Geographic Information Systems (GIS) as an Integrated Decision Support Tool for Municipal Infrastructure Asset Management

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Abstract

The three-year Municipal Infrastructure Investment Planning (MIIP) project is currently investigating investment planning and strategic asset management. The project proposes using geographic information systems (GIS) as the framework for decision support tools for municipal infrastructure managers, and more specifically, as tools to assist them to prioritize infrastructure maintenance and capital renewal.

GIS helps store, manage, analyze, manipulate and display data that are linked spatially. In essence, GIS relates database records and their associated attribute data to a physical location in "real" world coordinates, thereby creating a "smart map". Visualization of discrete parts of these data on a GIS map is possible by layering the data into different "themes". GIS applications can then display the intersection of various "themes". Typically, GIS applications in use today in Canadian municipalities primarily assist administrative functions; however, municipalities are recognizing the benefits of spatially related data to manage their municipal infrastructure assets.

The paper provides an overview of the state-of-practice for using GIS to manage municipal infrastructure. It outlines geospatial tools and technologies that augment GIS data collection such as global positioning systems, personal digital assistants, mobile computing, automated vehicle location, road weather information systems, and remote sensing. It describes associations and networks that assist GIS education, research, and technology transfer in the field. It provides examples of GIS implementations for managing municipal infrastructure from the body of GIS research and practitioner literature. Shortcomings of using GIS for managing municipal infrastructure include the high costs of data conversion, the lack of strong 3D capabilities, no ability to store "time-dependent" data, and the lack of object-oriented representation. The major opportunity for GIS for an organization is to create an "Enterprise GIS" solution where data, information and knowledge can be shared and flow freely throughout the enterprise and potentially to the general public.

INTRODUCTION

The three-year Municipal Infrastructure Investment Planning (MIIP) project, which started in June 2002, is investigating investment planning and strategic asset management of municipal infrastructure (www.nrc.ca/irc/uir/miip). The project proposes using geographic information systems (GIS) as the framework for decision support tools for municipal infrastructure managers, and more specifically, as a tool to assist them to prioritize infrastructure maintenance and capital renewal. This paper presents a global "state-of-practice", with emphasis on North America, of GIS for managing municipal infrastructure. The next four sections focus on:

- background information on GIS;
- geospatial technologies impinging on GIS; complementing GIS, or supporting GIS;
- support network for GIS to demonstrate the existence of a useful and active community of users, researchers and vendors, and
- review of GIS literature related to managing municipal infrastructure.

More importantly, this review identifies opportunities for research and development and demonstrates advantages as well as shortcomings of using the technology. The integration of GIS (i.e. interoperability) with other applications in an organization (i.e. financial management systems, enterprise databases, etc.) is outside of the scope of this paper.

BACKGROUND INFORMATION

A geographic information system (sometimes called geographical information systems) or GIS helps store, manage, analyze, manipulate and display data (i.e. sewer centreline location) that are linked

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spatially. In essence, GIS relates database records and their associated attribute data (i.e. water main type, diameter and age) to a physical location, thereby creating a "smart map". Visualization of discrete parts of these data on a GIS map is possible by layering the data into different "themes" (roads, buildings, forests, etc.). GIS applications can then display the intersection of various "themes", as well as the spatial relationships between various features (i.e. pipe condition and soil type). Typically, GIS applications in use today in Canadian municipalities assist administrative functions such as storing cadastral (i.e. survey) information or obtaining area demographic data. However, many municipalities are recognizing the benefits of spatially related data to manage their municipal infrastructure assets. This is later demonstrated with examples from a number of municipalities.

GEOSPATIAL TECHNOLOGIES

The following technologies warrant a brief description and discussion because they impinge on the selection of the most appropriate GIS implementation.

Global Positioning System (GPS)

GPS is a satellite-based positioning system operated by the US Department of Defense (Chivers 2003). The location of the GPS unit is determined by performing triangulation calculations on the location of reference satellites at the time of the reading, and the GPS unit while considering the time lag for the signal to reach the unit. The GPS unit must have an unobstructed view of the sky, a clear line of site to the satellites, and limited cloud cover. Multipath interference, caused by signals bouncing off neighbouring objects, alters signal travel time and reduces the accuracy of calculations (Chivers 2003).

Prior to 2000, GPS accuracy was limited to ± 100 metres because of random timings errors introduced by the US military to limit GPS misuse by their adversaries (Chivers 2003). Today, relatively inexpensive hand-held GPS units ($200US in 2003) are accurate to ± 10 metres depending on the number of reference satellites used (minimum four) and their location overhead.

Unfortunately, these orders of accuracy are of little use to the majority of municipal infrastructure applications. Differential GPS or DGPS relies on at least four satellites and a real time connection to a known local reference point; this dramatically increases accuracy to ± 1 metre (Oliver 1996). Depending on the type of reference points used, the amount of post processing, the duration of observation and the location of satellites, DGPS accuracy can be ±2 mm horizontally and triple that vertically (Oliver 1996).

Personal Digital Assistant (PDA)

The popularity of PDAs or Pocket PCs, as they are sometimes called, as business/personal notepads and aide-memoires has pushed this tool into specialized data collection. These handheld units greatly reduce the amount of paper needed in the field and eliminate potential transcription errors from paper to the corporate database. The PDAs can directly interface to GPS (to establish location); can download GIS maps (to georeference the user's location) and can collect distance and azimuth data from LASER range finders (to sight and geolocate neighbouring assets). PDAs can have upwards of 128 megabytes of RAM, a colour screen (320 by 320 pixels with 65,000 colours), and a 500 MHz processor.

Mobile computing

The term "mobile computing" is used in this paper to distinguish PDAs, Pocket PCs and similar devices from field rugged, full-blown computers. Pen-based computers and wearable computers with heads-up displays and voice recognition software provide faster processing speed, larger memory size and higher resolution graphics display than PDAs (Hartle 2000). An example of an application is the use of wearable computers to collect data for the Pennsylvania Department of Transport's Bridge Management System (Hartle 2000). Mobile computers are more robust that PDAs; can use the same Windows software and databases as the host database, and eliminate the need for the Windows CE or Palm OS operating system or "dumbed down" versions for data entry. The disadvantages of pen-based computers or wearable computers are the high costs (roughly $5000 US per unit in 2003).

Automated Vehicle Location (AVL)

AVLs are specialized data collectors/transmitters/receivers mounted on moveable assets such as emergency vehicles, snowplows, dump trucks, and the like. AVL can contain integral GPS and/or multiplexors that can step through multiple sensors on the vehicle and collect data and store or transmit these data to the vehicle operator or a central location. In most instances these units contain cell phone or satellite phone capabilities.

The types of sensors that can be used include simple ones, such as toggles for the cab door (open/closed) or plow blade position (up/down) to more sophisticated sensors that capture the vehicle speed, the snow pressure on the plow blade, or the rate of salt dispersion. Data received from the AVL (and other sources) can be analysed centrally to generate updated instructions to transmit to the vehicle or operator. For example, road temperature data and meteorological forecasts can be used to instruct the salt spreader to reduce the flow rate on a specific stretch of highway.

Road Weather Information Systems (RWIS)

RWIS is the term used to describe an integrated system of weather sensors to record road surface and environmental conditions at specific locations in a road network. RWIS can provide invaluable information to GIS systems and associated municipal databases (www.buckeyetraffic.org, www.nevadadot.com/traveler/rwis). For example, data that are currently collected include wind speed and direction, humidity, air temperature, road surface temperature, sub surface temperature, visibility, solar radiation, road surface status (dry, wet, icy) and type and amount of precipitation (C-SHRP 2000).

Remote Sensing

Remote sensing is described as imaging without touching, and within the scope of this paper refers to the use of aircraft or satellites to collect geographic information. "A satellite image is often the most practical way to acquire usable geographic information" (Huff and Johnson 2003). Although this type of imagery will not help the identification of buried utilities, it is a good way to identify roads and buildings and can assist in geolocating manholes, hydrants and catch basins by providing reasonably accurate spatial data. Commercial services supply high resolution, ortho-rectified images with a pixel resolution of 2.5 metres ($5000US in 2003) that are suitable for superimposition on, and validation of, existing GIS maps (www.spot.com).

Summary of Geospatial Technologies

Geographic data collection and validation is expensive (this is described later in the paper) and the related technologies described above greatly assist these operations. For example, inexpensive PDAs ($300US per unit in 2003) can be programmed so that trained operators can enter asset data (signs, manholes, catch basins, trees, etc.) and attribute data (types, size, age, condition, remaining service life, etc.) and can download and synchronize these data to the enterprise's main databases (Stasik 2003). PDAs, pocket PCs, pen-based computers or wearable computers can communicate between GPS and the central GIS databases and transmit spatial coordinates alongside conventional attribute data. Remote sensing can be used to develop preliminary asset maps and to validate existing engineering maps.

Although AVL technology appears to be peripherally related to GIS, the data collected by these vehicles can augment the "Enterprise GIS" by identifying roads that have been swept or plowed; by recording the surface temperature of a road at a given time, or by calculating its pavement condition index. RWIS can supplement GIS data by recording the road subgrade temperatures and environmental conditions that can be used for service life calculations.

ASSOCIATIONS AND NETWORKS

GIS associations and networks exist to meet the needs of international, national or regional GIS communities. This list of associations is not intended to be exhaustive and it might vary country to country and continent to continent.

The user communities of the two major vendors in the engineering field represent tens of thousands of installations, and their conferences, meeting, and networks provide for the rapid exchange of best practices and research experience. In addition, there are dozens of regional "GIS Users Groups" in the USA and Canada that address the needs of the users in specific cities, provinces, states, or national regions. The location, objectives, bylaws and activities of these can be found on the Internet.

CIB W106 deals with "Geographical Information Systems" and was formed in 2000 to address the needs of researchers in building and construction (W106 2000). The areas of interest to the group include: (Task Group 1) GIS standards, (TG2) analysis and modelling of flow and distribution of materials, (TG3) spatial dynamic modeling of the environment, and (TG4) education and information sources. This CIB working commission activity is championed by the Norwegian Building Institute and the Commonwealth Scientific and Industrial Research Organization (Australia). A number of national states-of-the-art reports related to GIS have already been published including contributions from Norway (cadastral data), France (waste management), Italy (historical assets), Canada (GIS survey) and Japan (earthquake data) to name a few (CIB W106 2003).

The Geospatial Information and Technology Association (GITA) provides education and training to meet the needs of those individuals interested in geospatial information and technology (www.gita.org). GITA has published a number of books and videos related to professional applications (www.gita.org/ book_store) including the results of recent surveys based on GIS usage in domains related to municipal infrastructure: electric, gas, pipeline, telecom, water, and public sector (www.gita.org/geo_report).

The Urban and Regional Information Systems Association (URISA) is a non-profit association of GIS professionals that promotes the effective and ethical use of geospatial information and information technologies. URISA also hosts conferences (www.urisa.org/annual.htm) and publishes monograms (www.urisa.org/store.htm), and supports a peer-reviewed journal (www.urisa.org/journal.htm).

GIS LITERATURE RELATED TO MANAGING MUNICIPAL INFRASTRUCTURE

One of the first references to GIS in civil engineering is from the early 1950's relating to developing quantitative methods in transportation studies (Miles 1999). GIS has also been a topic of civil engineering research for approximately 50 years (Brodie 1984) through specialty civil engineering conferences and papers, many are discussed in this paper (Lior et al. 1991; Wei et al. 1997; Zhao and Elbadrawi 1997; IWA 1999, DMinUCE 1998, 2000).

This section gives an overview of GIS technical literature related to civil engineering or municipal infrastructure. The section investigates five main categories: surveys on GIS usage, data conversion issues, domain-specific applications, advanced implementations, and systems integration.

Surveys on GIS Usage

A comprehensive survey on GIS usage in civil engineering in Great Britain identifies that 80% of local municipalities have purchased GIS and an additional 18% intend on purchasing (McMahon 1997). It also mentions that 83% of public sector consultants (36% of private sector consultants) in the field have already purchased GIS. The article also identifies that one software product predominated the field at that time. The survey finds that GIS is used on projects related to roads, transportation, environmental, drainage, pipelines and water supply. GIS's actual use in these projects relates to activities such as decision support, spatial analysis, information query, or data display.

Better Roads (2000) published a recent survey on GIS usage by US counties (149 participants). The survey identifies that 23% of those polled use GIS, whereas the remaining see the advantages and would implement GIS if funding were available. Two software applications from one vendor have a 57% market share whereas a half dozen other vendors make up the remaining percentage. The majority (82%) uses the Windows O/S (www.microsoft.com). A total of 35% of respondents indicate that they have seen costs savings, but one manager comments "We strive more for accuracy of information and better decision making over cost savings". The article goes on to quote another GIS manager: "… be prepared to continually fund the effort and embrace the technology. Be prepared to let GIS change the way you think and conduct business".

A recent (and annual) survey conducted by GITA (2002) also confirms that one software vendor is predominant in related engineering sectors: more specifically, 62% of the 55 water/waster/storm sector enterprises use software from one firm. The report also confirms that Windows (81%) is the prominent operating system in this sector and most other engineering sectors (electric, gas, pipeline and telecon). The survey also identifies the water/waste/storm sector as the fastest growing sector in the survey for the second year.

The current eight members of the MIIP consortium recently completed a 20 question survey to determine the extent of their GIS usage. The results of this survey indicate that:

- the majority use software from one specific firm (75%);
- half *also* use *other* software from *other* vendors;
- Windows O/S is predominant (100%);
- few of the respondents have data standards (38%);
- all respondents have completed at least 60% of their GIS data collection and conversion (for both spatial and attribute data);
- all respondents have spent over $200,000 for GIS implementation, with three municipalities spending $2 million;

- all respondents view GIS as a public works tool and many see that GIS is *also* an administrative and data visualization tool;
- one half have integrated their asset management tools to GIS, and
- one half have data sharing agreements with their regional partners.

In order to determine how the municipalities in the consortium currently use GIS and how they envisage using GIS, they selected responses from a list of 20 activities. The majority reported they are currently using GIS to support activities in both categories, such as data storage, mapping, data exchange, decision support, engineering analysis, and planning. Activities that are also envisioned as desirable include work management, client information, document management, and executive information. Few respondents see the need for using GIS for maintenance monitoring, trouble calls, records management, or failure model analysis. Although the results represent a small sample group, the consortium members are a cross-section of large Canadian municipalities (+100,000 population).

Data Conversion Issues

Data conversion and data collection have been identified as major obstacles to the successful implementation of GIS. Scanning drawings has been defined as tedious and time-consuming; however, newer technologies such as drawing vectorization are improving the situation (Udo-Inyang 1997).

Sometimes it is the volume of existing data to be converted that is intimidating. A large European water company in Belgium maintains over 300 A0 maps at various scales and 94,000 A4 maps on paper and Mylar. These maps were centrally located at company headquarters and were difficult to access. The maps were scanned and stored centrally and georeferenced into an overall framework. As a result, one dozen staff members can readily access the data (Reynaert and Horemans 2002)

One problem encountered by a US water company is data alignment. This company serves 125,00 people and manages 1100 kilometers of pipe, 22 pumping stations, and 24 storage tanks. When the digital tax parcel maps were overlaid with the newly scanned infrastructure drawings they did not align (DeGironimo and Schoenberg 2002). Additionally, unanticipated work was required to collect the correct data and to georeference these data to the existing GIS maps.

Retraining and re-education of staff is also an issue: in one case city staff were asked to abandon an existing computer-aided design (CAD) tool and move to a GIS environment. Although staff had initially resisted the change, they overwhelmingly accepted GIS as their tool, owing to the integration opportunities provided (Lopez 2002).

The literature provides some insight as to the cost of data collection and conversion. Data collection for a small town of 20,000 people and 11 square kilometers, took roughly 600 hours to digitize paper maps, to do engineering take-offs, and to provide historical age and material identification for water, sewer, and drainage services (Crafts 2002).

A major British water company manages 2 million water distribution features on more than 14,500 maps. The land base of 20,000 square kilometers contains one million water mains, 3.2 million property records, 50,000 kilometers of water mains and 50,000 kilometers of sewers. A multi-year, multi-million dollar project was required to digitize the existing records. The GIS system now functions as a technology platform for the enterprise, completely replacing the largely paper-based systems (Coolidge 2002).

Even after scanning maps and entering attribute data, some enterprises find they cannot do large-scale analysis of infrastructure systems (Fenner et al. 2000). Typically, the only data available for sewer installations, for example, include the pipe material, sewer type, pipe size and depth, and event history (breaks, leaks, etc.). However, Fenner et al. found that few enterprises systematically save pipe age, soil type, pipe loading or cost of pipe repairs. These researchers also state that few enterprises link their problem events properly to the asset location: more often than not, linking the event to a property lot number and not the sewer lateral.

Domain-Specific Applications

The number of papers published in the research literature about GIS assisting in managing municipal infrastructure is limited. Some relate to stormwater systems (Lior et al. 1991), sewer systems (Przybla and Kiesler 1991; Halfawy et al. 2000), cost estimating and risk assessment (Ashur et al. 1998), and water and sewer systems (Moutal and Bowen 1991). Other examples of GIS applications in civil engineering relate to transportation noise, wetlands analysis, storm water discharge, soil erosion, residential and business dislocation, and highway corridor analysis (Amekudzi and Baffour 2002).

Recent work at the City of Saskatoon outlines opportunities for GIS to support economic decision-making for sewer main rehabilitation projects (Clancy et al. 2002). The project selection process considers the maintenance and cleaning records alongside sewer characteristics. The process uses these characteristics along with the GIS spatial data to determine priorities for the closed circuit TV (CCTV) scanning. Clancy et al. state that GIS helps to determine the sewer CCTV priorities that, in turn, can improve on the economics of rehabilitation decisions. Other work by the same team of authors positions GIS as a tool to assist the holistic management of the municipal right-of-way (Higgins et al. 2002). In this research, GIS is proposed as a framework to identify the spatial relationships between the assets in the right-of-way and to assist in producing targeted work plans.

Recent research investigates the use of GIS to assist the study of pipe deterioration (Doyle and Grabinsky 2003). These researchers found that many cities are now using their GIS systems to monitor water main breaks and to identify areas at risk. Doyle and Grabinsky also found that the existing municipal GIS data about soil type is not sufficiently detailed to identify high-risk areas accurately. However, they do indicate, "GIS is a powerful tool for identifying the areas of the city where future investigations should be focused". An added benefit to georeferencing water main breaks in GIS is the elimination of duplication of paper-based records, pin charts, etc.

Advanced Implementations

In this paper, an advanced implementation implies that other technologies such as expert systems, artificial intelligence, or 3D visualization are used in conjunction with GIS. There are limited research examples for managing municipal infrastructure.

Not all reports present favourable results from integrating GIS to other applications. Wei and Gurdev (1997) identify the need for large relational databases and visualization techniques to do rational, effective, and efficient bridge management. However, Feeney (1997) indicates that 2/3D spatial information in conjunction with a standard bridge inspection significantly augments information display and exchange by combining photographs, CAD and video with location-specific data.

GIS has been used to improve the management of the architectural design, engineering and construction building project process (Sun and Hasell 2002): a similar process that could apply to the construction of water/sewage treatment facilities or utility networks. However, problems still exist as to how GIS saves and displays 3D data. GIS "supplies a framework in which to model spatially […] engineering phenomena" (Miles 1999); however, it is also poor at representing alternatives, displaying hypothetical states, representing uncertainty of boundaries, or representing interacting objects. In fact, GIS abstracts the real world to only a 2D environment and 3D has not found its way to mainstream GIS applications or research (Miles 1999). Similarly, attempts have been made to use GIS to model buildings, but experience has shown that the 3D capabilities are not currently mature enough to model buildings or other types of three-dimensional facilities from GIS data (Cote 2002).

Fenner et al. (2000) describes a GIS-based maintenance prioritization model to correlate problem events to specific squares on grid system superimposed on a municipal region. The author states that the lack of digital data (i.e. pipe age, soil type, pipe loadings, repair costs) hampers such implementations and restricts their utility.

The combination of GIS and expert systems has been used in a case study to plan snow removal and bridge inspection (Salim et al. 2002). These opportunities indicate that spatial data in combination with well-designed expert systems can increase staff efficiencies and improve productivity at both the design and operations levels.

Other recent examples of GIS implementations in the energy sector demonstrate that well-implemented "Enterprise GIS" increases business efficiency, reduce administrative overhead, and help the corporate bottom line (Harder 2002). Examples include:

(1) a GIS-based "expert system" to locate suspect faulty transformers after lightning strikes, based on spatial data of customers phoning about outages;
(2) a GIS system to manage leases on telephone poles (cable, pager, cell, etc.) and notify lessors of problems, billings, etc., and
(3) an application to spatially manage rights-of-way for transcontinental gas lines.

Systems Integration

A study of GIS integration to computerized maintenance management systems (CMMS) identifies many intangible business benefits such as: providing maps of the utility with the work orders; tracing water mains in the office prior to field work; reducing travel time of work crews, and scheduling multiple repairs in one area (McKibben and Davis 2002).

"Combining GIS functionalities with a network solving package, a complete powerful tool is created for giving information on the behavior of the system under each water demand or expansion scenario" (Tsakiris 1993). This type of implementation illustrates GIS potential when integrated with other applications. Other examples of integrated GIS approaches in municipal asset management include:

(1) managing irrigation usage in water zones under drought conditions (Cronin 2003);
(2) predicting ice buildup on roads for winter maintenance (Chapman and Thornes 2003);
(3) benchmarking "neighbourhood vitality" using key performance indicators such as road condition (Langely 2003);
(4) modeling water main shutdown strategies prior to terminating services (Coate 2003), and
(5) coordinating street repair projects (Perry 2003).

Implementations of "Enterprise GIS" enable large enterprises to move from "pockets of GIS" to centralized GIS and then to benefit from a common framework (Durham Region 2003). Although not originally directed at public works or utilities, a coordinated enterprise effort can provide GIS services throughout and can provide users with live access to data; in this case over 1,500 users have access to 60 thematic layers of data on the web-based service. Durham is planning to extend this GIS service to public works applications and to the public.

Summary of GIS Literature

The body of literature from trade magazines and scientific journals indicates that there is limited GIS research taking place at universities, centres of excellence or government labs in North America. The review of research papers also shows that GIS is currently being used as a visualization tool and not as an integral component of the engineering solution. The papers discussed in this section however do illustrate the potential of GIS by providing specific implementation examples. The papers also indicate where the technology is inadequate:

(1) a robust 3D capability is required that meets engineering requirements (Miles 1999);
(2) a time dimension is necessary to save versions of data during a project's conceptual phases, along the time line of a construction project, or during the service life of an asset. GIS does not address temporal variations (Fang and Elbadrawi 1997), and
(3) object orientation modeling is required to represent the complex hierarchical structures and attribute inheritance that is typical of municipal infrastructure assets (Miles 1999).

DISCUSSION

GIS is not a recent innovation, it has a long history of usage in civil engineering applications, but there has been relatively little research. Primarily, the technical literature focuses on the practitioner and describes site-specific implementations of GIS in municipalities. The review of the GIS surveys in this paper indicates that a large percentage of municipalities are using GIS. This last statement is confirmed by a recent survey of 35 Canadian and USA municipalities (Doyle and Grabinsky 2003).

A GIS shortcoming, identified by Miles (1999), is that there is no common forum in civil engineering to discuss issues, disseminate ideas or review criticisms about GIS and its applications. The literature on GIS and municipal infrastructure identified in this paper is scattered throughout a wide selection of journals, conferences, and association literature. As researchers recognize the utility of GIS for managing municipal infrastructure, more papers and discussions will appear in the scientific press.

Data conversion, collection and validation are expensive ventures. Perhaps the efficient usage of the geospatial technologies described will help reduce the costs. The equipment required to collect spatial data is rapidly reducing in price and a number of agencies are now using low-priced labour such as students, untrained labour and even the general public to collect data about asset location, asset condition, and asset defects. For example, providing GIS input at a "trouble call" centre can help: record time of call, name of complainant, and type of problem; spatially locate the problem (a pot hole or blocked drain), eliminate multiple copies of the same problem from different sources; spatially coordinate multiple repairs in the area, and notify the complainant when the complaint is resolved.

As mentioned earlier, the number of papers about GIS and civil engineering (in general) is surprisingly small, as compared to the volumes of work in research in CAD or IT in construction. However, the examples cited in this paper illustrate the many capabilities as well as the shortcomings of GIS for managing municipal infrastructure. Miles (1999) summarized some of the latter: no single package is sufficient; often in-house solutions are required; many existing tools are inefficient and inflexible, and "engineering models are concerned with state, process and relationships, whereas position-based GIS simply considers location". Three specific areas are significantly devoid of solid research from the municipal infrastructure community: (1) 3D capability that meets municipal engineering requirements; (2) a time dimension to save versions of data in GIS, and (3) object orientation representation of municipal infrastructure assets (complete with object classes, object hierarchies, and object inheritance).

CONCLUSIONS AND RECOMMENDATIONS

The paper provides an overview of the use of GIS to manage municipal infrastructure. It is hoped that the knowledge, information and data provided in this paper will assist others to implement and maintain a GIS environment to help manage municipal infrastructure.

AASHTO and FHWA have identified GIS and GPS as emerging technologies that "hold promise for asset management" (AASHTO/FHWA 1997). Many large Canadian municipalities are currently using GIS in closely related areas and are attempting to integrate this tool into enterprise solutions to manage municipal infrastructure. "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 (Doyle and Grabinsky 2003).

Because of the high cost of data conversion, collection and validation for GIS, it is recommended that the different types of geospatial technologies be investigated prior to the purchase of a GIS system. A municipality's decision to implement any of the aforementioned geospatial technologies can influence the choice of GIS tools, the GIS implementation strategy, or long-term usefulness of GIS in any enterprise. The obverse also can be true. Interoperability with other enterprise applications is essential, as it will increase the value of the GIS implementation.

It is advised that any group (municipality) venturing into the GIS field become familiar with some of the associations identified, even if they are vendor-specific (provided the municipality plans to use that product). It is recommended that a group such as CIB W106 be a mechanism to encourage the discussion of research results in this field. Researchers should familiarize themselves with this organization and participate in their meetings and workshops, as there are few research exchange networks in the domain.

Geographic information systems can support decision-making in municipal infrastructure; however, GIS cannot drive the research to make this possible. The components that are lacking in current GIS applications and implementations, and cannot be provided by the geographic or mapping community, are the engineering definitions and descriptions of "features" on a GIS map. That is, the features on GIS maps are not just roads, stormwater ditches or bridges that are spatially located on a map, but these are physical infrastructure assets consisting of hierarchical networks, object class structures, data attributes, 3D components, time-deterioration functions, etc. It is the responsibility of the civil infrastructure community to research these notions, to identify potential solutions, and to develop and supply the requisite structures to augment the geographic component of GIS.

ACKNOWLEGEMENT

The author would like to thank the MIIP consortium for support to this research. Specifically, I would like to thank the Cities of Calgary, Edmonton, Hamilton, Ottawa, and Prince George, the Regional Municipalities of Durham, Halton and Niagara, the Department of National Defence, and the National Research Council Canada.

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