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Data Modeling Standards for Developing Interoperable Municipal Asset Management Systems

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Abstract. Sustainable management of municipal infrastructure assets depends to a large extent on the ability to efficiently share, exchange, and manage life cycle information concerning the assets. Although software tools are used to support almost every asset management process in municipalities, data exchange is mainly done using paper-based or neutral file formats based on ad-hoc proprietary data models. The inability of municipal asset management systems to interoperate creates inefficiencies and impedes sustainability. Interoperability of various asset management systems is crucial to support better management of infrastructure data, to improve information flow and to streamline municipal workflow processes.

This paper surveys a number of available data standards that can potentially be used for implementing interoperable and integrated municipal asset management systems. The paper outlines the main requirements for standard data models and highlights the importance of interoperability from an asset management perspective. The paper also discusses the role that spatial data and GIS can play in enhancing the municipal asset management processes by increasing the efficiency of managing the asset data. Relevant efforts to develop and standardize data models for municipal assets are also presented. The paper argues that using standard data models can significantly improve the availability and consistency of the asset data across different software systems and platforms, can serve to integrate data across various disciplines, and can facilitate the flow and exchange of information between various parties involved.

Keywords: Municipal infrastructure management, sustainable infrastructure asset management, data standards, spatial data, GIS, integrated asset management.

1. Introduction

Sustainability of municipal infrastructure assets requires improving the cost-effectiveness of managing these assets throughout their life cycle. The use of municipal asset management applications has significantly improved the operational efficiency and maintainability of municipal infrastructure assets and is becoming a critical tool in achieving sustainability goals. Although software tools are used to support almost every asset management process in municipalities, data exchange is mainly paper-based or accomplished using semi-automated processes or neutral file formats based on ad-hoc proprietary data models that vary widely from one tool to another. The inability of municipal asset management systems to interoperate has created considerable inefficiencies, and thus has become a major impediment towards achieving the sustainability goals of municipalities.

Some municipalities have made significant investment in developing software systems to address the increasing complexity of managing infrastructure assets. Significant advances have been made during the past decade in

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developing municipal asset management systems in various domains such as sanitary and storm water sewers, water supply distribution systems, pavements, and bridges (Vanier, 2001; Halfawy, 2000; Halfawy, 2002a). These systems support a wide range of functions such as inspection and data collection, inventory and condition data management, maintenance management, and operations management. A number of municipalities have also implemented methods for condition assessment, probabilistic deterioration models, life cycle cost analysis, multi-objective optimization, planning and prioritizing maintenance operations, performance simulation and prediction, and evaluation of alternative technical and economic policies (Vanier and Rahman, 2004).

However, the majority of municipal asset management applications were developed to function as stand-alone systems, and therefore have limited or no capability to share and exchange information with other applications. Although these applications are used to support major activities within municipalities, the data exchange between various applications of this genre or with other municipal information systems (e.g. personnel, finance, etc.) is virtually non-existent.

Although these applications could share a substantial amount of asset data, users typically have to translate (or sometimes transcribe) the data from one representation and format to another in order to map the data between these applications (Kyle et al, 2000; Halfawy et al, 2002b). The translation process involves many time-consuming, error-prone, and inefficient non value-adding activities of getting output from one application in a paper or digital format, re-interpreting the output, and then re-entering the data into another application. This process involves a tremendous amount of redundancy in data extraction, interpretation, and re-entry. In addition, experience shows that many problems and inefficiencies in data access, exchange, and management have arisen as a result. A major challenge is how to support seamless integration and efficient sharing and exchange of data between different, possibly distributed and heterogeneous, applications. Enabling efficient access, exchange, and management of asset data plays a key role in supporting the decision-making processes at all levels of municipal asset management: operational, tactical, and strategic.

To address this challenge, consistent and standardized methods to model, represent, and exchange municipal asset data should be adopted. Data modeling standards define the structures, semantics, and mechanisms, for modeling and exchanging information. Standardizing the representation of municipal infrastructure data would enable these different systems to interoperate (i.e. to share and exchange data), and thus provide users of these systems with the capability to reuse existing data, coordinate work processes, and share vital information in an efficient and effective manner. A standard infrastructure data model provides a schema for representing and exchanging the multi-disciplinary data of the infrastructure assets, including the assets' spatial and non-spatial objects, their attributes and their inter-relationships. A typical data model of infrastructure assets identifies and represents the information requirements and semantics across the different disciplines of asset planning, design, construction, operation, and maintenance.

This paper highlights the need for data standards in municipal asset management systems and discusses various efforts to develop these standards. The paper also discusses the data requirements of interoperable municipal asset management systems, and some of the challenges of maintaining municipal assets' data in a form that enables efficient data access, retrieval, and sharing. The paper presents an overview of the most predominant spatial data standards, which can serve as the foundation to develop more comprehensive and integrated data standards for representing spatial and non-spatial data of municipal assets.

2. Need for Interoperability of Municipal Asset Management Systems

Lack of interoperability and integration between municipal asset management systems has been a major impediment to the efficient access, exchange, and management of asset information (Halfawy, 2004). The use of proprietary data models and formats has created many obstacles towards improving data availability, sharing, quality, and reusability. There is an obvious need in the industry to develop standard data models of municipal infrastructure assets, and to represent and exchange the data in a standardized format. In general, a standard data model defines the structures, organization, and mechanisms for modeling and exchanging information. A standard data model also defines common semantics of the data as well as a vendor-neutral file format. Recently, there has been an increasing interest in developing and using standard data models of municipal infrastructure assets.

Goodchild (1995) states that most GIS contain the following challenges and deficiencies:

- They are 2D or 2 ½D (2D with a height component)
- They are static representations of data
- They support strong attribute data, but represent relationships poorly
- They possess confusing data models

- The domain is dominated by GIS as a view of a map

However, a more recent report from Doyle and Grabinsky (2003) summarizes the situation related to GIS and municipal asset management systems: "The organizations that have a well-developed and deployed GIS appear to be benefiting from its use … Few enterprises completely rely on a GIS-based system to store, maintain, and retrieve records, but the trend is heading in that way."

To improve their operational efficiency, many municipalities want to ensure that their existing asset management systems and any new systems they implement can interoperate and exchange information in an efficient manner. Adopting a standard data model enables municipalities to streamline and coordinate their work processes by integrating data from various domains, which would enhance the collaboration among different departments in municipalities. A standard data model can support the integration of municipal workflow processes by supporting the implementation of a central data repository to integrate various aspects of the infrastructure asset management processes.

Using a standard data model can improve the data flow and sharing between different teams within municipalities and between municipalities and other organizations (e.g. utility companies). Different parties within or without municipalities can access, exchange, and manage data in a common manner consistent with the intended semantics of the data (i.e. objects, relationships, attributes). The standard data model can provide common definition of the asset data (e.g. entities, attributes, units of measurements, data quality metrics, etc.). The standard can also promote data consistency and enable the effective creation, use, management, and automation of municipal data. The standard data model can also provide the means of data "reusability" between different software applications and organizations. It can also help eliminate the duplication of efforts in collecting and managing data. Different parties can make their data compatible with the standards, and hence, make the data easily accessible and reusable.

By integrating various aspects of the infrastructure assets into the standard data model, municipalities will also be able to incorporate different asset management applications into an integrated environment that can support their seamless interoperation and efficient sharing of data. An integrated data model can also help municipalities manage different infrastructure assets (e.g. roads, sewers, and water mains) in an integrated manner, and to better coordinate their maintenance and renewal programs to reduce maintenance costs and disruption of the services.

The life cycle of municipal data is order or magnitude longer than the life span of any data format or software technology. Software systems and proprietary data formats typically go through extensive changes and upgrades, which may render their use after few years a cumbersome task that requires the use of special vendor-specific software to translate from old data formats to newer ones. The use of an open, standard, and neutral data format is one way to ensure that the created data will survive the anticipated changes in software or data technologies.

In addition, most municipalities lack a formal information handover and management strategy when a construction or rehabilitation project ends. The existing informal strategies (based on paper-based protocols) have resulted in data loss and inconsistencies, as well as the inability to reuse the data at later stages of the asset's life cycle. Using standard data models can also help municipalities to develop and implement an effective strategy for information management that supports formal information handover protocols and the reusability of data throughout the life cycle of infrastructure assets.

3. Interoperability and Data Modeling Requirements for Municipal Asset Management Systems

Municipal asset data are typically characterized by their sheer size, complexity, inter-dependencies, diversity and dynamic nature. The primary function of a municipal asset management system is to maintain the accuracy, consistency, and integrity of the data. A comprehensive municipal asset management system should implement methods to support the efficient modeling, management, integration, exchanging and sharing of data. The remainder of this section outlines the main requirements of a data model that represents municipal infrastructure assets.

Developing an integrated and comprehensive data model of municipal assets is a formidable and time-consuming task, as it:

- Requires the collaboration of various stakeholders;
- Must efficiently represent many aspects of each asset, including physical, functional, and performance data; as well as operational, maintenance, and cost data, among others, and
- Needs to be adopted by both industry and software vendors as a standard data model.

In general, exchanging data between different asset management systems is currently achieved in two main ways:

1) Through the use of special-purpose tools to translate the data between different formats and data models. Many asset management systems use file format standards developed by vendors. Data translators map the data between different systems and typically involve a tremendous amount of redundant data

extraction, interpretation, and re-entry by the end users. This process is known to be inefficient, time-consuming, and prone to inconsistencies due to mapping and/or interpretation errors. Also, the tool-specific nature of the translators imposes unnecessary constraints on end users by requiring the use of proprietary vendor-specific data models and software systems.

2) Through accessing a set of APIs (application programming interfaces) or software components (e.g. COM components). Many commercial applications offer API interfaces to allow other applications to access the internal data model and to input or extract data directly to and from the application. Although some of these APIs appear to be de-facto industry standard (such as COM or the Open Database Connectivity, ODBC), the majority of the APIs in GIS software are proprietary and tool-specific. As a result, this form of vendor-specific API-based interoperability is also limited.

Due to the inherent limitations of these two methods of data exchange, there has been a wide consensus within the industry and research community that the use and adoption of vendor-neutral standard data models and formats constitute the most viable option for software interoperability.

Interoperable asset management systems should support different modes of data access and exchange such as centralized database, application-to-application file exchange, and Intranet/Extranet access. Different applications or stakeholders typically have different requirements to access and share the data. A truly interoperable system should provide different mechanisms to facilitate the data sharing and exchange with other systems.

A standard data model should support the diverse requirements of the various disciplines of potential users, and should be based on industry wide consensus. A standard data model of municipal assets should also support an integrative and multidisciplinary approach to infrastructure management. Such an approach is necessary to support the different requirements and perspectives of the stakeholders. Different stakeholders typically have different data requirements, e.g. different feature details or map scale/accuracy. Also, non-technical high-end users (e.g. in administration) may find accessing or analyzing the data unintuitive or difficult; a data model should support a number of options to access, analyze, and report the data in ways that satisfy the varying requirements of different stakeholders.

Changes during the construction phase of a project or as a result of maintenance operations should be used to revise and update the database. A standard data model should be flexible enough to allow for changes and revisions of the data. It also should allow for recording the history and rationale of these changes. Once input into the database, the data should be continuously updated and maintained to reflect the actual condition of the assets for their entire life cycle.

Many asset management decisions are best supported by the integration of a number of software tools. For example, a sewer management system may need to link with analysis applications to perform sewer flow calculations to evaluate different alternatives to improve the capacity of the sewer system. Given the large number of software tools currently in use in municipalities, a standard data model should incorporate various aspects of the infrastructure assets in an integrated manner that would allow for the integration and interoperability of standalone software tools. The data model can also facilitate data sharing between asset management systems and other enterprise-wide systems (e.g. Enterprise Resource Planning, ERP, systems).

Municipal asset management is a multi-disciplinary process that involves a large number of inter-dependent operations that need to be managed in a coordinated manner. A municipal asset management system should support the efficient flow of information among various activities, integration of data with the workflow processes, and the coordination of workflow processes. Enabling easy and efficient access to the distributed data sources is a primary requirement through which efficient communication and collaboration among stakeholders can be supported.

4. Role of Spatial Data Models and GIS in Municipal Asset Management Systems

In recent years, there has been an increasing realization of the useful role that spatial data models and GIS systems can play to support municipal asset management activities (Halfawy et al, 2000; Vanier, 2004). As a result, there has been an increasing trend to augment existing asset management systems with GIS functionality. Several legacy asset management systems have already either implemented GIS functionality internally or supported links with other GIS systems. For example, an interface between the MicroPAVER pavement management system and ESRI's ArcView GIS software (PAVERGIS) was developed to enable the display of pavement information on GIS (www.cecer.army.mil/paver).

The majority of municipal data can be related to some form of spatial data. Municipal assets can be identified and referenced by their geographic location and spatial relationships. Spatial characteristics and inter-relationships of assets are the basis to build accurate asset inventories. Non-spatial asset information can also be linked to or associated with some spatial attributes. The capability to index and reference various forms of asset information based on the geographic location of these assets can clearly increase the efficiency of data access, management, integration, query, analysis and presentation.

Spatial data constitute the core of most municipal asset management systems and is central to many activities and decision-making processes in municipalities. It can be argued that the development of standard data models for municipal infrastructure assets must be founded upon comprehensive and standardized spatial data models. A spatial data standard of municipal assets can serve as the foundation to the development of comprehensive and integrated data models for interoperable asset management systems.

A major advantage of using GIS in municipal applications is its capabilities to integrate spatial data from different sources that could exist across several organizations. For example, creating a complete map of a specific municipality would require overlaying different layers to show infrastructure, utilities, and land information for that municipality. Again, integrating and linking spatial data from different sources requires the use of a consistent and standardized spatial data model that enables linking and exchanging spatial data regardless of the software or hardware used, or the method by which the data was created. This is particularly useful when spatial data is shared and exchanged over the Internet.

Spatial data representation has proved to be an ideal tool to enable more intuitive and efficient methods to manage, query, explore, visualize, and analyze municipal asset data in a spatial context. The GIS spatial analysis and visualization capabilities and its ability to integrate spatial and non-spatial data can significantly improve the data access and management and provide better support to various planning and decision making processes. Many municipal asset management services and processes can be effectively supported using the GIS spatial data modeling and management capabilities. The following outlines the role that GIS can play to support some of the most common asset management processes within municipalities.

GIS can play an important role to store and correlate a variety of spatial and non-spatial data of the municipal assets**.** Documents in virtually any data format (textual, graphics, multimedia, etc.) can be associated with their respective assets to provide valuable information to the user. The GIS also enables users to access and query the database visually, and obtain the results displayed directly on a map. This functionality can help to eliminate data inconsistency and redundancy, and enable easy data retrieval and update. Users can generate a variety of reports about various assets on the map. For example, to retrieve information about a specific sewer line, an engineer can point to that sewer on the map and, in response, obtain a detailed report on the physical and condition data, and the history of maintenance and repair work along with any other related documents (e.g. CAD drawings, photos, CCTV files, etc). Spatial relationships between different asset components can also be displayed, analyzed, and queried.

Municipal asset data typically come from many sources across different disciplines. Several GIS software systems support interfaces with DBMS through the use of a standard interface (e.g. Open Database Connectivity, ODBC) or vendor-specific APIs. These GIS software systems can integrate and manage data stored in multiple, potentially distributed, databases. The GIS capability to integrate data from different data sources will enable the development of asset management systems that integrate data with other enterprise-wide data (e.g. those stored in ERP systems). This would enable asset managers and other stakeholders to efficiently share and exchange information seamlessly.

The GIS can also interface with software that simulates performance under various conditions and to perform "what if" scenario analysis. For example, a sewer management system can interface with a hydraulic modeling application to simulate flow in sewers and to predict any flooding or overflow that could potentially occur as a result of heavy rain events. The GIS could also interface with design tools to plan and design new facilities, infrastructure, or utilities. For example, several design systems have implemented GIS functionality to support design activities for highways and sewers. The GIS could also interface with decision-support tools such as those used for maintenance planning and prioritization, risk analysis, and life cycle cost analysis.

Users can also interactively select a number of assets on the map and query the database to retrieve the attribute data of these assets. Users can also select a set of assets based on their attributes and/or spatial relationships by querying the database. The query results can be combined to create higher-level queries by using a set of Boolean operators (union, intersection, minus, and difference). Users can locate assets based on attribute criteria or retrieve attributes for specific assets. Users can also query the database based on the spatial relationships between assets such as proximity and enclosure relationships. After receiving the query result from the DBMS, including the unique identification of the assets that meet the query criteria, the system can highlight these assets on the map.

In addition to attribute data and spatial data queries, many GIS applications can perform a wide range of spatial analysis to *discover* spatial relationships between map features. This capability, known as spatial analysis**,** involves analyzing the features' data based on their geographic locations, and includes functions such as network analysis and terrain modeling/analysis. These capabilities are typically supported by add-on modules to the GIS system. The spatial analysis capability can be used for a variety of purposes such as planning and analysis of road and sewernetworks, selection of suitable routing of utility lines, etc. Network analysis, for example, aids in modeling and analyzing water distribution and sewer systems, road routes, etc. The GIS network analysis functionality can also aid in determining the optimum routes of utility lines. 3D terrain modeling and analysis is another spatial analysis function implemented in GIS. Terrain models are generally represented using a Triangulated Irregular Network (TIN) or a grid surface mesh. The map can be overlaid on the terrain model to provide a 3D view of the ground surface. The 3D terrain model can also be used by hydrology software to automatically extract the land slopes and to perform runoff calculations.

One important function of an asset management system is to support the operations and maintenance work in municipalities. This work involves inspection and routine maintenance work, issuing, assigning, and tracking work orders, and surveying and logging the conditions and performance of the asset. By supporting the integration of data with workflow processes, the GIS system can significantly enhance the coordination and information flow among various processes, which can lead to increasing the operational efficiency of municipalities. A typical GIS-based asset inventory can facilitate the task of locating, repairing, or replacing an asset. For example, an operations engineer could point to one or more assets on the map, schedule an inspection, issue an inspection work order, perform the assessment, and update the condition data. The GIS map also makes it easy to locate and identify the asset components, as well as similar assets in the vicinity, and to retrieve or update the data about these components.

5. An Overview of Spatial Data Standards for GIS-Based Municipal Asset Management Systems

Municipal assets are typically identified and referenced by their geographic location and spatial relationships. This kind of data lends itself naturally to the domain of GIS technology. A municipal asset management system should employ spatial data modeling and management methods to build a spatial representation of the municipal asset inventory, which would facilitate the storage, query, analysis, and management of data. Spatial asset data play a key role in the development of an accurate asset inventory and would facilitate the representation and access to other non-spatial data. The GIS spatial analysis and visualization capabilities can provide further support to asset managers in the planning and decision making process. Therefore, defining a spatial data model of the infrastructure asset will serve as a stepping stone in the process of developing a comprehensive and integrated data model. that can meet the aforementioned requirements.

A spatial data model of an infrastructure asset specifies the structure and organization of spatially related information, including the representation of both graphic and non-graphic data. Spatial data primarily address the content and accuracy of the positional and attribute data of spatial features, while non-spatial data include all other aspects of the infrastructure assets including physical, functional, and performance data as well as operational, maintenance, and cost data, among others.

During the past decade, there have been several efforts to standardize spatial data models and format. Parallel to these efforts, several software vendors and researchers have been developing data models for municipal asset management applications in various domains. Many of these data models have now reached a level of maturity that could enable their wide use and adoption as standard data models in the industry. For example, ESRI has provided users with application-specific data models in about 24 different application domains such as water utilities, energy utilities, land parcels, and transportation networks (support.esri.com/datamodels). However, vendor-specific data models are not generally intended to enable interoperability with other software systems. Rather, the main purpose of vendor-specific data models is to simplify and expedite the process of implementing GIS systems using the vendor's toolset by providing ready and tested data models. However, since ESRI has the majority of GIS installations in the world (GITA, 2003), the company can positively influence data models within individual disciplines.

The rest of this section provides an overview of the most predominant spatial data standards that are related to municipal assets. Four standards are presented: the Federal Geographic Data Committee (FGDC) standards, the GIS/CADD Center standards, the Open GIS Consortium (OGC) standards, and the International Standardization Organization (ISO) standards.

5.1. Federal Geographic Data Committee (FGDC) Standards

Since 1990, the Federal Geographic Data Committee (FGDC) FGDC (www.fgdc.gov) has been developing spatial data standards to enable the interoperability between GIS systems implemented in different agencies and organizations of the U.S. federal government. Over the past decade, the FGDC developed several spatial data standards (about 19 standards to date) that have been adopted by almost all organizations within the U.S. Department of Defence (DoD). Many other federal and local government organizations, municipalities and utility companies have adopted the FGDC data standards. Several software vendors have implemented support for the standard in their software products.

The FGDC defines three main sets of data standards: data content standards, data transfer standards, and geospatial metadata standards.

5.1.1. The Data Content Standards

FGDC standard data models were defined to support areas of facilities and infrastructure management. Within the FGDC, the Facilities Working Group (FWG) coordinates and oversees the development of data models to support municipal and civil works applications.

The data content standards (www.fgdc.gov/standards/standards.html) describe the "semantics" of a set of domain objects along with their attributes and inter-relationships. A data content standard in a specific domain describes the structure and content of what is known as the "Feature Attribute Tables" (FAT). A typical FAT includes a comprehensive listing of domain features and their associated spatial and attributes data within the domain of interest. The content standards also define a number of constraints to ensure data integrity and consistency. For municipal types of applications, the most important data content standards are the Cadastral Content Standard (FGDC-STD-003), and the Utilities Content Standard (FGDC-STD-010).

The Cadastral Data Content standard (http://www.fgdc.gov/standards/documents/standards/cadastral /cadstandard. pdf) aims to support the representation, integration, and sharing of land ownership records information. The main objective of this standard is to provide common and consistent definitions for cadastral information and to standardize attribute values which facilitate the effective use and sharing of land records data. The standard outlines the information that needs to be defined for cadastral features in GIS such as surveying data, property limits and description, etc. This standard is currently supported by a number of software vendors. For example, ESRI has already implemented a land parcels data model based on this standard in their ArcGIS suite of products (support.esri.com/index.cfm?fa=downloads.dataModels.filtered ateway&dmid=11).

The Utilities Content Standard (www.fgdc.gov/standards/status/sub3_1.html) aims at standardizing the spatial information of utilities systems. This standard is intended for use in engineering and maintenance management applications of utility systems. The standard defines utility system components by specifying the names and description of feature types and their spatial and non-spatial attributes, and specifying the domain (i.e. values range or list) of various attributes. The standard describes eleven (11) feature classes which include: water distribution, wastewater collection, storm drainage collection, saltwater, natural gas distribution, compressed air, electrical distribution, electrical monitoring/control, fuel distribution, heating/cooling systems, and industrial waste. The standard also incorporates several modeling concepts such as the concept of grouping utility system components into feature classes.

The FGDC data models are described using the Unified Modeling Language (UML). Although UML serves as a robust and rich data modeling method, UML models cannot be used for encoding and exchanging data. Therefore, another encoding and exchange data format is needed.

5.1.2. The Spatial Data Transfer Standards (SDTS)

The Spatial Data Transfer Standards (SDTS) (mcmcweb.er.usgs.gov/sdts) define methods and a data format to represent and exchange the spatial data in a vendor-neutral manner. SDTS has been endorsed as a Federal Information Processing Standard (FIPS 173). The SDTS specification is organized into two sets of specifications: the base specification (SDTS Parts 1, 2 and 3) and the profiles specifications (SDTS Parts 4, 5, 6, 7, and potentially others). The base specifications describe the spatial data model structure and content, and a format for exchanging spatial data. The remaining parts define what are known as *profiles*. A profile specification includes the definition of rules and formats for applying SDTS (i.e. the base specification) for the exchange of particular types of spatial data (e.g. vector, raster, etc.).

Many GIS software vendors have already implemented support for SDTS in their software products. In general, a software system supports this standard by providing users with two commands to import and export data in SDTS format. Other commands may also be provided to obtain general information about the data transfer, and list the individual modules within a transfer. A comprehensive list of SDTS implementers can be found at (mcmcweb.er.usgs.gov/sdts/implement-priv.html).

5.1.3. Spatial Metadata Standards

The proliferation of spatial data sources and the need to organize, maintain, share, reuse, and disseminate spatial data, have created a strong demand to assist spatial data users and GIS implementers in searching, reusing, and assessing the usefulness and suitability of a particular spatial dataset. The FGDC has developed a standard for Digital Geospatial Metadata (www.fgdc.gov/metadata/constan.html) to satisfy this need and to reduce the possibility of duplicating surveying and mapping work.

The Metadata Content Standard defines a standard schema to document the content and structure of the spatial data. The metadata schema includes information such as the data source, identification, quality, positional accuracy, extent, and other quantitative and qualitative characteristics that describe the data sets. Metadata could also provide information about the content, quality, precision, consistency, and integrity of the data. The metadata schema defines a long list of metadata elements. GIS user organizations, such as municipalities and utility companies, can search and retrieve spatial information by searching metadata databases. Also, municipalities can use the standard to provide municipal spatial information to other interested parties (e.g. utility companies) and make this information available for online search, query, and retrieval.

5.2. Spatial Data Standard for Facilities, Infrastructure, and Environmental Applications (SDSFIE)

One of the first spatial data standards that have been developed with a primary focus on facility management and civil infrastructure systems was the "Tri-Service Spatial Data Standards" (TSSDS) and "Tri-Service Facility Management Standards" (TSFMS), developed by the CADD/GIS Technology Center (tsc.wes.army.mil) and first published in 1992. Recently, the Facilities Working Group (FWG) within FGDC was merged into the CADD/GIS Technology Center, and many of the FGDC data content models standards have been integrated into the SDSFIE standards. This move has helped to harmonize and integrate the two standards, which will eventually promote and advance the implementation and adoption of the standards. Also, the SDSFIE standard was recently approved as a national standard by the U.S. National Committee for Information Technology Standards (NCITS) and became known as (NCITS 353).

The SDSFIE standards provide a consistent data model to define spatial features, such as buildings and utilities, and to describe a relational database schema to store the attribute data associated with these features. Attribute data associated with a particular feature are defined in an “attribute table” attached to that feature. The latest version of SDSFIE has added support to several areas such as asset management, work management, environmental management, public safety management, organization management, information security management, and financial management (tsc.wes.army.mil/products/tssds-tsfms/fms/projects/assets/assets.htm). The complete SDSFIEstandards can be downloaded from (tsc.wes.army.mil/products/tssds-tsfms/tssds/idef1x/tssds.asp). The SDSFIE standards have already been widely adopted as GIS standard in several Federal, State, and local government organizations, as well as municipalities, universities, and utilities companies across the U.S. Many software vendors have already implemented support for the SDSFIE standard.

The SDSFIE standards focus mainly on defining consistent and comprehensive attribute tables and a database schema in the form of a relational data model. However, the standards do not provide implementation level specifications or define a neutral data format for exchanging data and enabling interoperability. The standards provide some guidelines for implementing the schemas in some software that is commonly used within the U.S. DoD organizations, primarily ArcView and Autodesk Map (tsc.wes.army.mil/products/tssds-tsfms/tssds/projects/Guidance/draft.html).

5.3. The Open GIS Consortium (OGC) Standards

The OGC was founded in 1994 with the goal “to provide a single 'universal' spatio-temporal data and process model that will cover all existing and potential spatio-temporal applications; to provide a specification for each of the major database languages to implement the OGIS data model; and to provide a specification for each of the major distributed computing environments to implement the OGIS process model” (www.opengis.org). Unlike most other data standards, the OGC approach to interoperability involves defining standard software interfaces, rather than using a standard data format. OGC defines interface specifications to support open access to geospatial services and information. Heterogeneous and distributed GIS systems complying with the standards can communicate transparently and exchange spatial data in a vendor-, technology, and platform-independent manner. OGC standards are widely accepted in the industry and are already supported by many software vendors.

The OGC develops two main sets of standards: abstract-level and implementation-level specifications. The specifications define a set of interfaces that support standardized access to distributed spatial data and processes, and thus enable the interoperability and integration of spatial data resources across the Internet. Abstract Specifications define conceptual data models and interfaces that can be used to develop more detailed implementation specifications. Implementation Specifications, on the other hand, are detailed and unambiguous descriptions of software systems’ Application Programming Interfaces (API) that are based on the abstract standards.

The OGC standards also define a set of services and metadata standards to enable the discovery and access of spatial data and services across the Internet. The OGC reference architecture has adopted an XML-based web services model for integration and interoperability of different spatial data resources and data processing systems. According to OGC’s definition, web services are defined as “… self-contained, self-describing, modular applications that can be published, located, and invoked across the Web. Web services perform functions that can be anything from simple requests to complicated business processes." (www.opengis.org). The OGC has also defined an XML-based schema, known as the "Geographic Markup Language" (GML), for representing and exchanging spatial data. GML is becoming the most dominant standard for spatial data modeling and exchange. GML has been adopted by ISO/TC 211 as a Draft International Standard.

5.4. ISO/TC 211 Geographic information/Geomatics Standards

ISO/TC 211 develops international standards for representing and exchanging spatial data used in GIS. These standards provide specifications for the methods and tools for managing, acquiring, processing, exchanging, analyzing, accessing, and presenting spatial data (www.isotc211.org). ISO/TC 211 has about 40 different standards in active development. Up until now, TC 211 has defined about nine international standards (IS) and ten draft international standards (DIS), while the remaining is still under preparation. A complete list of these standards can be accessed on the TC 211 web site (http://www.isotc211.org/scope.htm). The first ISO/TC 211 standard in the series was published in 2000. The most important ISO/TC 211 standards for municipal GIS applications are: ISO 19107-Spatial schema, ISO 19115-Metadata, ISO 19111-Spatial referencing by coordinates, and ISO 19112-Spatial referencing by geographic identifiers. These standards can be directly implemented in municipal GIS systems. Similar to the FGDC data models, ISO/TC 211 data models are defined using the Unified Modeling Language (UML). The UML models of the defined standards can also be accessed through the ISO website (www.isotc211.org/hmmg/HTML/root.html).

The ISO/TC 211 committee has adopted a number of existing OGC specifications. Most notable is the OGC's Spatial Schema (ISO 19107). The spatial schema describes the spatial attributes of geographic features as well as a set of operations for data access, query, exchange, and management. Also, the OGC Service Architecture was adopted as ISO 19119. On the other hand, OGC adopted ISO 19115 on Metadata. GML development is currently undertaken by a joint team of OGC and ISO/TC 211, and is planned to be released as ISO 19136. A number of OGC specifications, such as the Web Mapping Services and the Web Feature Services, have also been submitted to ISO/TC 211for consideration.

5.5. ISO 15926-2: Integration of life-cycle data for oil and gas production facilities

This initiative on the integration of life-cycle data for oil and gas production facilities includes standardization of the data associated with the engineering construction and operation of oil and gas production facilities (ISO 15926-2 2003). This standard specifies the data model for computer representation of technical information about process plants. More, specifically, the standard deals with:

- Many types of process plants (oil, gas, electrical, steam, etc.)
- Associated structures
- Associated buildings and accommodation
- Installation and commissioning of plant equipment;
- Maintenance and replacement of equipment.

Unfortunately, this standard although it is related to pipes and pipelines does not deal directly with municipal infrastructure. It provides a generic data model that is capable of supporting the condition inspection requirements for municipal infrastructure, but it does not do so explicitly.

5.6. ESRI Water Utilities Data Model

This data model from ESRI is "ready to use" and can be customized and configured for different water utilities, as well as wastewater and stormwater utilities. The functions that these data models wish to address include: update GIS databases with as-built data, produce standards for the industry, integrate CAD with other spatial environments, integrate GIS with other municipal infrastructure systems, analyze utility networks, and manage utility operations. The ArcGIS Utilities data model is a good attempt at creating an object-oriented representation of high-level pipe and valve data, attributes and dimensions. These include data about pipe location, material, diameter and depth, date of installation, type of pressurization, type of valve, work order administration, and general information related to the pipe network (ESRI Water 2004).

6. Harmonization and Extension of Existing Infrastructure Data Models

During the past decade, there have been several efforts to develop standard data models for municipal infrastructure assets. Many data models that cover a wide range of municipal infrastructure systems have been proposed, and some of these models have already been in use for a number of years. However, most of these models primarily focus on the spatial and physical aspects of the infrastructure assets (primarily buildings), and little attention was given to modeling non-spatial life cycle aspects such as condition, performance, and cost data. There is an obvious need to extend these data models to support various life cycle aspects of the infrastructure assets, and to leverage their implementation and use across the industry.

One of the most important ISO data modeling standards that has been in active use is the ISO 10303 Standard for the Exchange of Product Model Data (STEP). STEP consists of a series of parts that cover areas of modeling methods, integrated resources, application protocols, implementation and data exchange methods, and conformance testing. A STEP-based data model provides a standard schema for representing the data and a neutral file format that enables different applications to efficiently interoperate by sharing and exchanging information. The industry has recognized the importance of such standards and there has been an increasing interest in using STEP-based data models across various domains.

A significant effort was undertaken by the Industry Alliance for Interoperability (IAI) (www.iai-na.org) to define a STEP-based standard data model for buildings projects. The data model, called the Industry Foundation Classes (IFC), is the culmination of over a decade of research and development. The IFC model defines an integrated schema that represents the structure and organization of project data in the form of a class hierarchy of objects which cover the core project information such as elements of buildings, the geometry and material properties of products, project costs, schedules, and organizations.

Although STEP provides robust and powerful methods for information modeling and exchange, it is the author's opinion that new data modeling efforts, especially in the municipal asset management domain, can achieve better and more cost-effective results by adopting UML and XML instead. The data modeling capabilities of UML and XML schema have proved to be equivalent to those found in STEP. The new 1.1 XML schema standards (www.w3.org/XML/Schema) can support the development of semantic rich object-oriented data models. Also, compared to the graphical notation of STEP data models (EXPRESS-G), UML offers far more capabilities. Besides, the availability of many affordable software tools that aid in the modeling and implementation of UML and XML-based data models can potentially make these models widely accessible and usable throughout the industry. In contrast, STEP modeling and implementation software tend to be far more expensive, are more difficult to develop and maintain, and are generally in limited use in the industry. Unlike STEP-based data, XML data can be easily integrated with other forms of data, which can potentially facilitate integrating data from various sources of municipal information. Moreover, accessing and exchanging XML data over the Internet can be facilitated by the existing web tools and infrastructure already in place in most municipalities.

There are several efforts in the industry to develop XML-based data models. Most prominent of these efforts is the development of LandXML (www.landxml.org) for land, roads, sewers, bridges, utilities, and cadastral data management applications. Another data model, aecXML, was developed to support buildings projects and facilities management applications (www.iai-na.org/aecxml). More recently, a research project was launched to develop a set of XML schemas, called TransXML, for transportation applications. TransXML address areas such as surveying/roadway design, highway bridge structures, and transportation construction/materials.

There are also several efforts to re-use existing STEP-based data models and re-define these models using XML. For example, IAI has developed an IFC XML schema (ifcXML) to be used as an equivalent data model of the IFC STEP schema. Similar efforts need to be undertaken to re-define existing content data models that have been developed over the years, such as FGDC models, SDSFIE, or vendor-specific data models, and re-encode these models using XML schemas. These schemas can then be harmonized and integrated with other ISO or OGC's spatial data schemas such as GML.

Standard data models of municipal assets have reached a high level of maturity, and several efforts are underway to merge, extend, and harmonize these different data models into fewer and more comprehensive ones. Of particular interest is the effort to extend the spatial data models to support other life cycle aspects of the asset management processes. One such effort is taking place as part of the MIIP (Vanier, 2003) project to define an integrated and comprehensive data model for sewer systems. This work builds on the spatial data model defined by ESRI and SDSFIE and will augment this model with other elements representing the condition, performance, cost, and maintenance aspects of the sewer system.

7. Conclusion and Future Directions

Lack of interoperability and inefficient data exchange between municipal asset management systems have been a major impediment to the efficient access and communication of asset information. Much inefficiency has been attributed to the use of inconsistent data models across different asset management applications. Interoperability plays a crucial role in supporting efficient operations and cost-effective decision-making processes at all levels of municipal asset management. Developing and adopting standard data models of municipal assets is a pre-requisite for enabling the interoperability of municipal asset management systems. The use of standard data models can significantly improve the availability and consistency of data across different software systems and platforms, can serve to integrate data across various disciplines, and can facilitate the flow and exchange of information between various parties involved.

The paper presented a number of data standards related to the domain of municipal asset management, and outlined the main requirements of standard data models in the domain. The importance of interoperability from an asset management perspective was highlighted. The paper also discussed the role that spatial data and GIS can play in enhancing the municipal asset management processes by increasing the efficiency of managing the asset data. The paper argued that using standard data models can significantly improve the availability and consistency of the assets' data across different software systems and platforms, can serve to integrate data across various disciplines, and can facilitate the flow and exchange of information between various parties involved, resulting in removing or eliminating deficiencies of information access and exchange.

Developing standard data models for municipal assets can be regarded as a long-term goal that can be realized through a number of incremental steps. Although the initial cost of developing a standard data model is significant, the long-term return on this investment can produce tremendous benefits. Municipalities need to actively participate in the development efforts of standard data models to ensure that their requirements are addressed and implemented. Also, municipalities should adopt software solutions that support existing data standards and encourage software vendors to implement these standards. Once a data model is standardized and endorsed by major bodies in the industry, software vendors will endeavor to make their products and solutions compatible with these standards.

In addition to the need to address the research issues more thoroughly highlighted by the requirements of interoperability and standard data modeling, we can identify some important directions for future research. Although some of the data standards have reached a relatively high level of maturity, more work is needed to maximize the benefits of using these data standards. Work is also needed to focus on augmenting the spatial data models with specific non-spatial data elements of particular asset classes, for example linking condition or performance data to spatial data. Because of the comprehensive nature of these data models, future work should focus on refining, harmonizing, and extending the existing data models, and developing data models for municipal assets that are not covered by current standards.

In our ongoing effort, the Centre for Sustainable Infrastructure Research (CSIR) is attempting to use GML to re-encode some of the FGDC and SDSFIE data models. Also, CSIR is working to harmonize GML with the LandXML and aecXML schemas. Another ongoing effort focuses on developing an integrated data model for sewer systems. This effort builds on the ESRI's water utilities data model (ESRI, 2004), previous work done at WRC, and the SDSFIE spatial data standards.

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