "IFC to CityGML Editor". The FME workbench provides numerous transformation functions that can be utilized to convert various types of data into different formats. The achieved transformations can be regarded as successful, as the models retained their geometric properties and the attributes supported by CityGML. However, it should be noted that there are differences in class types and the level of detail between IFC and CityGML, as IFC tends to contain more intricate information.

To summarize, the process of integrating BIM and GIS has been deemed important in the industry, despite being a long and challenging journey. Integration is needed at the data level, application level, and process level. Various methodologies have been developed and tested, ranging from the utilization of Application Domain Extensions in CityGML to complex transformations utilizing Semantic Web Technology. While none of the presently proposed methods can completely merge the two standards, significant progress has been achieved in recent years. Additionally, we explored the potential benefits of this integration, such as optimizing site planning in the pre-construction stage and enhancing facility management and operation. One of the main challenges in the integration process is the discrepancy in geometry representation, coordinate reference system, and level of detail between BIM and GIS. However, many of the discussed methodologies have managed to overcome these obstacles, particularly in terms of geometric representation, although there is still room for improvement.

5.2. Future work

The efforts dedicated to this subject over the past decade have brought us to this stage, but there is still substantial work required to reach the ultimate objective. BIM and GIS domains predominantly rely on proprietary data, necessitating multiple transformations between open source and proprietary formats. This process results in information loss and unnecessary steps.

A potential solution would involve the creation of a unified open source data format that encompasses all necessary information, effectively replacing IFC and CityGML. However, for successful interoperability between domains, software companies must adapt their products to comprehend and manipulate this open source data. The collaboration between Autodesk and Esri is a positive step towards comprehending the limitations of each software and working towards improvements.

Furthermore, semantic web technology has demonstrated its effectiveness in integrating the two standards. It is vital for buildingSMART and OGC to develop IFC and GIS compliant base ontologies that researchers and professionals can utilize. Proper collaboration and regulation are key to achieving the desired goal.

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