

Chapter 2: Literature Review

Introduction

This chapter covers all the important GIS concepts relevant to this research project. It serves as a theoretical framework supporting the data model for electrical utilities at the NWU Potchefstroom campus. The literature also explores the important steps to designing the data model that will be used for digital representation of geographic information inside a geodatabase for the purpose of analytical operations and analysis.

2.1 Geographical Information Systems

Goodchild (2000) defines GIS as a computing application that allows the user to create, store, manipulate, visualize and analyze geographic information. The strongest fields in which GIS proves to be most useful is resources management, utilities management, telecommunications, urban and regional planning, vehicle routing and parcel delivery as well as all the sciences which involves the surface of the earth.

The Environmental Systems Research Institute (ESRI, 2010) defines GIS as an acronym for geographic information system. It can be seen as an integrated collection of computer software and data used to view and manage information about geographic places, analyze spatial relationships, and model spatial processes. A GIS provides a framework for gathering and organizing spatial data and related information which can be displayed and analyzed. Therefore, GISs does not only have a central database, but it can also be used for organizing, exploring, analyzing, editing and viewing geographical data. Geographical data can range from a set of single geo-referenced features or point observations to more complex collections of data in database structures (Goodchild *et al.*, 2007). According to Zlatanova *et al.* (2002), the five most common tasks of a GIS is data capture, data structuring, data manipulation, data analysis and data presentation.

According to Dumitrescu & Smeureanu (2010), a GIS is a very effective tool for managing complicated networks. It integrates hardware elements, software and data for capturing. The system is ideal for managing, analyzing and illustrating geographically related information. GISs allow the user to view, understand and query data in various ways to show relationships

and patterns in the form of maps, reports or charts. The client can use GIS to look at existing data in an intuitive manner that helps with answers to questions and problem solving. The geographical information system can be divided into three parts: the database, the map and the model. By looking closely at the database part, the GISs are seen as a structured organization of data that describes the world in geographical terms (Dumitrescu & Smeureanu, 2010).

The maps created in GIS can be seen as a set of intelligent illustrations which characterized relations over the Earth. The model part of the GIS is seen as a set of tools that allows the user to transform information to obtain new derived datasets from existing data sets (Dumitrescu & Smeureanu, 2010). The tools are used to extract information from existing data to apply analytic functions that writes the results into new derived datasets.

In a GIS, data can be represented in raster or vector formats. Raster formats can be seen as any type of digital image represented as an array of pixels. The pixel is the smallest unit of an image. Combining these pixels creates an image that consists of rows and columns of cells, each cell with one stored value. Raster data is usually images with each pixel containing a value, usually a colour. Additional values can be recorded for each cell. It can be a continuous value like temperature or a null value if no data is available. Raster cells that stores only one value can be expanded through raster bands to represent RGB colours (red, green, blue), or an expanded attribute table with one row for every single cell unique value. Resolution in raster format can be seen as pixel size in physical units (Dumitrescu & Smeureanu, 2010).

Vector formats are used in GIS where geographical features are illustrated as vectors, by considering the different components as geometric forms. Different geographical elements are expressed by different types of geometry forms. Vector representations can be classified by dimension (Zeiller, 1999):

- Points represent geographic features too small to be depicted as lines or areas. They are zero-dimensional shapes stored as a single x,y coordinate with attributes.

- Lines represent geographic features too narrow to be depicted as areas. Lines are one-dimensional shapes stored as a series of ordered x,y coordinates with attributes. Line segments can be circular, elliptical, straight or splined.
- Polygons are stored as a series of segments that enclose an area. They are two-dimensional shapes that represent broad geographic features forming a set of closed areas.
- Annotations are descriptive labels that are associated with features to display names and attributes. It is also a type of vector data.

In order for the GIS to be effective, these three types of geometry forms must work properly and provide the requested information in a timely manner. One of the common problems of this type of system is the scalability and speed of processing queries. Scalability problems become a bigger issue when the system operates with more elements. Problems in repeated rendering of a large number of elements appear. An example is to move the map in a specific direction, find a particular item or query the system for the position of an element (Dumitrescu & Smeureanu, 2010).

This project will use raster and vector data. The raster data will mostly consist of satellite images of the study area that will be used as a base layer for the buildings. These detailed images will also serve as a reference in which to align the existing CAD data. Vector data will be created from the combination of the satellite images and the CAD data through digitizing in ArcMap10. The vector data will show the location of the different electrical components on campus and inside the three buildings in relation with the aerial photographs.

2.2 Coordinate systems

Coordinate systems are a very wide field and a study on its own. For the purpose of this project only a short overview about coordinate systems and its importance will be discussed.

2.2.1 Geographic coordinate systems

According to Kennedy and Kopp (2000) a three dimensional spherical surface is used by a geographic coordinate system (GCS) to define locations on the earth. Most people mistake a GCS for a datum which is incorrect because a datum forms only one part of a GCS. A GCS has an angular unit of measure, a prime meridian and a datum. A point on the earth's surface is referenced by its longitude and latitude values. Angles are measured from a line of reference (Greenwich and Equator) to the center of mass to the point on the surface (Kennedy and Kopp, 2000).

2.2.1.1 Datums

A geographic coordinate system's shape and size on a surface is defined by a sphere or spheroid. Although a spheroid represents the earth better, the globe is sometimes seen as a sphere for simpler mathematical calculations. "While a spheroid approximates the shape of the earth, a datum defines the position of the spheroid relative to the center of the earth. A datum provides a frame of reference for measuring locations on the surface of the earth. "It defines the origin and orientation of latitude and longitude lines." (Kennedy and Kopp, 2000:6).

In the past years, new technology and satellite data provided geodesists with a better understanding and measurements to calculate the best earth-fitting spheroid. Coordinates are related to the earth's center of mass, generating a geocentric datum. Satellite technology enabled cartographers to measure the earth's shape more accurately. Therefore a new ellipsoid was calculated called the World Geodetic Survey (WGS 1984). The reference point used today in the South African implementation is the Hartbeeshoek Radio Astronomy Observatory near Pretoria. The Hartbeeshoek 1994 datum was officially implemented on the 1st of January 1999. This is basically a local implementation of WGS 84 (Thomas, 2007). The WGS 84 datum is a combination of reference points and the WGS 1984 ellipsoid designed to fit areas around the world. In South Africa, the differences between the Hartbeeshoek 94 and WGS 84 datum is very small. The most common used datum is WGS 1984 which serves as a framework for locational measurements across the globe (Kennedy and Kopp, 2000). In South Africa, the most commonly used local datum is Hartebeesthoek 1994.

According to Thomas (2007), a datum can be seen as the combination of an ellipsoid and a local reference point. It is important to consider which datum to use for the datasets in the geodatabase. The most commonly used datum in South Africa was the CAPE datum. This datum is based on the CLARKE 1880 ellipsoid that was referenced to the observatory at Buffelsfontein near Port Elizabeth. The CAPE datum was based on the work of astronomers: Sir David Gill and Sir Thomas Maclear. Their objectives were to verify the size and shape of the earth in the southern hemisphere and provide topographic maps and navigation charts (MMS, 2011).

According to MMS (2011), the main difference between the Hartbeeshoek 1994 and the old CAPE datum is the 300 meter offset that is evident if a point on the earth surface is plotted in each datum respectively. Figure 2.1 illustrates the difference between the Hartbeeshoek 1994 and CAPE datum.

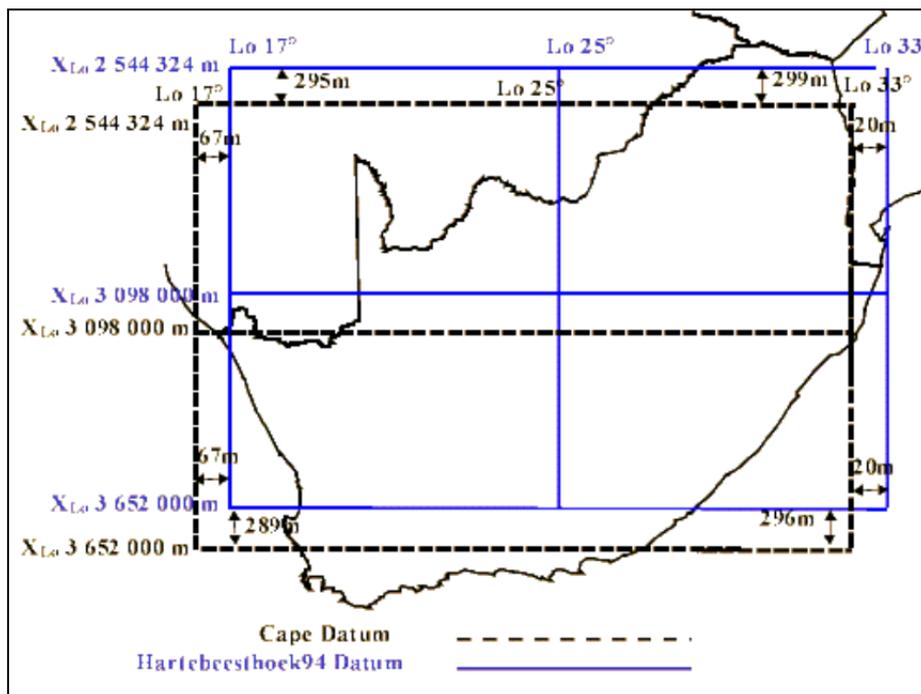


Figure 2.1: The approximate 300 meter difference between the CAPE and Hartbeeshoek Datum (MMS, 2011).

Considering the small difference between the Hartbeeshoek 1994 and the WGS 1984 datum in South Africa, the WGS 84 Datum is used in this thesis. Another contributing factor is that the satellite image used as the base data for referencing CAD drawings is predefined to the WGS 84 Datum.

2.2.2 Projected coordinate systems

Projected coordinate systems are developed for flat, two-dimensional surfaces. Projected coordinate systems have even lengths, angles and areas on a flat two dimensional surface. Locations on the earth's surface are identified by x,y coordinates on a grid, starting at the center of the grid. Each object or specific location has two values that determine the central position named the horizontal and vertical values (also called the x-coordinate and y-coordinate). When an object has to be located the user starts at the center of the grid where the x and y values are zero and then move towards the location on the x and y axis of the grid. A projected coordinate system is always based on a geographic coordinate system derived from a sphere or spheroid (Kennedy and Kopp, 2000).

2.2.2.1 Map projections

“Whether you treat the earth as a sphere or a spheroid, you must transform its three-dimensional surface to create a flat map sheet. This mathematical transformation is commonly referred to as a map projection.” (Kennedy and Kopp, 2000:11). Projected coordinate systems are used for calculating shape, areas, distance and direction. Projections map a part of the earth on a flat surface, but distortions are generated from the original shape. On world maps, continents may be heavily distorted from the center of the projection (Delmelle, 2001). Distortions will be caused in the shape, area, distance and direction of the data. According to Delmelle (2001), there are a number of ways dealing with the map projection process, but deformation will always be generated as it is not possible to flatten a three dimensional body on a flat surface.

Map projections consist of three main classes in cartography. Each of these classes has either a line or a point of contact with the sphere. The classes are the cylinder, the cone and the plane. The advantage of these shapes is that their curves are only in one direction. This means that they can be flattened onto a two dimensional surface without any further distortion (Delmelle, 2001). Figure 2.2 shows the three different classes of map projections.

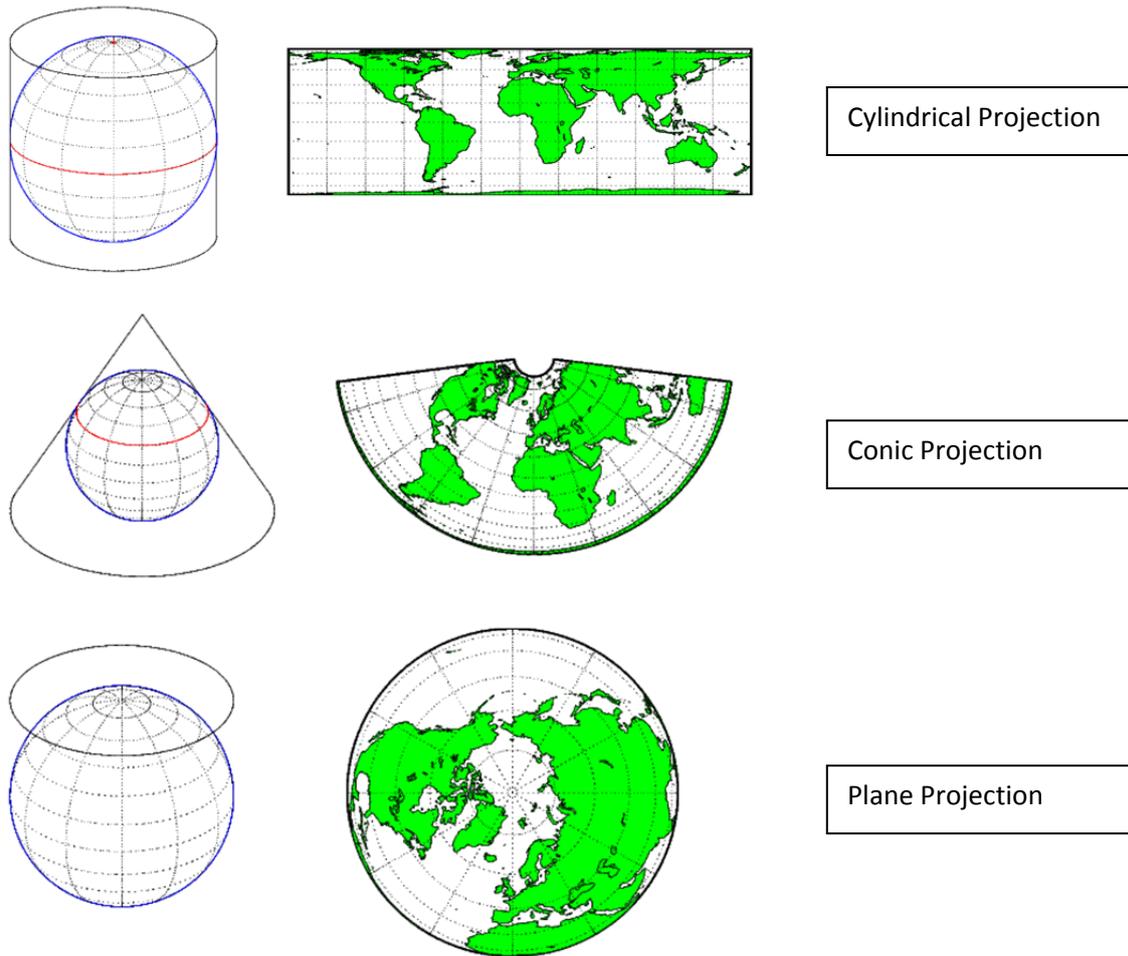


Figure 2.2: Different types of map projections (Mathworks, 2011).

According to Zhang (2005) it is very important to use the correct reference system while working with GIS data. Neglecting this step could pose significant risks due to the fact that map projections alters the angle, shape and distances causing a miscommunication between the user and the map, especially on small-scale projects if the shape of continental areas is altered (Delmelle, 2001). In most cases a GIS user will work with datasets from different sources who used different reference systems to capture the data. It is a major design effort just to bring these datasets together in a common reference frame but the user will find it beneficial further on, especially when working with data that has to be precise. An example is geologists and drilling engineers using GIS data. If their data has inconsistent datums or different map projections they are at risk of making wrong calculations because of incorrect reference systems. Figure 2.3 shows an example of a 70 meter offset between layers using an inconstant datum in a 1:2500 map of a town.

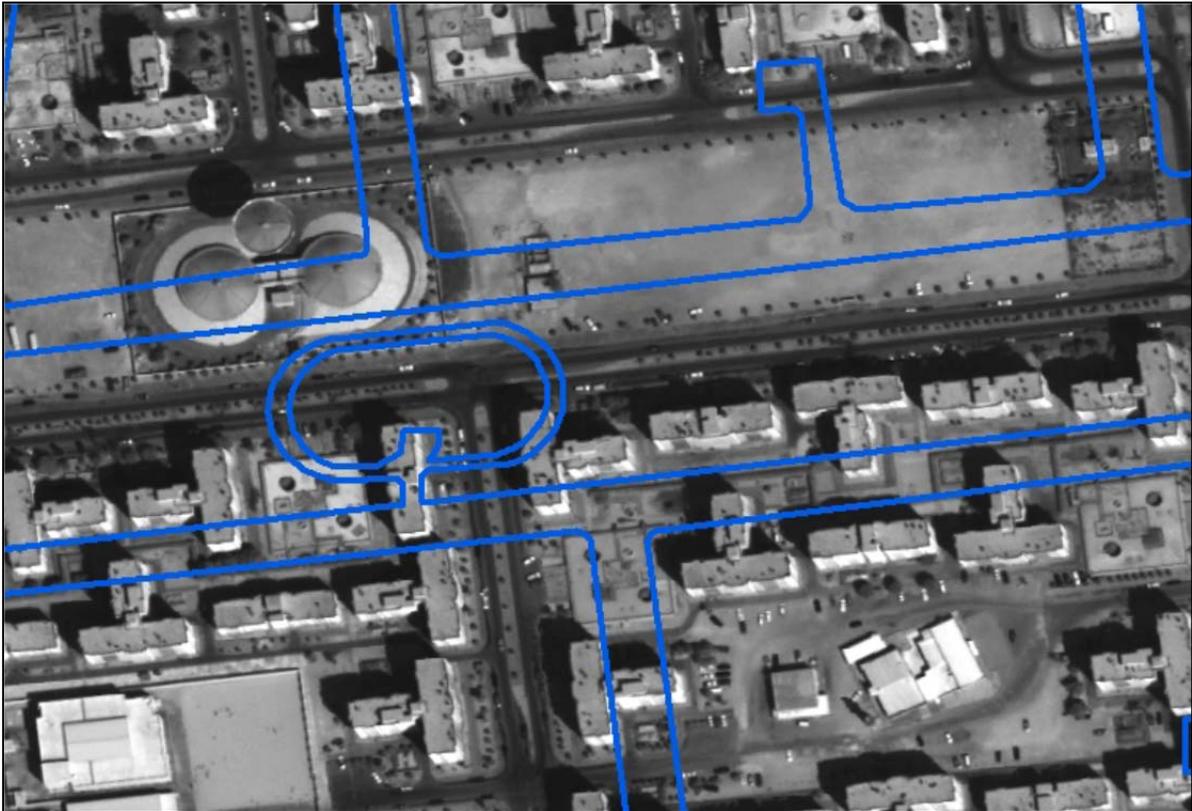


Figure 2.3: Illustrating a 70 meter offset between layers with an inconstant datum (Zang, 2005).

In practice, GIS datasets with different map projections are used directly for a variety of projects because projected coordinates are easily generated. According to Zhang (2005) Universal Transverse Mercator (UTM) and Lambert Conformal Conic (LCC) are some of the most widely used projections worldwide. Almost 90 % of base maps are created using these two projections. UTM projections allows minimum distortion for areas that lies north-south to extent and LCC projections does the same for areas east-west in extent.

Three map projections called Transverse Mercator (TM), Universal Transverse Mercator (UTM) and Albers Equal Area Conic (AEAC) were considered to model features in the geodatabase. The properties and limitations of the map projections were compared to each other to determine the best suited projection to model the electrical features inside the two specified buildings. Table 2.1 compares the three projections' properties with each other as described by Kennedy and Kopp (2000). The properties include the shape, area, direction distance and limitations of the projections.

Table 2.1: Different map projection properties and limitations

Projection	Shape	Area	Distance	Direction	Limitations
TM	Conformal Maintains small shapes. Larger shapes are distorted away from central meridian.	Distortion increases with distance from central meridian.	Accurate scale along the central meridian if the scale factor is 1.0	Local angles are accurate everywhere.	Data cannot be projected beyond 90 degrees from the central meridian. The extent on a spheroid or ellipsoid should be limited to 15-20 degrees on both sides of the central meridian. Data projected beyond that range using this projection may not project back to the same position.
UTM	Conformal Accurate representation of small shapes. Minimal distortion of larger shapes within the zone.	Minimal distortion within each zone.	Scale is constant along the central meridian. At a scale factor of 0.9996 to reduce lateral distortion.	Local angles are true.	Not designed for areas that span more than a few zones. Data cannot be projected beyond 90 degrees from the central meridian. The extent on a spheroid or ellipsoid should be limited to 15-20 degrees on both sides of the central meridian. Data projected beyond that range using this projection may not project back to the same position.
AEAC	Shape along the standard parallels is accurate and minimally distorted in the region between the standard parallels and those regions just beyond. The 90° angles between meridians and parallels are preserved. Final projection is not conformal.	All areas are proportional to the same areas on the earth.	Distances are most accurate in the middle latitudes. Along parallels, scale is reduced between the standard parallels and increased beyond them.	Locally true along the standard parallels.	Used for regions predominantly east-west in orientation and located in middle latitudes. Total limitations in latitude from north-south should not exceed 30-35 degrees. No limitations on the east-west range.

Source: Kennedy and Kopp (2000).

Considering the properties and limitations of the three possible projections, the Universal Transverse Mercator Projection will be used to model features in the geodatabase. The UTM projection is a specialized application of the Transverse Mercator Projection. This projection divides the earth into 60 north and 60 south zones. Each of these zones spans six degrees of longitude and has its own central meridian. The first zones from the left of Figure 4 start at -180° W. The north – south extent is limited to 84° N and 80 ° S. The north and south zones are divided at the equator. Kennedy and Kopp (2000) explain further that this projection alters the coordinate values at the origin to eliminate negative coordinates. Certain values are assigned called false easting and false northing. The Central meridian has a false easting

value of 500 000 meters while the north zone has a false northing of zero and the south zone a false northing of 10 000 000 meters.

Reasons for considering UTM is that it is a conformal projection more suited for smaller areas like specific regions at medium or large scale. It is well suited for equatorial and midlatitude locations or shapes. This projection works well with topographic data. Figure 2.4 represents an example of a UTM projection.

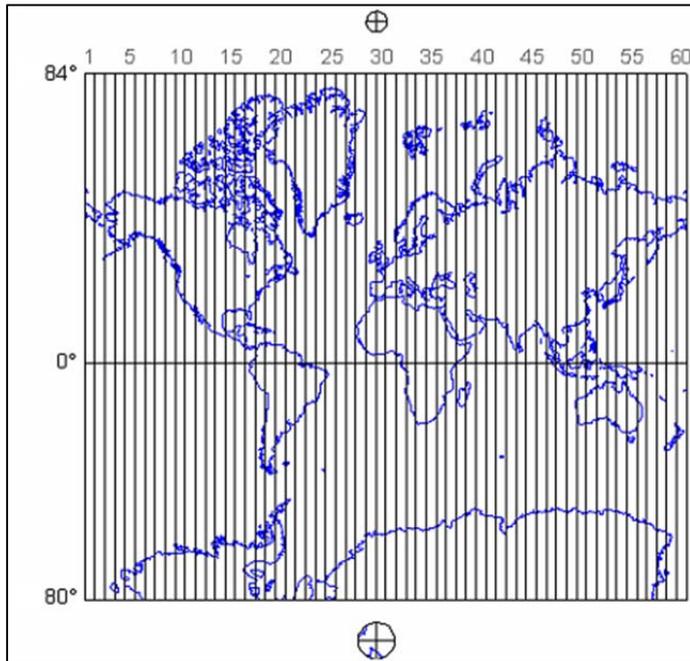


Figure 2.4: Universal Transverse Mercator projection (Dutton, 2010).

2.3 CAD and GIS

One of the challenges when managing GIS data is the two way conversion of data from CAD drawings to the GIS environment and back. The challenge of integrating CAD and GIS becomes even greater when working with infrastructure such as roads, railways, bridges and tunnels in urban regions (Tzvika, 2009). CAD software is used for the engineering and construction part of the projects while GIS software is used for the layout, planning and analysis. Large projects often use location based information which requires a combination of CAD and GIS services that enables the user to receive the relevant information for the correct positioning of features.

Over the years there has been a cultural divide between the systems. Tzvika (2009) explains that CAD and GIS is often referred to as “oil and water”. According to ANON (2004), CAD and GIS are two separate systems developed for two different purposes. CAD can be associated with precision data entry and editing tools for engineering tasks while GIS is developed for spatial analysis and mapping. Peachavanish *et al.* (2006) states that CAD data contains detailed drawings of features while GIS has the ability to provide location related information about those features. Integrating these two systems would allow seamless retrieval and analysis of data during all phases of construction, repairing and monitoring.

Different organizations use both CAD and GIS tools for related projects due to the fact that these tools offer different features. Van Oosterom *et al.* (2006) states that CAD is often used to represent the human made world such as detailed sketches of buildings while GIS is used to capture the natural environment. CAD and GIS systems may relate to the same real world objects, but the data are quite different and take different aspects into account.

CAD and GIS data are created for different purposes. Even though there are certain situations in which both CAD and GIS are used, there are similarities between the data and projects they support. CAD and GIS have been developed separately over a period of time resulting in difficulties integrating the two systems (Peachavanish *et al.*, 2006). Between the two software’s data models the files differ in construction and attributes. CAD drawings are in most cases much more accurate than GIS on a large scale, but often use different coordinate systems (ANON, 2005). Figure 2.5 illustrates the differences between CAD and GIS.

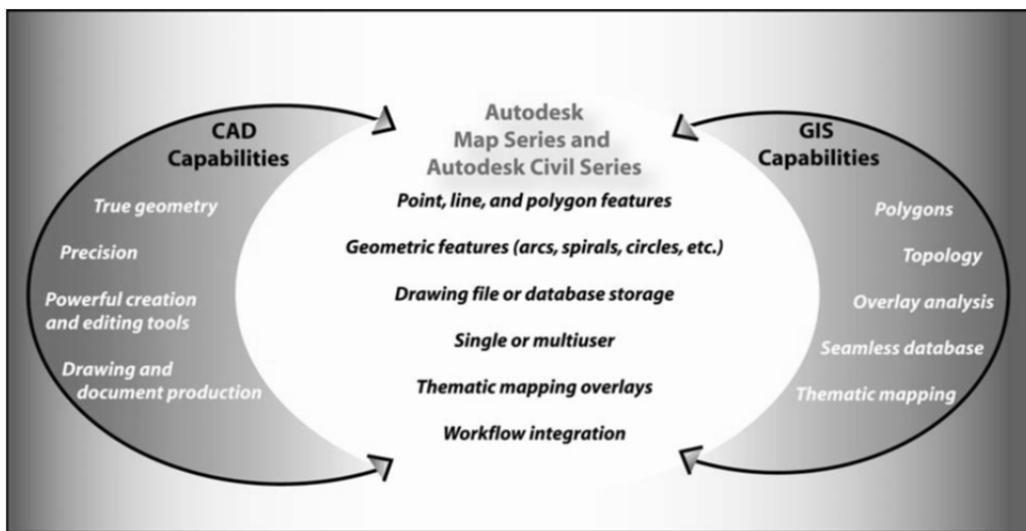


Figure 2.5: Illustrating various CAD and GIS capabilities (ANON, 2004).

In the past CAD drawings were frequently used for digitizing purposes in GIS but a lot of problems occurred because imported data lost accuracy and geometric precision. Another problem was that the modified GIS data did not support engineering precision and accuracy. Therefore it needed to be imported back into CAD drawings. These were frequent problems of early CAD and GIS integration (ANON, 2004.)

CAD drawings have limitations when it comes to analytical tasks due to the fact that it is difficult to create attributes describing and symbolizing the illustrated features. CAD systems, for example, can be used to visualize residential developments showing all the property lines separating individual land parcels. The CAD program generates smooth lines perfectly aligned, creating a detailed representation of the features. However, the system lacks the ability to store values in a database containing information about the features such as ownership, contact numbers or property values (Cowen, 1988).

The technical department at the NWU uses CAD drawings to illustrate electrical features on campus and inside buildings. According to the ANON (2005), CAD drawings are usually very accurate because in most cases the drawings are based on ground surveys done by a certified professional surveyor. Converting these CAD drawings to GIS data will enable the user to compare and analyze the drawings with other GIS data.

CAD-GIS integration generally takes place using CAD to capture and represent detailed information about the features of a facility and using GIS to perform analysis on those features at different scales (Peachavanish *et al.*, 2006).

Sometimes CAD drawings have no recognizable coordinate system. This means the drawing has a random, locally established point of origin. CAD data can be re-projected into a coordinate system in a GIS. Should the CAD data have no known coordinate system; the files can be spatially adjusted manually using georeferencing or spatial adjustment tools in a GIS. It's very important to identify a CAD file's coordinate system before importing it to a GIS (ANON, 2005).

According to Tzvika (2009) software developers are creating tools to integrate the two systems more effectively. The two systems remain unique and still operates in a familiar way thus providing the user with direct access to data regardless of how it is stored.

2.4 Geodatabase design

2.4.1 Representation

Geographic representations form a basic part of database design. Individual geographic entities can be seen as features. Different features can be seen as points, lines or polygons. Other features can be represented through continuous surfaces and imagery using rasters or triangulated irregular networks (TIN's). Text labels and symbols can also be applied to the features (Actur and Zeiler, 2004).

2.4.2 Thematic layers

One of the most important concepts on which GIS functions is thematic layers. “A thematic layer is a collection of common geographic elements, such as a road network, a collection of parcel boundaries, soil types, an elevation surface, satellite imagery for a certain date, or well locations” (Actur and Zeiler, 2004:4).

Early practitioners thought about how to represent GIS data through different layers instead of representing data as a random collection of objects. Therefore the concept of thematic layers was one of the early notions in GIS. Actur and Zeiler (2004) explain that these early GIS users organized their information in thematic layers illustrating the distribution of a phenomenon against how it should be distributed across a geographic extent.

2.4.3 GIS datasets

GIS datasets are collections of point, line and polygon representations. Information can be represented in single or multiple datasets. A single dataset can be a single collection of homogeneous features, such as soil types and well locations while multiple datasets such as a transportation network are represented through streets, intersections, bridges and highway ramps. Gridded datasets are used to represent continuous surfaces, such as georeferenced imagery, elevation, slope and aspect. These data collections can be organized as feature classes and raster based data layers in a GIS database (Actur and Zeiler, 2004).

2.4.4 GIS design steps

According to Actur and Zeiler (2004) a GIS design is built around a set of thematic layers of information that will deal with a set of requirements. The initial conceptual design steps help the user to characterize and identify each thematic layer. The logical design phase help the user to develop representation specifications, relationships, networks, subtypes, domains and at the end the geodatabase elements and their properties. In the physical design stage the user will test and refine the database through a series of tests, queries and implementations. The final step is to document the design.

Buliung & Kanaroglou (2004) conducted an experiment in the design and implementation of an object-relational database containing information about complex activity and travel behaviour in an urban environment. Figure 2.6 illustrates a schematic representation of the database design steps followed in their project.

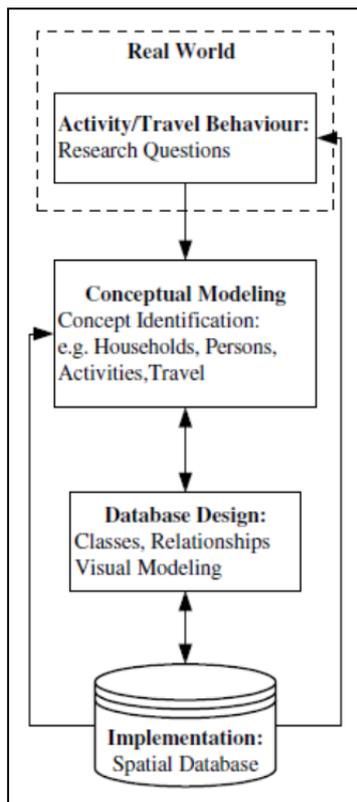


Figure 2.6: Database design steps in the modelling of complex activity and travel behaviour (Buliung & Kanaroglou, 2004).

Each of the frames in Figure 2.6 can be seen as steps in the database design that were followed. Table 2.2 illustrates the different steps and the associated design phase of the related project.

Table 2.2: Database design steps in the modelling of complex activity and travel behaviour

Design Steps	Description	Design phase
1) Activity/Travel behaviour	Detailed description of the research questions and objectives.	Conceptual design
2) Conceptual modelling and concept identification	Describing in detail the behavioural and non-behavioural units of interest and their relationships.	Conceptual design
3) Database design: Classes, Relationships and Visual Modelling	Structural or schematic representation of the database.	Logical design
4) Implementation of the spatial database	Fully documented spatial database. Designed to support short and long term research endeavors.	Physical design

Source: Buliung & Kanaroglou (2004).

According to Zeiler (1999) the structure of a geodatabase consisting of feature datasets, feature classes, relationships and topologies enables the user to design geographic databases that are close to their logical data models. Table 2.3 represents the basic steps presented by Zeiler (1999) in designing a geodatabase.

Table 2.3: Steps to building a geodatabase

Design steps	Description	Design phase
1) Model the user's view of data	Find out what the user wants. Perform interviews and understand the organization's structure.	Conceptual design
2) Define objects and relationships	Build the logical data model with the set of objects to be modelled. Identify the relationships between the objects.	Logical design
3) Select geographic representation	Determine which representation is best for the data of interest such as vector, raster, surface or location.	Logical design
4) Match the geodatabase elements	The objects in the logical design have to find their place in the geodatabase.	Physical design
5) Organize geodatabase structure	The structure of the geodatabase is created taking into consideration the thematic groupings and topological associations.	Physical design

Source: Zeiler (1999).

According to Zeiler (1999:182) design can be seen as “the process in which goals are defined, design alternatives identified, analyzed, and evaluated, and an implementation plan is agreed upon”. The design provides a framework of where you are in your project and where you are going. It helps you to cancel out overlooked problems as you progress. It also helps you add detail to your work without duplicating data.

A well designed database should provide a comprehensive architecture. It will allow the user to view the database as a whole and decisions can be made on how the various aspects need to interact. The user will definitely benefit to sacrifice the time to identify and resolve design issues early instead of having to expend greater resources later trying to solve what may well have become insurmountable problems (Zeiler, 1999). The steps presented in Table 2.4 outlines a version of the combined GIS database design steps by Actur and Zeiler (2004).

The three database design examples generally focus on the conceptual, logical and physical design of a database. The four design steps proposed by Buliung & Kanaroglou (2004) is a basic structure of database design based on an experiment to model complex activity and travel behaviour in an urban environment. These steps may be used as guidelines to database design. The only inadequacy is the lack of detail in describing the design process.

The five design steps by Zeiler (1999) are a more detailed description of the process to design a database. It provides more insight to the database design process in relation to the previous design steps. These steps provide a more solid design structure compared to the design steps proposed by Buliung & Kanaroglou (2004).

Actur & Zeiler (2004) expanded the design process even further by describing it in ten steps. This provides a more detailed description of the phases in the design process. The ten geodatabase design steps proposed by Actur and Zeiler (2004) will serve as the basic structure of Chapter Three in this thesis. The reason for choosing this proposed design is because of the detailed description of the different phases not evident in the other proposed designs. Each step guides the user to make certain decisions for a robust database design structure.

Although the design process is a very important step in any project, it often receives little attention, if any. A possible reason can be the fact that the process is time consuming with no end-use applications. There are risks involved if the design process is not done properly.

The user may end up with a poorly designed database that does not meet the requirements, now or in the future. Possible reasons for this may be from the use of unnecessary data, duplication and inappropriate representation of data or lack of proper data management techniques.

Table 2.4: Ten steps to designing geodatabases

Design steps	Description	Design phase
1) Identify the information products that will be produced with your GIS.	In this step the purpose of the project must be clear. The user should explore the expected results of the project.	Conceptual design
2) Identify the key thematic layers based on your information requirements.	The user must identify all the key features that will be represented. The user specifies the map use, map scale, accuracy, symbology, annotation, spatial representation and data source.	Conceptual design
3) Specify the scale ranges and spatial representations for each thematic layer.	The user determines if the data is represented as vector or raster representations.	Conceptual design
4) Group representation into datasets.	The features that will be represented will be grouped into feature datasets and feature classes with topology rules, subtypes, domains, relationship classes and network datasets.	Logical design
5) Define the tabular database structure and behaviour for descriptive attributes.	The user combines descriptive data and the features that are represented. The descriptive data are listed in attribute fields. The user also specifies subtypes and domains, assign topology rules, networks and relationship classes.	Logical design
6) Define the spatial properties of your datasets.	A network dataset will be created for the connected systems of features. Topology rules will be set for spatial integrity and shared geometry.	Logical design
7) Propose a geodatabase design.	Explore all the elements of the geodatabase and make informed decisions. The user studies existing designs for examples.	Logical design
8) Implement, prototype, review and refine your design.	From the initial design, build a geodatabase and load data. Test and refine your design through queries, implementation and problem solving.	Physical design
9) Design work flows for the management and creation of each layer.	Each layer has unique data sources such as accuracy, currency, metadata and access. The user defines different workflows to match the participating company's business practices.	Physical design
10) Document your design using appropriate methods.	The user illustrates the data model through the use of drawings, layer diagrams, schema diagrams and reports.	Physical design

Source: Actur & Zeiler (2004).

2.5 Geodatabase Data Model

Zeiller (1999) states that the geodatabase data model brings a physical data model closer to its logical data model. The data model allows the user to implement custom behaviours to features without the need for programming. Most behaviours are implemented through subtypes, domains, relationship classes, topology rules and other functions of the framework provided in ArcInfo.

GIS data models can be seen as abstract representations of geographic features in reality. This data model enables the user to represent these geographic features in digital format inside a database that has the ability to perform various analytical tasks (Mandloi, 2007).

According to ESRI (2008b) the geodatabase is the base structure on which ArcGIS functions. The geodatabase is the primary data format that is used for data editing and data management. It can be seen as a collection of datasets held in a common file system folder such as a Microsoft Access Database, Oracle, Microsoft SQL Server, IBM or DB2. A geodatabase can have a varying number of users accessing it. There are different types of geodatabases and they come in many sizes. Geodatabases can range between small single-user databases to larger workgroups, departments and enterprise geodatabases that can serve many users.

A geodatabase is a system put together that stores geographic features linked to tables in a relational database management system known as a RDBMS. ESRI (2010) defines a RDBMS as “an acronym for *relational database management system*. It can be seen as a type of database in which data is organized across one or more tables. Tables are associated with each other through common fields called keys. In contrast to other database structures, an RDBMS requires only a few assumptions about how data is related or how it will be extracted from the database.”

According to Pacurari (2002:49) a “geodatabase is a repository containing the spatial data inside a RDBMS. It could contain vector data, raster data, tables and other GIS objects.” The objective of geographical information systems is to provide spatial guidelines to support important decisions regarding the Earth’s resources and to manage man-made environments.

According to Goodchild (1995) and Zeiler (1999), different components form the basis of a GIS data model. These components may represent raster and vector data models separately or combined. A geodatabase can contain four representations of geographic data such as:

- Vector data to illustrate features
- Raster data for images, surfaces and gridded thematic data
- Triangulated irregular networks (TIN's) to represent surfaces
- Locators and addresses to find a specific geographic position

2.5.1 Raster data

According to Goodchild (1995) raster data models represents two dimensional data by assigning values to cells. Each cell is normally restricted to a single value.

In many cases the data collected in a geodatabase is in a grid form. The reason for this is that cameras and imaging systems create data as pixels in a two dimensional grid or raster. The pixel elements of a raster are called cells. Each cell has a value and it can display a variety of data. Cells have the ability to store reflectance of light for part of the spectrum, colour values for photographs, elevation values and thematic attributes such as surface values or vegetation types (Zeiller, 1999).

2.5.1.1 Raster datasets and raster catalogs

One of the important GIS data resources are raster images and raster datasets. These datasets can be managed in relational databases such as database management system (DBMS) and GIS that supports massive image collections allowing many users to access the data simultaneously. National and global datasets can be managed by using large multi-row raster datasets that provide high performance levels and multi-user access in the GIS. Behaviour can be added through a number of raster mechanisms (Actur and Zeiler, 2004).

2.5.2 Vector data

Goodchild (1995) explains that vector data models represent spatial variation through distributed points, lines and areas. Lines and areas are represented as connected sequences of straight lines.

Most features representing the real world have well-defined shapes. These shapes are precisely and compactly represented through vector data as an ordered set of coordinates with associated attributes. Vector data supports geometric operations such as identifying overlaps and intersections, calculating length and area and finding other features that are adjacent or nearby (Zeiller, 1999).

2.5.2.1 Feature datasets

An organized collection of feature classes can be stored in a feature dataset. The most basic reason for organizing feature classes in such a way is that spatial relationships, networks, projections and topologies can be managed in both simple standalone features as well as high level collections of data in a feature dataset (Actur and Zeiler, 2004).

2.5.2.2 Feature classes

Actur and Zeiler (2004) define a feature class as a collection of features representing the same geographic elements. The features in a feature class share the same spatial representation such as points, lines or polygons as well as a common set of descriptive attributes. Features in a feature class can have spatial relationships with other features. For example, linear features often form an interconnected network that can be used for tracing or analysis such as an electrical network or a road network.

Once the user has created or identified the feature classes that are going to be used, additional properties can be specified, e.g. which symbols will represent the features on a map, or a specification of descriptive attributes for each feature along with other rules that control feature representation and behaviour for maintaining data integrity (Actur and Zeiler, 2004).

2.5.2.3 Topologies and Networks

Topologies are a set of rules that defines how features share geometry. These rules help to maintain data integrity and editing behaviour of the participating features. Topology rules are part of the geodatabase schema that enables editing tools to create a rich environment for locating and correcting topological errors (Actur and Zeiler, 2004).

Networks are designed for a set of interconnected features, often points and lines, which offers high speed traces on an underlying logical network model. Complex edge and junction features can be modelled and a set of connectivity rules can be specified to determine which feature types can be connected to each other and how many edge connections at a junction are valid (Actur and Zeiler, 2004).

2.5.2.4 Subtypes

ESRI (2011) defines subtypes as a subset of features in a feature class that shares the same attributes. Instead of creating two feature classes to represent different types of one feature, subtypes can be used as a method to characterize the data.

Subtypes differ from domains because of the following (ESRI, 2011):

- When creating subtypes for features, a set of default values can be added to the attribute fields to describe the particular subtype. It will automatically apply when selecting the subtype in a drop down box.
- Coded or range domains can be created before a particular subtype and it can be applied when choosing the subtype. This allows the user to constrain input information to a valid set of values.
- Connectivity rules can be assigned between subtypes and other feature classes to maintain the integrity of the network.
- Topology rules can be specified between subtypes and other feature classes residing in a topology.
- Relationship rules can be assigned to subtypes, other feature classes as well as tables.

2.5.2.5 Domains

ESRI (2011) defines domains as a set of rules that describes the legal values of a field type to enforce data integrity. Attribute domains are used to limit the values allowed for any particular attribute for tables and feature classes. Different attribute domains can be assigned to features in a feature class or non-spatial objects in a table that have been grouped into subtypes. Whenever a domain is linked to an attribute field, the user can only select the values within that domain; the field will not accept values that are not in the drop down box. Assigning domains in a geodatabase helps to ensure data integrity by limiting the choice of values for the participating field. Domains can be assigned to feature classes, tables and subtypes.

2.5.2.6 Relationship classes

Relationships define how rows in one attribute table of a feature class (spatial objects) are connected to another attribute table of a feature class. It can also be defined for standalone tables (non-spatial objects) in a geodatabase. There are three types of relationship classes that show the direction of cardinality: one-to-one, one-to-many and many-to-many relationships (Actur and Zeiler, 2004).

Relationship classes have several properties to describe the connection between the origin objects and the destination objects (ESRI, 2011):

- Simple or composite types
- Origin and destination objects
- Primary and foreign keys
- Cardinality
- Message notification direction (custom cascade, update or delete behaviour)
- Ability to store attributes for each relation
- Name of the relationship between objects
- Forward and backward labels when the user navigates the related records in ArcMap

2.5.3 Types of geodatabases

There are different types of geodatabases. According to ESRI (2008a) there are three types of geodatabases: file, personal and ArcSDE geodatabases. This project will require a file geodatabase to achieve the objectives. There is no need for an ArcSDE geodatabase at this time, but it is recommended should the project continue for its enterprise functionality. One of the reasons why a file geodatabase is chosen above a personal geodatabase is that it has a much larger storage limit than a personal geodatabase. According to ESRI (2008a) the file geodatabase can be seen as a “collection of various types of GIS datasets held in a file system folder.” Table 2.5 lists some of the key characteristics between the three types of geodatabases as described by ESRI (2008a).

According to ESRI (2008a) the file and personal geodatabase are designed to support the full information model of the geodatabase. File and personal geodatabases are designed to be edited by a single user and do not support geodatabase versioning. According to ESRI (2010) geodatabase versioning is explained as “an alternative state of the database that has an owner, a description, permission (private, protected or public) and a parent version. Versions are not affected by changes occurring in other versions of the database.”

It is possible to have more than one editor at the same time in a file geodatabase as long as they are editing in different feature datasets, standalone feature classes or tables. The file geodatabase is a database type released in the ArcGIS9.2 version. This type of geodatabase aimed at providing simple, scalable solutions for all users. This database has the ability to handle very large datasets and work across operating systems (ESRI, 2008a).

Table 2.5 Comparisons between the different types of geodatabases

Key characteristics	Arc SDE geodatabase	File geodatabase	Personal geodatabase
Number of users	Multi-user Many readers and writers	Single user Small workgroups Some reader and one writer per feature dataset and standalone feature class or table.	Single user Small workgroups with smaller datasets. Some readers and one writer.
Storage format	Oracle Microsoft SQL Server IBM DB 2 Up to DBMS limit	Each dataset is a separate file on disk. File folder that hold its dataset files.	All contents in each personal geodatabase are held in a single Microsoft Access file.
Size limit	Up to DBMS's size limit	One terabyte for each dataset. Each file geodatabase can hold many datasets. Each feature class can scale up to hundreds of vector features per dataset.	Two gigabyte per access database. The effective limit before performance degrades is between 250 and 500 megabytes per access database file.
Versioning support	Fully supported across all DBMS's with cross database replication and updates	Not supported	Not supported
Platforms	Windows, Unix, Linux and direct connections to DBMS's than can potentially run on any platform on the user's local network.	Cross platform	Windows only
Database administration tools.	Full DBMS functions for backup, replication, recovery, SQL support and security.	File system management	Windows file system management
Notes	Requires the use of ArcSDE.	Allows the user to optionally store data in read only compressed format to reduce storage limits.	Often used as an attribute table manager through Microsoft Access. Effective string handling for text attributes.

Source: ESRI (2008a).

A file geodatabase provides excellent performance and scalability. The database supports individual datasets containing well over 300 million features and datasets that can scale beyond 500 GB per file with very fast performance. The reason for choosing a file geodatabase over a personal geodatabase is that these types of databases use about one third of the feature geometry storage required by shapefiles and personal geodatabases. An example can be that file geodatabases have the ability to compress vector data to a read-only format to reduce storage requirements even further. This database performs operations much more efficiently than shapefiles and it also has a larger data storage capacity other than shapefiles (ESRI, 2008a).

2.6 Creating a geodatabase in a GIS

According to ArcGIS Pipeline Data Model (APDM) one of the major benefits of using a geodatabase is the system's ability to centralize management of a wide variety of geographic information in a relational database management system (RDBMS). The geodatabase is ideal for the management of very large data sets in an integrated, continuous environment. Raster and vector data are stored in seamless layers and it offers full support for multi user editing at the same time (APDM, 2004).

According to Rhaman (2005), database management systems (DBMS) provide more efficient ways to manage and store data. One of the main characteristics of databases in GIS is the ability to control data redundancy. This reduces the risk of building a weak database with inconsistent and repeating data. Another important aspect of DBMS is multi-user accessibility which allows simultaneous access to data by different users at the same time. The data accessibility is further improved by the ability to query data by means of a Structured Query Language (SQL). This enables the user to update and delete data much easier. Rahman (2005) explains further that there are some disadvantages of DBMS such as high cost and complexity but this is cancelled out by the number of advantages geo-information gains from it.

Three dimensional analysis is a key factor for this project and a geodatabase supports advanced data types and geometry. APDM (2004) states that the database system has the ability to store 3D coordinate measures and true curves. The map features of the database are linked to the attribute tables containing the information about the different features. The geodatabase allows fast and efficient data entry with data rules and relationships and the ability to edit feature-linked annotation.

According to APDM (2004) the geodatabase functions to bridge the gap between the traditional GIS approach of storing features and attributes in separate tables or files. The database allows organizations to turn their business processes and real-world features into objects that have attributes and behaviours. The behaviour of each feature is locked in the database and it changes each time a feature is added, changed or updated, hence the so called name for a geodatabase: object orientated data model or an object relational data model. Each table in a geodatabase is actually a class with its own properties, methods and events.

The properties can be seen as physical attributes that describes rows in a table. Methods are actions that the feature performs while events are messages that the feature sends out when something occurs to the feature. When a feature is added to a geodatabase the user can add behaviour through subtypes, domains and relationships. APDM (2004:6) states that “the idea behind the geodatabase is to provide a uniform approach to reducing the complex behaviour of the real world to a set of tables with extended and customizable behaviour.”

Maps are the output of a GIS. “If a picture is worth a thousand words then a map is worth a million.” (APDM, 2004:3). GIS produce maps whether they are displayed on a computer screen, web browser, hard-copy output or hand-held device. It is the best way to illustrate geography in relation with other geography and show coordinate positions, vector directions and features in harmony with each other. Maps are an effective way to clarify issues because most people are familiar with and know how to read maps in a simple and intuitive manner. In a printed format they are an effective way of communicating patterns, structures, dispersion, aggregation and segmentation of events and features to a wide audience. “Printed maps capture the interest and imagination of people who want to know more about the world they live in.” (APDM, 2004:3).

2.7 Feature modelling inside buildings

According to Davis & Rich (2010) the spatial data used in a facility geodatabase has often been created by using aerial imagery and global positioning system (GPS)-enabled field data. One of the limitations of this type of data is the fact that it is blind to building interiors. For example, aerial photography cannot penetrate through the roof and GPS signals are not available inside buildings. As a result of this limitation, the rich geospatial data collection that describes the facilities have significant holes that need to be filled. These holes are connected to the most concentrated financial investments and the places where people spend most of their time – inside buildings.

Capturing existing information about the insides of a building, such as CAD floor plans or building information models (BIM), has become much easier because of the availability of new technologies (Davis and Rich, 2010). This integration makes it possible for the GIS user to visualize and analyze business processes inside buildings.

With today's technology it is possible for the GIS user to analyze the geographical aspects of various components inside building facilities in order to decrease cost and increase productivity. Up until now very few of the software applications used in this particular field have advanced spatial analytical capabilities to support complex scenario modelling that includes multidimensional visualization such as 3D (space), 4D (time) and 5D (money). GIS can be used as a software structure that supports the integration of information from all of these spatial, temporal and informational dimensions (Davis & Rich, 2010).

Davis & Rich (2010), states that GIS is becoming more widely used inside buildings. Facility managers are applying the insights gained from spatial data to the spaces inside buildings. Different layers are illustrated inside a building, just as there are layers at the landscape level, such as roads and parcels. Examples of layers inside a building includes floor levels, windows, doors, walls and the spaces occupied by architectural structures described in Figure 2.7.

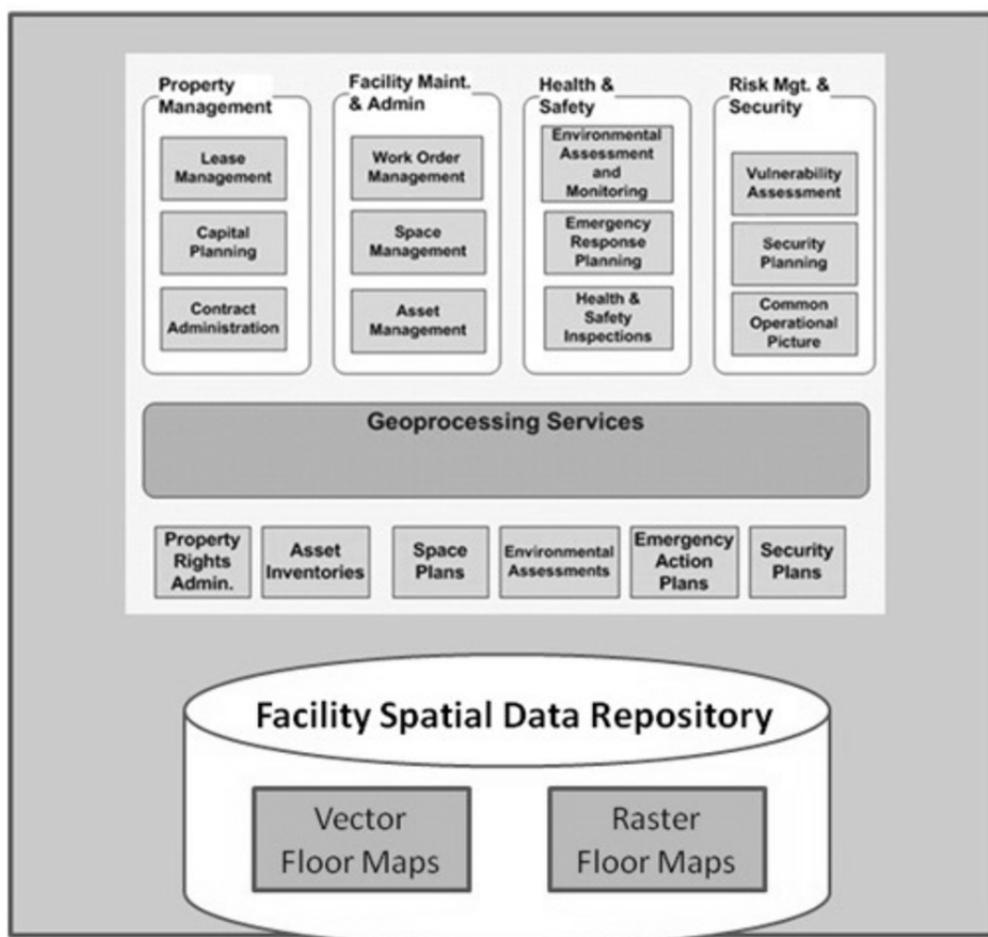


Figure 2.7: Spatial data infrastructure can spatially enable many enterprise systems (Davis & Rich, 2010).

As soon as the main architectural components of the building are created in the GIS, it is possible to derive a variety of other layers from the main objects. Examples of these layers can be:

- Security zones
- Asset locations
- Navigable routes
- Management zones
- Utility networks

Davis & Rich (2010) states that as soon as this basic data has been added to the GIS, the user has the ability to provide geospatial support to a wide variety of information systems and business processes for facility management purposes.

By using the GIS combined with all the data, the user can create a Building Information Spatial Data Model (BISDM) which runs several processes to obtain effective facility management. Examples of these processes as described by Davis and Rich (2010) are:

- Visualizing proposed space planning scenarios
- Modelling the potential impacts of proposed use changes on the supporting utility infrastructure
- Visualizing the impact of proposed building projects on the campus environment
- Analyzing space use, availability and optimization across campus or regional extent

2.8 3D Analyst

ArcGIS10 offers a 3D analysis capability that enables the user to visualize the utility networks inside a building on multiple levels. If the user has to represent a network that connects on several levels of a building in a 2D environment it would be very difficult to distinguish between lines that are on top of each other. The vertical lines would be seen as points. Viewing the features in 3D will enable the user to visualize the network much more efficiently. The user would be able to see vertical lines from a side-view angle on several levels of a building.

According to Booth & Bratt (2004), 3D Analyst provides the user with tools in ArcScene and ArcGlobe for analysis and visualization of 3D data. It allows the user to extend the possibilities in ArcCatalog and ArcMap for more efficient management of 3D GIS data such as 3D analysis in ArcScene and 3D feature editing in ArcMap. Three dimensional feature editing in ArcMap is in most cases done on features with z-values in their geometry. Zlatanova *et al.* (2002) also explains that 3D Analyst enables the user to manipulate data with methods such as surface generation, calculation of volumes, draping raster images and terrain visibility from one point to another. 3D Analyst works mainly with vector data. Raster data can be imported into 3D Analyst only to improve the visualization of the vector data.

The most common use for ArcScene is to visualize 3D data. It provides an interface for creating and analyzing surfaces and viewing multiple layers of GIS data with z-value geometry (Booth & Bratt, 2004).

3D Analyst allows the user to drape raster images or vector data over surfaces and extrude the vector features from the surface. It also allows the user to view features from a variety of viewpoints using different viewers. The user can change the properties of 3D features to use transparency or shading as well as the properties to change vertical exaggeration of terrain, the coordinate system and the extent of the scene (Booth & Bratt, 2004). These capabilities should prove very useful to view vertical lines, point features on different levels and to use transparency to view features inside buildings.

2.8.1 Setting heights for digitizing in 3D

According to ESRI (2011), the context of geographic data will be better defined through the ability to edit features in 3D. It allows the user to visualize the placement of data, locate errors that can be easily fixed and change values. A critical part of the 3D experience is assigning features with z-values in their geometry or setting the height. In many cases features do not need z-values in their geometry at all, such as roads on a flat surface. In order to illustrate features in multiple levels of a building, viewpoints on top of structures or even 3D flight paths, the features need z-values with their coordinates. The user has two options to assign base heights to features. It can either be within the geometry (shape) field or as a feature attribute. Either of the two options can be used for point features while the best option for line or polygon features is to store the z-values in the feature geometry. It is also

recommended to store z-values in the feature geometry for multipatch features representing for instance, the relative heights of a 3D object such as buildings (ESRI, 2011).

2.8.2 Vertical lines and 3D geometry

According to Rahman (2005) the geometry of an object is composed by its coordinate values x, y. Describing objects in the third dimension requires the use of a third coordinate called the z value. Most of the available DBMS supports commonly used geometric objects like points, lines and polygons. In most cases these geometric objects are only 2D predefined. In order to represent 3D objects, a combination of 2D objects with z-values in their geometry is used.

The user can model a connected system using geometric objects like vertical lines in a 3D environment. This requires the use of vertical lines, for instance, to connect features on different levels of a building. According to ESRI (2011), vertical lines can be created in a two dimensional environment in z-enabled feature classes. These lines must have identical x and y coordinates with different z-values in their geometry. Vertical lines can be used to connect a network consisting of edges and junctions across multiple levels of a building. The user creates the z-enabled features in 2D (ArcMap), after which the features can be viewed in a 3D environment using ArcScene.

2.8.3 3D Topology

Rahman (2005) explains that it is important to take the aspects of 3D spatial data into consideration. Three dimensional geometry and topology plays an important role when working in a 3D environment because they form a base for calculations. Two dimensional data operations are not as complex as operations in the third dimension. According to Rahman (2005) it is easy to implement 3D geometry but the most critical one, 3D topology, is very complex to implement.

It is important for features with z-values in their geometry to have topological rules. Topology rules define data integrity in a geodatabase. These rules can also be seen as one of the mechanisms describing relationships between features. Models using topology rules are seen as topological models and many researchers see these models as the best way to do

complex spatial analysis such as finding the best path between two objects (Zlatanova *et al.* 2004). These rules determine how different features in a geodatabase share geometry. An example could be to assume an electrical network inside a multi-storey building. The electrical features such as plugs, lights, heaters or air-conditioning will have z-values in their geometry and must be inside the rooms of a building. The rooms would be illustrated as cubes inside a 3D environment. Topological rules will ensure that the electrical features are inside a room. If not, there would be an error that has to be corrected.

According to Zlatanova *et al.* (2004) the development of topological models into the 3D environment is a complex process that is still being researched. The reason for this is that the third dimension poses a list of new challenges and issues for the representation of features and detecting their relationships towards each other. Significant improvements were made in 3D visualization, data access and animation but there are still areas left to address, e.g. full 3D geometry for 3D representation, topological relationships and analysis (Zlatanova, 2002). Gillgrass (2010) states that the development teams at ESRI are looking for new 3D topology options that would be implemented in the new versions of ArcGIS 10. At the moment ESRI software does not support detecting topology errors in 3D, only in two dimensional environments.

2.9 Network datasets and Geometric Networks

A network dataset is used to model features that form a connected network inside a geodatabase. It consists of a combination of features participating in the network. Point and line features are commonly used to form a network stored as a network dataset in ArcGIS10 Network Analyst (ESRI, 2011).

According to ESRI (2011), network datasets are well developed to model transportation networks. Network datasets are created from source features that include simple features such as points, lines and turns. These features must be connected to each other to form a connectivity of the source features. A network dataset can only be created by a set of features in the same feature dataset. It is essential that all the participating features are connected correctly, otherwise the user will end up with standalone features that will cause errors in the network dataset. When the user performs analysis by means of ArcGIS Network Analyst, the analysis is always done in a network dataset (ESRI, 2011).

Network datasets can also be implemented for utilities. Vertical line features and z-enabled features can form a network on several levels of a building. The user can do network analysis through Modelbuilder and ArcToolbox to determine the shortest path on the network from one feature to another in a 3D environment.

There are many examples of how GIS can be implemented inside buildings to find the best path from one point to another. The most common reason for this is to find the shortest routes inside a building for situations such as emergency evacuations. Crickard (2010) used ArcGIS Network Analyst to model a hallway as a network dataset and to find the shortest path inside a building from one point to another using the Network Analyst toolbar.

According to Actur and Zeiler (2004) a geometric network represents geographic features that comprise a network. Geometric networks are most commonly used for network tracing and analysis.

Perencsik *et al.* (2005) states that some vector datasets consisting of points, lines or polygon features are used to model communications, material, energy flow or transportation networks. These vector datasets need to support connectivity tracing and network connectivity rules. Geometric networks also allow the user to turn simple point and line features into network edge and junction features used for network analysis. The user can define connectivity rules inside a geometric network that will help to control what types of network features may be connected together when editing the network. Geometric networks, like network datasets, must also be created from a set of feature classes in the same feature dataset. Table 2.6 describes the differences between network datasets and geometric networks.

Table 2.6: Comparisons between Network Datasets and Geometric Networks

Network dataset	Geometric Network
Transportation network modelling	Utilities and Natural resources modelling
Operations for path finding and allocation	Functionality for network tracing
Supports turns	Do not support turns
Use point and line features	Simple or complex edge features and junctions
Contains a more robust attribute (weight) model	Weights only based on feature fields
User in control when connectivity is built	System in control during connectivity

Source: ESRI (2011).

According to Van Maren (2011), the ESRI software does not support 3D geometric networks in ArcGIS10. The teams at ESRI are looking at supporting this problem in the next release of the software called ArcGIS10.1. The alternative to this problem is to use a network dataset in 3D to determine the shortest route between two points inside a building. Therefore, the decision to use a network dataset instead of a geometric network was made. The analysis possibility for electrical networks is limited in a network dataset but the shortest route analysis can prove to be useful in scenarios where cable lengths have to be calculated. Another possibility is determining the optimum and shortest path for cable service routes inside the building currently and for future developments. Should the new release of the software support 3D geometric networks, the same prototype model can be used to implement geometric networks and to run further analysis possibilities.

2.10 Fishnet model

Locating electrical features outside buildings can be a difficult task. Pinpoint accuracy is needed to locate underground electrical features. The fishnet model is used as a substitute for expensive GPS devices to locate electrical features outside buildings. According to ESRI (2011), a fishnet can be seen as a sort of feature class that creates a grid of rectangular cells. A fishnet consists of three parts called the spatial extent, the number of rows and columns and the angle of rotation. Many different ways can be used to specify the parameters for a fishnet model. An example can be that the user does not know the exact number of columns and rows that has to be represented by the fishnet but the exact cell size is known. Therefore, the model would generate the amount of columns and rows using the cell size parameter that is set. The extent can be imported using the extent values of another feature class. This model will be used to create a grid containing specified cell sizes to enable the user to navigate electrical features outside the buildings in the study area.

2.11 Case studies

The following case studies represent scenarios in which solutions were found for similar problems encountered in this research project. The case studies provided valuable ideas that contributed to the final design of the prototype model called the PUK geodatabase.

2.11.1 A GIS data model for enhanced navigation in urban environments (Mandloi, 2007)

2.11.1.1 Introduction

The thesis is about how an object-oriented data model was developed to illustrate a multi-modal transportation network that can be used for navigation and to perform network analysis in urban environments. The data model had two main parts: one modelling the network for movement inside buildings and the other part modelling the network outside buildings by means of multiple modes (Mandloi, 2007).

The network illustrating movement inside buildings was developed in a 3D environment. For this to work, vertical connectivity had to be created to establish connections among floors. Mandloi (2007) modelled the features participating in the network in a 2D environment and used 3D for visualization purposes. Commercial off-the-shelf GIS software was used to capture the data.

The data model proposed by Mandloi (2007) was implemented for buildings with multiple levels as well as the transportation network on the North Campus at the University of Buffalo. In order to test this model's effectiveness, Mandloi (2007) performed path finding analysis in the study area using commercial GIS software.

The networks in multi-storey buildings that consist of corridors and access systems connecting one level to another are often similar to one another when viewed from a 2D point of view. The connectivity of the network on different floors needs to be modelled in such a way that the coincident factor is taken into consideration (Mandloi, 2007). ArcGIS software provides a solution to model this type of 3D connectivity within floors of a building.

The network outside the buildings was modelled in a 2D environment as a multi-modal network. This includes various modes such as walking, driving and using public transport. Mandloi (2007) states that the key to model multi-modal networks is to model the transfer points in the network where the transfer from one mode to another takes place. For instance when a person walks on a sidewalk and climbs on a bus. The point where the person switched modes is called a transfer point.

Mandloi (2007) used geo-spatial data from various sources such as aerial imagery, CAD drawings and paper maps to do shortest path or find best route analysis in a two or three dimensional environment. The end purpose of the model was to simulate and model different scenarios useful in many situations such as navigation on campus or emergency planning.

2.11.1.2 Challenge

Mandloi (2007) states that many of the buildings in urban environments are multi-storey buildings. This is evident especially in central business districts called CBD's. It is not only necessary to navigate through a street network to the location of a building but there is also a need to navigate to a location inside the buildings. There might, for example, be multiple routes inside a building to reach a specific office. So an interesting scenario was discovered to build a spatial data model that not only provides path finding analysis but also provide directions from the entrance of the building to reach a specific location inside the building.

2.11.1.3 Solution

In most cases, each floor is represented by a compartment consisting of rooms and corridors. Corridors can be seen as the main link between all the rooms and the entrance and exit points. Other features represented inside the building was stair cases, elevators and doors. Mandloi (2007) represented each floor with its corridors and destination points. The vertical connections between the floors were established by modelling the staircases and elevators. The different geometry types were specified as follows: The corridors was created as line features and organized in line feature classes. The stairs, elevators and doors were represented as point features organized in point feature classes.

To represent the floors on different heights specified z-values were added to the coordinates representing the vertices that make up the geometry of the different floors. The same was done for the line and point features on different levels in a building.

These different features on multiple levels in a building are best viewed in a 3D environment. According to Mandloi (2007), there are certain limitations in most GIS systems such as identifying topological relationships of connectivity in 3D space. GIS can store topological relationships in 2D only. The system should support 3D topological data models, but such data models although formulated in theory, have not yet been developed or implemented.

In this case study, Mandloi (2007) had several design approaches for a seamless database. The first approach was to create each floor network in a separate line feature class containing z-values in the attributes indicating the floor number and the relative height from the ground level. A problem with this approach was that in most cases high storey buildings have many floors. If this approach is adopted there will be many feature classes with many tables that will result in difficulty managing all the tables in a DBMS.

The second approach was to create feature classes that represented the floor networks for each level across the study area. For instance, one feature class represents all the first levels of all buildings. The next feature class represents all the second levels of all the buildings and so on. This approach reduces the number of feature classes as well as the number of tables in the DBMS. There is a limitation to this approach due to the fact that there are cases where an urban area has uneven distribution of high rise buildings. For example: there can be three buildings with eight floors where most of the other buildings can have only two floors. This approach may result in many feature classes having very few features (Mandloi, 2007.)

According to Mandloi (2007), the third and final approach to the design was to model the floor network for all the levels and for all the represented buildings in one feature class. Two floors can be modelled by placing each floor in a separate subtype and placing each subtype in a separate connectivity group. This approach uses a single feature class to store the entire floor network and it is much more efficient at database level.

It was important for the designer to realistically model the movement inside buildings such as the time or effort to travel between floors. Travel time was derived by actual measurements or average walking speed. Travel impedance was also taken into consideration. For

example: the time factor associated with using the elevator or traveling along the stairs. Statistical calculations were used to model movement preferences and travel time from one floor to another (Mandloi, 2007).

For the movement outside the buildings, the designer modelled the street networks, bus routes, walkways and transfer points. This part of the case study will not be described in detail due to the lack of relevance for this research project.

Mandloi (2007) created various feature classes that represents the participating features in the network. These feature classes were grouped in a feature dataset that was later used to create a network dataset built to store the connectivity and relationships of the participating features. The network dataset stores a set of tables consisting of connectivity information with network attributes in the form of travel impediments. The information stored is used for various network-based tasks such as finding the best paths to a specific destination.

Floor plans were used to represent the floor networks of each level in a building. These floor plans consisted of CAD drawings in AutoCAD format and were not geo-referenced. Mandloi (2007) geo-referenced the CAD drawings in UTM Zone 18 North by means of a world file. A world file is a simple text file that contains x and y coordinates of the two points in a CAD file and the respective coordinates that is used for reference in the NAD 1983 UTM Zone 18 North projection.

In order to reference the building corners from CAD to UTM Zone 18 N, one foot digital ortho photos was used. The CAD file was added, referenced and digitized to form the corridor lines. The corridor lines for each floor were stored in a separate subtype such as floor1, floor2 etc. The number of subtypes represented the maximum number of floors in any of the buildings in the study area (Mandloi, 2007).

2.11.2 Building Interior Space Data Model: 2008 ESRI User Conference (Grisé & Wittner, 2008)

2.11.2.1 Introduction

Grisé & Wittner (2008) developed a GIS data model to support interior space management. Some of the situations in which this model can be implemented include interior space

planning and tracking as well as the visualization of interior space data. This particular model can further be used as a foundation for other building data models such as facility management, landscape or city planning, emergency and environmental management.

2.11.2.2 Challenge

Several possibilities were explored to design a common, simple data model to support a variety of implementation styles and business functions (Grisé & Wittner, 2008).

2.11.2.3 Solution

The conceptual framework had several feature classes consisting of relationship classes between them. The geometry of the feature classes connected to each other consisted of point, line and polygon features. Several tables were also used to describe additional information about the represented features.

The outline of the implementation model was as follows: Grisé & Wittner (2008) developed a geodatabase called “BISDM”. The geodatabase contained a feature dataset called “Buildings”. All the point, line and polygon features were grouped in the feature dataset along with the relationship classes connecting them. The feature classes were also connected to tables with extra information in the geodatabase.

Grisé & Wittner (2008) describes how the primary and foreign keys were implemented to form the relationship class connections between the objects. Each feature class has a field in their attribute table named the “ID_field” that describes the identification of that particular feature. For instance, the “ID_field” in the building feature class contains a value of “MA”. The “M” stands for building M and the “A” describes the particular part of the building, in this case the Atrium part of the M building. Another example is the Floor feature class with an “ID_field” value of “M2A”. It still indicates building M and the Atrium part of the building, but the “2” indicates the floor number. The relationship classes are connected through the different “ID_fields” in each object. The data type for the different “ID_fields” is text.

There are several tables describing the objects in more detail. All the feature classes in this model have relationships with the associated information tables. The tables support visualization and analysis even if tabular and spatial data are managed separately. The information tables can be easily updated if there are changes in the different applications or cycles. Grisé & Wittner (2008) states that many implementations is combined with feature class and attribute table content. The “Identify” tool was also used to display the different relationship classes between the objects and the associated tables.

The idea of the unique key fields in the different feature classes was also implemented in this case study. The user can use queries to locate a specific object by means of a unique identifier. Grise & Wittner (2008) explains that it is not necessary to use unique fields for most projects: it only depends on the implementation and what the user wants from the data model.

2.11.3 GIS for federal buildings: BISDM Version 2 (Rich *et al.*, 2010)

2.11.3.1 Introduction

Rich *et al.* (2010) conducted a Building Interior Space Data Model (BISDM) for GIS in the summer of 2007. They described GIS as a core technology used to build the information systems such as cartographic, image, business analysis and faculty management. GIS is used to manage, analyze and report building data at all scales. The scales range from global, country, region, city, campus, building to the rooms inside the buildings. ESRI geodatabase data models were used as standardized templates for many of the fields.

ESRI’s BISDM was built as a template to support many scenarios and uses many compatible technologies. The project was tested to see if it could handle real-world scenarios and provide solutions for certain problems. There are two types of BISDM data models named split and merged models. Merged models are used only for GIS applications while split models are used for combinations of GIS and other systems such as Building Information Models (BIM). Rich *et al.* (2010) determined if a BIM can be used as a spatial data repository on its own. This issue was resolved through a set of criteria to measure the capabilities of a BIM. This indicated that the BIM should be file based and it should support a variety of data formats. It must be query-able across multiple facilities. A number of users

must be able to access the spatial data at the same time and the model should provide sufficient security. After consideration Rich *et al.* (2010) decided that BIM had several shortcomings and would not be a viable solution to be used as a spatial repository. So the team developed a split model in which GIS can be combined with BIM.

2.11.3.2 Challenge

The challenge was to improve the previous version of BISDM and to develop a better data model to serve many scenarios, in which the model can be useful, support compatible technologies as well as property, building and asset locations.

2.11.3.3 Solution

BISDM version one had a hierarchical structure diagram with eight feature classes connected to each other through relationship classes and topology rules. Version two had the same hierarchical diagram with extra tables, feature classes and raster features and photos added. It is basically just an improvement of the last version with extra features.

The floor feature class in BISDM 2.0 represents the floors contained in a building. Most of the feature classes in BISDM 2.0 contained “ID_fields” used as unique identifiers for the feature classes. These “ID_fields” is part of the primary and foreign keys connecting the feature classes through relationship classes. There are two interesting fields in the case study used in most of the feature classes that can prove to be very useful in this project. The two fields are the “Lastupdate” and the “Lasteditor” fields. These two fields show the last date and the user name recorded when the feature class was previously updated. These two fields can be useful in a maintenance table to show the person responsible and the date when utilities are updated or worked on in a network.

BISDM can also represent 3D transportation networks for interior networks integrated with exterior networks. The model can be used to represent different modes of transportation inside buildings such as hallways, stairs, escalators and elevators. The model will also have the ability to do route tracing and transportation analysis such as find the nearest facility, travel distance and time analysis as well as location/allocation. The only two analysis options in this case study that is relevant for this project is the routing tool and network reach. The

routing tool shows the most efficient way to get from one point to another inside a building while the network reach tool shows all the components connected to a network. The example of the routing tool can be used to find the shortest route between one electrical utility and another. This should help building managers responsible to make calculations, for example to determine optimum lengths of cable needed or choosing the best suitable path for electrical cables from distribution boards to utility endpoints. The network reach example found ways to ensure that all the different electrical components in the network are connected to each other. The use of a network dataset will ensure that all the features are connected to form a network. Rich *et al.* (2010) expanded the core model from 2D to 3D by storing z-values in the geometry of the participating features in the transportation network.

2.11.4 Building and Technology Passport of Masaryk University (Glos, 2008)

2.11.4.1 Introduction

The Masaryk University is the second largest Czech University with nine faculties supporting an estimated 32 000 students and 4000 employees. The study area consists of approximately 200 buildings with 17 000 rooms that covers 335 000 m². The data and voice network in the study area has about 50 000 cables, 10 000 patch panels and connectors, 5000 devices and 20 000 data ports.

2.11.4.2 Challenge

Glos (2008) used GIS to develop two systems named a Building Passport and a Technology Passport. Data was gathered, managed and provided for the buildings, the rooms inside the buildings and the technologies inside the buildings and rooms.

The challenge was to use the information gathered to increase performance for administration and building operations as well as to increase the efficiency in the way building spaces were used. The model should also decrease the operational costs of the buildings.

The database created from the gathered information should also support other information systems such as facilities management (FM), building management systems like SCADA and it should also support the BRNO Academic Computer network of the university.

2.11.4.3 Solution

Glos (2008) explained that the building passport should contain important information such as the limitations and delimitations of the buildings and rooms themselves.

Glos (2008) created feature classes for the locality, buildings, floors and rooms. Each feature class contains attributes with descriptive data. Relationship classes were also implemented to show the connections between the different feature classes.

A very useful idea from this case study is the use of a positional code that is unique for every location, building, floor and room. If the user knows how to use the code, the positional code or unique key can be used to locate a certain position by means of a query language. The process can even be turned around by means of the identifier tool to derive the unique code of a certain position.

Different technologies such as heaters, alarm systems, air units, energy meters and switch boards can also have their own positional codes or unique keys in the database used to locate them. Each technology is divided into three main parts. For instance:

- The alarm system
- The aggregates such as the alarm systems on each floor
- The devices such as the alarm panels on each floor

Each of these technologies can also be located with a unique code through the use of a query language.

2.12 Conclusion

Through the literature review it was determined that a GIS has the capabilities to obtain the goals set for this project. The WGS 84 Datum and the Transverse Mercator Projection were determined to be best suited to model features for the proposed geodatabase. The literature shows that CAD and GIS can be integrated and it is possible to add CAD data in a GIS environment and reference it. The ten steps to designing geodatabases by Actur and Zeiler (2004) provides a detailed description of the different phases and will form the basis on

which the database design will take place in Chapter 3. Different types of geodatabases were compared to each other and the “File Geodatabase” will be used to store the features modelled in this project. The 3D capabilities of ArcGIS10 will be used to model features with z-values in their geometry. Network Datasets and Geometric Networks were compared to each other to determine their limitations and abilities for 3D analysis. The result was that Network Datasets is the best option to model networks in 3D. The case studies provided insight to help with the design process through the ideas that came forth.

The following chapter’s framework will be based on the ten GIS design steps by Actur and Zeiler (2004). The chapter will cover the methodology used to build the geodatabase for the electrical utilities at the NWU campus. All the different approaches to the design of the geodatabase will be discussed in detail as well as the different design steps to obtain the goals for the project.